Revista Brasileira de Ciência do Solo

Division - Soil Processes and Properties | Commission – Soil Physics

Load-bearing capacity and critical water content of the coffee plantation soil with management in full sun and shaded

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Received: May 10, 2022

Approved: June 23, 2022

How to cite: Lacerda KS, Vargas RC, Ribeiro KM, Dias Junior MS, Ribeiro KD, Abreu D. Load-bearing capacity and critical water content of the coffee plantation soil with management in full sun and shaded. Rev Bras Cienc Solo. 2022;46:e0220051. https://doi.org/10.36783/18069657rbcs20220051

Editors: José Miguel Reichert and João Tavares Filho.

ABSTRACT: New management practices applied to coffee crops may influence the soil's capacity to tolerate vertical stresses. This paper aimed to evaluate the influence of two coffee crop management systems on the soil load-bearing capacity and critical soil water content to agricultural machinery traffic. This study was performed in the experimental area of the Federal Institute of the Southeast of Minas Gerais - Rio Pomba college, in Rio Pomba city, Minas Gerais, Brazil. Dystrophic Red-Yellow Oxisol (*Latossolo Vermelho-Amarelo distrófico*) (LVA7) with clayed texture predominating in the experimental unit. Undisturbed soil samples were collected from layers of 0.00-0.03, 0.12-0.15 and 0.27-0.30 m, randomly, in the center of the interrows of coffee plants (*Coffea arabica L.*) in monoculture plots under traditional management (in full sun) and in the plots of coffee plants intercropped with gliricidia (*Gliricidia sepium*) (shaded) to estimate pre-consolidation pressures, through uniaxial compression tests and adjustment of soil load-bearing capacity models. The average and maximum normal stresses applied to the soil and the vertical stress distribution of three agricultural tractors used in mechanized farming operations were estimated, and the critical soil water content to the traffic of these tractors was determined for both treatments, aiding in the decision-making process regarding additional compaction risks in the area. Cultivation of gliricidia in consortium with coffee did not influence the soil load-bearing capacity. The soil layer of 0.12-0.15 m was the most vulnerable to vertical stresses in both treatments. Agricultural tractors Agrale 4100, MF 265 and MF 275 presented values of vertical stresses of 335.76, 200.24 and 245.55 kPa, respectively, and the soil water content for the traffic of agricultural machines without plastic deformation was higher in the coffee plants in full sun for all studied depths.

Keywords: monoculture, agroforestry, pre-consolidation pressure, stress propagation, soil compaction.

INTRODUCTION

Society has been undergoing socioeconomic, political and technological transformations and consumer markets have increasingly opted for food produced ecologically and socially sustainably, in addition to being safe and nutritious (Macedo et al., 2000; Moura et al., 2015; Aquino et al., 2016). These new trends in consumer markets create opportunities for adopting alternative methods in coffee production, such as agroforestry coffee.

Along with these new trends, curiosities and comparisons of the diversity of invasive plants (Ricci et al., 2008), economic viability (Moraes et al., 2014), soil quality and coffee productivity (Vieira et al., 2015), as well as other topics such as the soil load-bearing capacity and critical soil water content of coffee plants in different production systems arise. The soil load-bearing capacity (LBC) is the ability soil structure to resist vertical stresses applied by agricultural machinery, people, animal and other bodies without irreversibly altering the arrangement of its particles (Alakukku et al., 2003; Dias Junior et al., 2019).

Load-bearing capacity is important in studies of soil compaction, sustainability of productive systems, evaluation of different agricultural management systems and traffic of machines and animals. In this regard, Tassinari et al. (2015), Watanabe et al. (2017) and Sousa et al. (2019) are some examples of the soil LBC theory applied in agriculture. The capacity of a soil to support load depends on several factors, such as the drying and wetting processes of the soil, texture and mineralogy, soil bulk density, use and management adopted in the agricultural area, structure and soil water content, being these last two parameters of great contribution (Dias Junior et al., 2019).

Load-bearing capacity models can be adjusted based on soil pre-consolidation pressure and soil water content values obtained from uniaxial compression tests of samples collected in the field (Dias Junior and Pierce, 1996). Pre-consolidation pressure can be understood as the highest pressure a soil can suffer without damaging its structure. When vertical stresses below this value are applied to soil, the deformation that occurs is reversible (or elastic), and the soil can return to its initial shape after the load is applied. When the normal stress is higher than the pre-consolidation pressure value, the deformation of the soil is considered irreversible (or plastic) and the original shape of the soil can not be resumed, harming the agricultural production system (Dias Junior et al., 2019).

Furthermore, based on the vertical stress values of agricultural machines, people or animals applied on soil, associated with the load-bearing capacity models, it is possible to determine critical soil water content to the traffic of machines and animals through the agricultural area (Araujo-Junior et al., 2011; Sousa et al., 2019). This study aims to evaluate the influence of the traditional (full sun) and agroforestry (shaded) management regimes in coffee plantations on the soil load-bearing capacity and to estimate critical soil water content for machinery traffic to contribute to the management plan for the agricultural area studied.

MATERIALS AND METHODS

Characterization of the experimental area

The study was carried out in an experimental area of the Federal Institute of Education, Science and Technology of the Southeast of Minas Gerais - Rio Pomba college, Rio Pomba city, Minas Gerais State, Brazil, located under the geographical coordinates 21° 14′ 46″ of South latitude, 43° 09′ 19″ of West longitude and 453 m of altitude. The region is in a humid subtropical climate zone with hot and rainy summers and dry winters with moderate temperatures, classified as Cwa in the Köppen and Geiger classification system (Melo and Teixeira, 2017). The predominant soil in the experimental area, according Brazilian

Soil Classification System (SiBCS), is classified as Oxisol or *Latossolo Vermelho-Amarelo distrófico* (Santos et al., 2018), and it was originated from gneissic rocks of magmatic and / or sedimentary origin (Pinto and Silva, 2014).

