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Macrofauna and soil properties in agroforestry system and secondary forest

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ABSTRACT: Atlantic Forest devastation has resulted in the search and introduction of management capable of promoting and reestablishing the quality and sustainability of the ecosystem. Agroforestry systems (AS) are recognized for many benefits due to their management. This study compares an agroforestry system macrofauna and physical and chemical soil properties to those of a secondary forest area in the Atlantic Forest biome in southeast Brazil. Agroforestry system with 8 years of establishment and the regenerating subcaducifolious tropical forest fragment with 28 years were examined. Samplings were conducted in two periods of the year (rainy and dry seasons) to evaluate physical and chemical soil fertility-associated properties, as well as soil organic matter (SOM) fractions and biological aspects (macrofauna). Higher clay content, moisture levels, basic cations, and greater values of the sorption complex, diversity indices, and uniformity in macrofauna were observed in the agroforestry plots. Agroforestry systems increased the levels of the most labile fraction of soil organic matter (SOM) compared to the forest fragment. Higher abundance, diversity indices, and evenness of fauna were observed in the agroforestry plots during both seasons. In terms of multivariate analyses, a higher correlation was observed among fauna, carbon fractions, P, K^+, pH, clay, potential acidity, moisture, and temperature in the Agroforestry plots. In general, AS promoted a positive relationship between physical and chemical properties and the macrofauna community of soil invertebrates, in a similar way and sometimes superior to the forest, confirming the study hypothesis and demonstrating the efficiency of management in maintaining soil properties and, consequently, ecosystem services.

Keywords: soil health indicators, sustainable management system, fragile soil.

INTRODUCTION

In the southeastern region of Brazil, the Mata Atlântica biome is predominant; it is in this context that Rio de Janeiro State is inserted, and stands out with the increase in deforestation by 95 % between 2020 and 2021 compared to the previous period (2019-2020) (Fundação SOS Mata Atlântica, 2022). In view of this, the introduction of agricultural practices based on conservationist practices in this Bioma has been extremely relevant, both for minimizing impacts resulting from the removal of natural vegetation and for restoring soil properties related to the quality and sustainability. Among these managers, the agroforestry system (AS) stands out as an important management option capable of generating various benefits for the soil.

Agroforestry systems consist of a set of agricultural practices integrating advances in plant ecology, agroecology, and evolutionary biology. These systems aim to enhance agricultural sustainability to maintain or increase agricultural production (Antonini et al., 2020). Agroforestry systems exhibit considerable functional significance by facilitating ecological restoration by integrating exotic species and native vegetation. These systems can be delineated as structured units within a predetermined environment where forestry, agricultural, and animal species engage in mutual interactions with each other alongside diverse biotic and abiotic elements. Their role extends to serving as a viable and sustainable soil cover, effectively mitigating soil erosion while enhancing various ecosystem services, notably carbon sequestration (Vicente et al., 2023). Therefore, complex AS are most recommended for environmental restoration and conservation purposes, as they are biodiverse, or successional, resemble the original ecosystems of the local context, mainly in terms of processes and functions, and are managed according to the logic of natural succession (Miccolis et al., 2016).

Agroforestry systems help protect and nourish biodiversity, mitigate climate change, and increase the capacity to adapt to its effects, promoting the regulation of the hydrological cycle, control of erosion and siltation, and improvements in aggregation processes, and porosity, nutrient cycling, therefore increasing soil fertility, and contributing positively to physical, chemical and biological properties (Miccolis et al., 2016; Matos et al., 2020; Vicente et al., 2023).

The soil, recognized as a reservoir of biodiversity, sustains biological diversity, regulates water and solute fluxes, degrades, immobilizes, and detoxifies organic and inorganic compounds, and plays a crucial role in nutrient cycling (Stork, 2018). Despite its immense significance, soil biodiversity is threatened due to anthropogenic actions, such as land use intensification and deforestation, leading to extreme climatic events (Winding et al., 2020).

Organisms that make up the soil invertebrate fauna vary in size and diameter, which gives them different abilities in their feeding strategy and adaptation to the habitat (Aquino et al., 2006). It influences soil processes by physically altering the litter and soil environment while interacting with the microbial community (Winding et al., 2020). Soil fauna is categorized based on size into three primary invertebrate groups: microfauna, mesofauna, and macrofauna (Alves et al., 2020). Considering the relatively quick response compared to other soil properties (Alves et al., 2006), evaluating these organisms can be considered an indicator of soil health (Casaril et al., 2019).

Soil fauna has been considered an indicator in environmental recovery processes and can be associated with other soil aproperties, such as soil organic matter (SOM) compartments and the regulation of soil biology. Furthermore, soil fauna is one of the main determinants of agricultural soil health (Ortiz et al., 2023). The SOM is indispensable for individuals' survival, diversity, and activity (Lima et al., 2021a). Elevated levels of organic carbon result in increased activity of organisms involved in the decomposition and humification of soil organic matter, thereby increasing nutrient availability (Negassa and Sileshi, 2018). The influence of fauna can also be observed through bioturbation, the creation of burrows, and other structures in the soil, promoting soil structure improvement, increased infiltration, drainage, soil's ability to store water and its role in controlling surface discharge of precipitation, aiding in erosion control and flood prevention. It also impacts biogenic aggregates' formation and stability (Lima et al., 2021b).

Considering the benefits resulting from agroforestry management, as well as the assessment of these benefits through various soil properties, the present study hypothesized that AS can promote conditions equivalent to or even superior to those found in forest areas concerning soil attributes indicating its quality. In this sense, the objective of this study was to evaluate the invertebrate macrofauna, together with the physical and chemical soil properties in an agroforestry system compared to a secondary forest area within the Mata Atlântica biome in the southeastern region of Brazil.

