



Division - Soil Processes and Properties | Commission - Soil Biology

Soil macrofauna, mesofauna and microfauna and their relationship with soil quality in agricultural areas in northern Colombia: ecological implications

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ABSTRACT: Soil fauna is an essential component of the soil ecosystem for maintaining nutrient cycling and biological soil fertility. This study assessed the soil biodiversity (macrofauna, mesofauna, and microfauna) to define strategies for the sustainable management of tropical agricultural soils. The study was carried out in 200 agricultural production units in the Department of Sucre, in northern Colombia. Physicochemical properties (organic matter, nitrogen, phosphorus, and pH) were determined for each soil sample. The Berlesse-Tullgren method was used to determine the composition of macrofauna and mesofauna, while the sown surface plate counting method was applied for microfauna. Community biodiversity was quantified with diversity indices, and Pearson correlation was carried out to determine the relationships between soil fauna and soil quality indicators. For the macrofauna, 1330 individuals were found, distributed in 22 orders and 65 families; the families Tenebrionidae, Formicidae, Staphylinidae, Scarabaeidae and Julidae presented the highest abundance and distribution. Mesofauna presented 1,171 individuals, distributed in the classes Arachnida with seven families and Collembola with four families; the Schelorbitidae, Isotomidae and Galumnidae families presented the highest abundance and distribution. The indices of richness, Shannon-Wiener diversity and Simpson dominance indicated that biodiversity was higher for macrofauna. Pearson's correlation indicated significant correlations between soil mesofauna and soil organic matter ($R^2 = 0.87$; $p \leq 0.05$) and phosphorous ($R^2 = 0.70$; $p \leq 0.05$). The relationships between fauna and soil chemical properties indicate that soil biological diversity is sensitive to changes in the soil environment. This study revealed the importance of investigating the three components of soil fauna (macrofauna, mesofauna, and microfauna), since all three contribute to soil enrichment to grow nourished crops that allow plants to survive under climate change. Finally, this study may serve as a baseline to define strategies for sustainable management of tropical agricultural soils.

Keywords: soil quality, agricultural units, sustainable systems, land-use, conservation.

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INTRODUCTION

Soil is the most important natural resource to support agricultural production systems (De Alba et al., 2003; Martínez-Mera et al., 2019). Soil results from transformations by various physical, chemical, and biological processes (Lehman et al., 2015). Anthropogenic activities, such as mining, land-use change due to agricultural intensification, and the use of agrochemicals in conventional agriculture have altered soil physicochemical properties (Kiani et al., 2017). These changes can modify soil microorganisms' distribution, diversity, and abundance (Gupta and Roper, 2010; Martínez-Mera et al., 2017). Soil quality and ecosystem development status can be objectively and directly reflected by quantitative evaluations of soil physical, chemical, and biological indicators (Valani et al., 2020; Vasu et al., 2021).

Biological biodiversity has a critical role in supporting soil functionality because soil-dwelling organisms are responsible for biogeochemical transformations (Pino et al., 2019). Macro and microorganisms are the main providers of nutritional substrates for the soil, and they are in constant interaction. They affect nutrient cycles, organic matter regulation, greenhouse gas emission, and carbon capture, and they can change soil physical structure (Guzmán et al., 2012). The ecological functions of soil microorganisms include benefits such as the nutrients mineralization, organic matter decomposition, degradation of toxic compounds, and regulation of pathogenic agents (Castellanos et al., 2015). Their abundance in the soil is associated with moisture and nutrient availability, which enables biomass production and biodiversity conservation, among other ecosystem services (Safaei et al., 2019). The role of soil biodiversity in regulating multiple ecosystem functions is poorly understood, limiting our ability to predict how soil biodiversity loss might affect ecosystem sustainability (Delgado-Baquerizo et al., 2020).

Previous research results indicated that macrofauna activity is influenced by soil properties, climate, and organic residues (Castro-Huerta et al., 2015; Asfaw and Zewude, 2021). These organisms are affected by complex interactions between abiotic and biotic factors and their spatiotemporal variations (Tibbett et al., 2019; Wang et al., 2019). Soil arthropods have been studied as biological indicators in natural ecosystems and agricultural production areas (Baretta et al., 2011; Morrison et al., 2018; Duran-Bautista et al., 2020). Some studies have addressed the relationship between soil fauna diversity and soil physicochemical properties to determine the relationship between soil fertility and land-use (Murillo-Cuevas et al., 2019; Royero-Mesino, 2019; Zavaleta, 2019; Travez, 2020).

