Revista Brasileira de Ciência do Solo

Division - Soil Processes and Properties | Commission – Soil Physics

Soil physical, chemical and biological properties in Conilon coffee intercropping systems

Joabe Martins de Souza[1], Fábio Ribeiro Pires[1]*, José Ricardo Macedo Pezzopane[2], Kristhiano Chagas[1], Alex Favaro Nascimento[3], José de Oliveira Rodrigues[1], Marcio Paulo Czepak[1] and Adriel Lima Nascimento[1]

[1] Universidade Federal do Espírito Santo, Departamento de Ciências Agrárias e Biológicas, São Mateus, Espírito Santo, Brasil.
[2] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Pecuária Sudeste, São Carlos, São Paulo, Brasil.
[3] Instituto de Defesa Agropecuária e Florestal do Espírito Santo, Pinheiros, Espírito Santo, Brasil.

*** Corresponding author:**
E-mail: pires.fr@gmail.com

Received: May 22, 2023

Approved: October 30, 2023

How to cite: Souza JM, Pires FR, Pezzopane JRM, Chagas K, Nascimento AF, Rodrigues JO, Czepak MP, Nascimento AL. Soil physical, chemical and biological properties in Conilon coffee intercropping systems. Rev Bras Cienc Solo. 2024;48:e0230056
https://doi.org/10.36783/18069657rbcs20230056

Editors: José Miguel Reichert and Milton César Costa Campos.

ABSTRACT: Shaded coffee systems may offer a series of benefits, however, studies on shaded cultivation of Conilon coffee crops are still scarce in the literature. This study aimed to evaluate the soil physical, chemical, and biological properties of two Conilon coffee intercropping systems from southeastern Brazil. Two commercial coffee crops – one shaded by macadamia trees and the other by green dwarf coconut trees – were evaluated according to three treatments: coffee plants in the inter-row of the tree species; coffee plants in the same row of the trees; and unshaded coffee. The experimental design was a completely randomized with four replicates. Coffee plants intercropped with macadamia trees, both intra- and inter-row, resulted in less soil compaction than unshaded systems. As for intercropping with green dwarf coconut trees, the unshaded system presented lower soil resistance to penetration. Differences in physical properties between treatments allow no inferences about intercropping systems influence on green coconut trees. Intercropped coffee improves soil chemical properties, resulting in greater soil fertility than unshaded systems, and showed greater soil organisms. These findings indicate that Conilon coffee-macadamia intercropped with tree species represents a promising alternative for sustainable soil management.

Keywords: *Coffea canephora* Pierre, shaded, soil management, soil quality, ecosystems.

INTRODUCTION

Coffea canephora Pierre cv. *conilon* (conilon coffee) production in Brazil, the world's largest coffee producer, is mainly done without shade (Gomes et al., 2020). The interest in growing coffee under shaded environments has recently increased due to the evidenced benefits, including abiotic (edaphic and microclimatic factors) and biotic conditions (physiological aspects, pests, diseases, and weeds occurrence). Shaded systems also improve beverage quality, directly influencing consumers' decision to purchase the final product, making coffee production more competitive and profitable (Valencia et al., 2016).

Soil and vegetation are intrinsically related (Wang and Zheng, 2021). For instance, aggregation is the main soil physical property affected by organic matter (OM) and roots amount (Hoffland et al., 2020), influencing other properties such as air-filled porosity and water retention capacity. In addition, other changes relating to edaphic aspects are reported, such as improved fertility, stable soil temperatures, less loss of nitrogen through volatilization and increased soil conservation, with greater recycling of nutrients and a reduction in erosion processes (Fahad et al., 2022).

Compared to non-intercropping systems, those involving the combination of coffee crops and tree species increase the amount of organic matter in the soil (Jácome et al., 2020). These authors showed that the association between Australian cedar and coffee as intercrops in agroforestry systems resulted in a 14 % increase in soil organic matter content. In a study carried out by Rigal et al. (2020), coffee-growing areas shaded by trees, particularly those in which Arabica coffee was intercropped with macadamia, showed substantial improvements in the amount of organic matter in the soil (10 % increase) and in the development of soil microbial communities (64 % increase), as well as deeper coffee root systems compared to monoculture coffee plantations. Agroforestry systems produce around 50 Mg ha^{-1} yr^{-1} of C to the litter layer and soil organic matter (Murta et al., 2021). Organic matter increase in intercropped systems is related to the greater deposition of biomass via leaf litter, to the attenuation of the sun's rays by the tree canopy, and the improvement of the microclimate decreases organic matter mineralization rate, contributing to its accumulation in the soil and also to tree species, such as Conilon coffee plants, which add plant remains to the soil, contributing to the increase of OM in the surface layer and to nutrient cycling in the soil (Thomazini et al., 2015).

Considered the primary source of energy and nutrients for all food chains, biomass production decreases when forests are converted into annual crops for an extended time, resulting in a soil chemical and biological impoverishment, which highlights the importance of understanding potential impacts of land management and use practices on soil fauna communities to guarantee proper functioning and biodiversity conservation in agricultural ecosystems. Soil macrofauna also contributes to soil structuring development by influencing the mixture of organic and mineral particles and the redistribution of OM (Balota, 2017).

Intercropping cultivation of coffee is more complex than monoculture cultivation, for shaded-grown coffee goes beyond traditional management practices. Such approach changes the understanding of the production system, under which the basic criteria for determining crops viability are agroecosystem and environment components, as well as production factors and growth analysis.

Evaluating the soil physical, chemical, and biological properties under shading conditions, conducted over the long term, is essential for assessing the system potential for production sustainability and provision of ecosystem services (Cerda et al., 2017). Shaded crops bring several benefits, but in tropical conditions, the edaphic properties play an even more important role, due to the accelerated dynamics of decomposition of organic matter and because they are very weathered soils.

Intercropping proposal seeks to mitigate extreme weather events through moderate shading (Quandt et al., 2023) and make systems more sustainable (Moreira et al., 2018; Gomes et al., 2020). They also provide an extra source of income for coffee growers and make better use of labor during the year, an important benefit for family farming (Almeida and Zylbersztajn, 2017). Given this analysis, it is possible to see the great potential for using the intercropping technique, especially in small areas, where there will be increases in productivity and the sustainability of production.

Although the literature on *Coffea arabica* is rather vast, we found no conclusive information regarding Conilon coffee (Souza et al., 2017). This study hypothesizes that shaded-grown Conilon coffee intercropped with macadamia nut trees (*Macadamia integrifolia* Meiden & Betche) for 19 years and with green dwarf coconut trees (*Cocos nucifera* L.) for 18 years promotes changes in the soil properties, improving its structure and fertility and consequently providing an environment that can favor the increase of productivity and quality of the coffee drink. However, these changes and benefits are expected to be different between macadamia and coconut, considering that they are morphologically different species. To bridge such a knowledge gap, related to the Conilon coffee culture, and present the system as a tool for sustainable production, this study aimed to evaluate the physical, chemical, and biological soil properties, sampled in the inter-row and intra-row of tree species, of two shaded-grown conilon coffee systems from southeastern Brazil.

MATERIALS AND METHODS

Experimental site, planting design, and treatment

The experiment was conducted on two commercial crops of Conilon coffee (*C. canephora* Pierre) located in the municipality of São Mateus, Espírito Santo, Brazil (18° 45’ S; 40° 11’ W). The first crop refers to a 19-year old cultivation shaded by macadamia nut trees (*Macadamia integrifolia* Meiden & Betche), whereas the second refers to an 18-year coffee cultivation intercropped with green dwarf coconut trees (*Cocos nucifera* L.) (Figure 1). Region climate is tropical with dry winter, classified as type Aw according to Köppen’s classification system, with 1,212 mm precipitation, 23.8 °C average annual temperature, 70 m altitude, and flat topography.

The soil of both areas was classified as *Argissolo Amarelo distrocoeso* (Santos et al., 2018) (Typic Hapludox - Soil Survey Staff, 2014), with clay, silt, and total sand contents of 370, 70, and 560 g kg^{-1} on horizon A, respectively; and 650, 40, and 310 g kg^{-1} on horizon B – a common soil type in the Coastal Tableland region of northern Espírito Santo.

In the coffee–macadamia intercropping, coffee plants were spaced 2.5 m between rows and 1.5 m between plants, with one row of macadamia trees at every four rows of coffee (12.5 × 7.0 m) (Figure 2). This configuration corresponds to a population of approximately 2,200 coffee plants ha^{-1} and 120 macadamia trees ha^{-1} (Figure 2a), which provided around 38 % attenuation of the incidence of photosynthetically active radiation to coffee plants (Pezzopane et al., 2010). In the green dwarf coconut–coffee intercropping, coffee plants were spaced 2.0 m between rows and 1.5 m between plants, with coconut trees distributed in 10 × 10 m spacing over the plot (Figure 2b). This configuration corresponds to a population of approximately 3,200 coffee plants ha^{-1} and 100 green dwarf coconut trees ha^{-1}, which provided around 28 % attenuation of the incidence of photosynthetically active radiation to coffee plants (Pezzopane et al., 2011).