The experimental area totals 0.46 ha and is planted with arabica coffee (*Coffea arabica L.*), cultivar Oeiras MG 6851, spaced at 3.0 × 0.9 m, as shown in figure 1. The southwest region of the experimental area, which totals 0.13 ha, is managed as an agroforestry system (shaded) with the consortium of coffee and gliricidia (*Gliricidia sepium*), while in the remaining 0.33 ha, coffee is managed as a monoculture under traditional shade management regime (full sun).

Coffee crop was planted in 2006 and pruned down in 2014. During the entire period of cultivation of the plantation (2006-2022), organic production practices were adopted, and weeds in the interrow were mechanically mowed.

Soil load-bearing capacity

Fifteen undisturbed soil samples were collected at three different layers (0.00-0.03, 0.12-0.15 and 0.27-0.30 m) for each treatment (full sun and shaded), totaling 90 soil samples, to estimate the pre-consolidation pressure and adjust the load-bearing capacity models of the soil in the experimental area. The samples were subjected to uniaxial compression tests, and one composite sample from each treatment was also collected to assess soil texture, using the method proposed by Bouyoucos (1962).

Undisturbed samples were collected randomly in the center of the coffee interrow, according to Araujo-Junior et al. (2011), using an Uhland sampler and aluminum sampling cylinders of 6.36 cm average diameter, 2.55 cm average height and 32 g average weight. After collection, the samples were packed in plastic film and immersed in paraffin solution to preserve their initial characteristics and integrity during transport. Soil sampling was carried out in the first half of June 2019.

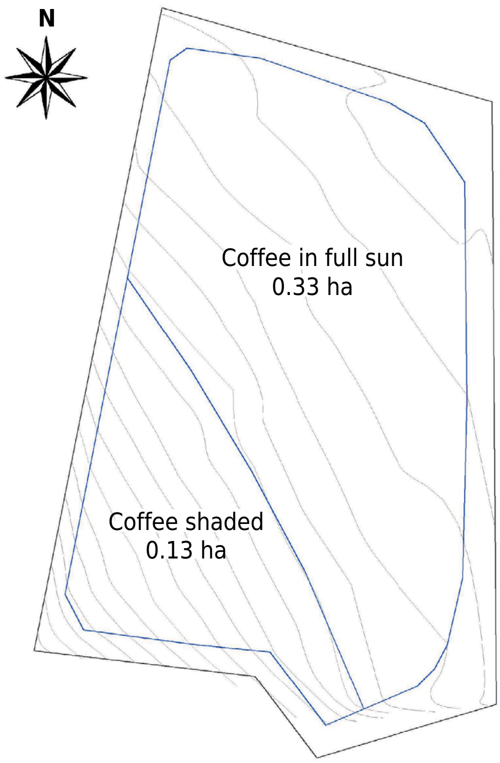

Figure 1. Planialtimetric survey of the experimental area.

In the laboratory, undisturbed samples were prepared for the uniaxial compression tests (Dias Junior and Martins, 2017). For that, 36 samples (18 for full sun and 18 for shaded regime) were saturated, for 24 h, in a tray filled with distilled water at ⅔ capacity. For each treatment, half of the saturated samples were suctioned at 10 kPa, and the other half was subjected to 100 kPa, using Richards extractor made by Soilmoisture Equipment Corp., model 1600. Another 18 samples (9 from each treatment) were dried in the sun. The remaining 36 samples (18 from each treatment) were air-dried in the laboratory in a controlled manner until the desired gravimetric water content of the soil was reached in the samples for the tests.

Uniaxial compression tests of the samples at different water content were performed in a Durham Geo-Enterprises consolidometer, model S-450 Terraload, at stresses of 25, 50, 100, 200, 400, 800 and 1600 kPa. The stresses were applied until reaching the deformation of 90 % of the sample and, after the tests, the samples were dried in an oven at 105-110 °C, for 24 h, to determine their dry mass and bulk density (Blake and Hartge, 1986). The laboratory tests were carried out in the second half of June and July 2019.

The methodology proposed by Dias Junior and Pierce (1995) was used to estimate the pre-consolidation pressure. Based on the values of gravimetric water content and pre-consolidation pressure of the soil samples, LBC models were adjusted for the experimental area using the method of least squares, according to the mathematical expression proposed in the equation 1.

$$\sigma_P = 10^{(a+bU)} \qquad \text{Eq. 1}$$

in which: σ_P is the pre-consolidation pressure (kPa); U is the gravimetric water content of the sample (kg kg^{-1}); "a" and "b" are the linear and angular coefficients, in order, of adjustment of the model.

The adjusted models were linearized and then subjected to the methodology described by Snedecor and Cochran (1989) for statistical comparison between LBC mathematical expressions obtained for the treatments and for the depths studied.

Vertical stresses applied to the soil by agricultural machinery

Management activities of the coffee crop in both treatments (full sun and shaded) are carried out using agricultural tractors. It is necessary to determine the real vertical stresses applied to the soil by the most frequently used tractors in the experimental area to estimate the critical soil water content for traffic of these agricultural machines and contribute to the management plan for the experimental area. For that, one agricultural tractor of the Agrale brand, model 4100 (with 10.8 kW of engine power at 2,750 rpm and 4 × 2 traction system), and two agricultural tractors of the Massey Ferguson brand, model 265 (with 48 kW of engine power at 2,200 rpm and 4 × 2 TDA traction system) and model 275 (with 56 kW of engine power at 2,200rpm and 4 × 2 TDA traction system), were studied.

