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SOIL PHYSICAL QUALITY OF AN ULTISOL IN COFFEE AREAS WITH DIFFERENT DEPLOYMENT TIMES

Maria Cecília Vieira Totti

Fabio Henrique Barbosa Sandoval

Elizeu De Souza Lima

Zigomar Menezes de Souza

Vinicius Ferreira Fernandes

Andres Olaya Montes

Junior Cesar Avanzi

Ingrid Nehmi de Oliveira Ziolli

Diego Alexander Aguilera Esteban

Lenon Henrique Lovera

Abstract: The mechanization of coffee crops changes the soil structure due to intense machinery traffic, causing soil compaction, especially during harvesting. Soil attributes are important for the development of sustainable coffee farming as they can be indicators of soil quality. Therefore, we aimed to evaluate the soil physical quality in coffee crops with different deployment times and a native forest, using a sensitivity index. The experiment was conducted in a Ultisol (Argissolo Vermelho amarelo) in Muzambinho, Minas Gerais, Brazil. The soil samples were collected in February 2017, in coffee crops of different deployment times (3, 16 and 32 years) and in an area of native forest for comparison purposes. The 32-year-old crop was harvested manually due to its age, while the 3 and 16-year-old areas were harvested with a self-propelled harvester. Samples were collected in the planting row (R), under the coffee canopy (UCC) and in inter-row center (IRC), at depths of 0.00-0.10, 0.10-0.20 and 0.20-0.40 m, with three replications. In general, the largest accumulations of organic matter (OM) are in the 0.00-0.10 m layer at the inter-row center, and the 16-year-old crop showed the highest OM contents at UCC and IRC. Soil compaction increases with proximity to traffic lanes, regardless of crop age. The sensitivity index proved to be an efficient tool for comparison, indicating high soil sensitivity to coffee crop management and deployment time. However, despite the high sensitivity of the attributes, they do not present values that limit crop development, close to values found at forest area.

Keywords: Soil structure, soil health, soil compaction, soil aggregates.

INTRODUCTION

Coffee is one of the most popular beverages. Its significant impact on the world economy and people's well-being has been recognized due to the increase in exports and re-exports, which have grown consistently over the past five decades (Sunarharum et al., 2018). According to Conab (2020), the area allocated for farming coffee (*Coffea* spp) in Brazil in the 2020 harvest totals 1,885.5 thousand hectares, for an estimated production of 62.02 million 60-kg bags, accounting for 46% of global production. The demand for high-quality coffee for consumption is steadily increasing, not only in consumingcountries, but also in producing countries. Coffee quality can be affected by several factors, such as the production environment, which includes type and quality of soil, local climate and crop management methods (Fiorese, 2019).

Currently, Brazilian coffee farming is undergoing a process of technological modernization using agricultural machinery in soil preparation, planting, pest, weed control and harvesting. However, improper soil management resulting from the intense traffic of agricultural machinery in these operations, as well as their use in high soil humidity conditions, can cause changes in the soil physical attributes, with consequent soil compaction and degradation (Santos et al., 2017).

Crop yield is influenced by the soil physical attributes (Fiorese, 2019). Therefore, ascertaining such properties is important to monitor the development of coffee trees, as they are essential to characterize the soil structural quality, determinant for the preservation of high-yield areas and for sustainable coffee farming (Santos et al., 2017). Fernandes et al. (2012), studying the relationship between soil compaction and the productivity of Catuí IAC 51 coffee, concluded that soil compaction can have a 26% to 65%

impact on crop productivity. The effects of soil preparation on its structural quality depends on the variability and sensitivity of its physical attributes.

The soil physical attributes can also be analyzed by means of indexes that indicate changes in soil management systems. Soil aggregation can be estimated by using aggregate stability indexes (ASI), percentage of aggregates with diameter greater than 2 mm (AGRI), geometric mean diameter (GMD) and mean weight diameter (MWD) (Torres et al., 2015). The influence of different soil management methods on its physical attributes can also be assessed by the sensitivity index (Si), which determines the similarity between different areas and can also determine the degree of change in their attributes. (Bolinder et al., 1999).

When used together, these indexes can indicate changes in soil management systems. An example is the work by Torres et al. (2015), who applied the sensitivity index to bulk density, macroporosity, microporosity and total porosity, comparing no-till, conventional, pasture and native field management systems, and found that the greatest variations of Si occurred for macroporosity in the superficial layers. These indexes are also commonly used individually to assess the physical quality of soil in short-term studies (Loss et al., 2015). However, their combined use still needs to be better assessed in long-term studies.

This study therefore tested the hypothesis that indicators of soil structure quality are differently influenced by management systems in coffee crops of different deployment times. The aim was to evaluate the physical attributes of the soil in three coffee crops of different deployment times using a sensitivity index.