Two coffee plots cultivated in unshaded system (US) for 18 years were used for comparison with shaded systems: one adjacent to the coffee–macadamia intercropping, with 2.5 m spacing between rows and 1.5 m between plants; and the other adjacent to the green dwarf coconut–coffee intercropping with 2.0 m spacing between rows and 1.5 m between plants. The management of both control crops was conducted according to the technical guidelines of the region.

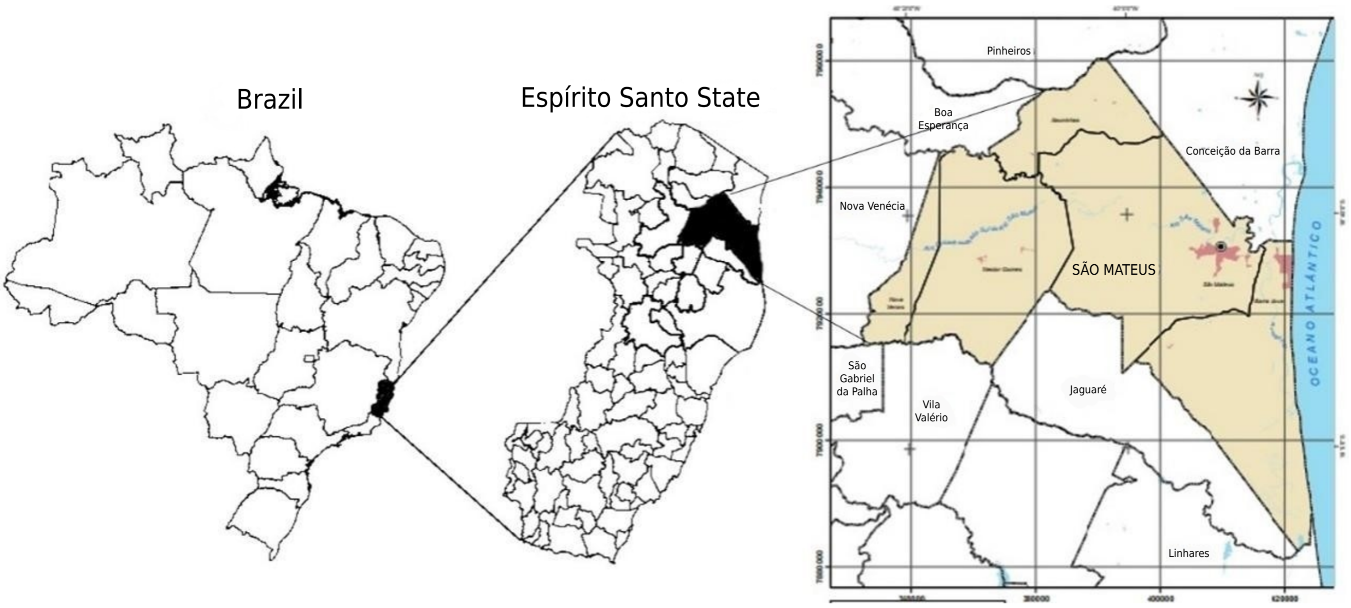

Figure 1. Geographical location of Conilon coffee intercropping systems, Municipality of São Mateus – Espírito Santo State - Brazil.

Experimental design was a completely randomized, the crop systems were compared using three treatments, which corresponded to the position of soil sample collection: 1) coffee in the inter-row of tree species; 2) coffee in the same row as tree species; and 3) coffee cultivated in unshaded system (control) – in this case, the unshaded area next to the shaded plot was considered. Commercial plots (shaded and unshaded) were sampled into four randomly chosen replicates considering each plot central area (400 m^2). Figure 2 illustrates the two partner areas and an experimental plot example with coffee rows that enable both treatments and sampling areas.

Evaluation and sampling strategy

Soil physical properties

In each plot, undisturbed soil samples were collected at the layers of 0.00-0.05, 0.05-0.20, and 0.20-0.40 m with the aid of a 100-cm^3 volumetric core to determine soil bulk density (BD), total porosity (TP), macroporosity (Ma), and microporosity (Mi) according to Donagema et al. (2011).

Soil mechanical resistance to penetration (RP) was assessed according to Stolf (1991) using an impact penetrometer (model IAA/Planalsucar/Stolf) with a 30° cone angle, 1.29 cm^2 cone area, 4 kg piston mass, and 0.40 m piston drop height, with measurements taken up to a 0.40 m depth. As these measurements varied greatly, six assessments were performed in each replicate of each treatment, and the mean was considered the repetition value. Soil RP was calculated using the following equation 1.

$$RP = \frac{5.6 + \dfrac{68.9}{\dfrac{P}{N}}}{10.2} \qquad \text{Eq. 1}$$

in which: RP is the soil mechanical resistance to penetration (MPa); P is the penetration (cm); and N is the number of impacts (strokes) per soil layer analyzed.

Soil gravimetric moisture content was determined according to Donagema et al. (2011), with soil samples collected during RP assessment with a Dutch auger, stored, and transported in plastic bags.

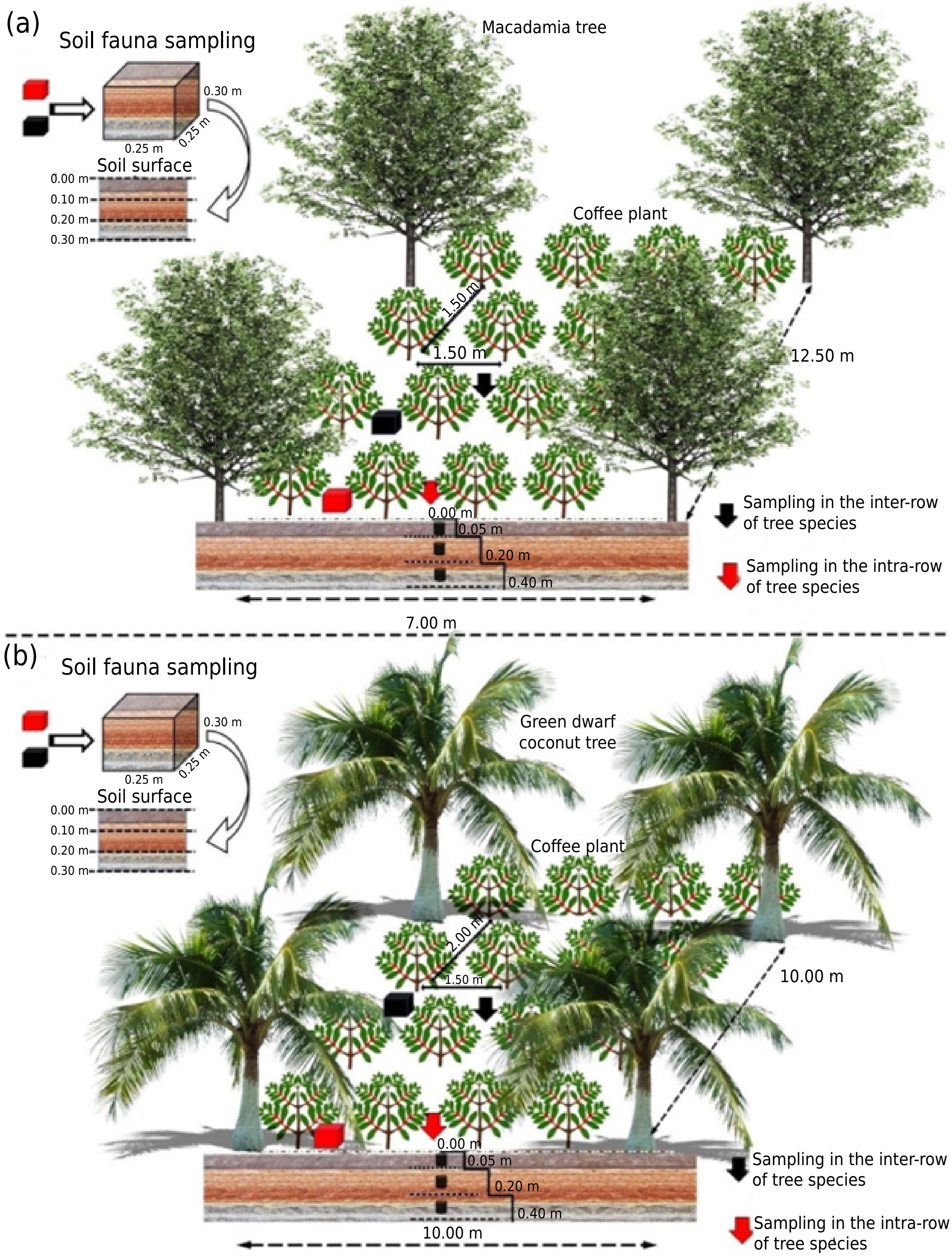

Figure 2. Illustrative scheme of coffee plots with macadamia (a) and green dwarf coconut tree (b), both located in the municipality of São Mateus, Espírito Santo State- Brazil.