MATERIALS AND METHODS

Site description and land uses

This study was conducted at the Federal Rural University of Rio de Janeiro, *Campus* of Seropédica, Rio de Janeiro, Brazil (22° 45′ 36″ S, 43° 42′ 00″ W). The site has moderate summers (Aw in the Köppen classification system) and dry winters (Dry) at an elevation of around 33 m. The mean annual temperature is 24.5 °C, and the mean annual rainfall is 1.213 mm, July and August are the driest months (Pereira et al., 2013). Soils at this site have a sandy texture and are predominantly Ultisols and Alfisols (Soil Survey Staff, 2014), which correspond to *Argissolo Amarelo* and *Planossolo Háplico*, respectively, according to the Brazilian Soil Classification System (SiBCS) (Santos et al., 2018), or Acrisols and Planosols in the FAO classification system (IUSS Working Group WRB, 2015). Atlantic Forest is classified as a Subdeciduous Tropical Forest because it largely dominates the native vegetation (Corrêa Neto et al., 2014).

Because it predominates over the original vegetation, it is called a tropical forest. We considered two current land uses in the studied area: (1) In the Atlantic Forest biome, a secondary forest (Forest) with a predominance of semi-deciduous tree species going through 28 years of regeneration, characterized by a closed canopy, promoting shading, with a substantial protective layer of litter that contributes to soil temperature and moisture retention; (2) Agroforestry system (Agroforestry) established for 8 years with the purpose of biodiversity regeneration and conservation; this system covers an area of approximately 2,000 m^2.

Agroforestry system was initially established with the intercropping of banana (*Musa* spp), coffee (*Coffea canephora*), and peach palm (*Bactris gasipaes*), which are economically significant crops. The interspersed strips feature densely planted gliricidia (*Gliricidia sepium*), flemingia (*Flemingia macrophylla*), vinhático (*Plathymenia reticulata*), aroeira (*Schinus terebinthifolius*), guapuruvu (*Schizolobium parahyba*), embaúba (*Cecropia pachystachya*), and urucum (*Bixa orellana*). These species serve as fertility renewers, climax species, and hold the potential for seeds, oils, and valuable timber. Subsequently, the following annual crops were introduced: pineapple (*Ananas comosus*), cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), peanut (*Arachis hypogaea*), yam (*Dioscorea*), arrowroot (*Maranta arundinacea*), and chaya (*Cnidoscolus aconitifolius*). These annual crops were implemented in the alleys between the main tree crops.

Sampling procedures

Samples were collected in each land use to assess soil biological, physical, and chemical properties during two periods of the year. The first sampling occurred at the end of the rainy season (summer), in April 2022, and the second at the end of the dry season (winter), in September 2022. Eight replications of each evaluated property in the samplings were conducted using a fully randomized methodology.

A transect was established for each land use type, and eight sampling plots were positioned approximately 15 m apart along the transect. The eight plots were viewed as duplicates within each land use. Five sub-samples (0.00-0.10 m soil layer) were shoveled into each sampling plot, with a distance of roughly 5 m between subsamples, to characterize the physical and chemical properties and analyze the soil organic matter (SOM). These subsamples were then combined to create one composite sample per sampling plot per season.

At each sampling point, the temperature was recorded using a digital thermometer. Soil moisture content was also determined through the gravimetric method, according to Teixeira et al. (2017). Samples were collected and then air-dried, crumbled, and sieved through a 2.00 mm mesh to produce the fine air-dried soil fraction (FASF), which was utilized in the studies that followed.

Particle size analysis was carried out using the pipette method to determine the amount of sand, silt, and clay fractions (Teixeira et al., 2017). The pH levels and the concentrations of Ca^{2+}, Mg^{2+}, Al^{3+}, K^+, Na^+, P, and H+Al were measured in relation to fertility analyses (Teixeira et al., 2017). Yeomans and Bremner (1988) provided the methodology for determining the soil organic carbon (SOC). The method of Bremner and Mulvaney (1982) was used to determine the total nitrogen (N). The stoichiometric C/N ratio was calculated based on the values of TOC and N. A 2.00 mm mesh was employed to filter 10 g of soil samples for the physical separation of the SOC. A volume of 30 mL of sodium hexametaphosphate solution (5 g L^{-1}) was added to each sample, and a horizontal shaker was used to agitate the mixture for 15 h (Cambardella and Elliot, 1992). Subsequently, a 53 µm sieve was passed through the suspension with the assistance of a water jet. The material retained in the filter is a representation of particulate organic carbon (POC). The mineral-associated organic carbon (MAOC), which is found by splitting the SOC from the POC in the silt and clay fractions, is the material that passes through the 53 µm filter.

The soil invertebrate macrofauna was assessed using the TSBF (Tropical Soil Biology and Fertility) method described by Anderson and Ingram (1989). This method involves extracting soil blocks using a 0.25 × 0.25 m frame. Initially, litter was removed and placed in properly labeled plastic bags at each sampling point. Subsequently, a small trench was opened beside the frame to extract the soil block from the 0.00-0.10 m layer. Edaphic macrofauna density, or the number of individuals per square meter, was calculated for each treatment based on the macrofauna data. Then, equitability ($e = H/\log R$; in which R is the richness, represented by the number of taxonomic groups), and Shannon diversity indices ($H = -\sum pi.\log pi$; in which $pi = ni/N$; ni is the density of each group, $N = \sum$ density of all groups) were computed.

Data analysis

A totally randomized design was taken into consideration when analyzing the data. First, the Shapiro-Wilk and Bartlett tests were used to determine whether the residuals were normal and whether the variances were homoscedastic. Variables that did not show homogeneity or a normal distribution were adjusted using the Box-Cox test, and these variables were then retested. Following the satisfaction of the homogeneity and normality requirements, the data were further subjected to an analysis of variance using the F-test (ANOVA). The non-parametric Kruskal-Wallis test was used for variables that, following transformation, did not match the assumptions.