Total mass and the mass per axis of the 3 agricultural tractors were quantified on a commercial scale by the partner company *Soma Nutrição Animal*. The diameter and width of the wheel sets were determined using a fiberglass measuring tape. The current and recommended air pressures of tractor tires were measured using an analog Bourdon manometer and a catalog of the tire manufacturers. The length of the tire contact area with soil surface (Equation 2) and the tire contact area with soil (Equation 3) were estimated using the methodology proposed by Keller (2005).

$$l_A = 0.47 + 0.11\ \varnothing^2_{tires} - 0.16\ LN\left(\frac{P_{current}}{P_{recommended}}\right) \qquad \text{Eq. 2}$$

$$AC = 0.785\ l_A w_A \quad \text{Eq. 3}$$

in which: l_A is the length of the tire contact area with soil-surface (m); ø corresponds to the diameter of the wheelset (m); $P_{current}$ is the current air pressure in the tire (kPa); $P_{recommended}$ is the air pressure recommended by the manufacturer of tires (kPa); AC is the area of contact between the tires and the soil surface (m²); w_A is the width of the tire contact area with the soil and which Keller (2005) assumes is equal to the width of the tire.

The relationship between the tire load and its contact area allows one to determine the average vertical stress (Equation 4) and the maximum vertical stress (Equation 5) applied by the machine on the soil, as proposed by Keller (2005).

$$\sigma_{average} = \frac{F_{tire}}{AC} \quad \text{Eq. 4}$$

$$\sigma_{max} = 34.4 + 1.13\ P_{current} + 0.72\ F_{tire} - 33.4\ LN\left(\frac{P_{current}}{P_{recommended}}\right) \quad \text{Eq. 5}$$

in which: $\sigma_{average}$ is the average vertical stress applied by the tractor on the soil (kPa); F_{tire} consists of the force applied by each tire to the soil (kN); σ_{max} is the maximum vertical stress applied by the tractor over a radial area, kPa.

Vertical stress distributions on soil, for the three agricultural tractors analyzed, were determined using the Tyres/Tracks and Soil Compaction (TASC) spreadsheet (Diserens, 2005). In simulations, the management - soil moisture, maximum tillage depth and soil texture input parameters used were farming soil, 0.50 m and the clay and silty results of the Bouyoucos (1962) test, in order. The dissipation depth and lateral extent of the vertical stresses applied on soil by the tractors studied were evaluated using the output data generated by the vertical stress distribution.

Critical soil water content for agricultural machinery traffic

Critical soil water content for the traffic of agricultural tractors in the treatments under full sun and shaded regimes were estimated by equating the maximum vertical stress of agricultural machines (Equation 5) to the pre-consolidation pressure in the soil load-bearing capacity models generated (Equation 1) adjusted for the three depths analyzed in each treatment.

RESULTS

Soil load-bearing capacity

The soil of the experimental area, in both treatments, was classified as clayey, with the soil sample from the area in full sun consisting of 560 g kg^{-1} of clay, 320 g kg^{-1} of silt and 120 g kg^{-1} of sand, while in the shaded treatment 420, 230 and 350 g kg^{-1} for clay, silt and sand respectively were recorded. Figure 2 illustrates the LBC models adjusted for the evaluated layers and treatments and table 1 describes the statistical comparison between LBC models of coffee plants in full sun and shaded areas.

The adjusted models of soil load bearing capacity (Figure 2) presented linear coefficients between 2.96 and 3.05 for the coffee plants in full sun and between 2.80 and 2.86 for the shaded treatment and did not differ statistically between at the different depths assessed (Table 1). The estimated angular coefficients ranged from -1.41 to -1.13 and from -1.68 to -1.04 in full sun and shaded treatments, respectively, and differed statistically in the three depths studied. The adjusted models (Figure 2) presented R^2 varying between 0.70 and 0.85 for coffee plants under full sun and between 0.61 and 0.77 for shaded treatment.

Results of the statistical tests presented in table 1 reveal that the soil LBC models adjusted for the full sun and shaded treatments cannot be grouped and that they are different. Table 2 summarizes the results of the statistical comparison, at 5 % significance, of the LBC at soil depth in full sun and shaded treatments.