To establish sustainable agricultural systems, it is necessary to have a fundamental knowledge of the different components that comprise the system (Vasu et al., 2021). Few studies have been carried out on this subject in Colombia (e.g., Mantilla-Paredes et al., 2009), particularly in agricultural areas (Martínez-Mera et al., 2017), where these soil services have been affected by the loss of vegetation cover, generated by climate change and human activities. Qualitative and quantitative information concerning soil biodiversity is scarce, and there are no reports on this aspect. Thus, it is necessary to generate information on the health of agricultural soils, and analyze its ecological implications. Therefore, the present study assessed soil biodiversity (macro, meso, and microfauna) in agricultural areas in northern Colombia.

MATERIALS AND METHODS

Study area

The study was carried out in the Department of Sucre, which is part of the Colombian Caribbean region in northern Colombia. Its surface covers 10,917 km², which represents 0.95 % of the Colombian territory (PNUD, 2015). Five municipalities were prioritized

based on the subregions that exist in the Department, namely: San Onofre (Morrosquillo), Morroa (Montes de María), Corozal (Sabanas), San Marcos (San Jorge) and Majagual (Mojana) (Figure 1). Table 1 describes the relevant characteristics of the studied subregions and municipalities in the Department of Sucre. The soils in the sampled municipalities of Sucre are classified as Alfisols, Inseptisols, Mollisols, Ultisols, Vertisols, and Histosols (IUSS Working Group WRB, 2015; IGAC, 2016).

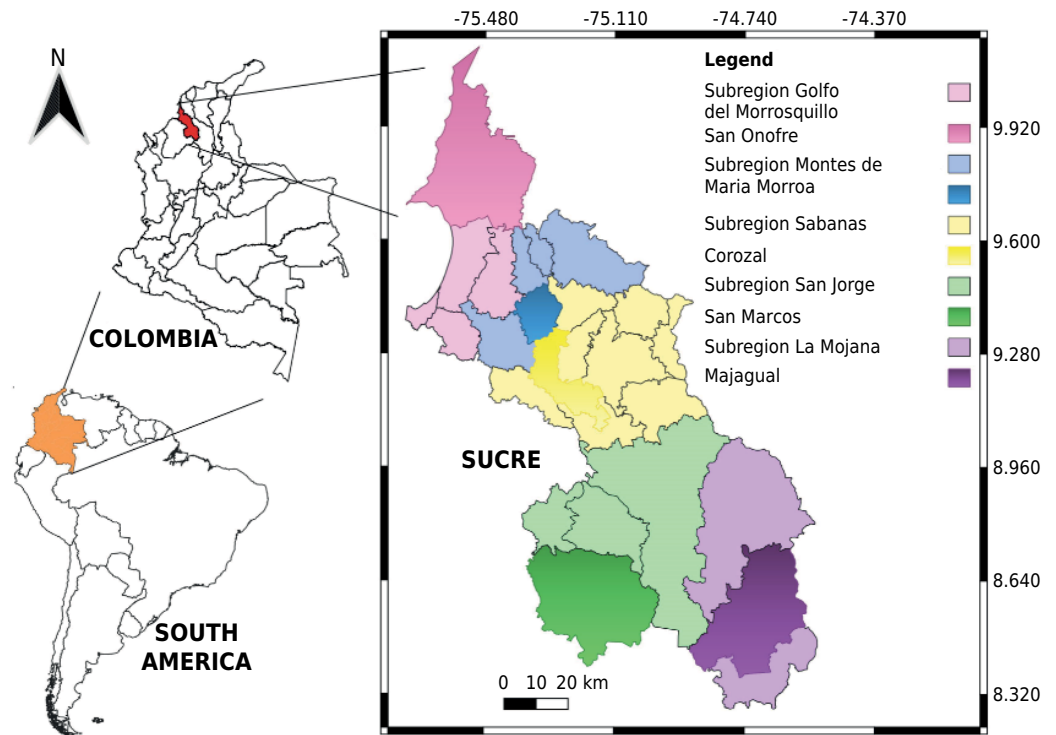


Figure 1. Geographic location of the prioritized municipalities in the five subregions.