For each set of chemical, physical, and biological soil data, a Principal Component Analysis (PCA) was conducted to explore the variable distributions in the land uses. Following this approach, permutation tests were performed to compare the use of a statistical test with random data permutations (Monte Carlo test). Subsequently, for the macrofauna groups, an abundance matrix was generated, which was used to ordain the experimental treatments through non-metric multidimensional scaling (NMDS). Additionally, co-inertia analysis was employed to explore the covariance and overall similarity in structure between two sets of data (chemical properties vs. soil fauna; physical and chemical properties vs. soil fauna). All tests were conducted at a 5 % significance level using the R software with the “ExpDes.pt” and “ade4” packages in R (R Development Core Team, 2020).

RESULTS

Groups *Blattodea, Chilopoda*, and “*Others*” showed no variations in soil macrofauna during the wet season based on land use. However, differences were observed in the groups Formicidae, Isopoda, and Oligochaeta, with higher average values observed in the agroforestry related to the forest plots. For the group *Diplopoda*, the highest averages were observed in the Forest plots. There was also a difference in organism density, with the highest average values recorded in Agroforestry. No differences were found for species richness and the Shannon and Pielou indices between land uses (Table 1).

Concerning the *Araneae*, *Diplopoda*, *Formicidae*, and *Oligochaeta* groups, the Agroforestry exhibited distinct average values from the Forest throughout the dry season. No difference was observed between the land uses for Blattodea, Isopoda, and “Others” groups. Soil macrofauna density varied between land uses, with the highest values observed in Agroforestry. No differences were found for richness, the Shannon index, and the Pielou index between land uses (Table 1). Through the analysis of NMDS and PERMANOVA results, it is evident that the Agroforestry separated from the Forest plots. In both seasons, the separation was associated with differences in individual density and *Oligochaeta* and *Isopoda* (Figura 1).

Physical parameters, such as soil texture, differed between the land uses. For example, the highest sand fraction contents were observed in the Forest site compared to agroforestry. Silt content did not differ. Regarding the clay fraction, higher levels were quantified in the Agroforestry compared to Forest (Table 2). Concerning the textural class in the 0.00-0.10 m soil layer, the agroforestry was classified as loamy sand, while the forest area was classified as sandy loam (Table 2).

Table 1. Number of individuals per square meter, density, richness, Shannon index, and Pielou index of soil fauna groups in Agroforestry and Forest plots, Southeastern Brazil

Macrofauna	Rainy season			Dry season		
	Agroforestry	Forest	p-value	Agroforestry	Forest	p-value
	Ind. m²			Ind. m²		
Araneae	-	-	-	2.25ª	0.62ᵇ	0.030
Blattodea	6.25ª	4.75ª	0.536	1.75ª	0.50ª	0.159
Chilopoda	0.75ª	0.50ª	0.590	-	-	-
Diplopoda	0.37ᵇ	5.37ª	0.001	5.00ª	0.25ᵇ	0.002
Formicidae	21.87ª	1.87ᵇ	0.023	16.50ª	3.24ᵇ	0.032
Isopoda	11.12ª	1.51ᵇ	0.014	2.37ª	0.75ª	0.143
Oligochaeta	18.24ª	6.37ᵇ	0.003	19.37ª	5.62ᵇ	0.002
Others	2.75ª	1.12ª	0.076	3.25ª	2.50ª	0.586
Density	61.1ª	22.72ᵇ	0.019	44.12ª	19.87ᵇ	0.006
Richness	5.25ª	5.22ª	0.924	4.75ª	5.12ª	0.471
Shannon	2.43ª	1.51ª	0.543	2.35ª	1.74ª	0.456
Pielou	0.62ª	0.41ª	0.502	0.59ª	0.45ª	0.432

Means followed by different letters differ from each other according to the F Test ($p<0.05$).

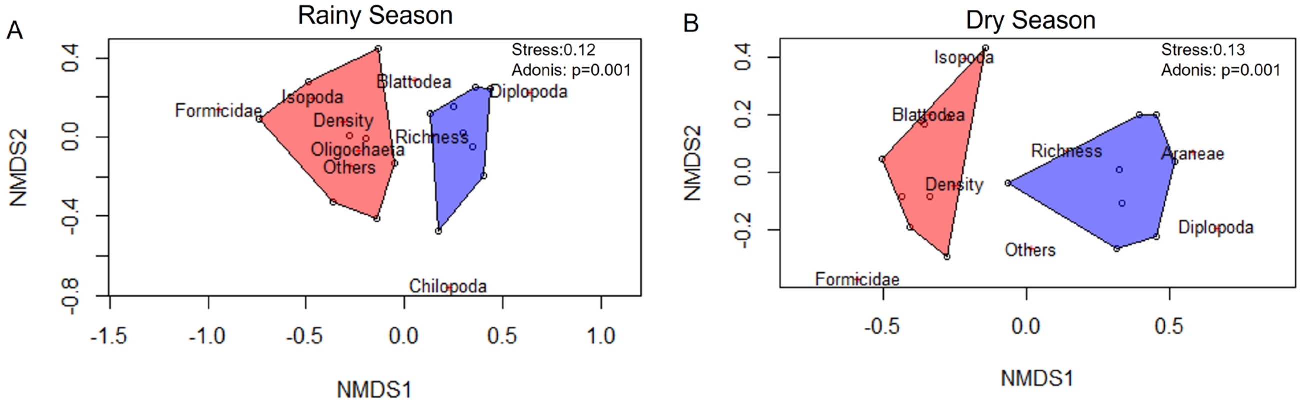

Figure 1. Nonmetric multidimensional scaling (NMDS) relating groups that representing more than 5 % of total density from plots sampled in the rainy season (a) and dry season (b), respectively. Forest (blue) and Agroforestry (red).