MATERIAL AND METHODS

The experiment was carried out in coffee farming areas belonging to *Fazenda Nossa Senhora*, in the municipality of Muzambinho-MG, located at 21º29'19.7" S and 46º30'02.27" W, at an average altitude of 1,026 m. The region's climate is mesothermal with dry winter (Cwa), according to the Köppen climate classification, with temperatures above 22 °C in the warmest month and below 18 °C in the coldest (ALVARES et al., 2013). The annual mean rainfall at the property is 1,408 mm, with more concentrated rainfall from November to March (Cepagri, 2019). The soil was classified as Argissolo Vermelho amarelo according to the Brazilian Soil Classification System Argissolo Vermelho amarelo (Santos et al., 2018) and Utisol according to Soil Taxonomy System (Soil Survey Staff, 2014).

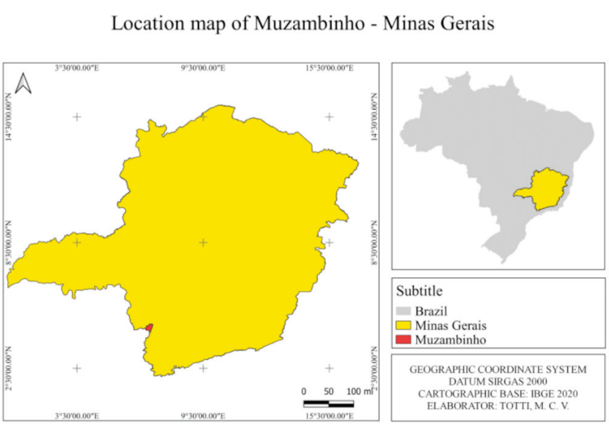


Figure 1. Location map of Muzambinho, state of Minas Gerais, Brazil

The experimental design consisted of randomized blocks subdivided into plots, with sampling depth included as a sub-factor. The experiment was carried out in three coffee crop (*Coffea arabica*) areas of different deployment times at the time of the study in 2016: 3-year-old crop of the Red Catuaí 144 variety, planted in 2014 with 3.6 x 0.6 m spacing in an area of 3.7 ha, totaling 17,000 trees, which were manually harvested in the first year due to their height and age; 16-year-old crop of the Red Catuaí 144 variety, planted in 2001 with 3.6 x 0.7 m spacing in an area of 10.2 ha, totaling 40,500 trees; 32-year-old crop of the Yellow Catuaí 62 variety, planted in 1985 with 4.0 x 1.5 m spacing in an area of 1.5 ha, totaling 2,500 trees. The mechanized farming and harvesting were only introduced in 2012.

Soil tillage consisted of subsoiling operations with a Stara subsoiler, liming (2.0 Mg ha^{-1} of dolomitic limestone), plowing and harrowing with 24-disc harrow with 18” x 3.0 mm blades and mass of 570 kg. Three hundred grams of simple superphosphate and 2 liters of poultry manure applied per linear meter in the furrows. The seedlings were originally planted manually in the pits, after which soil analysis was performed every year to dose the correctives and fertilizers to be applied over the year. The correctives were applied once between June and August and the mineral fertilizer with 20-00-20, 25-00-25 and 20-05-20 was applied in four portions separated by 40 days on average.

The three crops received mechanized cultural and phytosanitary treatment with the use of a Massey Fergusson 275 coffee tractor coupled to an Arbus 400 jet sprayer with a turbine for spraying and leaf fertilization. For herbicide application, an application kit was mounted in the inter-row centers. Fertilization was performed with a 450-kg capacity Commander H10S Kmaq fertilizer attached to the tractor. Harvesting was done with a TDI Electron self-propelled harvester and the fruits on the ground were collected with a Mogiana sweeper collector, model Spirlandelli 25C, coupled to the coffee tractor, following the passage of a Bertanha blower connected to a Yanmar 1150 tractor.

Characterization of soil particles was performed by collecting disturbed soil samples close to the trees at depths of 0.00-0.20 m and 0.20-0.40 m. The particle fractions (sand, silt and clay) were determined by the pipette method using fine soil aired-dried, with 0.1 N sodium hydroxide solution (NaOH) with a dispersing agent (Teixeira et al., 2017) (Table 1).

Depth	Sand	Clay	Silt	Texture
m	------------- **g kg^{-1}** ---------------			
		0.00-0.20		
3 years	327	454	219	Clayey
16 years	331	437	232	Clayey
32 years	242	534	224	Clayey
Forest	295	394	162	Clayey
		0.20-0.40		
3 years	305	469	226	Clayey
16 years	277	488	235	Clayey
32 years	213	559	228	Clayey
Forest	285	422	150	Clayey

Table 1. Characterization of soil particles in coffee crops of different deployment times (3, 16 and 32 years) at 0.00-0.20 and 0.20-0.40 m deep and native forest (0.00-0.10, 0.10-0.20 and 0.20-0.40m).