Table 1. Characteristics of the five sub-regions of the Department of Sucre, in northern Colombia (Ingeominas, 2002)

Sub-region	Area km ²	Mun	Av T/Av A °C / m a.s.l.	AP mm	Site coordinates	Vegetation
Montes de María	6466	Morroa	26.8 °C 160 m a.s.l.	1000-1200	9° 20' 42" N 75° 18' 21" W	Tropical dry forest, mountain landscape
Sabana	2101	Corozal	27 °C 143 m a.s.l.	990-1275	9° 19' 3" N 75° 17' 29" W	Tropical dry forest, hills landscape, extensive grassland area
Golfo de Morrosquillo	1886	San Onofre	27.4 °C 17 m a.s.l.	900-1300	9° 43' 59" N 75° 31' 59" W	Tropical dry forest, anthropic grasslands, hills landscape, mangrove forest
San Jorge	2934	San Marcos	28 °C 25 m a.s.l.	1300-2300	8° 40' 1" N 75° 7' 59" W	Tropical humid forest, tropical dry forest, natural grassland
Mojana	2337	Majagual	28 °C 28 m a.s.l.	2320-3000	8° 32' 9" N 74° 39' 23" W	Tropical humid forest, wetland area

Mun: municipality; Av T: average temperature; Av A: average altitude; AP: annual precipitation.

Sucre is the Department of Colombia with the highest percentage of area under land-use conflicts. It is known that 75.5 % of its soils present inappropriate use due to overuse and underutilization. Agricultural production in this Department is affected because small producers do not use traditional technology, practice poor soil management, and make inappropriate use of agrochemicals (DNP, 2003). The livelihoods of the small farm families consist primarily of diversified agricultural systems, which are more at the subsistence than the commercial farming level (Abera et al., 2020; Phondani et al., 2020). The prevailing crops are mechanized and manual-cropping rice (*Oryza sativa* L., 1753), mechanized and traditional corn (*Zea mays* L., 1753), Ñame (*Dioscórrea villosa* L., 1753), sweet and industrial yucca (*Manihot esculenta* Crantz, 1766), plantain (*Musa* sp. L., 1753), watermelon (*Citrullus lanatus* [Thunb] Matsum and Nakai, 1920), among others (República de Colombia Departamento de Sucre, 2020).

Sample collection and laboratory analyses

We selected 200 AUs (agricultural units) throughout the Department of Sucre, distributed in 40 AUs for each prioritized municipality. The experiment was established in each AUs using a randomized complete block design. The samples, collected in triplicate to determine the precision of tests and sample handling, were stored in sterile polyethylene bags and kept at 4 °C for transport.

Macrofauna and mesofauna individuals were counted and classified up to the family level (Oliveira et al., 2021). To this end, using the Berlesse-Tullgren method (Oliveira et al., 2021), the sample was moistened during the first 72 h, and as the samples dried, the individuals began to concentrate in the lower part of the funnel and dropped into a collector located at the end of the funnel, which contained alcohol 70 % as fixing and conserving agent. The seeded surface plate count method was used (Wehr and Frank, 2004; AOAC, 2016) for microfauna (bacteria, actinomycetes, fungi, N-fixing bacteria, phosphate solubilizing bacteria and cellulolytic microorganisms),.

Physicochemical properties such as organic matter (OM), nitrogen (N), phosphorus (P), and pH were determined in the laboratory for each soil sample. Soil OM was determined by the Walkley - Black method; total nitrogen was measured by the Kjeldahl method; total P was determined by Bray II method; and pH was measured by the electrometric method (Icontec, 2018).

Data analysis

Community structure of macrofauna, mesofauna and microfauna was estimated using percentage stacked bar chart. The diversity of soil fauna communities was quantified using the Shannon-Wiener diversity index (H) (Shannon, 1948), Simpson dominance index (D) (Simpson, 1949), Pielou evenness index (J) (Pielou, 1969), taxonomic richness (S is the number of taxa in the sample) (Bobrowsky and Ball, 1989), and individual rarefaction is displayed on a graph (Bobrowsky and Ball, 1989). Diversity indexes were calculated with the software EstimateS, 9.1.0 (Colwell, 2019). Software R (R Development Core Team, 2020) was used to perform the Pearson correlation and principal component analysis (PCA) to determine the relationship between soil fauna and soil chemical properties.

