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Structural quality and load-bearing capacity of an Ultisol (*Argissolo Vermelho amarelo*) in mechanized coffee areas with different deployment times

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ABSTRACT: The mechanized management systems used in Brazilian coffee plantations generate heavy machine traffic and lead to the application of loads on the soil that affect the soil structure and lead to widespread compaction. This study aimed to evaluate the influence of mechanized operations on coffee plantations with different deployment times on the soil structural quality of an Ultisol, based on its soil physical properties and soil load-bearing capacity. The experiment was carried out in Muzambinho, São Paulo State, Southeast Brazil, in coffee plantations (*Coffee arabica L.*) with 3, 16, and 32 years of service. In each area, corresponding to the coffee plantation's establishment period, soil samples were collected in the planting row (R), under the coffee canopy (UCC), and inter-row center (IRC) at the layers of 0.00-0.10, 0.10-0.20, and 0.20-0.40 m to evaluate soil penetration resistance, bulk density, porosity, wet aggregate stability, and preconsolidation pressure, to model soil load-bearing capacity. The deployment time of the coffee crop was a decisive factor in reducing the deterioration of the soil structure in the row, which was confirmed by better structural quality in the plantations with 16 and 32 years of establishment. Irrespective of crop deployment time, the effects of intensive machinery traffic on the coffee crop in the middle between the rows and in the area under the canopy are similar, resulting in high soil compaction, reflected in soil penetration resistance, soil bulk density, macroporosity, and load-bearing capacity. The longer the deployment time of the coffee cultivation areas (32 and 16 years), the higher the stability of the soil aggregates, and the larger the mean aggregate size.

Keywords: machinery traffic, preconsolidation pressure, soil properties, uniaxial compression, soil compaction.

INTRODUCTION

Brazil is the largest producer and second-largest consumer of coffee in the world and stands out for being the sole producing country to consume a significant part of its production (MAPA, 2017). The development of coffee production is related to the ever-increasing use of agricultural machines and implements, which can alter the soil structure by modifying some soil physical and mechanical properties and hinder the development of the plants' root system (Cunha et al., 2016).

One of the factors that lead to a greater concern with coffee culture is that it is a perennial crop, so the effects of traffic machines last for many years. Due to the difficulties in implementing long-term studies, there are not many references in the literature evaluating coffee plantations established for more than 30 years.

Different management systems used in coffee cropping, especially mechanized ones, are associated with increased traffic and load applied on the axles of tractors, harvesters, and agricultural implements (Silva et al., 2015), which may exceed 15 operations per year (Pais et al., 2013). Machinery traffic affects soil structure and aggregation, properties that affect porosity, soil bulk density, permeability, infiltration, water retention capacity, and soil compaction (Souza et al., 2015), especially in clayey soils (Santos et al., 2010).

The use of mechanization as a production tool is inevitable and increasing, as it allows greater efficiency in operations and provides viability for coffee crops. Thus, knowing the soil capacity, which allows the resistance to these compressive forces is essential to the sustainability of the production system (Fidalski et al., 2015).

In this context, the identification of soil compaction has become an important factor for crop cultivation and production, and its understanding is facilitated by the study of soil compressibility (Hamza et al., 2011). Soil compressibility is related to the capacity of unsaturated soils to suffer volume reduction when subjected to external pressures (Keller et al., 2011). Therefore, it has become increasingly important to understand soil compressive characteristics from a physical point of view, aiming at reducing the harmful effects of machinery traffic to the soil structure (Lima et al., 2015).

Additional compaction problems occur when the pressure applied by machine wheels surpasses the soil load-bearing capacity, generating plastic deformations in its structure (Mazurana et al., 2017). Thus, compaction can last in coffee areas over the years, which is more concerning given it is a perennial crop and of paramount importance to the Brazilian and international scenario. In addition, it is relevant to know the effects of time on the structural quality of the soil.

The assessment of soil physical properties over time allows a better understanding of the process of physical degradation in mechanized production systems. Also, evaluating the soil load-bearing capacity under a range of moisture conditions and different handling systems is very important, not only to determine the maximum pressure possible that the soil can bear under such conditions, but also to minimize the risk of compaction in soils cultivated with coffee (Sant'Ana et al., 2013).

We aimed to evaluate the influence of mechanized operations on coffee plantations with different deployment times on the soil structural quality of an Ultisol, based on its soil physical properties and soil load-bearing capacity.

MATERIALS AND METHODS

Study site description

The study was carried out in areas belonging to *Fazenda Nossa Senhora*, municipality of Muzambinho, state of Minas Gerais, Southeast Region of Brazil (21° 29′ 19.7″ S and

46° 30’ 02.27” W) and 1,026 m of altitude. The local climate is mesothermal with dry winter (Cwa), according to the Köppen climate classification system, with temperatures above 22 °C in the hottest month and under 18 °C in the coldest month, and annual mean rainfall of 1,408 mm, with more concentrated rain events from November to March (INMET, 2018).

The soil was classified as Ultisol according to Soil Survey Staff (2014), which correspond to *Argissolo Vermelho amarelo* according to the Brazilian Soil Classification System (Santos et al., 2013). Soil physical properties at the layers of 0.00-0.20 and 0.20-0.40 m are presented in table 1.

Coffee crop areas and field management

The study was carried out in coffee plantations with different deployment times: 3, 16, and 32 years of establishment. The three years coffee area had been cultivated with the coffee variety Red Catuaí 144 and established in 2014 with 3.6 × 0.6 m spacing (planting row × plant), in a total area of 3.7 ha, amounting to 17,000 plants, and manual harvesting had been carried out. The 16 years area was established in 2001 with the same variety (Red Catuaí 144) as well as 3.6 × 0.6 m spacing, in a total area of 10.2 ha, comprising 40,500 plants. In this area, mechanized harvesting has been carried out for the last 13 years. The 32 years coffee area was established in 1985 with a variety Yellow Catuaí 62 with 4.0 × 1.5 m spacing (planting row × plant) over an area of 1.5 ha and containing 2,500 plants; in this areas, the mechanized harvest has only been carried out during the last six years.

The same cultural and phytosanitary treatments were used in all the studied areas. Mechanization was performed with a Massey Fergusson 275 coffee tractor (power of 55 kW, mass of 2,640 kg, front track width of 1.39 m, and rear track width of 1.56 m) coupled to an Arbus 400 jet sprayer, with a turbine or pulverization and leaf fertilization. The application of herbicides involved the use of a kit mounted between the lines. Fertilizations were performed by coupling a 450 kg capacity Commander H 10 S Kmaq fertilizer to the tractor.