Soil chemical properties

Soil chemical properties were assessed using random soil samples collected in the coffee canopy projection at the layers of 0.00-0.05, 0.05-0.20, and 0.20-0.40 m with a Dutch auger on both sides of the plant. For each treatment, eight subsamples were collected per plot, homogenized in a composed sample weighting approximately 0.5 kg, and analyzed as to pH(H_2O), P, K, Ca, Mg, Fe, Cu, Zn, Mn, Al, cation exchange capacity ($CEC_{pH\ 7.0}$) (T), sum of bases (SB), base saturation (V%), aluminum saturation (m), and organic matter (MO), according to Donagema et al. (2011).

Soil biological properties

Soil fauna sampling was performed according to (Vincent et al., 2018), by collecting five 0.25 × 0.25 × 0.30 m soil blocks at the layers of 0.0-0.10, 0.10-0.20, and 0.20-0.30 m (Figure 2), as well as the litter deposited on the soil surface. Soil blocks were carefully examined, and macrofauna (invertebrates with a body diameter greater than 2 mm) species were extracted, placed in glasses containing 70 % alcohol, identified in laboratory, and classified according to the functional group (phytophagous, saprophagous, predators). From these results, population density, expressed in number of individuals per square meter (ind. m^{-2}), and soil fauna biomass (g m^{-2}) were estimated.

Basal soil respiration (RBS) or C-CO_2 involvement was assessed using 50-g soil samples of each plot, collected at the layers of 0.00-0.05, 0.05-0.20, and 0.20-0.40 m. Samples were placed at the bottom of a hermetically sealed vials. Titrations were performed 1, 3, 5, 7, 10, 15, 20, 25, and 30 days after the start of incubation.

Statistical analysis

Data on soil properties from each intercropping system were submitted to analysis of variance (ANOVA). When significant, means were compared as a factorial considering three sampling layers and three soil sampling positions at a 5 % probability level using Tukey's test with the aid of GENES computer application (Cruz, 2013).

RESULTS

Soil physical properties

Coffee–macadamia intercropping systems showed a significant interaction with soil properties. Unshaded coffee system presented the highest BD values at soil surface (0.00-0.05 m). On the other hand, it also presented BD lowest values at soil deep layer (0.20-0.40 m) (Figure 3a). Comparing the layers within each system, the soil was denser at 0.05-0.20 and 0.20-0.40 m layers when coffee plants were placed intra-and inter-rows.

In the shaded system, TP decreases with depth increase from 0.00-0.05 to 0.05-0.20 m, remaining statistically equal from 0.05-0.20 to 0.20-0.40 m (Figure 3b). Shaded coffee TP was superior to unshaded coffee only at soil surface (0.00-0.05 m), for intra- and inter-row treatments.

In both systems, Ma was higher in the first soil layer for shaded and unshaded crops. Among shaded crops, Ma was higher at 0.00-0.05 m in intra-row than in inter-row coffee plants, showing no statistically significant differences at other layers (Figure 3c). The Mi behaved similarly to TP, especially for unshaded treatments (Figure 3d), showing a tendency to increase with depth – except for intra-row unshaded coffee.

In the coffee–macadamia intercropping system (Figure 3e), RP showed significant differences at varying depths, with a tendency to increase with depth. Regarding green dwarf coconut–coffee intercropping, we found lower BD values at soil surface for intra-row coffee plants (Figure 4a). Intra-row plants TP values decreased at 0.20-0.40 m, showing lower values than inter-row plants. Despite the decrease in Mi values with depth, differences were not statistically significant (Figure 4d). In absolute values, Ma values were relatively stable in the coffee–macadamia intercropping system.

Soil chemical properties

Regarding coffee–macadamia cultivation, the interaction between soil depth and intercropping treatments was not significant only for K and Na. In all treatments, chemical properties showed higher values at 0.00-0.05 m (Table 1), except Al contents and saturation

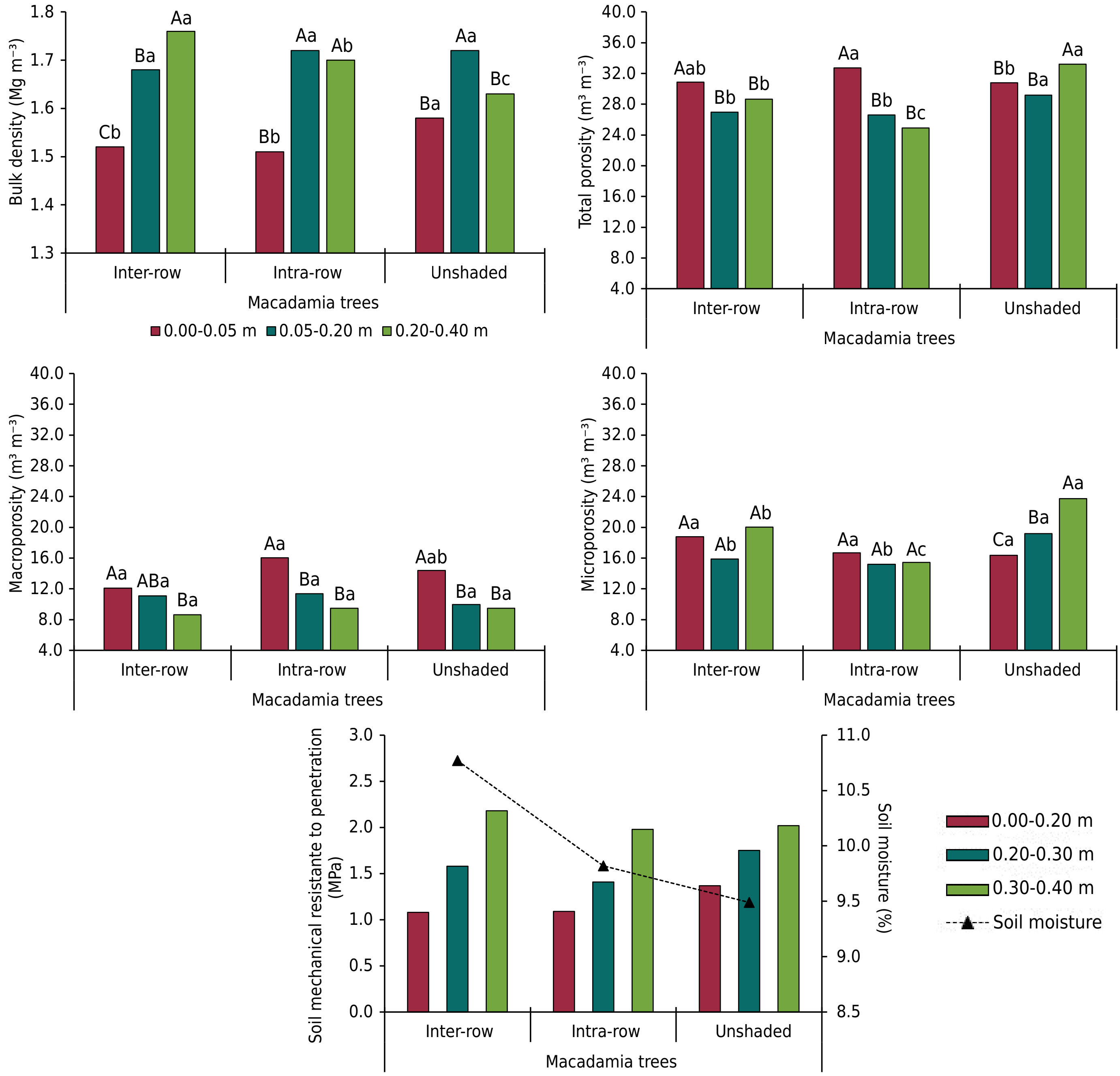

Figure 3. Bulk density (a), total porosity (b), macroporosity (c), microporosity (d), and soil mechanical resistance to penetration (e) of the coffee–macadamia intercropping system at three sampling layers and positions. * Averages followed by the same uppercase letter for layer and lowercase for position do not differ statistically according to Tukey's test, at 5 % significance level.

and Fe. Potassium content differed only among layers, with 54.67 mg dm^{-3} at 0.00-0.05 m, 28.33 mg dm^{-3} at 0.05-0.20 m, and 25.00 mg dm^{-3} at 0.20-0.40 m.