RESULTS

Macrofauna, mesofauna and macrofauna community structure

A total of 1,330 macrofauna individuals were found, distributed in 7 classes, 22 orders and 65 families. The class Insecta was the most representative in terms of abundance and wealth. The families Tenebrionidae, Formicidae, Staphylinidae, Scarabaeidae and Julidae displayed the greatest abundance and distribution in the municipalities (Figure 2a). The families Anapidae, Ascalaphidae, Blattellidae, Buthidae, Cantharidae, Chrysomelidae,

Coreidae, Cydnidae, Dermestidae, Elateridae, Elipsocidae, Endomychidae, Erotylidae, Gnaphosidae, Gryllidae, Ixodidae, Largidae, Lepismatidae, Lygaeidae, Meloidae, Neobisiidae, Nitidulidae, Palpimanidae, Paradoxosomatidae, Pentatomidae, Porcellionidae, Ptilodactylidae, Reduviidae, Salticidae, Scolopendridae, Scolytidae, Scytodidae, Silphidae, Stratiomyidae, Teratembidae, Tetrablemmidae, Theraphosidae, Theridiidae, Thyreocoridae, Zalmoxidae and Zoderidae presented frequencies lower than 1 %.

A total of 1171 mesofauna individuals were found, distributed in the classes Arachnida with seven families and Collembola with four families. The families Scheloribatidae, Isotomidae and Galumnidae displayed the greatest abundance and distribution in the municipalities (Figure 2b). The Heterotrophic and Actinomycetes bacteria were the nitrogen-fixing organisms with the highest abundance (Figure 2c).

The taxonomic richness (*S*), Simpson dominance index (*D*), Shannon–Wiener diversity index (*H*), and Pielou evenness index (*J*) of the soil macrofauna were greater than for the soil mesofauna and microfauna (Table 2). Because the diversity results were similar between municipalities, in the subsequent analyses, the average was used. Individual-based rarefaction indicates the number of operational taxonomic units (OTU) expected in different sample sizes. Figure 3 shows that as the number of samples increases, the richness stabilizes.

Quality parameters of soil and correlation analysis

Nitrogen and P presented average values of 21.65 ± 10.65 and 40.35 ± 67.21 mg kg⁻¹, respectively. Soil pH presented a maximum value of 7.68 and a minimum of 4.19, with an average of 6.05 ± 0.80 . The OM presented an average value of 1.05 ± 0.51 % (Table 3).

Pearson correlation indicated statistically significant correlations between some of the variables analyzed ($p \leq 0.05$). There was a high positive correlation between soil