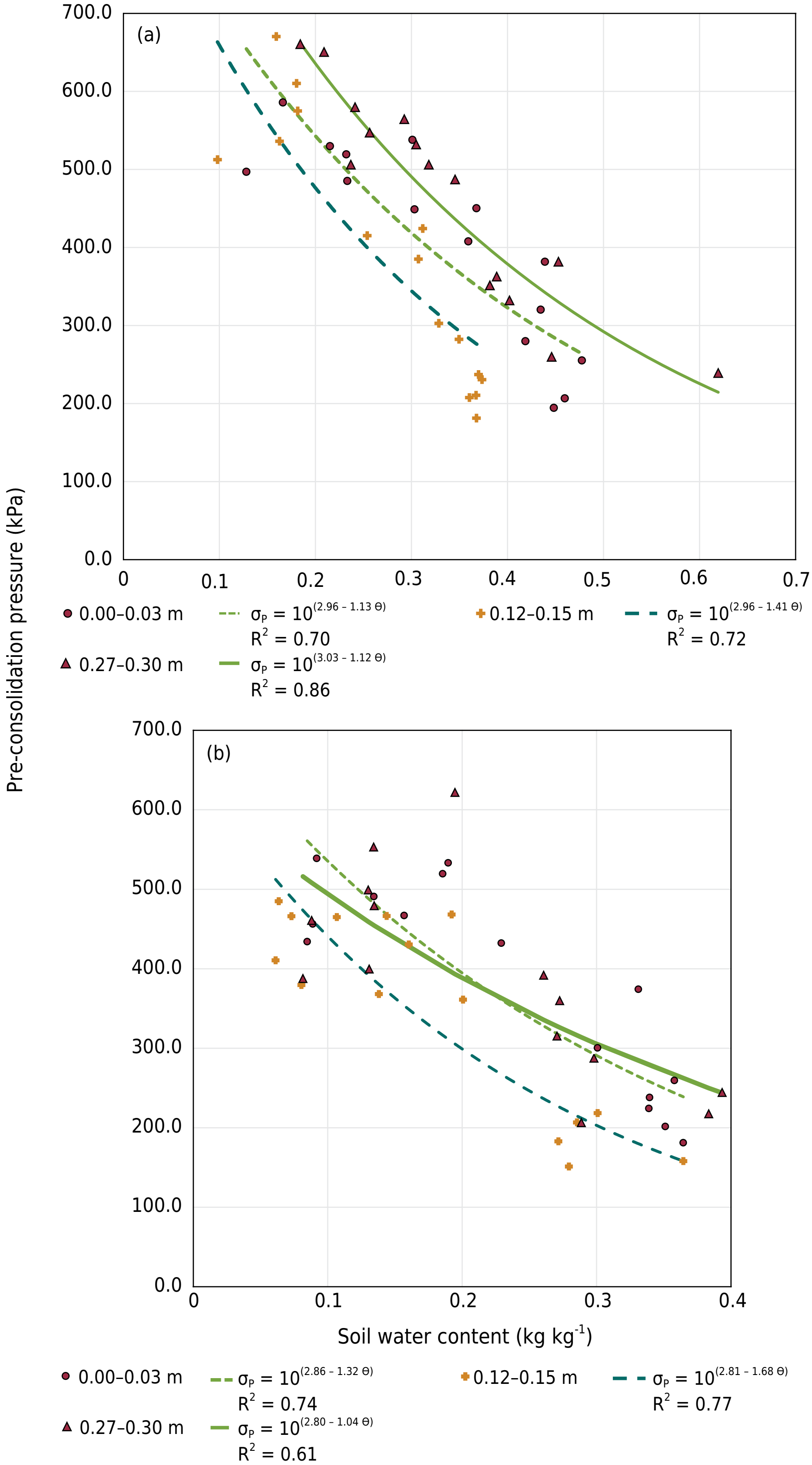

Figure 2. Soil load-bearing capacity models for coffee plantations under full sun (a) and shaded (b) management regimes.

Table 1. Statistical comparison between soil load-bearing capacity models for full sun and shaded treatments

Layer	Homogeneity	Linear coefficient (a)	Angular coefficient (b)
0.00-0.03 m in full sun × 0.00-0.03 m shaded	H	ns	*
0.12-0.15 m in full sun × 0.12-0.15 m shaded	H	ns	*
0.27-0.30 m in full sun × 0.27-0.30 m shaded	NH	ns	*

H and NH correspond to the homogeneity or non-homogeneity of the data and * and ns correspond to significant or non-significant, at 5 % probability, according to Snedecor and Cochran (1989).

Table 2. Statistical comparison of load-bearing capacity in soil depth occupied by coffee plantations under full sun and shade management regimes

Layer	Homogeneity	Linear coefficient (a)	Angular coefficient (b)
In Full Sun			
0.00-0.03 × 0.12-0.15 m	H	*	*
0.00-0.03 × 0.27-0.30 m	H	*	ns
0.12-0.15 × 0.27-0.30 m	H	*	*
Shaded			
0.00-0.03 × 0.12-0.15 m	H	*	*
0.00-0.03 × 0.27-0.30 m	H	ns	ns
0.12-0.15 × 0.27-0.30 m	H	*	ns

H corresponds to homogeneity and NH to non-homogeneity between the soil LBC models; * and ns are the significant or non-significant statistical difference of the observations, at 5 % probability, according to Snedecor and Cochran (1989).

The results in table 2 show that the soil LBC in the treatment under full sun varies at the three studied layers and that the models cannot be grouped (Snedecor and Cochran, 1989; Dias Junior et at., 2019). For the same level of soil water content, the pre-consolidation pressure values are higher at the layer of 0.27-0.30 m, followed by the 0.00-0.03 m and 0.12-0.15 m soil layers, as shown in figure 2a.

Statistical comparison of the shaded coffee plants demonstrated that the 0.00-0.03 / 0.12-0.15 and 0.12-0.15 / 0.27-0.30 m layers are statistically different (Table 2) and cannot be grouped in a single mathematical model. However, 0.00-0.03 and 0.27-0.30 m layers are homogeneous and statistically equal in terms of the soil LBC, which allows, according to Snedecor and Cochran (1989), the convergence of the observations on the two layers in a single mathematical model, as illustrated in the figure 3.

The LBC model adjusted for the 0.00-0.03 and 0.27-0.30 m layers of the shaded treatment presented a linear coefficient (a = 2.84) and angular coefficient (b = -1.22) close to the arithmetic mean of the observed values in individual models (a = 2.86 and b = -1.32 for the 0.00-0.03 m layer and a = 2.80 and b = -1.04 for the 0.27-0.30 m layer). The statistical test between mathematical models adjusted for the 0.12-0.15 m layer and the 0.00-0.03 / 0.27-0.30 m layers show that the models are different, cannot be grouped and the pre-consolidation pressure for the same soil water content value is higher in the 0.00-0.03 / 0.27-0.30 m layer, as shown in figure 3.