Treatments comparison showed that pH, Ca^{2+}, Mg^{2+}, SB, and V tend to present higher values in shaded treatments at all layers – different than Al and m (Table 1). Organic matter was significantly higher for shaded treatments than unshaded ones (Table 1). The CTC only differed for 0.00-0.05 m, with highest values for the inter-row coffee–macadamia intercropping, followed by intra-row and unshaded treatments (Table 1). Inter-row coffee–macadamia intercropping also showed higher sodium contents (7.83 mg dm^{-3}), followed by intra-row (5.50 mg dm^{-3}) and unshaded treatments (3.92 mg dm^{-3}) (Table 1).

Regarding green dwarf coconut–coffee intercropping, the analysis of variance showed no significant differences for layer and isolated treatments, nor for their interaction, whose

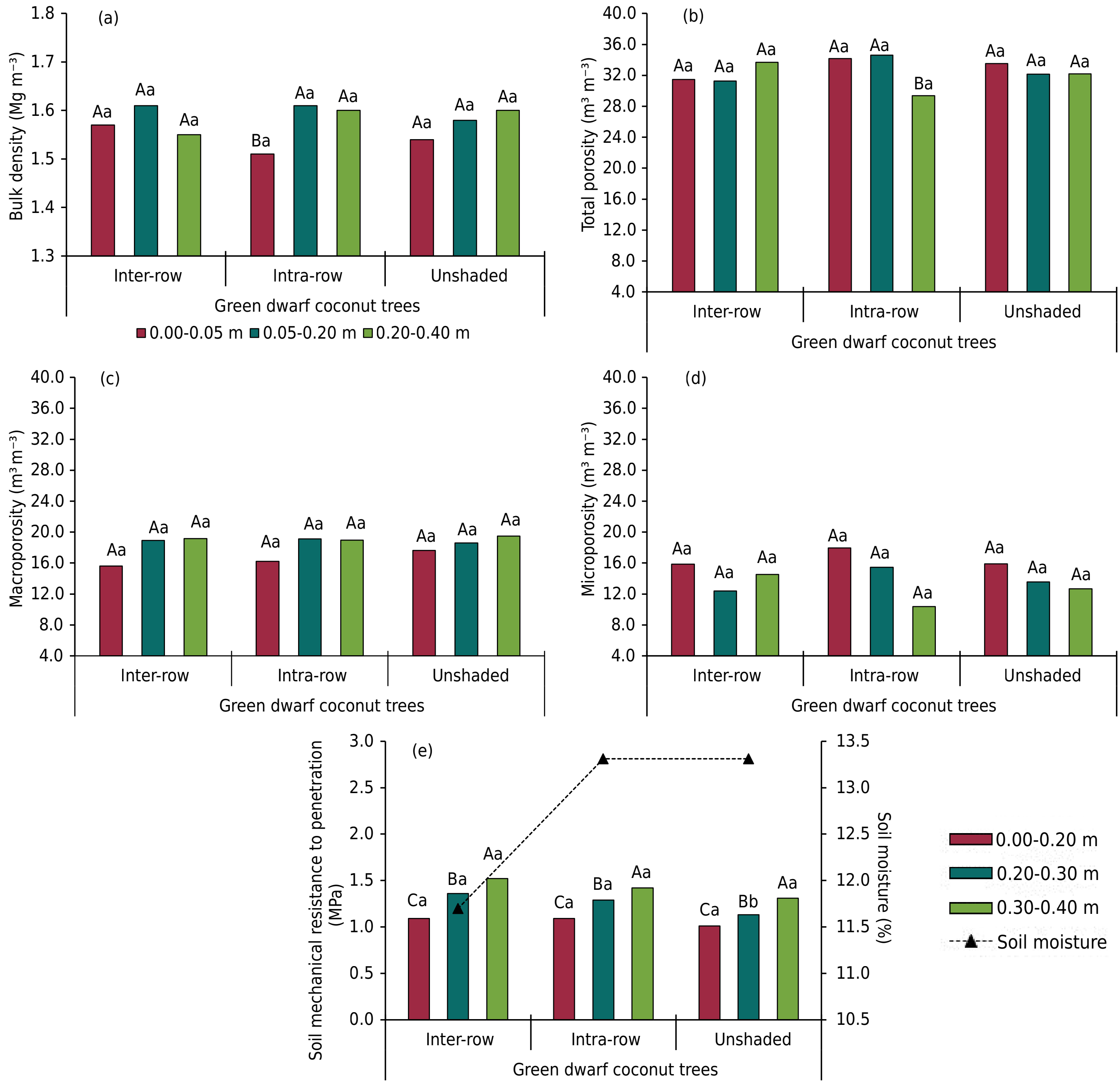

Figure 4. Bulk density (a), total porosity (b), macroporosity (c), microporosity (d), and soil mechanical resistance to penetration (e) of the green dwarf coconut–coffee intercropping system at three sampling layers and sampling positions. * Averages followed by the same uppercase letter to layer and lowercase to position, do not differ statistically according to Tukey's test, at 5 %.

general means of each property are also presented in table 1. The exception was soil pH, presenting higher values at 0.00-0.05 m (Table 1).

Soil biological properties

Shaded intercropped systems presented more groups, including soil organism components, than non-shaded systems, both intra- and inter-row (Figure 5). Fungivores and Saprophages were the most expressed groups in both intercropping systems, accounting for approximately 36 and 38 %, respectively, in dwarf coconut trees–coffee, and 38 and 37.5 % in coffee–macadamia (Figure 5).

Regarding dwarf coconut trees–coffee intercropping, macrofauna density differed among the three evaluated treatments at both soil surface and at 0.00-0.10 m (Table 2), with a greater number of individuals. The same was observed for macadamia intercropping

(Table 2), with a greater density at the surface when compared to other layers. We found no difference regarding population density between surface and 0.00-0.10 m for inter-row and unshaded treatments.

As for microfauna biomass, we verified a higher value at 0.10-0.20 m for inter-row treatment in green dwarf coconut–coffee intercropping (Table 3). The same was observed for intra-row treatments at 0.00-0.10 m. We verified no difference among layers for unshaded treatment.

In macadamia–coffee intercropping, the higher values of macrofauna biomass were recorded for intra-row treatments to surface (2.31 g m^{-2}) (Table 3). Analyzing only in the inter-row of arboreal species, the layer of 0.00-0.10 m presented higher values of macrofauna biomass (1.81 g m^{-2}).

We found no significant differences in basal soil respiration in the green dwarf coconut–coffee intercropping. Furthermore, the 25-day cumulative basal respiration was quite similar for both intercropping systems. At the evaluated layers, unshaded coffee plants showed higher CO_2 emission by microbial activity, followed by intra-row and inter-row cultivation (Figure 6). Microbial activity, evaluated by the average daily CO_2 emission, was 28 % lower in the shaded system than in the unshaded one (2.31 *vs*. 1.67 mg g^{-1} CO_2 of dry soil).

We observed a slight drop in basal respiration with increasing depth of soil profile, especially for macadamia intercropping. Unshaded system showed higher baseline respiration values (Figure 7).

DISCUSSION

Soil physical properties

Unshaded soils retain less water on their surface due to increased evaporation, thus favoring BD. When coffee plants were grown in the inter-rows, shaded soil was more compacted than unshaded ones at 0.10-0.20 and 0.20-0.40 m layers. It is possible that with the presence of two crops in the same area, there was greater

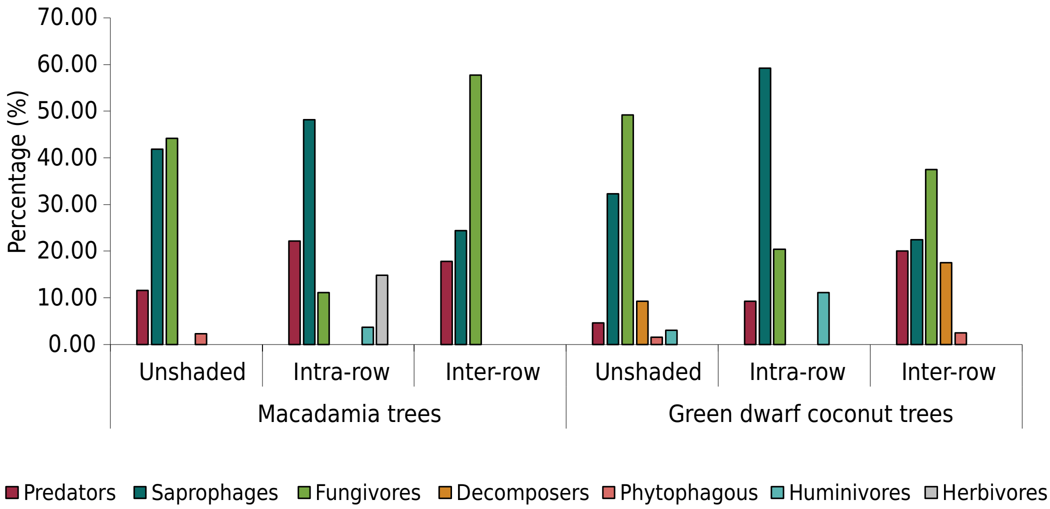

Figure 5. Percentage of functional groups for areas of coffee intercropped with macadamia trees and green dwarf coconut trees.