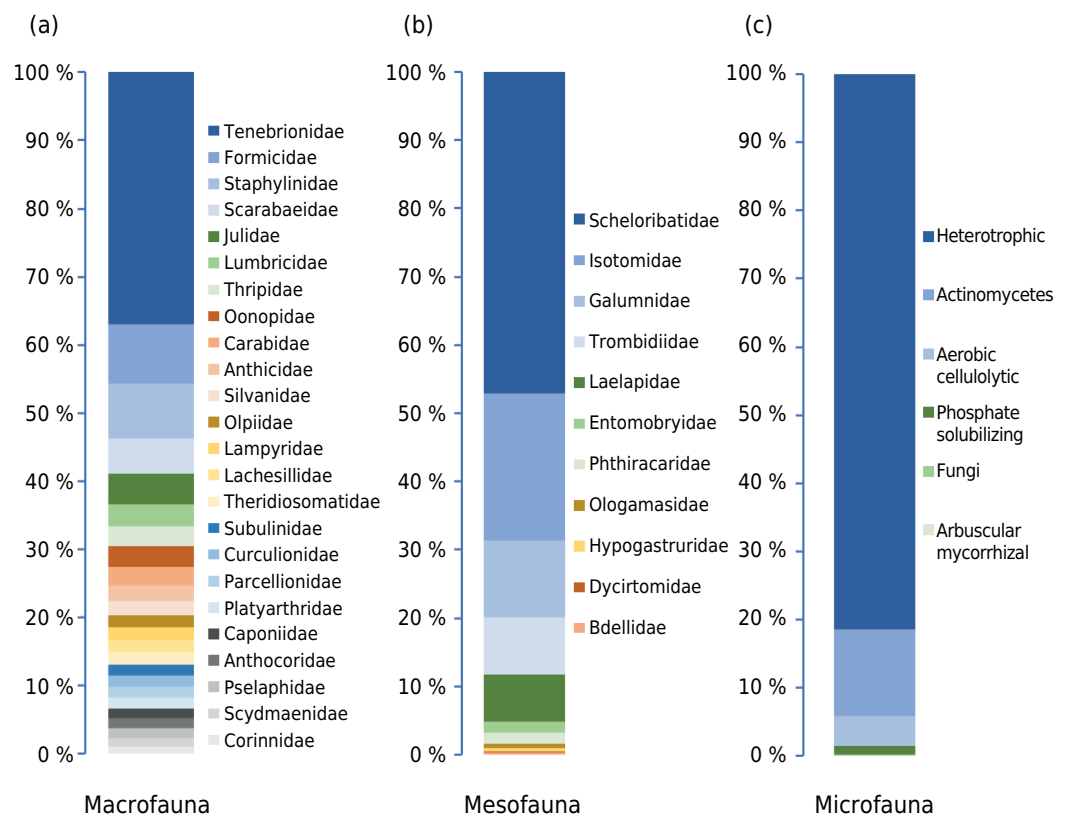


Figure 2. Macrofauna, mesofauna and macrofauna community structure. (a) Families macrofauna (families excluded with percentages less than 1 %); (b) Families mesofauna; and (c) Groups microfauna.

Table 2. Diversity indices of the soil macrofauna, mesofauna and microfauna

Index	Municipality					MEAN
	San Onofre	Morroa	Corozal	San Marcos	Majagual	
MACROFAUNA						
Taxa_S (OTU)	35	35	48	33	29	36
Individuals	185	216	475	231	223	266
Simpson_1-D	0.87	0.89	0.84	0.82	0.89	0.86
Shannon_H	2.71	2.84	2.67	2.48	2.62	2.66
Equitability_J	0.76	0.80	0.69	0.71	0.78	0.74
MESOFAUNA						
Taxa_S (OTU)	6	4	6	8	8	6
Individuals	38	65	464	312	292	234
Simpson_1-D	0.60	0.53	0.51	0.57	0.63	0.56
Shannon_H	1.20	0.83	1.09	1.28	1.39	1.15
Equitability_J	0.67	0.60	0.61	0.62	0.67	0.63
MICROFAUNA						
Taxa_S (OTU)	6	6	6	6	6	6
Individuals	5.E+07	4.E+07	1.E+07	2.E+07	2.E+07	3.E+07
Simpson_1-D	0.20	0.38	0.37	0.40	0.35	0.32
Shannon_H	0.40	0.73	0.71	0.72	0.64	0.63
Equitability_J	0.23	0.41	0.40	0.40	0.36	0.35