Table 2. Physical and chemical attributes of Agroforestry and Forest plots, Southeastern Brazil

Soil properties	Rainy season			Dry season		
	Agroforestry	Forest	CV%	Agroforestry	Forest	CV%
Sand (g kg^{-1})	726.20^{b}	835.00^{a}	13.73	-	-	-
Silt (g kg^{-1})	146.20^{ns}	97.50	85.87	-	-	-
Clay (g kg^{-1})	127.50^{a}	67.50^{b}	41.12	-	-	-
Temperature (°C)	25.90^{ns}	24.00	24.03	24.60^{ns}	22.80	27.34
Moisture (%)	10.70^{a}	3.60^{b}	19.37	3.40^{ns}	1.20	33.11
pH (H_2O)	6.08^{a}	5.09^{b}	6.53	5.48^{ns}	5.28	5.12
Ca^{2+} (cmol$_c$ dm^{-3})	2.17^{a}	0.77^{b}	13.75	2.23^{a}	1.00^{b}	34.10
Mg^{2+} (cmol$_c$ dm^{-3})	1.57^{a}	0.53^{b}	27.88	1.49^{a}	0.46^{b}	32.18
Al^{3+} (cmol$_c$ dm^{-3})	0.00	0.00	0.00	0.00	0.00	0.00
H+Al (cmol$_c$ dm^{-3})	1.41^{ns}	1.16	32.18	2.53^{a}	1.72^{b}	25.51
K^{+} (mg dm^{-3})	308.00^{a}	86.00^{b}	11.34	131.00^{a}	34.00^{b}	24.32
Available P (mg dm^{-3})	147.00^{a}	6.00^{b}	20.14	49.00^{a}	4.00^{b}	24.31
SB (cmol$_c$ dm^{-3})	5.00^{a}	2.00^{b}	0.56	4.00^{a}	2.00^{b}	28.87
CEC (cmol$_c$ dm^{-3})	6.00^{a}	3.00^{b}	20.37	7.00^{a}	3.00^{b}	13.76
BS (%)	76.00^{a}	58.00^{b}	13.44	61.00^{a}	47.00^{b}	18.99
SOC (g kg^{-1})	21.32^{ns}	22.07	17.36	22.23^{ns}	20.41	13.62
N (g kg^{-1})	4.00^{ns}	4.00	21.22	4.00^{ns}	5.00	31.95
C/N	5.95^{ns}	6.11	18.88	5.96^{ns}	4.35	29.53
POC (g kg^{-1})	4.55^{ns}	3.59	7.41	1.93^{ns}	1.52	24.16
MAOC (g kg^{-1})	16.76^{ns}	18.48	19.05	20.29^{ns}	18.89	13.75

Means followed by different letters differ from each other by the F test ($p<0.05$). ^{ns} Absence of significance by the F test ($p>0.05$). pH: active acidity; Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; Al^{3+}: exchangeable aluminum; H+Al: potential acidity; K^{+}: exchangeable potassium; P: available phosphorus; SB: Sum of bases; CEC: Cation exchange capacity; BS: Base saturation; SOC: Soil orgânic carbon; POC: Particulated Organic Carbon; and MAOC: mineral-associated organic carbon.

No difference was observed between the land uses for soil temperature in both assessment periods. Concerning soil moisture determined by the gravimetric method (Ug), differences were noted only during the rainy season, with lower values in the forest and greater values in the agroforestry (Table 2).

In the rainy season, the pH values and concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}) were higher in Agroforestry related to the Forest. Elevated levels of these cations influenced the higher values of the soil cation exchange capacity (sum of bases and saturation by bases). As for exchangeable aluminum (Al^{3+}) and potential acidity (H+Al) levels, there were no differences, with notable emphasis on the null values of Al^{3+}. Available phosphorus (P) concentrations in the Agroforestry were approximately 24 times higher compared to those quantified in the Forest (Table 2).

During the dry season, a similar pattern of chemical property results was observed compared to the rainy season, except for pH and H+Al values. The pH values did not differ; however, the H+Al values were higher in the Agroforestry related to the Forest. Notably, phosphorus (P) levels in the agroforestry were around 12 times higher compared to the levels quantified in the forest plots (Table 2).

Regarding the compartments of SOM, similarities in the results of organic fractions were observed between the land uses (Table 2). Soil organic carbon, total nitrogen (N), and the C/N ratio did not differ, as well as the contents of POC and MAOC in both assessment periods (Table 2). However, it is worth noting that the short-term adoption of Agroforestry led to an approximately 21 % increase in the content of the most labile fraction of SOM (POC) compared to Forest, regardless of the assessment period.

In the rainy season, the first two axes of PCA explained 58.2 % of the total data variability. Along axis 1, the Agroforestry is positioned opposite to Forest due to soil CEC, pH, clay content, moisture, and temperature values, showing a tendency towards a higher proportion of sand and H+Al (Figure 2a). Axis 2 mainly represented MAOC and SOC associated with the forest plots (Figure 2a). Physical and chemical soil properties varied between land uses (31.9 % of the variance explained, p-value: 0.001).