In February 2017, 45 disturbed and undisturbed soil samples were collected in each coffee crop area, in five trenches at the following sites: planting row (R), under the coffee canopy (UCC) and inter-row center (IRC), and in three layers (0.00-0.10, 0.10-0.20 and 0.20-0.40 m) (Figure 2) to determine the physical properties of the soil. Additionally, to represent the natural condition of the soil, 15 disturbed and undisturbed soil samples were collected in an area of native forest close to the coffee crops with five replicates.

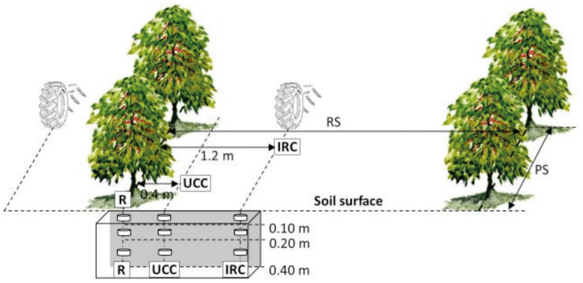


Figure 2. Soil sampling sites and identification of trenches in the experiment areas in the municipality of Muzambinho, state of Minas Gerais, Brazil. R = planting row; UCC = under the coffee canopy; IRC = inter-row center.

Soil bulk density (Bd) was calculated by the relationship between soil mass dried in an oven at 105 °C and sample volume (Teixeira et al., 2017). Microporosity (Mi) and Macroporosity (Ma) were calculated from the tension table at -0.006 MPa (Teixeira et al., 2017). Soil penetration resistance (PR) was calculated based on field measurements using an IAA/Planalsucar impact penetrometer according to Stolf et al. (2014). Details of the procedures for obtaining the aforementioned properties and their results for the coffee crops were presented in Sandoval et al. (2020).

Aggregate stability indexes were determined using soil aggregates with diameters between 4.76 mm and 9.52 mm, obtained by dry sieving from previously air-dried disrupted soil samples. Subsequently, the soil samples (20 g) were subjected to mechanical agitation by wet method according to Kemper and Chepil (1965). Five sieves with diameters of 4.76, 2.0, 1.0, 0.5 and 0.25 mm were used to obtain the following classes of aggregates: C1 (9.52-4.76 mm), C2 (4.76-2.0 mm), C3 (2.0-1.0 mm), C4 (1.0-0.5 mm), C5 (0.5-0.25 mm) and C6 (<0.25 mm). The geometric mean diameter (GMD), the aggregate stability index (ASI) and the percentage of aggregates with diameter greater than 2 mm (AGRI) were determined. GMD represents an estimate of the size of the most common aggregate class and was calculated by Equation 1 according to Wendling et al. (2005).

$$GDM = \exp\{\sum[(\ln[xi] * [wi])]/[wi]\} \quad (1)$$

where ln [xi] = natural logarithm of the mean diameter of the classes; WI = weight (g) retained in each sieve.

ASI was calculated by equation 2 and represents a measure of total soil aggregation, without considering distribution by aggregate class; therefore, the greater the amount of aggregate, <0.25 mm, the lower the ASI. AGRI represents the percentage of aggregates greater than 2 mm and was calculated according to Wendling et al. (2005) (Equation 3).

$$ASI = \left[\frac{SW - wp > 0{,}25}{SW}\right] * 100 \quad (2)$$

where SW = sample weight (g); wp <0.25 = weight of the class aggregates <0.25 mm (g).

$$AGRI = (wi > 2) * 100 \quad (3)$$

where wi>2 = percentage of aggregates >2 mm.

Organic matter (OM) content was determined according to the methodology proposed by Raij et al. (2001), based on the oxidation of organic carbon by potassium dichromate in the presence of sulfuric acid.

Changes in soil physical quality were compared between coffee crops using the sensitivity index (Si) according to Bolinder et al. (1999) (Equation 3). Si estimates the intensity of change in soil physical attributes due to different management methods, with native forest included as reference. Therefore, Si was obtained from the attributes of Bd, TP, Mi, Ma and PR for the coffee crops, as well as the same attributes for the native forest area and for the OM, GMD, ASI and AGRI attributes of both the coffee crops and the native forest area determined in this work.

$$Si = as/ac \quad (3)$$

where Si = sensitivity index; as = value of considered variable; ac = value of variable obtained in the native forest area close to the coffee crops. The closer Si is to the reference (forest, Si = 1), the less the evaluated attributes will be changed.