Table 1. Soil chemical properties at three sampling layers and positions of an area of coffee intercropped with macadamia nuts trees and green dwarf coconut trees, located in São Mateus, Espírito Santo State - Brazil

Property	Layer	Macadamia trees			Green dwarf coconut trees
		Inter-row	Intra-row	Unshaded	Averages
	m				
pH	0.00-0.05	6.27 Aa	6.47 Aa	6.41 Aa	6.33 a
	0.05-0.20	5.76 ABb	5.87 Ab	5.30 Bb	5.15 b
	0.20-0.40	5.46 Ab	5.51 Ab	4.51 Bc	4.97 b
P (mg dm^{-3})	0.00-0.05	13.70 Aa	14.69 Aa	12.48 Ba	7.12
	0.05-0.20	4.20 Ab	2.59 Bb	4.07 Ab	
	0.20-0.40	1.93 Ac	1.63 Ab	2.13 Ac	
Ca^{2+} (cmol$_c$ dm^{-3})	0.00-0.05	3.56 Aa	3.55 Aa	2.67 Ba	2.02
	0.05-0.20	1.69 ABb	1.80 Ab	1.47 Bb	
	0.20-0.40	1.41 Ab	1.36 ABc	1.10 Bc	
Mg^{2+} (cmol$_c$ dm^{-3})	0.00-0.05	2.03 Aa	1.81 Ba	1.38 Ca	0.65
	0.05-0.20	0.90 Bb	1.16 Ab	0.76 Bb	
	0.20-0.40	0.76 Ab	0.68 ABc	0.47 Bc	
Al^{3+} (cmol$_c$ dm^{-3})	0.00-0.05	0.01 Aa	0.00 Aa	0.00 Ac	0.19
	0.05-0.20	0.06 Ba	0.03 Ba	0.25 Ab	
	0.20-0.40	0.10 Ba	0.10 Ba	0.64 Aa	
Organic matter (g kg^{-1})	0.00-0.05	30.07 Aa	28.70 Aa	22.38 Ba	21.44
	0.05-0.20	14.68 Ab	16.04 Ab	16.64 Ab	
	0.20-0.40	10.82 Ab	11.24 Ac	13.25 Ab	
CTC (cmol$_c$ dm^{-3})	0.00-0.05	8.26 Aa	7.36 Ba	5.71 Ca	5.02
	0.05-0.20	5.32 Ab	5.57 Ab	5.22 Aa	
	0.20-0.40	4.79 Ab	4.89 Ab	5.37 Aa	
Sum of bases (SB) (cmol$_c$ dm^{-3})	0.00-0.05	5.76 Aa	5.53 Aa	4.21 Ba	2.83
	0.05-0.20	2.70 ABb	3.05 Ab	2.33 Bb	
	0.20-0.40	2.29 Ab	2.12 Ac	1.64 Bc	
Base saturation (V) (%)	0.00-0.05	70.11 Aa	75.12 Aa	73.85 Aa	2.83
	0.05-0.20	50.12 ABb	54.78 Ab	44.97 Bb	
	0.20-0.40	48.00 Ab	43.36 Ac	30.63 Bc	
Aluminum saturation (m) (%)	0.00-0.05	0.22 Aa	0.00 Aa	0.00 Ac	9.88
	0.05-0.20	2.91 Ba	1.27 Ba	9.64 Ab	
	0.20-0.40	4.22 Ba	4.57 Ba	27.69 Aa	
Fe (mg dm^{-3})	0.00-0.05	46.40 Ac	55.45 Ac	48.05 Ac	75.35
	0.05-0.20	131.78 Bb	156.00 Ab	97.07 Cb	
	0.20-0.40	154.25 Ba	199.63 Aa	123.64 Ca	
Cu (mg dm^{-3})	0.00-0.05	0.52 Ba	0.70 Aa	0.58 Ba	0.34
	0.05-0.20	0.44 Bab	0.49 ABb	0.55 Aab	
	0.20-0.40	0.37 Bb	0.50 Ab	0.47ABb	
Zn (mg dm^{-3})	0.00-0.05	3.31 Aa	3.03 Aa	1.17 Ba	1.22
	0.05-0.20	0.88 Ab	0.92 Ab	0.37 Ab	
	0.20-0.40	0.44 Ab	0.35 Ab	0.27 Ab	
Mn (mg dm^{-3})	0.00-0.05	16.49 Aa	18.91 Aa	10.01 Ba	7.97
	0.05-0.20	6.62 Ab	8.36 Ab	4.92 Ab	
	0.20-0.40	3.13 Ab	3.78 Ac	3.49 Ab	

Continue

Continuation

Property	Layer	Macadamia trees			Green dwarf coconut trees
		Inter-row	Intra-row	Unshaded	Averages
Na (mg dm^{-3})	Not significant for depth	7.83 A	5.50 B	3.92 B	NS
K (mg dm^{-3})	0.00-0.05		54.67 a		NS
	0.05-0.20		28.33 b		
	0.20-0.40		25.00 b		

Averages followed by the same uppercase letter in the row and lowercase letters in the column do not differ statistically from each other, according Tukey's test, at 5 % probability.

movement of machines to carry out cultural treatments. This traffic over the years, even of small machinery, may have contributed to greater BD inter-row of coffee. Shaded systems contribute to intake of plant residues by the soil, especially from 0.00-0.05 m, thus increasing OM content and Ma while reducing BD, thereby improving soil physical quality (Souza et al., 2016).

Regarding macadamia intercropping, coffee shaded showed the lowest values of RP at up to 0.30 m, and soils were more structured than those unshaded. However, below 0.30 m, coffee plants grown in the inter-rows of macadamia trees resulted in higher RP, which, according to Arshad et al. (1996), may affect the root system. The presence of macadamia in the area, in addition to the cultural treatments required by the Conilon coffee, requires pruning, fertilization, harvesting, and phytosanitary treatments, all of which are mechanized. Over the years, it may have contributed to increase in RP in the subsurface, correlating with the results obtained by BD.

Higher RP values in unshaded system indicate that a less protected soil surface may lack OM. This occurs because shaded systems imply the presence of related tree components, which favors the continuous deposition of plant residues and enables soil OM maintenance. These factors contribute to the close arrangement of soil particles due to the effects of OM incorporation into the soil. Layer compaction in the subsurface restricts root growth, causing roots to concentrate close to the surface (Gonçalves et al., 2006).

Soil physical alterations promoted a significant reduction in Ma and a small reduction in Mi, most evident at the highest layers. These results differ from those observed by Carmo et al. (2014) and Jácome et al. (2020), who found no differences in BD, Ma, Mi,

Table 2. Macrofauna density (individuals m^{-2}) at three sampling layers and positions of an area of coffee intercropped with macadamia nuts trees and green dwarf coconut trees, located in São Mateus, Espírito Santo - Brazil

Vegetation	Layer	Inter-row	Intra-row	Unshaded
	m			
Macadamia trees	Surface	104.0 Aa	88.50 Aa	65.5 Aa
	0.00-0.10	106.75 Aa	21.25 Bb	64.0 ABa
	0.10-0.20	0.0 Ab	8.0 Ab	16.0 Aa
	0.20–0.30	0.0 Ab	0.0 Ab	0.0 Aa
Green dwarf coconut trees	Surface	116.0 Aa	93.0 ABb	56.0 Bab
	0.00-0.10	96.0 Ba	147.25 Aa	96.0 Ba
	0.10-0.20	40.5 Ab	20.0 Ac	19.5 Abc
	0.20-0.30	0.0 Ab	0.0 Ac	0.0 Ac

Averages followed by the same uppercase letter in the row and lowercase letters in the column do not differ statistically from each other, according to Tukey's test, at 5 % probability.

Table 3. Macrofauna biomass at three sampling layers and positions of an area of coffee intercropped with macadamia nuts trees and green dwarf coconut trees, located in São Mateus, Espírito Santo - Brazil

Vegetation	Layer	Inter-row	Intra-row	Unshaded
	m		$g\ m^{-2}$	
Macadamia trees	Surface	0.41 Bb	2.31 Aa	0.59 Ba
	0.00-0.10	1.81 Aa	1.28 Ab	0.04 Ba
	0.10-0.20	0.00 Ab	0.13 Ac	0.64 Aa
	0.20-0.30	0.00 Ab	0.00 Ac	0.00 Aa
Green dwarf coconut trees	Surface	2.14 Ab	0.26 Bc	0.72 Ba
	0.00-0.10	1.37 Bb	3.25 Aa	0.45 Ba
	0.10-0.20	4.23 Aa	1.61 Bb	0.18 Ca
	0.20-0.30	0.00 Ac	0.00 Ac	0.00 Aa

Averages followed by the same uppercase letter in the row and lowercase letters in the column do not differ statistically from each other, according Tukey's test, at 5 % probability.

and total porosity between agroforestry and conventional coffee management systems. This may be justified since the use of unlike tree species in the consortia with Conilon coffee and other times and management of the areas influence soil physical properties in different ways (Souza et al., 2016).