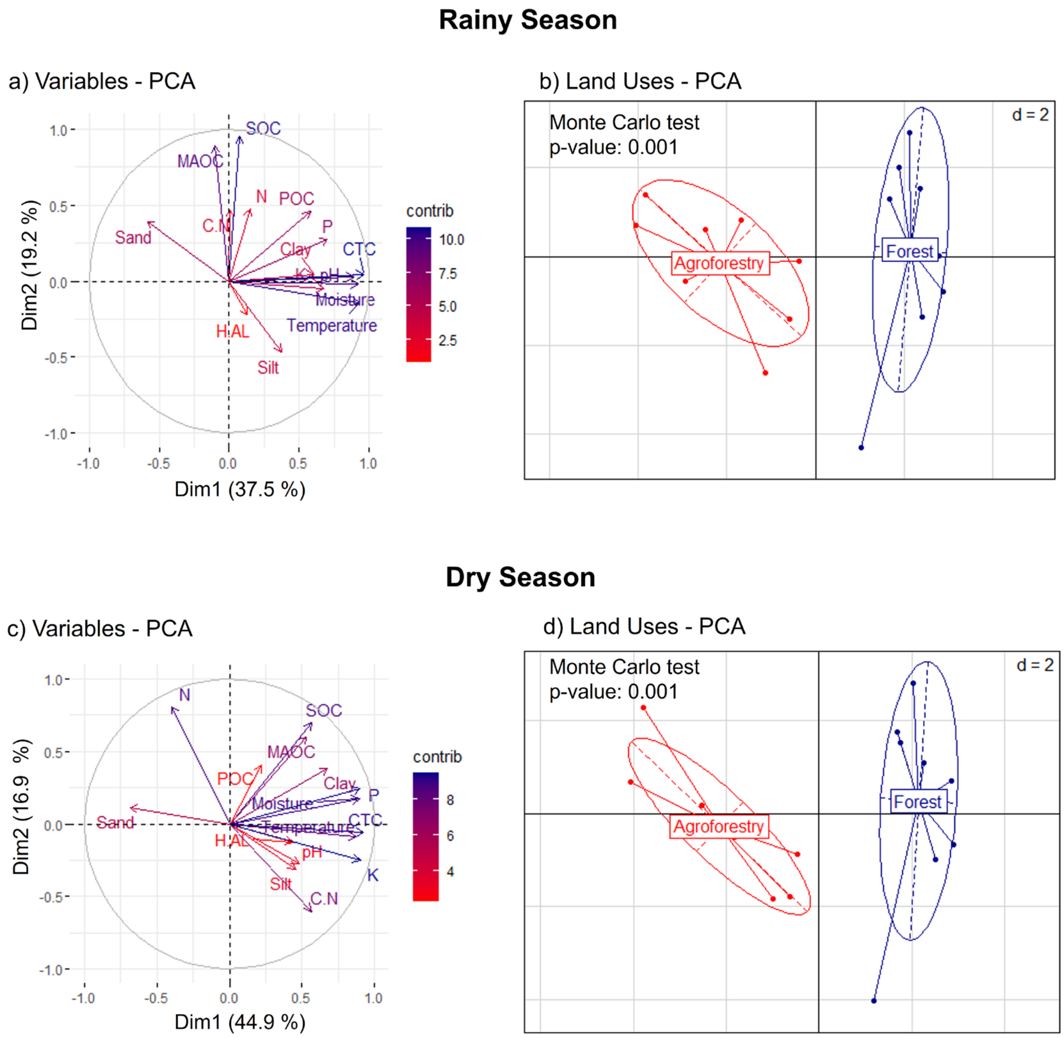

Figure 2. Projection of soil physicochemical variables on the factorial plane Dim1/Dim2 and of the sites.

In the dry season, the first two axes of PCA explained 61.8 % of the total data variability. The same trend was observed, with axis 1 highlighting the opposition of Agroforestry to Forest concerning higher values of soil CEC, pH, clay content, moisture, and temperature, showing a tendency towards a higher proportion of sand, pH, and H+Al values (Figure 2b). Axis 2 primarily represented N associated with Forest (Figure 2). Physical and chemical soil variables varied between land uses (36.8 % of the variance explained, p-value: 0.001).

All correlation coefficients in the matrix (RV coefficient is calculated as the total co-inertia, sum of the eigenvalues of a co-inertia analysis) calculated between the data tables were significant (p<0.001), with percentages of explained variation ranging from 57 % (Macrofauna communities vs. physical and chemical soil properties in the rainy season) to 56 % (Macrofauna communities vs. physical and chemical soil properties in the dry season) (Figure 3). In the rainy season, the *Isopoda* and *Oligochaeta* groups were associated with temperature and humidity; *Blattodea* was associated with K content and POC, while *Formicidae* was associated with H+Al. Richness was correlated with SOC, nitrogen, and MAOC levels. The *Chilopoda* group was the most abundant in the Forest, characterized by a sandier texture in the surface layer. In the dry season, the *Oligochaeta* group was again related to humidity, and *Blattodea* to SOC and MAOC levels. Richness was correlated with nitrogen levels. Density was related to high CEC. *Isopoda* and *Formicidae* groups were associated with temperature and fertility, while the "*Others*" group was associated with C/N (Figure 3).