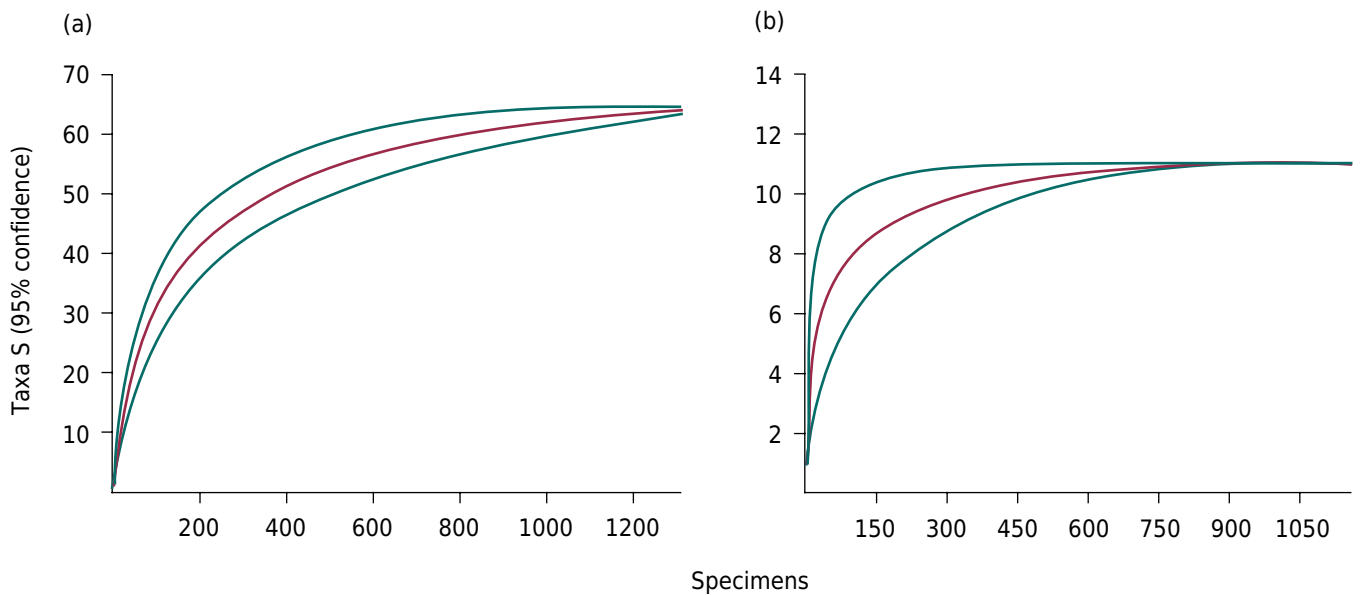

Figure 3. Individual-based rarefaction curves, with their respective confidence intervals, for (a) macrofauna and (b) mesofauna.

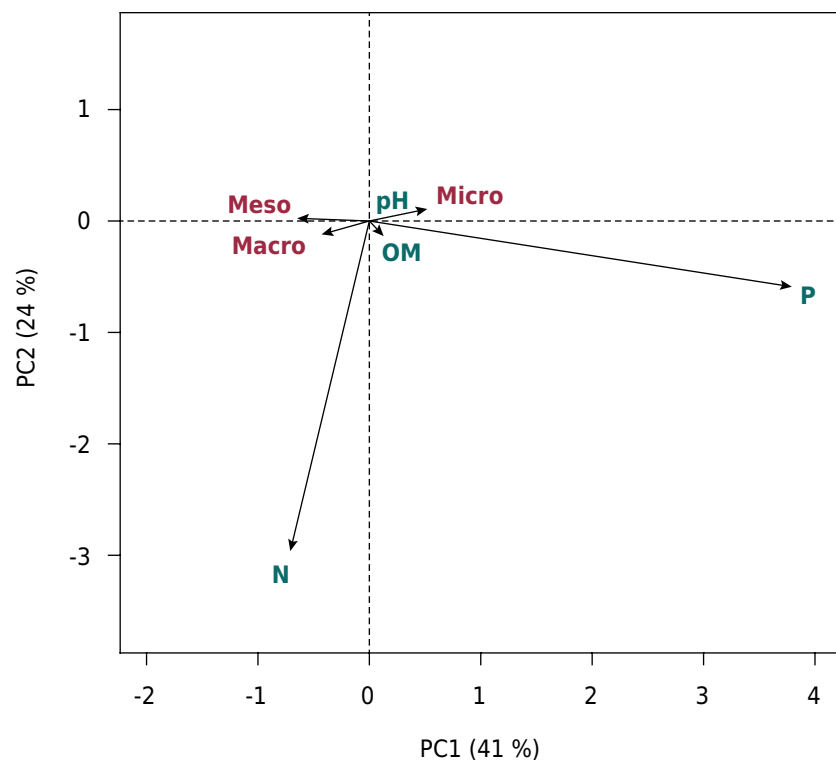
Table 3. Soils properties of the Department of Sucre, in northern Colombia

Soil property	MIN	MAX	Mean	SD
OM (%)	0.15	3.58	1.05	0.51
P (mg.kg ⁻¹)	2.60	401.49	40.35	67.21
N (mg.kg ⁻¹)	5.40	63.20	21.65	10.65
pH	4.19	7.68	6.05	0.80

Table 4. Pearson correlation matrix between soil fauna and quality parameters of agricultural soils of the Department of Sucre, in northern Colombia

Soil property	OM	P	N	pH	Macro	Meso	Micro
	p-value						
OM		0.93	0.31	0.04	0.97	0.00	0.17
P	0.01		0.20	0.12	0.96	0.02	0.69
N	0.08	-0.12		0.00	0.82	0.75	0.24
pH	0.15	-0.14	0.29		0.49	0.70	0.23
Macro	0.00	0.01	-0.03	0.09		0.32	0.29
Meso	0.87	0.70	0.11	0.13	-0.33		0.54
Micro	-0.65	-0.21	-0.57	-0.57	0.52	-0.32	

OM: organic matter; P: phosphorus; N: nitrogen; Macro: macrofauna; Meso: mesofauna; Micro: microfauna.