The values of soil physical attributes for each soil layer were subjected to analysis of variance using R software (R Core Team, 2017). The F test was applied for significance and Tukey's test ($p < 0.05$) was applied for comparison of means.

RESULTS

The highest accumulation of organic matter (OM) was found in the 0.00-0.10 m layer at the inter-row center (IRC). In the same soil layer, the 16-year-old crop had a higher OM content under the coffee canopy (UCC). In the 0.20-0.40 m layer, significant differences in OM content were only found between the 16- and 32-year-old crops at IRC, with the highest OM content obtained in the 32-year-old area.

The geometric mean diameter (GMD) reduced in depth for all crops and sites (Table 2). GMD showed a significant difference in all layers; however, the highest value (2.32 mm) was in the 0.00-0.10 m layer at IRC in the 3-year-old crop. At UCC, the 3-year-old crop had the lowest geometric mean diameter values in the 0.00-0.10 and 0.20-0.40 m layers (1.21 and 0.56 mm, respectively). There is a reduction in values with depth: the deeper the layer, the lower the DMG valueThe aggregate stability index (ASI) decreased with depth, with the exception of the 0.10-0.20 m layer in the 3- and 16-year-old crops at the UCC and IRC sites, respectively, which showed an increase in ASI compared to the upper layer (Table 2). In the 0.20-0.40 m layer, the 3-year-old crop at UCC and the 32-year-old crop at IRC presented the lowest ASI values (73.84% and 76.09%, respectively).

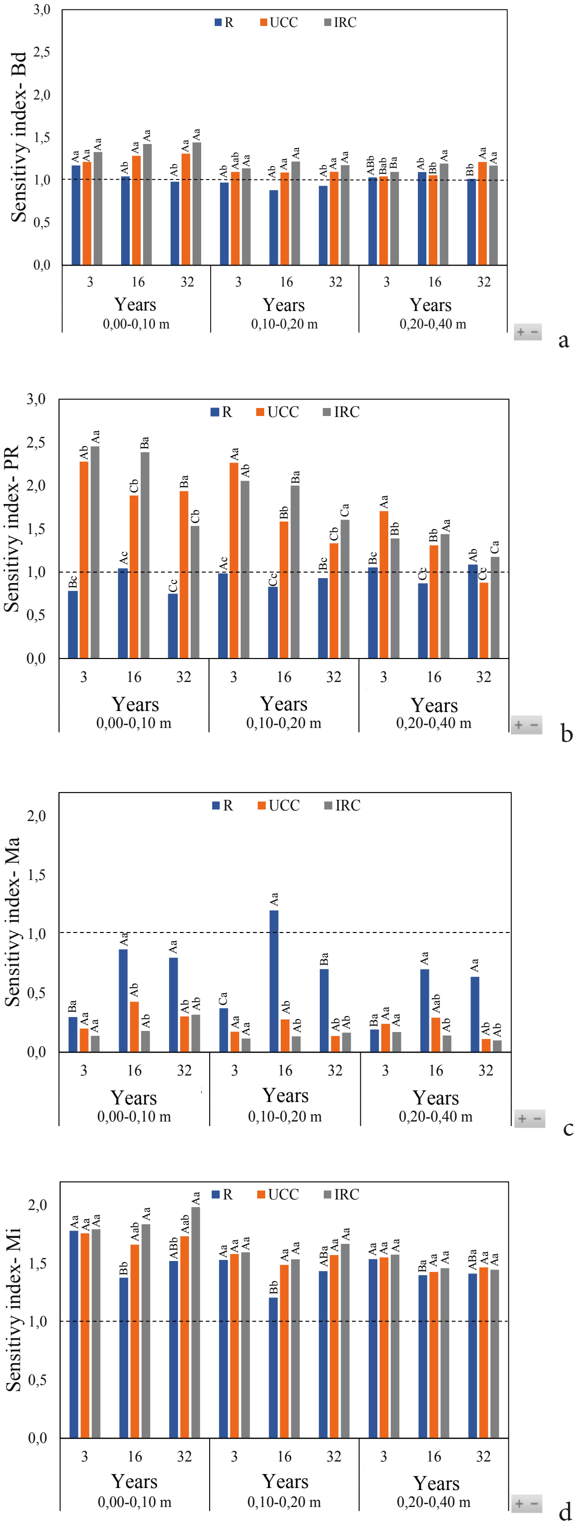
The percentage of aggregates with diameter greater than 2 mm (AGRI) showed significant differences between crops and sampling sites (Table 2). In the 0.00-0.10 m layer, the 3-year-old crop at IRC showed a higher AGRI value (69.08%) compared to the 16- and 32-year-old crops. In the 0.10-0.20 m layer at the R and UCC sites, AGRI increased with increasing crop age (3<16<32). In the 0.20-0.40 m layer, AGRI only showed significant differences between crops at the UCC site, with the lowest value obtained in the youngest crop (3 years old -, 11.50%).