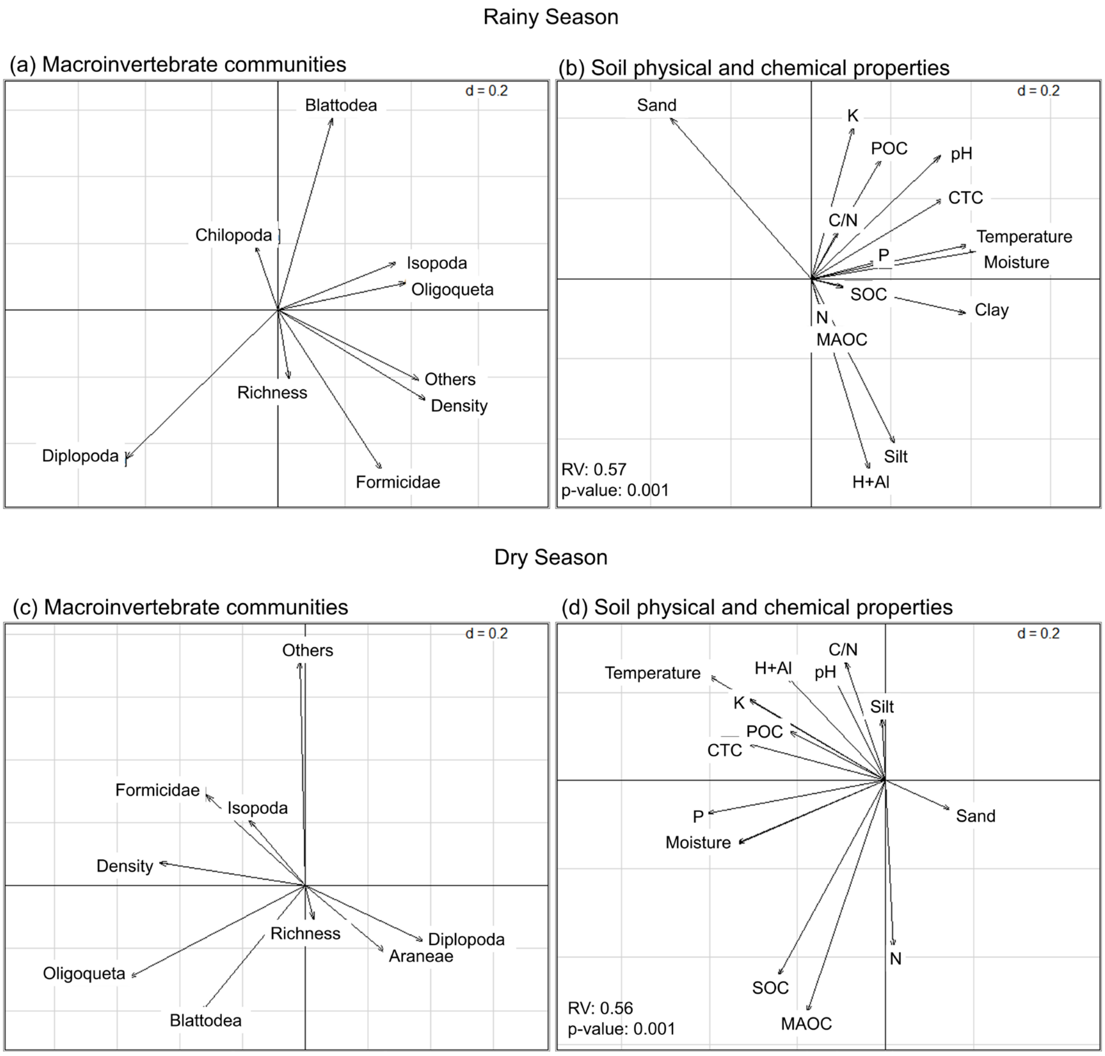

Figure 3. Projection of macroinvertebrate communities (a and c) and of soil physical and chemical properties (b and d) in the Coinertia Analysis F1/F2 plane in rainy (a and b) and dry (c and d) season.

DISCUSSION

Influence of Agroforestry on soil macrofauna

The highest macrofauna organism densities were recorded in the agroforestry plots. This pattern may be related to its positive influence on the invertebrate community, providing food and shelter for soil organisms, thus promoting positive changes in their abundance and diversity (Barrios et al., 2013; Fragoso et al., 2017). The handling techniques used in the AS area influence soil pH, soil organic carbon and total soil nitrogen stocks (Laskar et al., 2021), thus making it an enabling environment for soil fauna development.

The higher occurrences of the *Isopoda* group observed in the Agroforestry plots may be related to the effect on this group primarily mediated by the rapid growth of plants, increased litter production, and favorable temperature and moisture conditions (Barros et al., 2003; Martins et al., 2019). Notably, the Isopoda group was found in both land uses, which is good because members of this group are crucial primary decomposers who help break down plant material (Correia et al., 2008). Saprophagous macrofauna, such as *Isopoda* and other groups, contribute to litter fragmentation, thus aiding in decomposition, the movement of organic matter along the soil profile, and soil carbon dynamics and decomposition rates (FAO, 2020).

The presence of the *Formicidae* and *Oligochaeta* groups in the agroforestry indicates that it may be undergoing structural changes (Coelho et al., 2021). The high frequency of these two groups in the agroforestry plots, verified in the two sampling periods, may have been favored by the management of the system, which helped to maintain an edaphoclimatic condition more conducive to the presence of these organisms. Amaral et al. (2019) found that the richness of the *Formicidae* group is greater in complex and well-structured environments and with diverse ecological niches, especially in areas where native species predominate. Among macrofauna groups, *Oligochaeta* has been widely used as bioindicators of greater or lesser degrees of sensitivity and has demonstrated soil quality conditions in the face of a high degree of anthropogenic interventions in the most diverse environments (Santos et al., 2015).

The values for the Shannon index are related to the diversity of present groups, where the reduction in values is a consequence of the dominance of some groups compared to others (Souto et al., 2008). Felfili and Rezende (2003) suggest that Shannon values range between 1.3 and 3.5, reaching 4.5 in tropical forest environments. These Shannon values are observed in studies conducted in the same municipality, as can be seen in Ferreira (2020) and Lima et al. (2021a).

These values indicate significant variation in the Shannon index, depending on the forest area conservation status and successional stage (Tavares et al., 2018). Structural complexity and botanical composition promote the richness and diversity of soil macrofauna and its relationship with soil physical quality, creating a favorable environment for developing and establishing a soil community (Araújo et al., 2018).