Figure 4. Principal component analysis (PCA) between soil biological diversity and soil chemical properties. Macro: macrofauna, Meso: mesofauna, Micro: microfauna.

mesofauna and OM ($R^2 = 0.87$; $p \leq 0.05$) and P ($R^2 = 0.70$; $p \leq 0.05$) (Table 4). The PCA used soil chemical properties as independent variables and soil fauna as a dependent variable. The first two principal components explained 65 % of the total variance of the data set. A relationship was found between pH and the microfauna abundance (Figure 4).

DISCUSSION

Our study revealed the importance of investigating the three components of soil fauna (macrofauna, mesofauna and microfauna), since all three contribute to soil enrichment to grow nourished crops that survive climate change conditions. In this research, 1330 individuals of macrofauna were found in the studied agricultural soils. The overall density of soil macrofauna tends to decrease to low levels on cultivated land (Rossi et al., 2005). The values found in our study coincide with those reported in the literature. Densities

ranging from 429 to 592 individuals of macrofauna in crops analyzed in Colombia were reported by Decaëns et al. (1994). A recent study carried out in the Andes (Colombia) reported 1317 individuals in farming systems (Galindo et al., 2022). The order Coleoptera was the most representative in terms of abundance and biological richness, whereas Tenebrionidae, Formicidae and Staphylinidae were the most abundant families.

Tenebrionidae family predominates throughout the five municipalities because they have similar environmental characteristics that enable their growth and development. They are considered bio-indicators of soil quality (Velasquez and Lavelle, 2019). These individuals have morphological, physiological, and etiological adaptations to live in these environments with temperatures ranging between 26 and 35 °C, or even higher (Duncan and Dickman, 2009). The Formicidae family also presented high abundance in the Department of Sucre. Individuals from this family are considered soil engineers and indicators of disturbance of the edaphic environment; they improve soil structure, thus allowing aeration, drainage, decomposition, and predation of insects (Cabrera, 2012; Machado-Cuellar et al., 2021).

Staphylinidae family also stands out in the five prioritized municipalities, with very similar values among them. These individuals are general predators that are very common in agricultural soils, and they feed on ants, aphids, caterpillars, and insect eggs, among others. They also limit the growth of certain populations of crops pests (Martins et al., 2013). Galindo et al. (2022) reported in their study carried out in the Colombian Andes that the most representative group was Formicidae (47.4 % of the individuals collected), while Coleoptera was the third most abundant group with 5 % of the total individuals collected.

Oonopidae was the most abundant family of the order Araneae. The presence of this family has been reported in other studies carried out in tropical forests and cultivated areas (Rosa et al., 2018; Pereira et al., 2021). Dupérré and Tapia (2017) also found that the Oonopidae family was the most abundant and concluded that this family is a very important component in Neotropical forests. Li et al. (2018) proved the hypothesis that spiders are more diverse in semi-natural habitats, because of the greater diversity of plants than in plantation lands with lower vegetation and subject to poor agricultural practices. This behavior may be related to the low number of individuals found in these municipalities. This family plays an important role in crops, acting as biological control of other predatory pests by feeding on them, and it has characteristics that are useful for detecting different environmental and anthropogenic changes (Simó et al., 2011; Ibarra-Núñez, 2014). The disturbances caused by inadequate agricultural practices, such as the use of insecticides, herbicides, fungicides, fertilizers, and pruning, among others, also reduce the population of these insects by altering the habitat, which puts constant pressure on spiders and reduces their population (Benamú et al., 2017). Dias et al. (2005) showed that oonopids constituted more than 20 % of the captured adult spiders and more than 9 % of the total species diversity, being the second group after Salticidae, both in abundance and diversity.

A total of 1171 individuals of mesofauna were found in this study, and the families Isotomidae and Scheloribatidae were the most representative. Fekkoun et al. (2021) found that the Scheloribatidae family was the most abundant, with 48 % of the total abundance. The family Isotomidae stands out in the Collembola class because of its frequency in the five municipalities. Like in this study, Gómez-Anaya et al. (2010) reported that the most dominant family was Isotomidae, with 29.3 % of the total abundance. Similarly, Villarreal-Rosas et al. (2014) reported that, among the Collembola, the most abundant family was Isotomidae. These organisms are recognized by their slim bodies covered with abundant fungi, and by their bodies covered with silk or scales (Daghighi et al., 2013; Palacios-Vargas, 2014). They adapt easily to different habitats, with different temperature and rainfall levels, such as forests and desertic shrubs (Villarreal-Rosas et al., 2011),

and live in soil, fallen leaves, tree bark, moss and under stones, among others (Montejo-Cruz et al., 2018). Scheloribatidae species are the most frequently collected oribatid mites (Knee, 2017).