When mechanized harvesting was done in the 16- and 32 years areas, it was carried out by a TDI Electron automotive harvester (power of 49 kW, mass of 7,870 kg, and track width of 3.00 m). Coffee fruits which fell on the ground were collected using a Mogiana-brand sweeper collector coupled to the tractor, model Spirlandelli 25C (mass of 1,950 kg and track width of 1.55 m), where a Bertanha blower (mass of 650 kg and minimum landscape rake range 1.39 m) passed by before, connected to a Yanmar 1150 tractor (power of

Table 1. Soil physical characterization of an Ultisol in areas cultivated with coffee with different deployment times (3, 16, and 32 years), at 0.00-0.20 and 0.20-0.40 m layers

Soil layer	Sand	Clay	Silt	Texture	PD	BD	MaP	MiP	TP
m		g kg^{-1}			Mg dm^{-3}			m^3 m^{-3}	
				3 years					
0.00-0.20	327	454	219	Clayey	2.17	1.25	0.16	0.40	0.56
0.20-0.40	305	469	226	Clayey	2.22	1.32	0.12	0.39	0.51
				16 years					
0.00-0.20	331	437	232	Clayey	2.34	1.3	0.14	0.37	0.51
0.20-0.40	277	488	235	Clayey	2.37	1.26	0.13	0.37	0.50
				32 years					
0.00-0.20	242	534	224	Clayey	2.25	1.29	0.09	0.44	0.53
0.20-0.40	213	559	228	Clayey	2.47	1.25	0.09	0.47	0.56

PD: particle density (picnometer method); BD: soil bulk density (volumetric ring method); MaP: macroporosity; MiP: microporosity (MaP and MiP by the tension table method); TP: total porosity (saturation method). All methodologies were performed according to Teixeira et al. (2017).

40 kW, mass of 1,540 kg, and track width of 1.24 m), to throw the fallen leaves and grains in the center, between the plant rows, where the grains were collected.

Soil physical-mechanical properties

In each area, the soil physical-mechanical properties were assessed at the 0.00-0.10, 0.10-0.20, and 0.20-0.40 m soil layers, in three sampling positions: planting row (R) - corresponding to the coffee planting line; the inter-row center (IRC) - the area between the planting lines, located 1.40 m from R; and under the coffee canopy (UCC) - in between R and IRC, located at 0.40 m from R. For each area, five replicates were sampled (Figure 1).

Soil sampling was carried out in February 2017, in the three coffee areas. Disturbed samples were collected in each sampling site for analyses of granulometry, particle density, and wet aggregate stability. Undisturbed soil cores were collected in the same positions using stainless steel rings (48-mm diameter and 53-mm height) through an Uhland auger, for determination of bulk density and soil porosity. Additionally, undisturbed soil cores were collected in volumetric cylinders of 60 mm diameter and 25 mm height, with five repetitions per soil layer and sampling site, for determination of soil load-bearing capacity.

Fractions of sand, clay, and silt were obtained by the pipette method, with NaOH 0.1 mol L^{-1} as a dispersing agent, and particle density (PD) was quantified using the volumetric flask method (Teixeira et al., 2017).

Soil mechanical penetration resistance (PR) was determined using an IAA/Planalsucar impact penetrometer, with a cone area of 1.29 cm^2 and a conical tip angle of 30° (Stolf et al., 2014), where five PR determinations were performed per plot. Penetration resistance (PR) was calculated based on field measurements of the cone penetration resistance. The number of impacts (N) by depth (dm^{-1}) was used to calculate PR (MPa) by equation 1, adapted from Sene et al. (1985):

$$PR = 0.098\ (5.6 + 6.98\ N) \qquad \text{Eq. 1}$$

In the same layers, disturbed soil samples were collected on the same day by assessing the gravimetric soil moisture (U) at the time of soil penetration resistance, with two

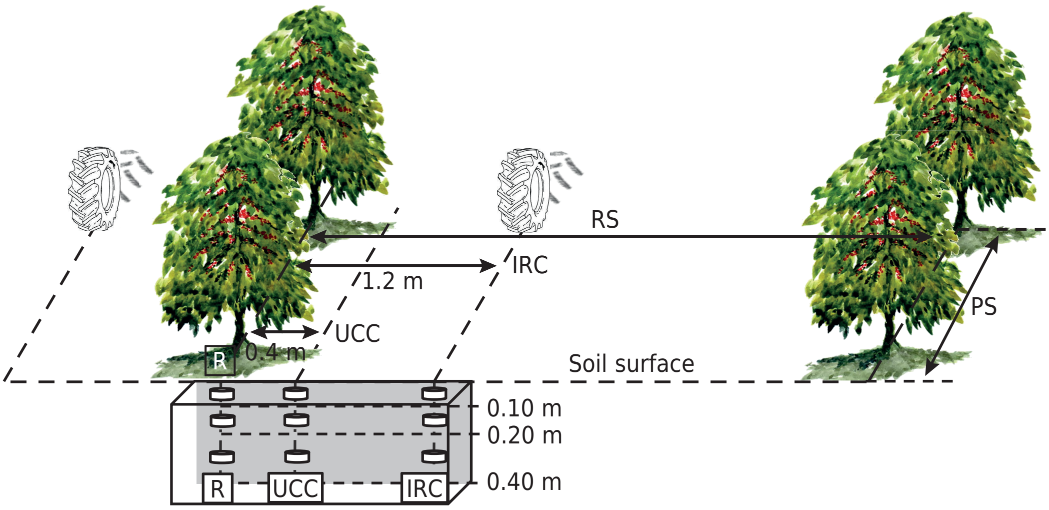

Figure 1. Sampling scheme of undisturbed and disturbed soil samples in coffee plantation areas. R: planting row; UCC: under the coffee canopy; IRC: inter-row center; RS: spacing between planting rows (3.6 m for 3 and 16-years areas, and 4.0 m for 32-years area); PS: spacing between plants (0.6 for 3- and 16 years areas, and 1.5 m for 32-years area).

samples per PR point. Samples were placed in aluminum cans, weighted, and kiln-dried with a forced air circulation at 105 °C for 24 hours (Teixeira et al., 2017).

Soil samples with undisturbed structure were saturated for 24 h by applying a suction of 0.60 m water column. Soil bulk density (BD) was determined by the volumetric ring method, and pore size distribution (macroporosity – MaP and microporosity – MiP) by the tension table method (Teixeira et al., 2017), using the tension of 6 kPa as a criterion to distinguish between MaP and MiP. Wet aggregate stability was assessed through the wet sieving method, as described by Kemper and Chepil (1965), shown in equation 2.

$$WMD = \sum (x_i\, w_i) \qquad \text{Eq. 2}$$

in which WMD (mm), x_i is the mean class diameter (mm), and w_i is the proportion of each class in relation to the total.

Soil load-bearing capacity

Soil load-bearing capacity curves were developed for each coffee cropping area based on the quantification of soil pre-consolidation pressure (σ_p). The σ_p was determined through the uniaxial compression tests using an automatic CNTAIHM/ BR001/07 consolidometer (Silva et al., 2015), coupled to the software CA LINKER, with pressure and deformation values adequately treated, and plotted onto a graph, whereby the soil compression curve was obtained, which expressed bulk density in function of the logarithm of the applied pressure (Silva et al., 2007).

Soil cores were saturated and subsequently had their moisture content equilibrated in the laboratory at room temperature, to obtain samples encompassing a moisture range varying from dry to saturated soil, i.e., in four moisture groups (0.05, 0.15, 0.28, and 0.40 kg kg^{-1}), also simulating extreme water content in the soil (saturation) as suggested by Silva et al. (2010).