Vertical stresses applied on soil by agricultural machinery

Table 3 summarizes the physical parameters and values of contact area, average and maximum vertical stress estimated for the three agricultural tractors used in the management of the coffee crop installed in the experimental area. Figure 4 illustrates the stress bulbs in the soil simulated in the TASC spreadsheet (Diserens, 2005). Table 3 describes maximum vertical stresses of 335.76, 200.24 and 245.55 kPa for the front tires and 239.58, 196.94 and 190.91 kPa for the rear tires of the Agrale 4100, MF 265 and MF 275, respectively.

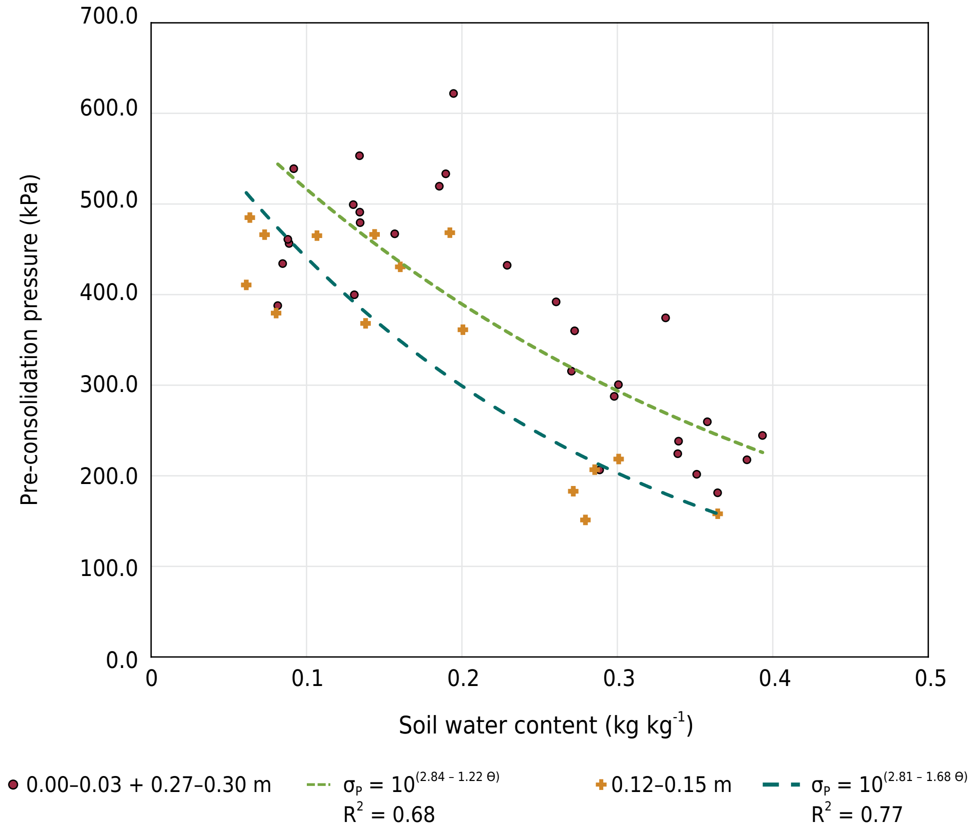

Figure 3. Load-bearing capacity model of shaded treatment after grouping data from the 0.00-0.03 and 0.27-0.30 m layers.

Table 3. Physical properties, contact area, average and maximum vertical stress of the agricultural tractors Agrale 4100, MF 265 and MF 275 used in the agricultural activities of the experimental area

Physical properties	Agrale 4100		MF 265		MF 275	
	Front	Rear	Front	Rear	Front	Rear
Mass (kg)	500.00	610.00	1809.52	2540.28	1869.84	2540.16
$Ø_{tire}$ (m)	0.60	0.98	1.11	1.55	1.13	1.49
w_A (m)	0.12	0.22	0.32	0.46	0.32	0.47
$P_{current}$ (kPa)	255.00	172.00	124.00	117.00	174.00	110.00
P_{recomm} (kPa)	358.00	221.00	221.00	221.00	221.00	221.00
AC (m²)	0.05	0.11	0.17	0.30	0.16	0.30
$σ_{average}$ (kPa)	48.11	28.12	51.38	41.24	57.11	41.10
$σ_{max}$ (kPa)	335.76	239.58	200.24	196.94	245.55	190.91

Mass, $Ø_{tire}$, w_A, $P_{current}$ and $P_{recomm.}$ corresponds to mass of the agricultural tractors, diameter and width of the wheelset and current and recommended air pressure in the tire, respectively. AC, $σ_{average}$ and $σ_{max}$ are contact area between the tires and the soil surface, and average and maximum vertical stress applied by the tractors on the soil.

Critical soil water content for agricultural machinery traffic

The maximum vertical stress observed for the Agrale 4100, MF 265 and MF 275 tractors and the LBC models of the 0.12-0.15 m soil layer (critical and more vulnerable to deformations layer) were used to estimate the critical soil water content for the machine traffic in coffee plantation and the results are shown in table 4. The highest critical soil water content was observed in the full sun treatment and for the MF 265 tractor, followed by the MF 275 and the Agrale 4100 (Table 4).