Results found by Matos et al. (2020) in the same biome corroborate with this study, where in the agroforestry system exhibited high Shannon indices similar to those of the native forest. This similarity is associated with the time of adoption of the system, demonstrating patterns of similarity between the sites regarding diversity. Pielou's evenness values were higher in Agroforestry than in Forest plots, indicating the distribution of the number of individuals among the groups was more equitable in agroforestry (Martins et al., 2019). Pielou's evenness index can vary between 0 and 1, with values reflecting the dominance of groups and uniformity in the distribution pattern of individuals among species (Pasqualin et al., 2012).

Forest plots were associated with higher values of H+Al (Figure 2). This may be due to increased leaching resulting from better drainage conditions, which occurs in soils with a higher percentage of sand and consequently lower soil CEC, base saturation (V%), sum of bases (SB), pH, and carbon content (Usowicz et al., 2004; Behera and Shukla, 2015). Chemical soil quality of agroforestry systems with an establishment time between 6 and 13 years showed that these systems promoted an increase in pH values, reduced aluminum saturation, and increased nutrient content. This effect is related to the organic matter added to the surface layers, providing greater nutrient cycling in these areas (Iwata et al., 2012).

The significant difference between the Forest and Agroforestry plots, observed through NMDS and PERMANOVA analysis, is primarily attributed to the difference in individual density, especially for the *Oligochaeta* and *Isopoda* groups. This difference may be directly related to soil moisture, temperature, and SOM, as these groups are directly associated with these properties. According to Ortiz et al. (2023), the NMDS ordination was efficient in segregating the plots with agroforestry systems and forest systems, showing a positive correlation in the Agroforestry System. In Brazil, most native *Oligochaeta* species may be associated with areas practicing sustainable management, favoring the diversity of these communities (Brown and James, 2007; Bartz et al., 2009). The continuous input of organic matter and the high diversity of species in the Agroforestry System (Iwata et al., 2012; Stöcker et al., 2020) may have contributed to this gradient in fauna within the agroforestry plots.

Influence of agroforestry on physical and chemical properties

Soil texture is one of the properties that significantly influences nutrient and water retention capacity, the decomposition of organic matter, and the nature of the parent material conditions. Soil parent material in the study sites consists of colluvial and alluvial sediments derived from the weathering of acidic rocks (leuco and mesochromatic gneisses) (Kaiser et al., 2021). Soil granulometry formed by these sediments exhibits a texture ranging from sandy to loamy, especially in the superficial horizons, which justifies the observed results of textural classes in the Agroforestry (loamy sand) and Forest (sandy loam) plots (Table 2). Sandy texture on the surface, particularly in the Forest plots, reduces the soil ability to retain water and nutrients, favoring the decomposition of SOM.

Temperature and water content changes in the soil are greater in the most superficial layers, where most of the soil fauna is located (Corrêa Neto et al., 2018). Soil temperature is considered the main factor that influences metabolic regulation in soil individuals, and together with humidity, determines its spatial distribution and periods of greatest activity (Pompeo et al., 2016). In tropical forest ecosystems, increased temperature stimulates the activity of decomposing microbiota, which contributes to accelerating SOM decomposition rates (Corrêa Neto et al., 2018). Therefore, measuring soil temperature is essential, especially correlating it with soil biota.

The greater water retention capacity in Agroforestry was due to the greater availability of water during the evaluation period (rainy) associated with the soil texture, which had twice as much clay (127 g kg^{-1}) compared to Forestry (67 g kg^{-1}) (Table 1). The environment provides better humidity conditions, creating a more favorable place for developing soil organisms (Souza et al., 2020). Therefore, the greater the soil moisture, the greater the number of soil fauna groups (Calheiros et al., 2019).

Regarding the fertility of the soil surface layer, the Agroforestry stood out in terms of exchangeable cation levels (Ca^{2+}, Mg^{2+}, and K^{+}) and pH values. This is reflected in higher values of the cation exchange complex in the two evaluation periods. The slightly acidic pH in both areas falls within the ideal range for crop development (Lira et al., 2012), promoting nutrient availability, with no presence of aluminum (Al^{3+}) observed as well (Prezotti and Guarçoni, 2013) (Table 2).

The high levels of accessible phosphorus (P) in the agroforestry plots during the two evaluation periods are highlighted by the average Ca^{2+} and Mg^{2+} contents (Freire et al., 2013) (Table 2). Except for the soil's cation exchange capacity in the Forest plots, the observed values of the cation exchange complex varied from medium to high (Prezotti and Guarçoni, 2013). Sand-textured soils are more prone to leaching losses because they often have low cation exchange capacity values and, as a result, little nutrient retention (Lima et al., 2010; Câmara et al., 2020). Because perennial plants help retain and introduce organic matter into the soil, more nutrients are available (Cotrufo and Lavalle, 2022).

Higher levels of K^+ and P in Agroforestry systems are associated with conservation practices (fertilization, soil cover, species diversification, etc.) (Soares et al., 2021). Soil P and K levels may decrease or increase in conservationist agroforestry systems due to the number of leaves dropped on the soil (Kotowska et al., 2016).

In this study, it was found that the increase in soil fertility in the Agroforestry (8 years of adoption) compared to the Secondary Forest plots (28 years of regeneration) was satisfactory (Table 2). Such results may be associated with various factors, such as greater efficiency in nutrient cycling in the conservationist system; increased absorption and utilization of nutrients from the sub-surface layers of the soil by the roots of perennial species; reduced nutrient loss through surface runoff and/or leaching due to greater soil surface protection; better utilization of the benefits of soil correction and mineral fertilization, and proper management of pruning for green manure and fertility-renewing species.