In the uniaxial compression test, each soil core was exposed to loads of 25, 50, 100, 200, 400, 800, and 1,600 kPa. Each pressure was applied until 90 % of the maximum deformation was achieved, after that being increased according to Taylor (1971). Following the compression tests, samples were kiln-dried at 105 °C until constant mass, to determine the bulk density. The σ_p was estimated from the compression curve (bulk density × pressure). Experimental data were adjusted to the model proposed by Dias Júnior (2003), according to equation 3:

$$\sigma_p = 10^{(a + bU)} \qquad \text{Eq. 3}$$

in which σ_p is the soil preconsolidation pressure (kPa), "a" and "b" are linear and angular coefficients of the equation, respectively, and U is the soil gravimetric moisture (kg kg^{-1}).

Statistical analyses

The soil physical properties were analyzed using a completely randomized split-plot design, in which the plot referred to the age of the plantation (3, 16, and 32-years) and the subplot referred to the sampling positions (planting row - R, under coffee canopy - UCC, and inter-row center - IRC), with five repetitions, in the 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers. Experimental data were submitted to analysis of variance and F-test, and subsequently, the Tukey test was applied ($p<0.05$) for means comparison, using the statistical software R Studio (1.1.463, R Foundation for Statistical Computing).

The soil load-bearing capacity models were fitted to equation 3 using the Sigma Plot 11.0 software (Systat Software Inc®) for the adjustment parameters "a" and "b". After linearization by a logarithmic transformation, the models obtained for σ_p were compared based on the F-test of data homogeneity by Snedecor and Cochran (1989).

RESULTS

Soil physical properties

Soil physical properties were sensitive to the deployment time of the coffee crop (Tables 2, 3, and 4). Soil penetration resistance (PR) showed significant differences between sampling positions (planting row - R, under coffee canopy - UCC, and inter-row center - IRC) for the three treatments (deployment times) for the 0.20-0.40 m layer (Table 2). An increase in the age of establishment of the coffee crop resulted in decreased soil penetration resistance, in the sequence 3 years > 16 years > 32 years (4.60, 4.01, and 3.30 MPa, respectively).

For the 16- and 32-years treatments, at all layers, PR revealed higher soil compaction in the inter-row, compared to UCC and R (IRC > UCC > R). In contrast, the 3 years had the highest PR under canopy for the 0.10-0.20 and 0.20-0.40 m layers with values of 6.59 and 5.68 MPa, respectively. For the second and third soil layer, the PR decreased over the years under the canopy and in the inter-row (Table 2).

Soil gravimetric moisture (U) showed double interactions (sampling positions × treatments) significant for the 0.00-0.10 and 0.10-0.20 m layers (Table 2), with higher U in the planting row, decreasing in the sequence R > UCC > IRC, ranging from 0.30 to 0.37 kg kg^{-1} for R, 0.29 to 0.31 kg kg^{-1} for UCC, and 0.27 to 0.33 kg kg^{-1} for inter row.

Differences in soil bulk density (BD) were significant between deployment times only under the coffee canopy at 0.20-0.40 m layer, with higher BD for the 32 years area (1.44 kg dm^{-3}) (Table 3). However, in all areas, significant differences between sampling positions were verified in all layers, with lower BD in the row sampling site. In the deepest

Table 2. Soil penetration resistance and gravimetric moisture of an Ultisol, in areas cultivated with coffee with different deployment times (3, 16, and 32 years), at 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers, and different sampling sites

Coffee area	Soil penetration resistance				Gravimetric moisture			
	R	UCC	IRC	Mean	R	UCC	IRC	Mean
	MPa				kg kg^{-1}			
				0.00-0.10 m				
3 years	1.85	5.42	5.84	4.37	0.34 Ba	0.30 Ac	0.32 Ab	0.32 A
16 years	2.47	4.49	5.68	4.21	0.31 Ca	0.29 Aab	0.29 Bb	0.29 B
32 years	1.77	**4.61**	4.56	3.65	0.37 Aa	0.31 Aa	0.27 Bc	0.32 A
Mean	2.03 b	4.84 a	5.36 a	-	0.34 a	0.30 b	0.29 b	-
				0.10-0.20 m				
3 years	2.82	**6.59**	**5.98**	5.13	0.35 Aa	0.31 Ab	0.33 Aab	0.33 A
16 years	2.04	**4.61**	**5.82**	4.16	0.30 Ba	0.30 Aa	0.28 Ba	0.29 B
32 years	2.69	3.88	**4.67**	3.75	0.33 Aa	0.30 Ab	0.30 Bb	0.30 B
Mean	2.51 b	5.03 a	5.49 a	-	0.33 a	0.30 b	0.30 b	-
				0.20-0.40 m				
3 years	**3.49 Ab**	5.68 Aa	4.63 Aab	4.60 A	0.35 Aa	0.32 Aa	0.33 Aa	0.33 A
16 years	**2.88 Ab**	4.36 Ba	4.79 Aa	4.01 AB	0.31 Aa	0.31 Aa	0.29 Aa	0.30 B
32 years	**3.06 Aa**	2.92 Ca	3.92 Ba	3.30 B	0.31 Aa	0.31 Aa	0.24 Bb	0.28 B
Mean	3.15 b	4.32 a	4.45 a	-	0.32 a	0.31 a	0.29 b	-

R: planting row; UCC: under the coffee canopy; IRC: inter-row center. Means followed by the same letter, lowercase in the row and uppercase in the column do not differ among themselves by Tukey test (p<0.05).

Table 3. Soil bulk density, macroporosity, and microporosity of an Ultisol, in areas cultivated with coffee, with different deployment times (3, 16, and 32 years), at 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers, and different sampling sites