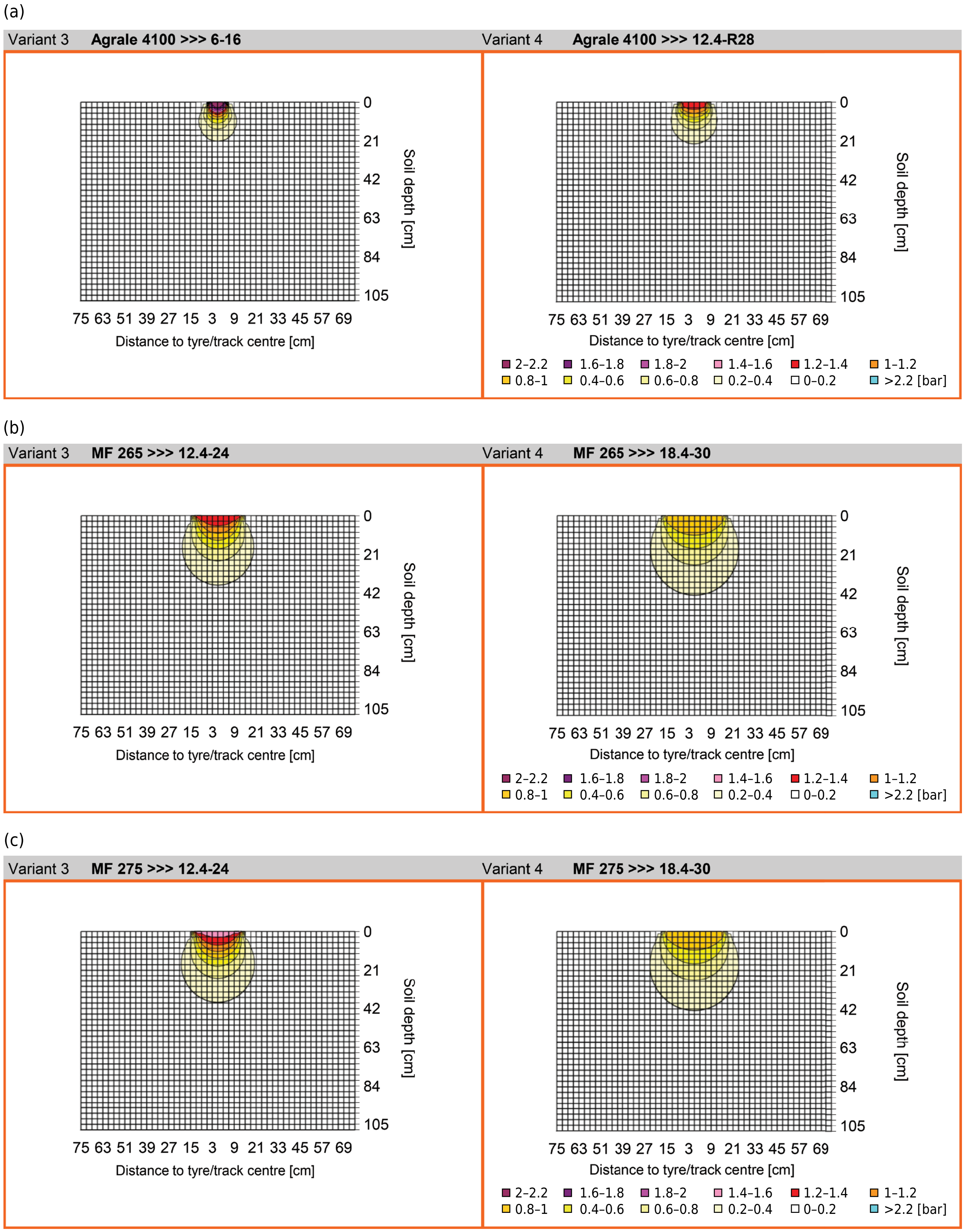

Figure 4. Front (left side) and rear (right side) tire stress bulbs of (a) Agrale 4100, (b) MF 265 and (c) MF 275.

Table 4. Values of critical soil water content for the traffic of agricultural tractors in coffee plantations managed in full sun and shaded

Tractor model	In full sun	Shaded
	kg.kg^{-1}	
Agrale 4100	0.31	0.17
MF 265	0.47	0.30
MF 275	0.40	0.25

DISCUSSION

Soil load-bearing capacity

Results of the soil texture analysis in the experimental area were in line with fine granulometry and plasticity observed during the field inspections and relate to high soil LBC, since iron and aluminum oxides present in clay fraction of the Oxisols act as inorganic cementing agents and become soil aggregates more resistant to deformations (Kondo and Dias Junior, 1999; Mauri et al., 2011).

Linear and angular coefficients estimated for the LBC models (Figure 2) are close to those found by Silva et al. (2003) (a = 2.73 and b = -1.65) in a study of the superficial layer (0.00 to 0.05 m) of Red Dystrophic Oxisol (*Latossolo Vermelho distrófico*) from the Cerrado region, by Pires et al. (2012) (a = 2.69 and b = -1.88) in the research on the LBC of Red Yellow Oxisol (*Latossolo Vermelho-Amarelo distrófico*) with natural forest, and by Castioni (2017) (a = 2.62 and b = -1.17 for the 0.00-0.10 m layer and a = 2.63 and b = -1.28 for the 0.10-0.20 m layer) in the evaluation of the pre-consolidation pressure in Red Oxisol (*Latossolo Vermelho*) planting line.

The determination coefficients in the adjusted mathematical expressions (Figure 2) are similar to those found by Vischi Filho et al. (2015), Castioni (2017) and Costa et al. (2019) in the mathematical modeling of the LBC of Oxisols. The complexity and quantity of variables that influence the soil pre-consolidation pressure, such as texture and mineralogy, soil structure and bulk density, soil use and management (Dias Junior et al., 2019), justify the absence of greater R^2 values.

Soil LBC models adjusted for full sun and shaded treatments are different and cannot be grouped, as shown in table 1. Since higher angular coefficients are associated with higher LBC, it can be said that, in both treatments, at a depth of 0.27-0.30 m, the soil showed greater capacity to withstand vertical stresses, followed by layers of 0.00-0.03 and 0.12-0.15 m. In general, the soil LBC for the coffee plant in full sun is superior to the shaded treatment.