In absolute terms, Ma was not as affected in green dwarf coconut–coffee intercropping as in coffee–macadamia. This may be because coffee consortia with green dwarf coconut is a newer method that includes fewer plants when compared with the macadamia. For this reason, this system presents higher BD values and slightly lower TP values, which is consistent with the soil type (characteristically more compressed, whose texture is medium on horizon A and clayey in horizon B). Besides coffee plants, the presence of macadamia and green dwarf coconut trees account for part of the soil mass, which improves root pressure looking for space. This may increase BD and reduce porosity, for root growth brings soil particles closer, thus compacting the soil (Reichert et al., 2009). In macadamia intercropping area, porosity values are close to or below 0.10 $m^3\ m^{-3}$ – the minimum suitable value for liquid and gaseous exchanges between the external environment and soil, a critical factor for root growth of most crops (Taylor and Ashcroft, 1972).

Together with treatments, the pedogenetic aspect explains depth profile results. Shaded systems contribute to plant residue intake by the soil, which increases OM content in the surface layers and reduces RP values, especially at 0.00-0.05 m. In areas shaded with coconut trees, even the highest soil moisture (0.00-0.20 m) was insufficient to reduce RP (Figure 4e). These results are in line with those reported by Souza et al. (2017) when evaluating unshaded treatment with secondary forest shading.

In opposition to results for the macadamia intercropping system, unshaded coffee always presented the lowest RP at the two deepest layers to intercropping with green dwarf coconut (Figure 4e). This finding may indicate that coffee plants intercropped with coconut trees promote no improvements in soil physical quality. Nevertheless, besides being below the critical value for root development, green dwarf coconut–coffee intercropping reached lower values than macadamia intercropping, possibly due to this area higher soil moisture (Figure 4e).

Soil chemical properties

All treatments showed higher pH, P, Ca^{2+}, Mg^{2+}, OM, CTC, SB, V, Cu, Zn, and Mn at 0.00-0.05 m, probably due to the application of correctives and fertilizers without incorporation into the soil. These findings corroborate those reported by Jácome et al. (2020), who verified a significant difference for pH, OM, and P content at 0.00-0.10 m when comparing mean values of agroforestry and conventional coffee cultivation. However, the authors found no differences regarding other chemical properties (Ca^{2+},

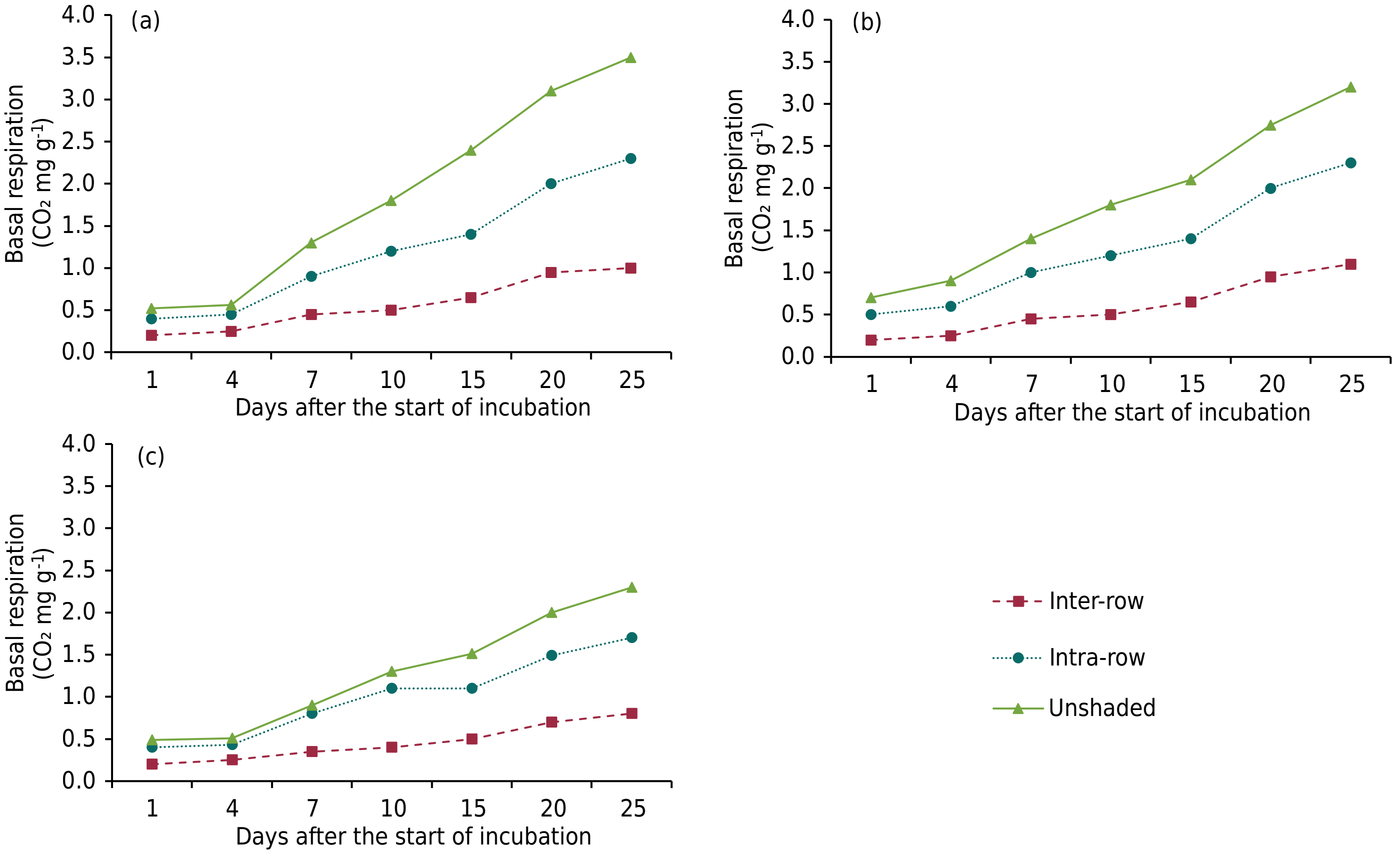

Figure 6. Basal soil respiration in an area of coffee intercropped with macadamia trees at three sampling layers – 0.00-0.05 m (a), 0.05-0.20 m (b), and 0.20-0.40 m (c).

Mg^{2+}, S, B, Cu, Fe, Mn, Zn, and base saturation) between both production systems, thus opposing our results. This suggests that, despite changing the production system and incorporating organic residues from coconut leaves into the soil, coffee plants intercropped with green dwarf coconut exerts no influence on soil fertility. One of the reasons may be the high degree of lignification and higher C/N ratio of coconut leaves compared to macadamia, which gives it a slower mineralization rate and nutrient cycling. This also may be explained by the trees nutritional demand and possible competition among roots, for this system requires large amounts of nutrients for fruit formation. In addition, the incorporation process itself is slow, as the residues remain on the surface for a long time. The same was observed for coffee plants intercropped with inga tree and grevillea, which did not improve soil chemical conditions when compared to the unshaded system (Salgado et al., 2006).

Aluminum I exchangeable and Al saturation levels differed only when coffee was grown under unshaded environment. This may be attributed to the low mobility of corrective in perennial systems, which may lead to chemical impedance for root growth due to exchangeable acidity when insufficient to provide neutralization. Therefore, Fe contents may be related to the soil type in question – a Typic Hapludox (*Argissolo Amarelo*), whose abrupt transition between horizons A and B occurs around 0.25 m depth, on average, below which the high contents of Goethita mixed with Caulinite originate the typical yellow color (Moreau et al., 2006).