Coffee area	Bulk density				Macroporosity				Microporosity			
	R	UCC	IRC	Mean	R	UCC	IRC	Mean	R	UCC	IRC	Mean
	kg dm^{-3}				m^3 m^{-3}							
0.00-0.10 m												
3 years	1.26 Aa	1.27 Aa	1.36 Aa	1.29 A	0.08 Aa	0.07 Aa	0.02 Ab	0.05 B	0.42	0.39	0.35	0.38
16 years	1.10 Ac	1.27 Ab	1.45 Aa	1.27 A	0.18 Aa	0.11 Ab	0.02 Ac	0.11 A	0.36	0.36	0.39	0.37
32 years	1.11 Ab	1.34 Aa	1.39 Aa	1.28 A	0.18 Aa	0.04 Ab	0.06 Ab	0.09 A	0.40	0.37	0.40	0.39
Mean	1.15 c	1.29 b	1.40 a	-	0.15 a	0.07 b	0.03 c	-	0.39	0.37	0.37	-
0.10-0.20 m												
3 years	1.17 Ab	1.24 Aab	1.35 Aa	1.26 A	0.05 Ba	0.04 Aa	0.02 Aa	0.03 B	0.42 Aa	0.40 Aa	0.36 ABb	0.39 A
16 years	1.10 Ab	1.36 Aa	1.44 Aa	1.30 A	0.20 Aa	0.04 Ab	0.02 Ab	0.08 A	0.37 Ba	0.35 Bab	0.33 Bb	0.35 B
32 years	1.20 Ab	1.35 Aa	1.35 Aa	1.30 A	0.14 Ba	0.02 Ab	0.03 Ab	0.06 B	0.39 ABa	0.37 ABa	0.39 Aa	0.38 AB
Mean	1.16 b	1.32 a	1.38 a	-	0.13 a	0.03 b	0.02 b	-	0.39 A	0.37 AB	0.36 B	-
0.20-0.40 m												
3 years	1.25 Ab	1.26 Bab	1.38 Aa	1.30 A	0.05 Ca	0.03 ABab	0.02 Ab	0.03 B	0.41 Aa	0.41 Aa	0.40 Aa	0.40 A
16 years	1.30 Ab	1.29 Bb	1.44 Aa	1.34 A	0.08 Ba	0.05 Ab	0.02 Ac	0.05 AB	0.37 Ba	0.37 Ba	0.34 Bb	0.36 B
32 years	1.18 Ab	1.44 Aa	1.38 Aa	1.33 A	0.14 Aa	0.02 Bb	0.02 Ab	0.06 A	0.39 ABa	0.33 Cc	0.35 Bb	0.36 B
Mean	1.25 b	1.33 a	1.39 Aa	-	0.09 a	0.03 b	0.02 c	-	0.39 a	0.37 b	0.37 b	-

R: planting row; UCC: under coffee canopy; IRC: inter-row center. Means followed by the same letter, lowercase in the row and uppercase in the column, do not differ among themselves by Tukey test (p<0.05).

Table 4. The weighted mean diameter of an Ultisol, in areas cultivated with coffee with different deployment times (3, 16, and 32 years), at 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers, and different sampling sites

Coffee area	Weighted mean diameter			
	R	UCC	IRC	Mean
	mm			
0.00-0.10 m				
3 years	1.97 Bb	2.00 Ab	3.00 Aa	2.32 A
16 years	2.08 ABa	2.29 Aa	2.39 Ba	2.25 A
32 years	2.52 Aa	2.35 Aa	2.19 Ba	2.34 A
Mean	2.20 b	2.20 b	2.52 a	-
0.10-0.20 m				
3 years	1.88 Ba	1.55 Bb	1.74 Bab	1.72 B
16 years	1.96 Ba	2.08 Aa	1.96 ABa	2.00 AB
32 years	2.50 Aa	2.24 Ab	2.09 Ab	2.30 A
Mean	2.13 a	1.95 b	1.93 b	-
0.20-0.40 m				
3 years	1.40	1.17	1.33	1.30 A
16 years	1.46	1.80	1.65	1.64 A
32 years	1.76	1.67	1.73	1.72 A
Mean	1.54 a	1.55 a	1.57 a	-

R: planting row; UCC: under coffee canopy; IRC: inter-row center. Means followed by the same letter, lowercase in the row and uppercase in the column, do not differ among themselves by Tukey test (p<0.05).

layer (0.20-0.40 m), BD decreased from IRC to UCC to Rfor the 3 and 16-years treatments, while in the 32 years treatment the highest BD occurred in the under the canopy and decreased through the sequence from UCC to IRC to R (Table 3).

Macroporosity (MaP) was more sensitive to the effect of deployment times, where significant interactions were found in each soil layer (Table 3). The planting row - the positions without machinery traffic - presented the highest MaP values for all layers in relation to under canopy and inter-row center, with values greater than 0.14, 0.08, and 0.05 $m^3 m^{-3}$ in the areas of 32, 16, and 3 years; however, only in the 0.10-0.20 and 0.20-0.40 m layers significant differences between deployment times were observed. In the inter-row and under the canopy, the BD values were lower than 0.10 $m^3 m^{-3}$ in all layers and coffee plantations, except in the 16 years treatment, at under canopy, in the 0.00-0.10 m layer. For all soil layers, a significant reduction in the mean of MaP was observed in the 3 years, when compared to other treatments.

Microporosity (MiP) was significantly influenced by the establishment times in both 0.10-0.20 and 0.20-0.40 m layers (Table 3), with higher MiP in R for the treatment with 3 years of establishment (0.42 and 0.41 $m^3 m^{-3}$). In the same treatment and layers, the mean values of MiP for all sampling positions resulted in the highest MiP (0.39 and 0.40 $m^3 m^{-3}$, in the layers 0.10-0.20, and 0.20-0.40 m, respectively).

A double interaction ($p<0.05$) was found between coffee crop treatments and sampling positions for weighted mean diameter (WMD) in the upper layers (0.00-0.10 and 0.10-0.20 m), ranging from 1.55 to 3.00 mm (Table 4). The area with the longest establishment time (32 years) showed the highest WMD values in all sampling positions and soil layers, except in the inter-row for 3 years of establishment (3.00 mm). For sampling positions, WMD values ranged from 1.88 to 2.52 mm for R, from 1.55 to 2.35 mm for under canopy, and from 1.74 to 3.00 mm for inter-row in the 0.10-0.20 m layer.

Load-bearing capacity models

The explained variance in the data (R^2) of the load-bearing capacity models for each coffee crop treatment varied from 0.50 (3-years – in a row – 0.10-0.20 m) to 0.87 (16-and 32-years – under the coffee canopy – 0.20-0.40 m) (Table 5). The load-bearing capacity models in the planting row, at layers 0.00-0.10 and 0.20-0.40 m, between the areas of 16- and 32-years, did not show homogeneous based on the homogeneity test (Table 5), indicating that the load-bearing capacity models have different capacity to withstand load. Differences between models were also found under the canopy at 0.20-0.40 m layer, between the 3- and 16-years, and between the 16- and 32-years treatments, and in the layer at 0.10-0.20 m for 16- and 32-years treatments. Between coffee treatments with the shortest and longest establishment times (3 × 32 years), differences in the load-bearing capacity models were obtained only in the inter-row for layers of 0.10-0.20 and 0.20-0.40 m. Differences were observed between higher load-bearing capacity models, in treatments with longer establishment time (16 × 32 years). Although the load-bearing capacity models for 3 × 16 years and 16 × 32 years, in the planting row, at 0.10-0.20 m layer, were homogeneous, the linear coefficient (a) differed significantly, having different load-bearing capacities.

Figures 2, 3, and 4 show the soil load-bearing capacity models for all three deployment times in the planting row, under the coffee canopy and inter-row center, respectively. The preconsolidation pressure in the planting row and all layers was higher for the 3 years coffee treatment, in most of the soil moisture range (Figure 2), only being exceeded by the treatment of 32 years, in layers 0.00-0.10 and 0.10-0.20 m, in the range of low soil moisture (0 to 6 kg kg^{-1}). For both layers, 0.00-0.10 and 0.20-0.40 m, where the load-bearing capacity models showed significant difference between coffee crop treatments (Table 5). Although the models for the layer 0.10-0.20 m, between 3 × 16 years and 16 × 32 years, were homogeneous, the linear coefficient (a) differed significantly (Table 5), indicating different load-bearing capacities (Figure 2b).