In the first soil layer (0.00-0.10 m), the 16- and 32-year-old crops showed a significantly lower BdSi at R (1.04 and 0.90) compared to UCC (1.28 and 1.31) and IRC (1.42 and 1.44), with the R values being closest to the ideal (1.0) (Figure 3a). In the 0.10-0.20 m layer, significant differences were found in BdSi between sampling sites, with lower BdSi values at R (0.97, 0.88 and 0.93) than UCC (1.09, 1.08 and 1.09) and IRC (1.13, 1.21 and 1.17) in the 3-, 16- and 32-year-old crops, respectively. There were significant differences in BdSi between crops in the 0.20-0.40 m layer, with a highest BdSi value in the 32-year-old crop at UCC (1.21) and values increasing with crop age in all analyzed layers.

Crop	GMD				ASI				AGRI			
	R	UCC	IRC	Mean V	R	UCC	IRC	Mean	R	UCC	IRC	Mean
	---------------mm-------------				---%--------------------------------							
					0.00-0.10 m							
3 years	1.62Aab	1.21Ab	2.32Aa	1.71 A	91.41Aa	80.92Aa	95.97 Aa	89.43 A	49.50Ab	40.61 Ab	69.08 Aa	53.06 A
16 years	1.36Aa	1.46Aa	1.59Ba	1.46 A	89.89Aa	92.09Aa	90.90 Aa	90.96 A	42.87Aa	45.33 Aa	49.53 Ba	45.90 A
32 years	1.75Aa	1.45Aa	1.27Ba	1.48 A	90.49Aa	88.15Aa	86.98 Aa	88.54 A	55.95Aa	48.06 Aa	39.73 Ba	47.91 A
Mean	1.57 a	1.37 a	1.72 a		90.59 a	87.05 a	91.28 a		49.43 a	44.66 a	52.77 a	
Forest	-------------------1.91------------------				--------------------95.17-------------------				---------------53.43----------------			
					0.10-0.20 m							
3 years	1.14Ba	1.04Aa	1.28Aa	1.15 B	88.13Aa	89.98Aa	89.49 Aa	89.19 A	30.93Bb	25.09 Cc	38.14 Aa	31.38 B
16 years	1.19Ba	1.24Aa	1.27Aa	1.23 AB	86.78Aa	88.22Aa	91.06 Aa	88.68 A	38.80Ba	35.88 Ba	35.38 Aa	36.68 B
32 years	1.60Aa	1.31Aab	1.12Ab	1.34 A	89.90Aa	85.86Aa	86.57 Aa	87.44 A	50.55Aa	48.28 Aa	37.03 Ab	45.28 A
Mean	1.31 a	1.19 a	1.22 a		88.27 a	88.01 a	89.04 a		40.09 a	36.41 b	36.84 b	
Forest	-------------------1.86------------------				--------------------95.26----------------				---------------56.35----------------			
					0.20-0.40 m							
3 years	0.74Aab	0.56Bb	0.84Aa	0.71 A	79.84Aab	73.84Bb	84.91 Aa	79.52 A	19.68Aa	11.50 Ba	19.55 Aa	16.91 A
16 years	0.82Aa	0.89Aa	0.74Aa	0.81 A	83.77Aa	84.18Aa	79.29 ABa	82.41 A	20.88Aa	25.52 Aa	16.42 Aa	20.94 A
32 years	0.87Aa	0.88Aa	0.74Aa	0.82 A	82.64Aa	82.97Aa	76.09 Ba	80.56 A	27.47Aa	25.39 Aa	20.73 Aa	24.53 A
Mean	0.81 a	0.77 a	0.77 a		82.08 a	80.32 a	80.09 a		22.67 a	20.80 a	18.90 a	
Forest	-------------------1.60-----------------				---------------------94.30-----------------				------------------45.25-------------			

Table 2. Values of geometric mean diameter (GMD), aggregate stability index (ASI) and aggregate percentage index (AGRI) of a Argissolo Vermelho amarelo in coffee crops of different deployment times (3, 16 and 32 years) and different sampling sites and in a forest area, at depths of 0.00-0.10, 0.10-0.20 and 0.20-0.40 m.

R = planting row; UCC = under the coffee canopy; IRC = inter-row center; CV = coefficient of variation. Means followed by the same uppercase letters in the column compare the different crops and lowercase letters in the line compare the sampling sites, which do not differ from each other by Tukey's test ($p<0.05$).