We found a tendency for pH, Ca^{2+}, Mg^{2+}, SB, and V to present higher values in shaded treatments, which is in line with results reported by Carmo et al. (2014), who found higher levels of Ca^{2+}, Mg^{2+}, and V% and lower levels of Al^{3+} at 0.00-0.20 m for coffee intercropped with banana, eucalyptus, and native trees when compared to conventional cultivation. The higher amount of OM in shaded soils increases carbon and humic acid contents, which indicates greater carbon stabilization in forms responsible for OM charges, thus

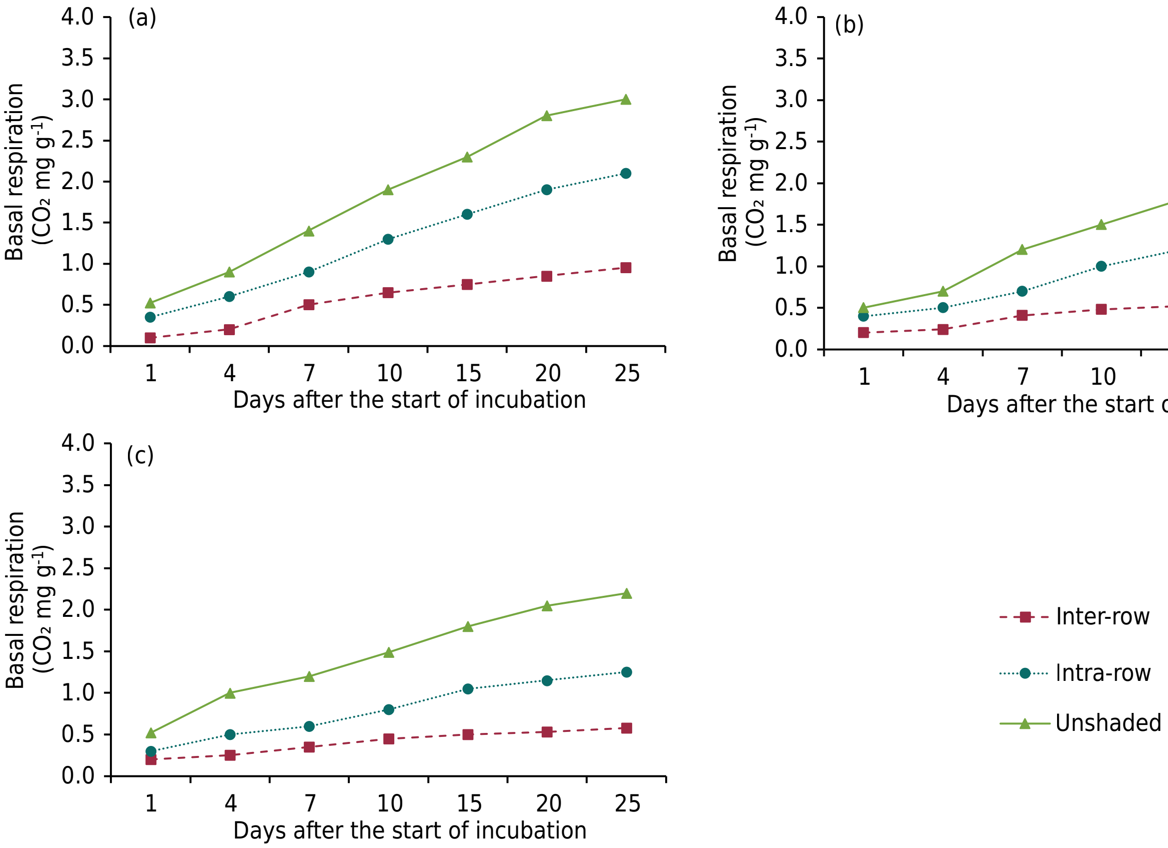

Figure 7. Basal soil respiration in area of coffee intercropped with green dwarf coconut trees at three sampling layers – 0.00-0.05 m (a), 0.05-0.20 m (b), and 0.20-0.40 m (c).

contributing to CEC, water retention capacity, and micro-aggregates stability (Baldotto and Baldotto, 2014).

Regarding the OM, CEC, and V%, we found significantly higher levels on the surface layer of shaded treatments when compared to unshaded ones, but not on other layers, indicating that litter influence does not reach subsurface. We found similar trends for Zn, Mn, and P (Table 1). Coffee plants located in the same row as macadamia trees tend to present higher levels of Cu, which may be because Cu is the micronutrient that most interacts with soil organic compounds, forming stable complexes (Dhaliwal et al., 2019).

Coffee intercropped with macadamia trees showed the best fertility in a general analysis, which may be due to an increase in OM, nutrients recycling, and maintenance of a litter layer in the soil (macadamia trees have a larger canopy than green dwarf coconut), whose plant residues are at different stages of decomposition (Tanga et al. 2014).

Soil biological properties

Higher values of macrofauna density in the intercropping systems are probably due to environmental improvement, which provided the ideal moisture and nutrient conditions for soil organisms establishment. Edaphic fauna is sensitive to physical and chemical environmental changes, as well as to changes arising from soil management practices (Alves et al., 2020). In this scenario, the microclimate is an important factor for both crops and soil microorganisms, which set nutrients cycling upon finding lower temperature, high humidity, among other factors (Martius et al., 2004).

Higher percentage of functional groups of Saprophages in the intercropping systems also entails a greater increase of OM. This occurs because these insects ingest, fragment, and modify OM, thus providing nutrients such as N, P, K, Ca and Mg to the soil. Thus, the role of saprophagous organisms in decomposition is fundamental for nutrient cycling. These organisms also act on the movement of manure in the soil depth; construction of mounds, galleries, and nests; ingestion and excretion of active materials; participation in biogeochemical cycles; availability of nutrients; and contribution to soil structure (Kitamura et al., 2020).

Besides its association with OM, the greater density and biomass of macrofauna in intercropped systems can be explained by the fact that it provides ideal conditions for the development of higher-mass groups such as annelids and blattodeas. This is especially true for dwarf coconut intercropping systems, in which straw management occurs in the soil, in between crop rows. Macrofauna biomass relies heavily on the management of applied practices, food availability, and OM content, as well as humidity and temperature, for these organisms are susceptible to environmental changes so that intercropping systems may result in an environment with decaying OM (Pompeo et al., 2016). On the other hand, unshaded systems include a lower density and biomass of macrofauna, which owes to the lower content of organic residues in the soil.

Greater evolution of CO_2 in unshaded coffee can be due to types of soil carbon, which are less recalcitrant than those found in intercropping treatments. This may be justified by the greater decomposition speed of leaves and senescent plant material, resulting from the higher radiation and temperatures under the unshaded treatment. Decomposition rate of soil OM increases with temperature, generating CO_2, which is released in the atmosphere.

The difference between the wooded treatments may be due to the greater supply of inter-row residues or the presence of low-molecular-weight organic-acids, whose exudation can be influenced by macadamia and green dwarf coconut trees in the inter-row of coffee plants. In general, the faunal community structure is stable in systems shaded by woody vegetation and less affected by soil management practices in more conventional systems.

CONCLUSION

When compared to unshaded systems, coffee plants intercropped with macadamia trees, both intra- and inter-row, result in less resistance to penetration. As for intercropping with green dwarf coconut trees, the unshaded system presents lower soil resistance to penetration. Differences among treatments do not suffice to allow inferences about the influence of intercropping systems on soil density, total porosity, and macro- and microporosity. Coffee–macadamia intercropping improves soil chemical properties, resulting in higher soil fertility than the unshaded production system; however, the same is not true for green dwarf coconut–coffee intercropping. Both intra- and inter-row intercropping cultivation provides greater soil organisms. Unshaded coffee cultivation resultes in greater CO_2 production by microbial activity, followed by intra- and inter-row systems, respectively. Coffee intercropping with tree species represents a promising alternative for good soil management, aiming at environmental sustainability.

ACKNOWLEDGEMENTS

This study was supported by the National Council for Scientific and Technological Development (CNPq). The authors also thank the Universidade Federal do Espírito Santo for granting scholarships.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-48-e0230056/1806-9657-rbcs-48-e0230056-suppl01.pdf

AUTHOR CONTRIBUTIONS

Conceptualization: Fábio Ribeiro Pires (lead) and José Ricardo Macedo Pezzopane (supporting).

Data curation: Fábio Ribeiro Pires (lead), Joabe Martins de Souza (equal) and Adriel Lima Nascimento (equal).

Formal analysis: Fábio Ribeiro Pires (lead), Kristhiano Chagas (equal), Alex Favaro Nascimento (equal) and José de Oliveira Rodrigues (supporting).

Funding acquisition: José Ricardo Macedo Pezzopane (lead).

Investigation: Fábio Ribeiro Pires (lead), Marcio Paulo Czepak (equal), Joabe Martins de Souza (equal) and José Ricardo Macedo Pezzopane (supporting).

Methodology: Fábio Ribeiro Pires (lead).

Project administration: Fábio Ribeiro Pires (lead), Alex Favaro Nascimento (equal) and Adriel Lima Nascimento (equal).

Resources: José Ricardo Macedo Pezzopane (lead).

Supervision: Fábio Ribeiro Pires (lead) and José Ricardo Macedo Pezzopane (supporting).

Writing – original draft: Fábio Ribeiro Pires (lead), Joabe Martins de Souza (equal), Marcio Paulo Czepak (equal), José Ricardo Macedo Pezzopane (equal) and Adriel Lima Nascimento (equal).

Writing – review & editing: Fábio Ribeiro Pires (lead), Joabe Martins de Souza (equal) and Adriel Lima Nascimento (equal).