Overall, regardless of the soil moisture content, the load-bearing capacity models which shown significant difference (Table 5) were the 3 and 16 years, under the coffee canopy,

Table 5. Linear "a" and angular "b" coefficients of the soil load-bearing capacity models, in function of gravimetric moisture, and a statistical comparison according to Snedecor and Cochran (1989) for an Ultisol, in areas cultivated with coffee with different deployment times (3, 16, and 32 years), at 0.00-0.10, 0.10-0.20, and 0.20-0.40 m layers, and different sampling sites

Fitted parameters						Comparison of models					
Coffee area	Sampling site	Soil layer	Parameter		R^2	Coffee areas	Soil layer	Sampling site	Statistics		
			a	b					F	a	b
		m					m				
3 years	R	0.00-0.10	2.71	-1.19	0.83			R	ns	ns	ns
		0.10-0.20	2.71	-1.07	0.50		0.00-0.10	UCC	ns	ns	ns
		0.20-0.40	2.76	-1.11	0.65			IRC	ns	ns	ns
	UCC	0.00-0.10	2.68	-1.65	0.71			R	ns	*	ns
		0.10-0.20	2.63	-1.13	0.75	3 x 16 years	0.10-0.20	UCC	ns	ns	ns
		0.20-0.40	2.66	-1.23	0.81			IRC	ns	ns	ns
	IRC	0.00-0.10	2.70	-0.86	0.76			R	ns	ns	ns
		0.10-0.20	2.69	-0.96	0.77		0.20-0.40	UCC	**	ns	ns
		0.20-0.40	2.66	-0.97	0.81			IRC	ns	ns	ns
16 years	R	0.00-0.10	2.67	-1.32	0.77			R	ns	ns	ns
		0.10-0.20	2.65	-1.94	0.73		0.00-0.10	UCC	ns	ns	ns
		0.20-0.40	2.66	-1.23	0.86			IRC	ns	ns	ns
	UCC	0.00-0.10	2.56	-0.79	0.58			R	ns	ns	ns
		0.10-0.20	2.81	-1.69	0.78	3 x 32 years	0.10-0.20	UCC	ns	ns	ns
		0.20-0.40	2.74	-1.56	0.87			IRC	*	ns	ns
	IRC	0.00-0.10	2.68	-0.61	0.81			R	ns	ns	ns
		0.10-0.20	2.70	-0.99	0.86		0.20-0.40	UCC	ns	ns	ns
		0.20-0.40	2.70	-1.53	0.81			IRC	*	ns	ns
32 years	R	0.00-0.10	2.75	-1.97	0.77			R	*	ns	ns
		0.10-0.20	2.76	-1.90	0.73		0.00-0.10	UCC	ns	ns	ns
		0.20-0.40	2.71	-1.30	0.77			IRC	ns	ns	ns
	UCC	0.00-0.10	2.70	-1.28	0.74			R	ns	**	ns
		0.10-0.20	2.68	-0.66	0.70	16 x 32 years	0.10-0.20	UCC	*	ns	ns
		0.20-0.40	2.83	-1.70	0.87			IRC	**	ns	ns
	IRC	0.00-0.10	2.72	-1.40	0.81			R	*	ns	ns
		0.10-0.20	2.74	-1.27	0.62		0.20-0.40	UCC	**	ns	ns
		0.20-0.40	2.74	-1.67	0.72			IRC	ns	ns	ns

R: planting row; UCC: under the coffee canopy; IRC: inter-row center; a: linear coefficient; b: angular coefficient; ns: nonsignificant; ** and *: significant at 1 and 5 % of probability, respectively.

in the layer 0.20-0.40 m. Both had similar behaviors, with the highest σ_p value for the dry soil condition of 457 and 550 kPa (Figure 3c), respectively, while the 32-years crop area presented the highest σ_p of 676 kPa. Thus, under the coffee canopy (UCC) site, in the layer 0.10-0.20 m, for the 32-years treatments, showed higher σ_p for low soil moisture levels (642 kPa), and a more accelerated reduction in the pre-consolidation curve, with increased soil moisture, in relation to the other treatments (Figure 3b). Furthermore, the maximum σ_p values for field capacity (soil water content at 10 kPa) were found in the 32-years plantation, where the layers 0.10-0.20 and 0.20-0.40 m showed σ_p of 290 kPa and 186 kPa, respectively.

The inter-row center (IRC) for dry soil conditions had the highest σ_p in all layers of the coffee area with 32 years of establishment (Figure 4). For the layer 0.10-0.20 m, the 3- and 16-years areas showed the same σ_p (236 kPa), at field capacity moisture, and were higher than the treatment of 32 years (209 kPa) (Figure 4b). Also, higher load-bearing

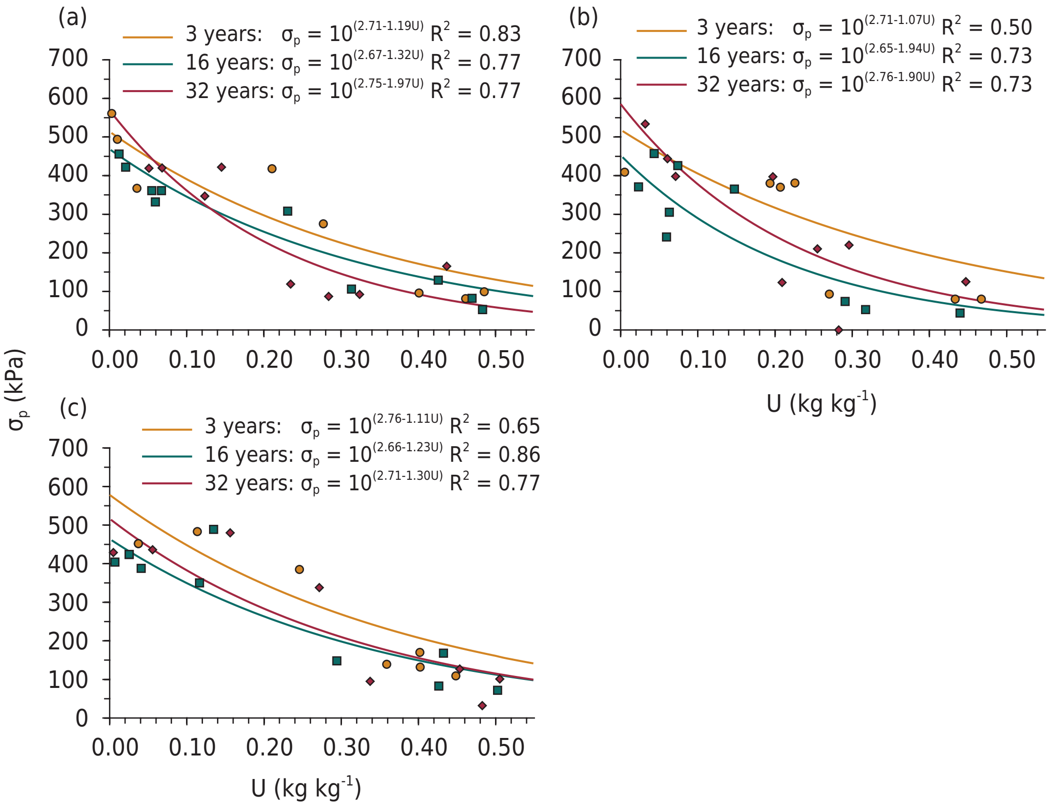

Figure 2. Soil load-bearing capacity models in function of the water content (U) of an Ultisol, in areas cultivated with coffee with different deployment times (3, 16, and 32-years areas), under mechanized management systems, in the planting row, at different soil layers: 0.00-0.10 m (a), 0.10-0.20 m (b), and 0.20-0.40 m (c).