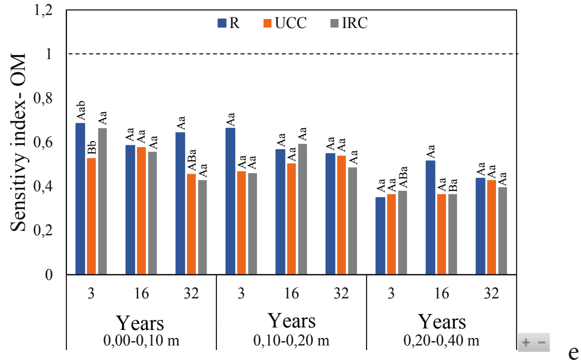


Figure 3. Sensitivity indexes (Si) of the attributes of a Argissolo Vermelho amarelo in coffee crops of different deployment times in relation to a native forest area. a = Bulk density Si (BdSi); b = penetration resistance Si (PRSi); c = macroporosity Si (MaSi); d = microporosity Si (MiSi); e = organic matter Si (OMSi) in a Red Yellow Argisol; R = planting row; UCC = under the coffee canopy; IRC = inter-row center. Means followed by the same uppercase letters (crops) and same lowercase letters (sampling sites) do not differ from each other by Tukey's test (p <0.05). The dashed line indicates the ideal value of Si = 1.

Regarding the sensitivity index for soil penetration resistance (PRSi), a reduction is observed in PRSi values with increasing crop age at the UCC and IRC sampling sites, in all layers (Figure 3b). The R site had the closest PRSi to the ideal, with values between 0.74 and 1.08 in the 32-year-old crop in the 0.00-0.10 m and 0.20-0.40 m layers, respectively. Elsewhere, the only value below the ideal (0.87) was at UCC in the 32-year-old crop, at the depth of 0.20-0.40 m, while the others showed values above the reference value (1.0), varying from 1.17 to 4.45.

Sampling site row (R) has the highest macroporosity sensitivity index (MaSi) values in the 0.00-0.10 and 0.10-0.20 m layers (Figure 3c). The sensitivity index value increased with crop age at IRC in the 0.00-0.10 and 0.10-0.20 m layers, while the opposite was observed in the 0.20-0.40 m layer, i.e., the older the crop, the lower the sensitivity index value. MaSi values closest to the ideal were obtained at R in the 16-year-old crop, at the depths of 0.00-0.10 and 0.10-0.20 m, with values of 0.87 and 1.20, respectively. The other sampling sites showed values below the ideal (between 0.09 and 0.80).

A contrary behavior to macroporosity was verified for the microporosity sensitivity index (MiSi), which reached values almost twice as high as the ideal (Figure 3d). Among crops there was a similar reduction in MiSi values according to sampling site (R>UCC>IRC), except for the 3-year-old crop in the 0.00-0.10 m layer and the 32-year-old crop in the 0.20-0.40 m layer, but with no statistical differences. A reduction in MiSi values was noted in the 16-year-old crop compared to the3-year-old area, followed by an increase in the 32-year-old crop, except in the 0.00-0.10 and 0.20-0.40 m layers at IRC. The 16-year-old crop had the lowest values in all layers at site R.

Regarding organic matter content, the sensitivity index (OMSi) showed values that were far from the ideal in all crops, with values between 0.34 and 0.68 at IRC in the 0.20-0.40 m and 0.10-0.20 m layers, respectively (Figure 3e). However, significant differences in OMSi were only found in the 0.00-0.10 m and 0.20-0.40 m layers. In the 0.00-0.10 m layer, the 3-year-old crop showed differences at the UCC site, with a higher OMSi value in the 16-year-old crop and a lower value in the 32-year old crop. In the 0.20-0.40 m layer at IRC, the 16-year-old crop had a significantly lower OMSi compared to the 32-year-old crop.

DISCUSSION

The greater accumulation of OM at the inter-row center (IRC) in the 0.00-0.10 m surface layer results from the mechanized coffee harvesting system. In this system, fruit that are lying in the planting row are moved to the inter row center together with the fallen leaves and beans, where the beans are collected with machines (described in the material and methods section). Moreover, spontaneous plants appear in the inter row center, which also contributes to the production of organic matter (Souza et al., 2016).

The under the coffee canopy (UCC) site showed the lowest levels of OM. This area, besides having its plant litter removed in the coffee sweeping process, receives no fertilization, which is limited to the planting row (R). Similar results were observed in a study by Vieira et al. (2015) in which OM accumulation was higher in the inter-row center under conventional management, which was related to the cleaning of the area under the coffee canopy and the definite relocation of straw and fallen beans to the inter-row center.