The proposed coffee and gliricidia consortium sought to improve the natural fertility of the soil through the abscission of the gliricidia's leaves on the surface and, therefore, a higher LBC was expected at the 0.00-0.03 m layer of the shaded treatment to the detriment of the coffee plant in full sun. However, Campanha et al. (2007) highlight that the higher temperatures observed in coffee areas in full sun, when compared to shaded coffee plants, favor the decomposition of organic matter present on the soil, which contributes significantly to the structure of the superficial soil and explains the greatest resilience in the 0.00-0.03 m layer of this treatment. Soil analysis carried out in 2015 in the experimental area showed indexes of 1.66 and 1.03 dag kg^{-1} of organic matter in the 0.00-0.20 m layer in full sun and shaded treatments, respectively, in line with the reports of Campanha et al. (2007) and Machado et al. (2014). Moreover, the full sun area offers better climatic conditions for the development of invasive plants and the mowing, control method adopted in the experimental area, removes only the aerial part of the plants and leaves the root systems of the invasive plants penetrating the soil, improving the structure (Bertollo and Levien, 2019) and the soil LBC in the surface layer.

Heterogeneous behavior of pre-consolidation pressure in the soil profile in full sun treatment (Table 2) differed from the results observed by Araujo-Junior et al. (2011), who identified non-significant differences in the pre-consolidation pressure values for the same gravimetric water content when advancing in the depth of a Dystrophic Red Oxisol (*Latossolo Vermelho distrófico*) occupied by coffee plants and using mowing in the management of invasive plants. However, the heterogeneous behavior observed in this study showed similarity with the results presented by Vischi Filho et al. (2015), who found that the pre-consolidation pressure values fluctuated in the soil profile. The lack of a pattern in the LBC in the soil profile observed in this study allows us to infer the heterogeneity of the attributes of the studied soil profile.

According to Araujo-Junior et al. (2011), in grouped layers, as occurred in the case of 0.00-0.03 and 0.27-0.30 m layers, the homogeneous behavior of pre-consolidation pressure is possibly associated with the proximity of soil bulk density at the depths evaluated and with the influence of root system of local plants. In addition, when using soil LBC models (Figure 2a and Figure 3) in the planning and management of the traffic of agricultural machines and / or animals in the experimental area, the layers less resistant to deformation must be considered, which for both treatments were the depth of 0.12-0.15 m.

Vertical stresses applied to the soil by agricultural machinery

The agricultural tractors Agrale 4100, MF 265 and MF 275 presented a mass / power ratio of 101.85, 90.62 and 78.85 kg kW^{-1}, respectively. For the tractors Agrale 4100 and MF 265, the values observed were above those indicated by the Brazilian Association of Motor Vehicle Manufacturers (ANFAVEA), namely between 54.00 and 82.00 kg kW^{-1}, which indicate that there is an excess of mass in the structure of these tractors in relation to air pressure and current tires. This excess of mass results in environmental damage to the agricultural area (Neres et al., 2012; Cortez et al., 2014; Mion et al., 2016) and energy loss for the agricultural machines (Monteiro et al., 2013; Lopes et al., 2019). Therefore, we recommend reviewing the weights of the Agrale 4100 and MF 265 tractors to operate within the technical recommendations and with tractive and energy efficiency, as highlighted by Fiorese et al. (2019).

During data collection in the field for Agrale 4100, we observed that this tractor has been used in heavy operations and is incompatible with its purpose, helping to explain the excess weight of the tractor. Schlosser et al. (2005) point out that class I agricultural tractors (ANFAVEA), such as the Agrale 4100, are indicated for activities that demand less strength and more speed. Since there are other powerful agricultural machines in the experimental area, such as MF 265 and MF 275 tractors, with the capacity for heavier jobs, it is necessary to review the management of machinery, rationalizing the use of tractors and respecting their characteristics in line with the requirements of the operation, as highlighted by Lacerda et al. (2019).

Mass of the machines is directly related to the vertical stress applied by them to soil. The maximum vertical stresses were observed in the front tires of the agricultural machines. Agrale 4100 is the tractor that applies the highest vertical pressure on soil (Table 3). Mion et al. (2016) quantified the maximum vertical stresses applied on the soil surface by finite elements and highlighted that their values are approximately equal to the air pressures recommended by the manufacturers of agricultural tires. This information differs from that presented in the present study, which shows the difference between σ_{max} and $P_{recommended}$ of up to 30 kPa.

The maximum vertical stress applied by Agrale 4100 on soil is equivalent to the pressure applied by cattle (σ_{max} = 330.00 kPa) (Lull, 1959). Vertical stresses of this magnitude, when applied in inadequate conditions of soil water content, can cause plastic deformations that are not recoverable in the soil (Paulo and Almeida, 2016), changing soil physical properties, and limiting the root system growth and reducing productivity. The results found in the case of Agrale 4100 call attention to the size of the agricultural tractor (class I), the excess mass already mentioned and the low contact area of the tire with the soil. During field inspections, it was observed that the front tires used on this tractor did not correspond to those recommended by the agricultural machine manufacturer. Furthermore, in the TASC simulations, 60 % of the maximum vertical stress applied by this tractor dissipates in the first 0.14 m of the soil (Figure 4a), that is, the soil layer with the lowest LBC (0.12-0.15 m), as illustrated in figures 2a and 3, which highlights the importance of planning mechanized operations.