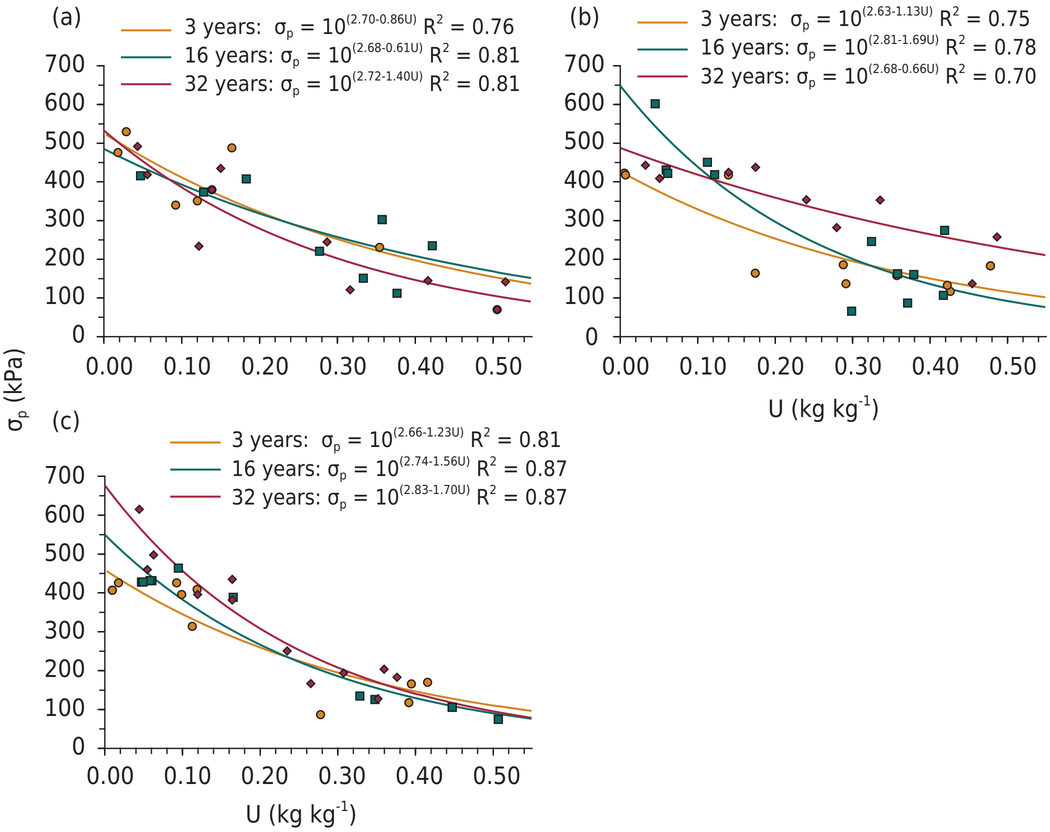

Figure 3. Soil load-bearing capacity models in function of the water content (U) of an Ultisol with coffee cultivation in areas with different deployment times (3, 16, and 32-years areas), under mechanized management systems, under coffee canopy, at different soil layers: 0.10-0.20 m (a), 0.10-0.20 m (b), and 0.20-0.40 m (c).

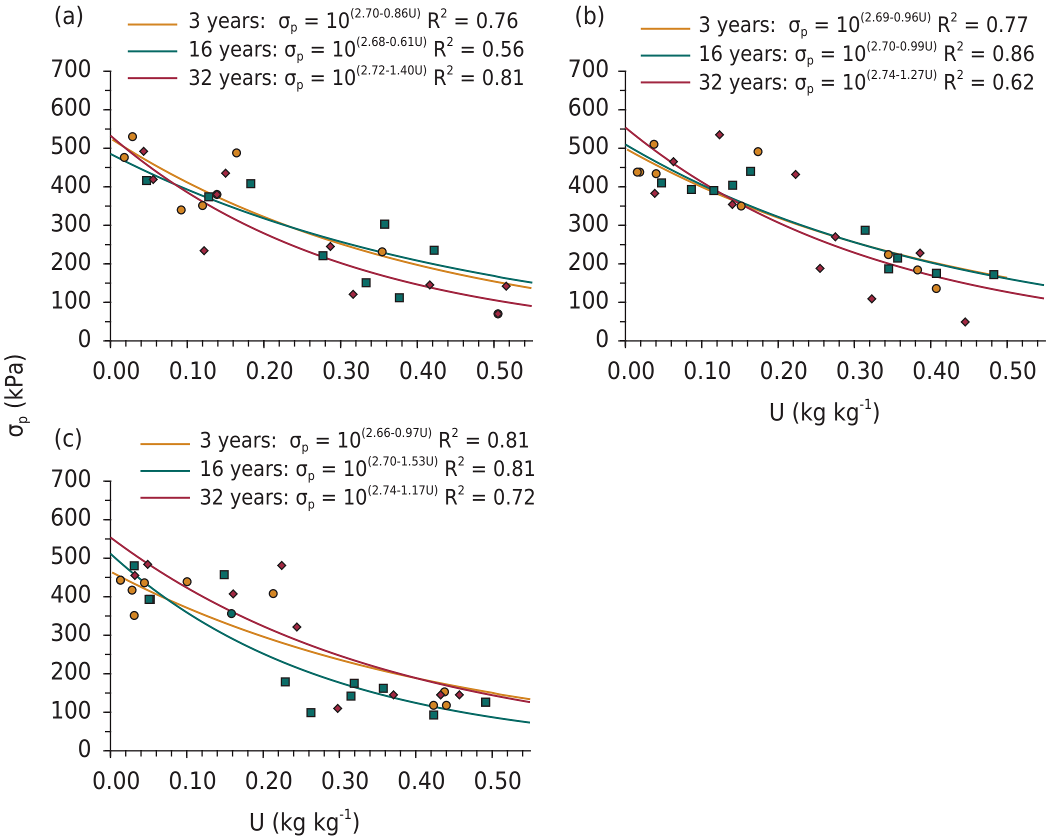

Figure 4. Soil load-bearing capacity models in function of the water content (U) of an Ultisol with coffee cultivation in areas with different deployment times (3, 16, and 32-years areas), under mechanized management systems, in the inter-row center, at different soil layers: 0.10-0.20 m (a), 0.10-0.20 m (b), and 0.20-0.40 m (c).

capacity was reported for the 32 years coffee plantation, at soil moisture lower than field capacity (Figure 4c) with σ_p values of 226, 157, and 219 kPa for the 32, 16, and 3-years plantation areas, respectively, with little difference in the σ_p values between the areas with 3 and 32-years.