The type of SOM and, thus, the availability of food for soil decomposer communities in agroforestry systems can be determined by the amount and quality of litter, the input of biomass from pruning, and the addition of organic residues derived from the root system (Sileshi and Mafongoya, 2007; Matos et al., 2020). As well as derivatives from microbial biomass, the composition of SOM consists of an unlimited number of organic compounds in various stages of transformation, ranging from simple and easily mineralizable organic wastes to more complex and resistant products (Sileshi et al., 2020). Each of these substances adds to the overall soil organic carbon reservoir.

Agroforestry Systems play an essential role in carbon storage above and below the ground through the continuous deposition of plant residues (Vicente et al., 2023). The absence of differences in SOC, total nitrogen (N), C/N ratio, POC, and MAOC between Agroforestry and Forest plots may be related to soil texture and/or plant composition. The predominantly sandy texture in the surface layer of the study sites promotes the oxidation of SOM due to the limited protection provided to the organic material by the sand fraction.

Due to their fragile character and difficulty in raising SOM content, sandy-textured soils have different requirements for SOC levels and composition than other soil types (FAO, 2020). The SOC is the main soil quality indicator (Reichert et al., 2016). Soil organic matter plays a major role in the generation and stabilization of soil aggregates; ongoing addition of organic residues and a decrease in soil disturbance might lessen SOC losses (Šimanský et al., 2019; Pinto et al., 2023; Vicente et al., 2023). The similarity in nitrogen levels between land uses may reflect the plant composition, as they include many species from the *Fabaceae* family. Approximately 21 % of Atlantic Forest species belong to this family (Tavares et al., 2018). Remarkably, to guarantee soil health and ecosystem services, management strategies that support a positive C balance and its persistence in the soil must be used to enhance the soil C reservoir (Vicente et al., 2023). Both carbon and nitrogen have a direct role in many essential soil activities. Once biomass breaks down and deposits itself on the soil surface as litter, the carbon is indirectly stored as soil organic carbon (Gama-Rodrigues et al., 2011). In many agricultural conditions, nitrogen is the greatest limiting factor for plant growth, making it the element most needed in larger quantities to ensure crop output (FAO, 2020).

The C/N ratio values in the land uses were below 20, indicating higher nitrogen mineralization (Table 2). By creating high-quality litter with a low carbon-to-nitrogen ratio and encouraging the release of nitrogen into the soil, nitrogen-fixing plants, which are frequently found in agroforestry and forests, improve soil fertility (Duarte et al., 2013). Stöcker et al. (2020) claim that agroforestry is effective in recovering soil carbon since it fosters a noticeable increase in SOC over time.

The POC, or any organic material with a particle size ranging from 53 to 2000 μm, makes up a sizable portion of SOM (Cambardella and Elliot, 1992). Although the quality and utility of this fraction for decomposers can vary based on its chemical and nutritional content, which often follows the quality of plant inputs, it is more easily available (Lavallee et al., 2020; Pinto et al., 2023).

The POC is considered an efficient indicator of soil quality, mainly because significant changes may occur first in its levels compared to MAOC and SOC. We observed a percentage increase in POC content in the agroforestry plots, although it was not statistically significant. Perennial plants in agroforestry can enhance nutrient availability by converting them into more labile forms of SOM. These plants increase SOM levels by producing and adding plant residues, reducing losses through erosion (Sileshi et al., 2020). The observed pattern of percentage increase in POC in agroforestry (Table 2) suggests that conservationist practices progressively influence the more labile compartment of SOM in soil texture conditions that hinder its stabilization and accumulation. In contrast to this pattern, MAOC is less affected by management practices as it is a stable fraction, especially in soils with high clay content (Dortzbach et al., 2020).

Covariance and overall similarity between soil attributes in Agroforestry and Forest plots

The result of co-inertia reveals associations between soil chemical and physical properties and macrofauna.There is an association between soil fauna and levels of organic matter and phosphorus, since the diversity of soil organisms is linked to the availability of nutrients in the soil (Wang et al., 2016). Percentage of clay and organic matter content determines the chemical, physical, and biological properties of the soil, such as structure, water retention capacity, nutrient availability for plants, and cation retention capacity (Luchese et al., 2002). Soil organisms, especially the *Formicidae*, *Oligochaeta* and *Isopoda*, depend significantly on the presence of organic matter to establish themselves, in addition, the pH, porosity and moisture of the soil also play a key role for these groups (Jacquemin et al., 2012). The rate of MO decomposition depends on the quantity and quality of the organic waste added to the soil, which can influence the activity of soil organisms (Pech et al., 2021). The process of decomposition and humidification of soil organic matter is stimulated by high levels of COT, which increases the availability of nutrients (Negassa and Sileshi, 2018). Figure 3 illustrates how temperature and humidity have a strong correlation with the macrofauna of the soil. The two primary factors affecting the metabolic regulation of soil organisms are moisture content and temperature. The whole food chain benefits when soil temperature and humidity levels stay constant (Rosa et al., 2015; Lima et al., 2021a).

CONCLUSIONS

In the short term, management with an agroforestry system promoted environmental conditions favorable to the development of the soil invertebrate macrofauna community to surpass the ecological indices observed in the forest. Agroforestry system (AS) was equal in maintaining the soil physical and chemical properties, with an emphasis on increasing fertility. Simultaneously, the system progressively incorporated carbon into the particulate compartment of soil organic matter in the same proportion as the forest. In general, AS promoted a positive relationship between physical and chemical properties and the macrofauna community of soil invertebrates, in a similar way and sometimes superior to the forest, confirming our hypothesis and showcasing how well management works to preserve soil characteristics and, in turn, ecosystem services.

DATA AVAILABILITY

The data will be provided upon request.

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