For the MF 265 and MF 275 tractors, vertical stresses on soil and stress bulbs were similar, given the physical similarity between the two tractor models. The difference in maximum vertical stress on soil observed in the front tires of the two machines occurred due to the increased air pressure in one of the tires of the MF 275 ($P_{current}$ = 174.00 kPa). The vertical stress values observed for the rear tires of both machines (Table 3) are equivalent to anthropic pressures applied on soil (σ_{max} of 190.00 kPa according to Lull, 1959), which can lead to additional compaction and/or degradation of the soil structure, over time, when applied on soil with high water content (Thebaldi et al., 2012; Rocha et al., 2018). Figures 4b and 4c show that 60 % of the maximum normal stresses dissipate in the first 0.21 m of the soil for both agricultural machines when comparing stress bulbs.

Vertical stress values for MF 265 and MF 275 tractors in table 3 coincide with the observations reported by Richart et al. (2005). They highlighted that the average stresses applied on soils by agricultural machines are between 50 and 300 kPa. However, they differed from those presented by Cardoso (2007), who also evaluated an MF 275 4 × 2 TDA tractor and found stress of σ_{max} of 253.00 kPa for front tires and σ_{max} of 271.00kPa for rear tires. The differences in the vertical stress values for the MF 275 found in this study and that found by Cardoso (2007) can be attributed to the parameters of the wheelsets. In this study, we observed current tire pressure of 174.00 kPa and tire contact area with the soil of 0.16 m^2 for the front tires and 110.00 kPa and 0.30 m^2 in the rear tires, while Cardoso (2007) found 110.00 kPa and 0.17 m^2 in front tires and 144.80 kPa and 0.21 m^2 in rear tires, respectively. The data presented in table 3 and findings by Cardoso (2007) reveal the complexity of the studies involving vertical stresses applied to the soil by agricultural machines, in which all variables related to the mass distribution in the chassis and the wheels of the tractors must be considered (Keller, 2005; Lanças et al., 2005), so that the final results are not directly related to the sizes of the tractors and agricultural implements.

Critical soil water content for agricultural machinery traffic

Critical soil water content was inversely proportional to the vertical stresses applied to the soil by agricultural tractors, as expected, and was higher in coffee plants in the full sun regime when compared to the shaded treatment (Table 4). The critical water content values of both treatments differed from those observed by Figueiredo et al. (2000) that using disturbed soil samples and Proctor test evaluated the critical water content of a Purple Oxisol (*Latossolo roxo*) and highlighted that the $U_{critical}$ corresponds to 90 % of the soil plasticity limit and 90 % of the water retained at 10 kPa, approximately equal to the water retained at 33 kPa. For the treatment in full sun ($U_{10\ kPa\ of\ 0.12\text{-}0.15\ m}$ = 0.3678 kg kg^{-1}), the critical soil water content values were equal to 84, 127 and 108 % of the water retained at 10 kPa, while for shaded treatment ($U_{10\ kPa\ of\ 0.12\text{-}0.15\ m}$ = 0.2997 kg kg^{-1}) the percentages were 56, 100 and 83 % for Agrale 4100, MF 265 and MF 275 tractors, in that order. However, the critical water content value for Agrale 4100 in full sun treatment (Table 4) was close to that estimated by Araujo-Junior et al. (2011), who found $U_{critical}$ equal to 0.30 kg kg^{-1} (critical volumetric water content = 0.35 m^3 m^{-3} and bulk density = 1.20 Mg m^{-3}) using data from a Valmet tractor, model 68, and a Dystrophic Red Oxisol (*Latossolo Vermelho distrófico*) occupied by coffee plantation in full sun and mowing as a method for the management of invasive plants.

Critical water content values higher than field capacity water content (water content at 10 kPa) can be understood as a soil-machine arrangement in which the vertical stresses acting on the soil are low or that the soil has high pre-consolidation pressure values, emphasizing the ability of the studied Red Yellow Oxisol (*Latossolo Vermelho-Amarelo*) to withstand vertical stresses. The entry of agricultural tractors studied in the experimental area must occur when the soil water content is below the values described in table 4, so that the vertical stresses applied by the machinery do not exceed the pre-consolidation pressure and result in elastic or recoverable deformations in the soil structure, without the additional compaction (Kondo and Dias Junior, 1999; Araujo-Junior et al., 2011; Dias Junior et al., 2019).

In this context, the use of critical water content is indicated (Table 4) in the management of the mechanized operations of the coffee plantations in the experimental area, with special attention to the soil water content replacing the Agrale 4100 in both treatments and the MF 275 in the shaded treatment. The chances of additional soil compaction are minimal for combinations that show critical water content higher than the field capacity moisture.

CONCLUSIONS

The load-bearing capacity of the dystrophic Red Yellow Oxisol (*Latossolo Vermelho-Amarelo distrófico* - LVA7) was not influenced by the cultivation of gliricidia (*Gliricidia sepium*) in consortium with arabica coffee (*Coffea arabica L.*), cultivar Oeiras MG 6851, and the highest pre-consolidation pressure values were observed in coffee plantations in full sun management regime.

The agricultural tractors Agrale 4100, MF 265 and MF 275 present current maximum vertical stresses of 335.76, 200.24, and 245.55 kPa, respectively, and all these values were observed in the front tires of the agricultural machines.

The critical soil water content for the traffic of agricultural tractors was higher in the coffee plantations in full sun, and it was inversely proportional to the maximum vertical stress applied to the soil by the agricultural tractors analyzed.

Soil load-bearing capacity data, tractor vertical stresses applied on soil, and critical soil moisture can be used to manage mechanized operations in coffee plantations.

ACKNOWLEDGMENTS

We are grateful to Lavínia Rodrigues de Faria and João Paulo Augusto Borges, for helping with the uniaxial compression tests of the soil, to the company Soma Nutrição Animal for offering its installations for establishing the mass of agricultural tractors, to Mr. Etienne Diserens for the guidance on the use of the spreadsheet TASC, and to the Federal Institute of Education, Science and Technology of the Southeast of Minas Gerais for the financial support.

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