The curves between deployment times for all layers differed more for the position in a row, while for the other sampling positions, the curves were closer. In addition, the humidity of 0.10 kg kg^{-1} was the crossing point between the curves for the evaluated layers, except for in row in the 0.20-0.40 m layer, where there were no intersections (Figure 2c), and for the 0.20-0.40 m layer.

DISCUSSION

Soil physical properties

Soil compaction was found for all deployment times, at the inter-row center (IRC) and under coffee canopy (UCC), in all soil layers, and in the planting row (R) at the 0.10-0.20 and 0.20-0.40 m layers, with RP values above 2.92 MPa (Table 2). A consensus in the literature is yet to be achieved regarding the critical threshold for the development of root systems. Sene et al. (1985) registered values between 6.0 and 7.0 MPa as critical for the full growth of plant roots in sandy soils, and 2.5 MPa for clay soils, while Silva et al. (2008) state that the PR which limits root growth, acceptable for most cultures, is 2.0 MPa.

In the area trafficked by the machines (on the inter-row center and close to the inter-row center), the soil mechanical penetration resistance decreases with increasing age of the coffee crop (Table 2), which can be possibly justified by the organic material accumulation in these soils. For the surface layer, this occurs because of the deposition of pieces of branches, leaves, and fruits accumulated under the coffee plants, whereas for the subsurface layer it results from the renewal of the root system, which favors the development of soil macro and micro-fauna constructing galleries, decomposing organic material, transforming such residuals, and providing the soil with these nutrients.

Our study verified bulk density values at all three layers and deployment times below 1.44 kg dm^{-3}, except for the 0.00-0.10 m layer in the inter-row center in the 16-year plantation treatment (1.45 kg dm^{-3}; Table 3). Therefore, the BD alone is not an impeding factor for root development. According to Araujo et al. (2004), the critical values for plants' root development is about 1.45 kg dm^{-3} for clay soils.

The macroporosity should be at least 0.10 m^3 m^{-3} to avoid limitations to root development, water percolation, and gas exchange (Mota Júnior et al., 2017). Our study verified that macroporosity values under the coffee canopy and inter-row center for all coffee crop treatments were below of this critical limit, excluding under the coffee canopy at 0.00-0.10 m, for the 16-years treatment. Furthermore, only in the planting row, the macroporosity was above the critical limit for 16 and 32-years. Overall, lower macroporosity and microporosity led to higher soil penetration resistance and bulk density under the coffee canopy and inter-row center (Tables 2 and 3). This proves that heavy machinery traffic in these positions has caused soil compaction, constraining the normal root development. Machinery traffic increases the bulk density and reduces total porosity because of increased friction forces between soil particles (Keller et al., 2011).

Pore size distribution revealed reduced macroporosity under the coffee canopy, probably resulting from lateral compaction, which was caused by the machinery traffic in the area, without the presence of controlled traffic farming, from the use of three-wheeled harvester and as well as from different width track of the machinery used in all coffee crop areas. Lima et al. (2017) state that a macroporosity above 0.15 m^3 m^{-3} indicates a good aeration capacity since it is a measure of oxygen diffusion rate in the soil, which meets the roots respiratory demands and the adequate growth of microorganisms' activity. The above-mentioned values were found in this study only in the planting row, for layer 0.00-0.10 m, for 16 and 32 years deployment times (0.18 m^3 m^{-3}- Table 3), and for layer 0.10-0.20 m (0.20 m^3 m^{-3}; Table 3). It is noteworthy that the UCC and IRC did not present values higher than 0.15 m^3 m^{-3} at any time, confirming the soil bulk density and penetration resistance data about compaction. Consequently, the low macroporosity found may directly affect plants' productivity because of its low drainage and aeration, possibly caused by high soil compaction – upon the occurrence of increased microporosity and reduced macroporosity (Braga et al., 2015).

As general behavior for all coffee crop treatments, the highest soil compaction was verified at the layer of 0.10-0.20 m, in the inter-row center, and under the coffee canopy, as well as in the deepest layer (0.20-0.40 m) in the planting row. This fact can also be explained by the highest stress distribution of loads applied to the surface layers in the area trafficked for the positions in the inter-row and under the canopy. This occurs due to the higher pressure exerted from the soil's surface layers, which is subsequently being attenuated to the other depths due to the stress absorption by the upper layers of the soil (Lamandé and Schjønning, 2011). Tolon-Becerra et al. (2011) also documented that the highest values of soil resistance to penetration and bulk density, between 0.00 and 0.20 m of depth, presented a direct relation with the pressure applied at the soil-tire interface.

Soil compaction conditions under the coffee canopy, regardless of the time of establishment, can compromise the correct functioning and development of the crop's root system. Most of the active roots of the coffee tree are concentrated near the canopy projection (under coffee canopy), and soil compaction hinders root development, and consequently the availability of nutrients and water for the crop (Fernandes et al., 2012).

The longest deployment times of the coffee crop treatments (32 and 16-year) resulted in better stability of the soil aggregates, with the highest weighted mean diameter values (WMD; Table 4), where the culture has been stabilized. This is related to the highest organic matter accumulation over time, and roots renewal acting on particle aggregation, which benefits high-sized clustering and more water-stable aggregates (Matos et al., 2008). Mean values of WMD remained constantly higher in the oldest coffee crop treatments, which associated with a lower soil penetration resistance, indicates that, despite compressed, these treatments remain structured to withstand an erosive process. Mota Júnior et al. (2017) highlighted that the original structure of a soil exposed to intensive cultivations and heavy agricultural implements use, as is the case of the younger crops, changes and contributes to forming compacted layers. These cause reduced pore volumes and increased bulk density, leading to changes in the stability of soil aggregates.

Soil preconsolidation pressure

The high determination coefficients indicate that the load-bearing capacity models are suitable to estimate the preconsolidation pressure (σ_p) from soil moisture. The linear coefficient "a" ranged from 2.56 to 2.83 and the angular coefficient "b" ranged from -0.61 to -1.97, representing a negative relation between preconsolidation pressure and soil gravimetric moisture, and all models were significant ($p<0.05$) through the F-test. Among the linear coefficients, the lowest "a" value (2.56) was found in the 16-year plantation under the coffee canopy and at a layer of 0.00-0.10 m. A lower linear coefficient indicates that soil has a lower initial load-bearing capacity (363 kPa), according to Sant'Ana et al. (2013).

Overall, σ_p values decrease as soil moisture increases, which can be attributed to the handling, inducing disaggregation and weaker contact between primary soil particles, which in its turn leads to a lower load-bearing capacity at high moisture levels, as found by Iori et al. (2012) and Sant'Ana et al. (2013). The internal resistance of the particles decreases following an increase in water content of the soil, because it forms a liquid layer involving both particles and soil aggregates, leading to lower friction and enabling deformation (Silva et al., 2009).