In depth, the 32-year-old crop provided the highest OM content at IRC. This occur due to pruning of the coffee trees, which incorporates a large part of the pruned material to the soil, generating an imbalance of the root system, with the death of up to 80% of roots, and incorporating a large amount of organic matter to the soil (Nair, 2021). In addition, according to Resende et al. (2014), water deficiency, lack of aeration (anaerobiosis) and low amount of nutrients in the soil hinder the action of microorganisms, favoring OM accumulation.

The soil aggregation indexes (GMD, ASI and AGRI), decreased with depth in all studied areas, which is consistent with the reduction of organic matter in depth. Soil organic matter directly influences soil aggregation by the joint action of vegetation and microorganisms, which exert physical action on bonding between soil particles, being the main soil cementing agents humic substances and high-viscosity polysaccharides (Matos, 2020).

Even with the greater soil compaction in IRC shown by higher values of soil bulk density (Bd) and penetration resistance (PR) and lower values of macroporosity (Ma), organic matter (OM) increases the aggregation of soil particles, so higher levels of OM in the 0.00-0.10 m layer at IRC resulted in better soil aggregation, resulting in higher GMD. Iori et al. (2014), studying the physical attributes of a Latossolo Vermelho-Amarelo in tropical climate coffee crops, observed that soil GMD values were higher in younger crops, decreasing in older plantations. The UCC sampling site showed low values, justified by the low OM content at the site.

The 3-year-old crop at R differs from the 16- and 32-year-old crops in IRC, presenting the lowest ASI values. There was a reduction in values with depth, showing the influence of OM, since it also decreases with depth. These values corroborate those found by Silva et al. (2013) who, in a vegetation cover system with *Braquiaria sp*. in the inter-row center of a coffee crop, observed the highest ASI values due to the high OM content of that area.

High ASI values occur due to soil protection by coffee remains and spontaneous plants, which, according to Torres et al. (2015), provide protection against soil disintegration caused by the impact of raindrops and sudden variations in humidity, besides providing energy and nutrients for microbial activity in the OM. Such activity leads to the production of substances responsible for the formation and stabilization of soil aggregates, in addition to the aggregating effect of the crop's roots.

The values found for ASI (73.84% to 95.97%) can be considered good when compared with those found by Oliveira et al. (2008) in a forest area with a clay texture Oxisol, which were above 79% of ASI, given that OM is a key agent for the formation and stabilization of soil aggregation and, in the forest, the continuous production of organic matter contributes to better soil aggregation (Vieira et al., 2015).

It is noteworthy that the 32-year-old crop had the highest AGRI values in all layers at the R and UCC sampling sites. This can be related to age, since the older the crop, the longer the time of resilience and decomposition and input of organic matter. The higher AGRI values at ICR in the 3-year-old crop still show signs of soil managing at planting, in accordance with Bicalho et al. (2011) who, studying aggregation changes in coffee grown in a dystrophic Red Oxisol under different management systems, observed the highest AGRI values in areas with greater soil disturbance.

In the 32-year-old crop, the longer time since planting resulted in better soil aggregation, which is related to the high OM content accumulated over time and the renewal of roots, which contribute to particle aggregation, favoring aggregates that are larger and more stable in water (Matos et al., 2008). According to Mota Junior et al. (2017), the use of heavy agricultural machinery and tools contribute to the formation of a compacted layer in the soil that can modify its original structure, leading to reduced pore volume, which increases bulk density and causes changes in soil aggregation. Silva et al. (2017) found that, over time, perennial crops can improve soil water quality due to action of their denser root system and greater contact with soil particles, increasing infiltration and hydraulic conductivity.

The sensitivity index (Si) proposed by Bolinder et al. (1999) was used to analyze the Bd, Ma, Mi, OM and RP attributes. The index estimated the degree of change between the attributes of the studied crops and a forest area used as reference, evaluating the influence of soil management by comparing the two areas. The index is a comparison of the value of the study area with an area of original vegetation (native forest), with the unit (1.0) being the weight of the forest's attribute value (reference value), so the closer to 1.0, there is less influence of soil management.

The values of the sensitivity indexes indicated that regardless of their age, all coffee crops present soil compaction, except at the planting row site. In the 0.00-0.10 m layer, the older the crop, the greater the soil compaction at UCC and IRC and the lower the soil compaction at R. This behavior is shown in the 32-year-old crop, which probably presented greater root development and OM input. Added to the lack of traffic at the site, this causes a decrease in sensitivity index values for bulk density, coming close to the ideal and corroborating the work by Silva et al. (2016) who, in a study on coffee root development in a Oxisol, observed that the older the coffee trees, the greater the root development, especially in the superficial layers.

The best sensitivity index value for bulk density occurred at R in the 16-year-old crop, reaching the ideal value. Compared to the other layers, there was a reduction in bulk density in the 0.20-0.40 m layer, indicating a diminishing effect of machine traffic with depth. Shah et al. (2017) point out that reduced compaction with depth occurs due to the pressure exerted on the soil surface, which is subsequently reduced at increased depths due to the absorption of the stress exerted by the upper layers of the soil.