REFERENCES

Almeida LF, Zylbersztajn D. Key success factors in the brazilian coffee agrichain: Present and future challenges. Int J Food System Dynamics. 2017;8:45-53. https://doi.org/10.18461/ijfsd.v8i1.814

Alves MV, Naibo G, Sbruzz EK, Machado JS, Nesi CN. Soil fauna in different land uses. Acta Biol Catarinense. 2020;7:37-45. https://doi.org/10.21726/abc.v7i1.159

Arshad MA, Lowery B, Grossman B. Physical tests for monitoring soil quality. In: Doran JW, Jones AJ, editors. Methods for as-sessing soil quality. Madison: Soil Science Society of America; 1996. p. 123-41.

Baldotto MA, Baldotto LEB. Humic acids. Rev Ceres. 2014;61:856-81. https://doi.org/10.1590/0034-737X201461000011

Balota EL. Manejo e qualidade biológica do solo. Londrina: Mecenas; 2017.

Carmo DL, Nannetti DC, Dias Junior MS, Lacerda TM, Nannetti AN, Manuel L. Chemical and physical attributes of a Latosol and coffee crop nutrition in agroforestry and conventional management systems. Coffee Sci. 2014;9:122-31.

Cerda R, Allinne C, Gary C, Tixier P, Harvey CA, Krolczyk L, Mathiot C, Clément E, Aubertot JN, Avelino J. Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. Eur J Agron. 2017;82:308-19. https://doi.org/10.1016/j.eja.2016.09.019B

Cruz CD. GENES - A software package for analysis in experimental statistics and quantitative genetics. Acta Sci Agron. 2013;35:271-6. https://doi.org/10.4025/actasciagron.v35i3.21251

Dhaliwal SS, Naresh RK, Mandal A, Singh R, Dhaliwal MK. Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review. Environ Sustain Indic. 2019;1-2:100007. https://doi.org/10.1016/j.indic.2019.100007

Donagema GK, Campos DVB, Calderano SB, Teixeira WG, Viana JHM. Manual de métodos de análise do solo. 2. ed. rev. Rio de Janeiro: Embrapa Solos; 2011.

Fahad S, Chavan SB, Chichaghare AR, Uthappa AR, Kumar M, Kakade V, Pradhan A, Jinger D, Rawale G, Yadav DK, Kumar V, Farooq TH, Ali B, Sawant AV, Saud S, Chen S, Poczai P. Agroforestry systems for soil health improvement and maintenance. Sustainability. 2022;14:14877. https://doi.org/10.3390/su142214877

Gomes LC, Bianchi FJJA, Cardoso IM, Fernandes RBA, Fernandes Filho EI, Schulte RPO. Agroforestry systems can mitigate the impacts of climate change on coffee production: A spatially explicit assessment in Brazil. Agr Ecosyst Environ. 2020;294:106858. https://doi.org/10.1016/j.agee.2020.106858

Gonçalves WG, Jimenez RL, Araújo JV, Assis RL, Silva GP, Pires FR. Root system of cover crops under soil compaction. Eng Agric. 2006;26:67-75. https://doi.org/10.1590/S0100-69162006000100008

Hoffland E, Kuyper TW, Comans RNJ, Creamer RE. Eco-functionality of organic matter in soils. Plant Soil. 2020;455:1-22. https://doi.org/10.1007/s11104-020-04651-9

Jácome MGO, Mantovani JR, Silva AB, Rezende TT, Landgraf PRC. Soil attributes and coffee yield in an agroforestry system. Coffee Sci. 2020;15:e151676. https://doi.org/10.25186/.V15I.1676

Kitamura AE, Tavares RLM, Alves MC, Souza ZM, Siqueira DS. Soil macrofauna as bioindicator of the recovery of degraded Cerrado soil. Cienc Rural. 2020;50:e20190606. https://doi.org/10.1590/0103-8478cr20190606

Martius C, Garcia MVB, Hanagarth W, Höfer H, Römbke J, Förster B. Microclimate in agroforestry systems in central Amazonia: Does canopy closure matter to soil organisms? Agrofor Syst. 2004;291-304. https://doi.org/10.1023/B:AGFO.0000024419.20709.6c

Moreau AMSS, Costa LM, Ker JC, Gomes FH. Genesis of hardened horizons, fragipan and duripan in soils of the coastal tablelands of south bahia. Rev Bras Cienc Solo. 2006;30:1021-30. https://doi.org/10.1590/s0100-06832006000600011

Moreira SLS, Pires CV, Marcatti GE, Santos RHS, Imbuzeiro HMA, Fernandes RBA. Intercropping of coffee with the palm tree, *macauba*, can mitigate climate change effects. Agr Forest Meteorol. 2018;256-257:379-90. https://doi.org/10.1016/j.agrformet.2018.03.026

Murta JRMM, Brito GQB, Mendonça Filho SF, Hoffmann MR, Salemi LF. Understanding the effect of an agroforestry system with high litter input on topsoil permeability. Soil Use Manage. 2021;37:802-9. https://doi.org/10.1111/sum.12647

Pezzopane JRM, Marsetti MMS, Souza JMM, Pezzopane JEM. Microclimatic alterations in a conilon coffee crop grown shaded by macadamia nut tree. Cienc Rural. 2010;40:1257-63. https://doi.org/10.1590/S0103-84782010005000098

Pezzopane JRM, Souza OS, Rolim GS, Gallo PB. Microclimate in coffee plantation grown under grevillea trees shading. Acta Sci Agron. 2011;33:201-6. https://doi.org/10.4025/actasciagron.v33i2.7065

Pompeo PN, Santos MAB, Biassi JP, Siqueira S, Rosa MG, Baretta CRDM, Baretta D. Fauna and its relation to edaphic attributes in Lages, Santa Catarina - Brazil. Sci Agrar. 2016;17:42-51. https://doi.org/10.5380/rsa.v17i1.46535

Quandt A, Neufeldt H, Gorman K. Climate change adaptation through agroforestry: Opportunities and gaps. Curr Opin Envir Sust. 2023;60:101244. https://doi.org/10.1016/j.cosust.2022.101244

Reichert JM, Suzuki LEAS, Reinert DJ, Horn R, Håkansson I. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Till Res. 2009;102:242-54. https://doi.org/10.1016/j.still.2008.07.002

Rigal C, Xu J, Vaast P. Young shade trees improve soil quality in intensively managed coffee systems recently converted to agroforestry in Yunnan Province, China. Plant Soil. 2020;453:119-37. https://doi-org.ez43.periodicos.capes.gov.br/10.1007/s11104-019-04004-1

Salgado BG, Macedo RLG, Alvarenga MIN, Venturin N. Evaluation of soil fertility in agroforest systems with coffee trees (*Coffea arabica* L.) in Lavras-MG. Rev Arvore. 2006;30:343-9. https://doi.org/10.1590/s0100-67622006000300004

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.

Souza GS, Alves DI, Dan ML, Lima JSS, Fonseca ALCC, Araújo JBS, Guimarães LAOP. Soil physico-hydraulic properties under organic conilon coffee intercropped with tree and fruit species. Pesq Agropec Bras. 2017;52:539-47. https://doi.org/10.1590/S0100-204X2017000700008

Souza GS, Dan ML, Araújo JBS. Soil physical quality on conilon coffee intercropping and monoculture. Coffee Sci. 2016;11:180-6.

Stolf R. Theory and experimental test of transformation formulas of impact penetrometer data in soil resistance. Rev Bras Cienc Solo. 1991;15:229-35.

Tanga AA, Erenso TF, Bekele L. Effects of three tree species on microclimate and soil amelioration in the central rift valley of Ethiopia. J Soil Sci Environ Manage. 2014;5:62-71. https://doi.org/10.5897/jssem12.060

Taylor SA, Ashcroft GL. Physical edaphology. The physics of irrigated and non irrigated soils. San Francisco: W.H. Freeman; 1972.

Thomazini A, Mendonça ES, Cardoso IM, Garbin ML. SOC dynamics and soil quality index of agroforestry systems in the Atlantic rainforest of Brazil. Geoderma Reg. 2015;5:15-24. https://doi.org/10.1016/j.geodrs.2015.02.003

Valencia V, Naeem S, García-Barrios L, West P, Sterling EJ. Conservation of tree species of late succession and conservation concern in coffee agroforestry systems. Agr Ecosyst Environ. 2016;219:32-41. https://doi.org/10.1016/j.agee.2015.12.004

Vincent Q, Auclerc A, Beguiristain T, Leyval C. Assessment of derelict soil quality: Abiotic, biotic and functional approaches. Sci Total Environ. 2018;613-614:990-1002. https://doi.org/10.1016/j.scitotenv.2017.09.118

Wang Z, Zheng F. Impact of vegetation sucession on leaf-litter-soil C:N:P stoichiometry and their intrinsic relationship in the Ziwuling Area of China's Loess Plateau. J For Res. 2021;32:697-711. J. https://doi.org/10.1007/s11676-020-01149-z