Heterotrophic and Actinomycetes bacteria were the most abundant group of microfauna. Xia et al. (2022) found that the relative abundance of heterotrophic bacteria was significantly higher compared to other groups of microfauna. This group has a wide diversity of demands in carbonated substrates; the majority are saprophytes common in the soil and effective at transforming edaphic substrates into biomass (Terrado et al., 2017). These bacteria feed on organic compounds and, thanks to their reproductive capacity, they generate large populations in a short time, rapidly colonizing degradable substrates. They are also responsible for increasing or reducing the supply of nutrients. Unfortunately, poor agricultural practices by farmers, such as continuous mechanization, monoculture planting, irrigation systems, application of synthetic agrochemicals and fertilizers, soil compaction, and residue burning decrease the microbial flora, which can drastically reduce soil fertility (Terrado et al., 2017). Slaughter (2021) indicated that bacteria, including actinomycetes, are the most numerous rhizosphere inhabitants, although they represent only a smaller portion of the total biomass due to their small size.

The diversity index indicated that macrofauna was the most diverse. This result is consistent with those obtained in other studies in Colombia (Stanturf et al., 2014; Tulande et al., 2018). Gongalsky (2021) stated that the macrofauna accounts for most of the total soil animal biomass in some ecosystems, and substantially contributes to soil food-web functioning. Additionally, the macrofauna can be among the most diverse groups in the soil environment. According to Shannon (1948), the diversity value of the macrofauna is high ($H' > 3$) and, according to the rarefaction curve based on individuals of the macrofauna, it is estimated that the total richness is good compared to the expected total richness. Soil fauna diversity is related to increased available food resources of plant roots and litter inputs into soils (Heinze et al., 2010).

Soil physical and chemical properties determine the community structure of soil fauna (Nisa et al., 2021). Several studies have evaluated correlations between the physicochemical properties and the edaphic fauna (Martínez-Mera et al., 2017; Wang et al., 2019; Galindo et al., 2022). Soil mesofauna was significantly and positively correlated with organic matter (OM) and P. Soil fauna influence soil physical and chemical properties related to soil fertility (Tantachasatid et al., 2017). These organisms are the main ones responsible for fragmentation and incorporation of OM in the soil, to promote favorable conditions for activity of soil microorganism and distribution, and their activities lead to the formation of biogenic structures (galleries, chambers, fecal pellets and casts), thus influencing soil aggregation, water properties and OM assimilation (Lavelle et al., 1997).

Phosphorus is a limiting factor in the early stage of the litter decomposition process (Bargali et al., 2015). The dynamics of P during litter decomposition can be strongly affected by soil fauna, and such effects could be moderated by nutrient availability and environmental conditions (Peng et al., 2019). Wang et al. (2016) also found an association between soil fauna with organic matter and phosphorus, which suggests that soil diversity is associated with the availability of soil nutrients.

According to the PCA, soil pH was related to soil microfauna. Xia et al. (2022) obtained this same relationship from the results of a correlation analysis, finding that soil pH was the most important factor related to the soil bacterial community. Generally, the results indicate that soil pH is more important than nutrients in shaping bacterial communities in agricultural soils, including their ecological functions and biogeographic distribution (Wang et al., 2019). Soil properties determine invertebrates' functional characteristics and population dynamics. A previous study on the global topsoil microbiome also revealed that environmental factors, especially soil pH, had a greater impact on the soil bacterial community than geographic distance (Bahram et al., 2018). Low pH affects microfauna

community organization and other components of the soil food web (Matute et al., 2013). In some related studies, pH between 5 and 7 seems favorable for fauna soil (Warner, 2009).

CONCLUSIONS







Soil physicochemical properties influenced the community structure of the edaphic fauna in tropical agricultural soils, with the relationship varying according to the edaphic fauna group. Macrofauna was influenced by organic matter, mesofauna by P, and microfauna by pH. The diversity index indicated that macrofauna was the most diverse group, and this group presented variations in the analyzed municipalities. Finally, this research can serve as a baseline to define strategies for the sustainable management of tropical agricultural soils.




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


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