The higher sensitivity index values for bulk density (BdSi) at IRC are in accordance with Mota et al. (2018), who explain that machine traffic exerts pressure on the soil at the inter-row center, generating soil compression, which induces compaction. Consequently, there is a reduction in macroporosity, which is highly related to bulk density. The high BdSi values at IRC, regardless of crop age, are attributed to weed management and fertilization operations with the Massey Fergusson 275 coffee tractor, the TDI electron self-propelled harvester, the Mogiana sweeper collector and the Yanmar 1150 tractor in the 16- and 32-year-old crops.

The sensitivity index for bulk density values show that soil compaction occurred due to the lack of soil preparation over the years and continuous traffic. Possibly due to the low levels of organic matter indicated by organic matter sensitivity index and the effect of machinery traffic in inadequate humidity conditions, causing soil deformation and increasing BdSi values. Despite the high bulk density sensitivity index values, according to Araujo et al. (2004), the local density does not present impediments to the root development of the coffee trees. These high values are due to the fact that the index is being used to compare the study area with a native forest, where bulk density is low due to lack of traffic and high input of organic matter.

In general, lower macroporosity sensitivity index (MaSi), together with higher bulk density under the coffee canopy and in the inter-row center, proves that machinery traffic caused soil compaction at these sites, limiting root development. According to Keller et al. (2011), machinery traffic is responsible for increasing bulk density, reducing total porosity due to increased friction between soil particles.

Macroporosity sensitivity index (MaSi) values were not close to the ideal in the 3-year-old crop at all sampling sites and in the 16- and 32-year-old crops at UCC and IRC, indicating high bulk density and soil compaction. As a result, low macroporosity directly affects coffee productivity due to low drainage and aeration (Braga et al., 2015). Therefore, in older crops, the effect of soil compaction over time leads to soil strengthening (Jensen et al., 2020). Such strengthening generates the structural restoration of the soil over time due to the rearrangement of soil particles and clay flocculation, changing the porosity and the cementing effect of the soil, increasing bulk density (Ferreira et al., 2019).

Regarding microporosity sensitivity index (MiSi), all crops and sampling sites showed values up to twice above the ideal (1.0). These high MiSi values, together with low MaSi values, reinforce the fact that the soil is compacted. The high values can be explained by bulk density, whose increase is accompanied by a reduction in the size of the soil pores, which cease to be macropores to become micropores (Tormena et al., 2008).

Studying different planting systems in an Oxisol, Torres et al. (2015) found high microporosity sensitivity index values, ranging from 1.6 to 3.1 in the fallow area, where the soil is not tillaged. The high MiSi values can also be explained by soil particle characteristics, as clay content increases the physical-chemical reactivity of the soil, which in turn favors its contraction (Hillel, 2004), and resistance to compaction (Horn and Smucker, 2005), especially in soils with low water content (Dastjerdi and Hemmat, 2015).

Regarding organic matter sensitivity index (OMSi), values below 1.0 are due to the greater production and deposition of organic matter in the native forest area (Souza et al., 2016). The trees in the forest area provide a large amount of vegetable debris on the soil, which contributes to increase orgnic matter on the surface and cycle nutrients in the soil (Caldeira et al., 2020).

Penetration resistance sensitivity index (PRSi) shows that soil compaction occurred in all crops at the UCC and IRC collection sites, in all soil layers except UCC 0.20-0.40 m. In the machinery traffic area (IRC), soil penetration resistance decreases with increased crop age, which is justified by the accumulation of organic material. According to Sandoval et al (2020), heavy machinery traffic in the inter-row center causes soil compaction, which consequently limits the development of roots.

CONCLUSIONS

Crop age and machinery traffic are the factors that most affected the physical attributes of the studied soil. Soil compaction increased with proximity to the traffic lane, regardless of crop age. In addition, the older the crop, the greater its soil aggregation.

Machinery traffic was a determining factor for increased soil compaction and decreased soil porosity. Soil organic matter was greater in the inter-row center due to soil management and sweeping of plant litter to this area.

The sensitivity index for all attributes, when comparing them with native forest, proved to be valid for a better understanding of the effects of soil compaction over the years. Added to this, it was also possible to see the effect of deployment time on the physical attributes of the soil, especially in old plantations (32 years old).

As a result, it was possible to see that not turning over for more than 30 years and the maintenance of plant remains in the soil brought benefits not only in the physical attributes of the soil but also in fertility (organic matter). This is important information for both the producer and researchers, as the non-revolving and maintenance of organic matter in the soil brought benefits that left the soil with indicators close to that of a native forest.

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