In this study, we assumed the preconsolidation pressure (σ_p) as an indicator of the internal strength of soils, which resulted from anthropogenic effects (machinery traffic – time and loads), pedogenetic processes, or hydraulic site-specific conditions (Horn et al., 2004).

In the planting row, models of soil load-bearing capacity for the 3-years treatment only showed differences when compared to the 16-years treatment, at a layer of 0.10-0.20 m. Higher soil load-bearing capacity for the 3-years treatment (Figure 2) reflects the soil compaction condition resulting from high soil penetration resistance and microporosity, and lower macroporosity (Tables 2 and 3). However, machine traffic does not occur on this site. This result can be explained by two factors: the hole planting system used in the farm, where only a small volume of soil was tilled for the transplantation of the coffee; and the site assessed in the planting row corresponds to the midpoint between two coffee plants. Thus, the two factors indicate that the soil in this site already carried loads higher than those imposed in the other treatments, possibly due to its previous use, since the preconsolidation pressure reflects the history of the stress (loads) to which the soil mass has been submitted (Silva et al., 2009).

At positions under the coffee canopy and inter-row center, differences occurred between the treatments, when compared to the 16-year treatment (Figure 3 and Table 5). However, the similarity of the properties' behavior, between under canopy and inter-row, could be explained by the traffic occurred under the coffee canopy region, if mechanical implements passed by this region because of the densification of plants, or simply due to the size of the machinery.

Esteban et al. (2019) found that where there is no traffic control, traffic occurs in the seedbed region of sugarcane. Mota et al. (2018) found that in coffee areas, machine traffic also occurred under the coffee canopy, depleting soil physical properties, which was also verified in this study (Tables 2, 3, and 4).

In addition, it is noteworthy that in the 32-years treatment, traffic began to occur only 6 years prior to the experiment, bringing it closer to the machine traffic that occurred in the 3-years treatment. Thus, the 16-year treatment had had traffic for more than 10 years before, which, when compared to the 32-years treatment, results in a difference between the preconsolidation pressures. In this study, although different machines were not evaluated, it can be noticed that the most intense traffic (16 years) increased the preconsolidation pressures in both under coffee canopy and inter-row center positions. It is also notable that the 32-year-old treatment is the oldest one, with no deep ground turnover; the little turnover observed in this treatment occurred only near the surface, caused by the dry leaf removal with a Bertanha blower machine, connected to a Yanmar 1150 tractor unit.

These results agree with the age-hardening effect described by Moraes et al. (2016), in which treatments with long planting periods will experience a strengthening of the soil and restoration of the soil structure. This is due to the rearrangement of the soil particles over time, in particular the clay flocculation, which changes the porous structure of the soil, and the cementing effect of the soil, which increases its tensile strength (Tormena et al., 2008).

The soil compaction in the areas between planting rows (on the inter-row center and close to under the coffee canopy), regardless of the deployment time, is attributed to the high traffic machines used in the mechanized operations of the weed management and fertilization (Massey Fergusson 275 coffee tractor) and harvesting that happened in the 16- and 32-years (TDI Electron harvester, Bertanha blower, Mogiana-brand sweeper collector and Yanmar 1150 tractor). Therefore, degradation of soil physical quality in the coffee crop with shorter time of establishment (3 years) is due to the tractor-induced compaction in the management of weeds and fertilization. Kamimura et al. (2012) found that the use of tractors in agricultural operations (Massey Ferguson 275 - the same used in our study) on a *Latossolo Vermelho-amarelo* (Oxisol) degraded the soil structure more than harvester operations, since soil bulk density, microporosity, and preconsolidation pressure were higher in the tractor track than in the harvester track. The same authors state that this higher soil compaction induced by the tractor is due to the frequency of operations and time of the year (rainy season), resulting in greater soil compaction compared to the harvester, which performs in the dry season.

The coffee crop treatments with 16 and 32-years showed that areas with longer cultivation periods, increased heavy machinery traffic and absence of soil management, result in lower soil load-bearing capacity (Figures 2, 3, and 4). Overall, 16-year and 32-year crop treatments presented lower soil penetration resistance, higher macroporosity and weighted mean diameter, when compared to the most recently implemented area. However, it can be concluded that there is a better soil structure in such treatments, due to the soil's physical stabilization and higher root density. Rocha et al. (2016) emphasized that not only the soil moisture determines the soil susceptibility to changes caused by farm machinery traffic, but also handling, soil class, granulometry, organic matter content, and presence of cultural residues in the area. Perennial crops improve the physical and water quality of the soil over time, due to the direct action of the roots at structuring the soil, which occurs because of a longer aggregating action in annual plants, and the presence of a denser root system with stronger contact with soil particles (Silva et al., 2017).

The soil load-bearing capacity models obtained will allow the identification of the correct time at which to operate the machines in the coffee crop, given the soil water content, hence minimizing the risk of additional soil compaction. In particular, the traffic is not recommended when the water content of the soil is greater than the field capacity (Müller et al., 2011). When the soils are drier, their load capacity can withstand the applied pressures, and the soil compaction can be insignificant (Silva et al., 2009). However, if the soil load-bearing capacity is not respected, as well as its critical moisture – especially over the periods of higher soil humidity, i.e., higher rainfall periods, the risk of compaction will be greater (Iori et al., 2014). It should be stressed that this is an important factor for the producer, as traffic frequently occurs at a higher humidity than field capacity, which may accelerate compaction and cause long-term irreversible effects in the area due to traffic above preconsolidation pressure.

A highlight of this study is that, besides the evaluation of the times when the treatments were implemented, there was also a difference between the mechanization times that occurred. With this, the deployment time is fundamental for the answers obtained regarding the suspicion of the higher content of organic matter or roots. However, we found that mechanization time of the area had relevant participation in the answers of this study, especially for the preconsolidation pressure than the deployment time.

The intense use of mechanized operations in the coffee crop since its establishment, the control of weeds and pests, fertilization, and harvesting, jeopardize the physical quality of the soil under the coffee canopy and along the traffic lines, which may affect the correct root development of the crop. In addition, the authors sustain that, in order not to have additional compaction, crop management should always be performed at optimal soil moisture, ensuring that mechanized operations are carried out at soil moisture levels below field capacity, where load-carrying capacity is higher.

CONCLUSIONS

Deployment time of coffee cropping was a determining factor to reduce soil structure degradation in the planting row, confirmed by better structural quality in the 16 and 32 years treatments.

Regardless of crop deployment time, the effects of intense machinery traffic on coffee cultivation are similar in the inter-row center and in the area under the coffee canopy, resulting in high soil compaction, which reflects on the soil penetration resistance, soil bulk density, macroporosity, and load-bearing capacity, which may impact the crop development.

Coffee crop treatments with the longest deployment times (32 and 16-year) resulted in better stability of the soil aggregates, with the highest weighted mean diameter values.

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