Revista Brasileira de Ciência do Solo

Division - Soil Processes and Properties | Commission - Soil Physics

Mechanized and irrigated coffee cultivation promotes physical subsurface constraints in Oxisols

Katherine Martinez Escobar[(1)], **Laís Maria Rodrigues Silva**[(1)], **Keise Duarte Bacelar de Morais**[(1)], **Júlio César Lima Neves**[(1)] **and Teogenes Senna de Oliveira**[(1)*]

[(1)] Universidade Federal de Viçosa, Programa de Pós-Graduação em Solos e Nutrição de Plantas, Departamento de Solos, Viçosa, Minas Gerais, Brasil.

ABSTRACT: Soils of the Cerrados (Brazilian Savanna) are deep, well-structured, and well-drained, with flat to gently undulating terrain that favors mechanization for coffee cultivation. However, these soils are susceptible to compaction. This study aimed to assess the effect of mechanization on the physical characteristics of an Oxisol under irrigated coffee cultivation in the Alto Paranaíba-Minas Gerais State. We selected eight areas with different cultivars and years of Arabica coffee plantation, sampling five positions: right soil under the tree crown (RSC), right tractor lines (RTL), interrows (IR), left tractor lines (LTL), and left soil under the tree crown (LSC) at layers of 0.00-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.40 m. We conducted principal component analysis (PCA) and analysis of variance, comparing means through Tukey's test ($p<0.05$). The PCA selected three principal components (PC1, PC2, and PC3) composed of 12 physico-chemical properties from a total of 27 evaluated. Total porosity (TP), mean penetration resistance (PRmean), volumetric moisture (θ) at 100 kPa (θ 100 kPa) and 300 kPa (θ 300 kPa) tensions, particle density (PD), and granulometric fractions (clay, fine sand, and coarse sand) were among the most influential attributes. Total porosity and PRmean demonstrated the existence of compaction in the tractor wheel tracks, particularly in the 0.00-0.20 m layer. The 3.5-year-old plantation did not show significant variations in these properties. The θ 100 kPa and θ 300 kPa were higher in the compacted areas, indicating increased water retention but potentially limiting aeration. Clay content increased with depth, while sand fractions decreased, influencing the soil susceptibility to compaction. The vigor of coffee plants, as identified by satellite images (NDVI), could not be fully associated with the physical constraints of the subsurface, as even areas with low vigor did not consistently correlate with poor physical properties in laboratory analyses. These findings highlight the complex interplay between soil physical properties and coffee plant performance, emphasizing the need for comprehensive management strategies in mechanized coffee cultivation.

Keywords: subsurface, compaction, total porosity, NDVI, *Coffea arabica*.

*** Corresponding author:**
E-mail: teo@ufv.br

Received: August 01, 2024

Approved: January 10, 2025

How to cite: Escobar KM, Silva LMR, Morais KDB, Neves JCL, Oliveira TS. Mechanized and irrigated coffee cultivation promotes physical subsurface constraints in Oxisols. Rev Bras Cienc Solo. 2025;49:e0240111.
https://doi.org/10.36783/18069657rbcs20240111

Editors: José Miguel Reichert and João Tavares Filho.

Copyright: This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided that the original author and source are credited.

INTRODUCTION

Coffee is one of the most economically important commodities for Brazil. The total area cultivated with Arabica coffee (*Coffea arabica* L.) and conilon (*Coffea canefora* Pierre ex Froehner) is 1.876 million ha, of which the area cultivated with the Arabica variety is estimated at 1.488 million ha, 79.3 % of the total area destined to national coffee cultivation. Minas Gerais concentrates the largest area with arabica coffee (Coffea arabica*)* at the national level, and in the 2023 harvest, about 6.999 million bags were produced in the Cerrado region in this state (Conab, 2023).

Coffee cultivation in Minas Gerais began in the nineteenth century, when plantations were established in the South and Zona da Mata regions (Alcântara and Ferreira, 2000). Over time, the coffee plantations in Minas Gerais expanded to new areas, such as the Triângulo Mineiro and Alto Paranaíba (Azevedo, 2018), regions with flatter terrain, which favors mechanization, but with the need for irrigated systems (Gomes et al., 2020). These regions add up to 51 municipalities and a coffee-growing area of 211.9 thousand ha (Coffee Geoportal, 2023). The soils of this region have severe chemical limitations that restrict the effective depth for the development of the root system (Burak et al., 2012), such as high acidity and toxicity of Al^{3+} (Silva et al., 2003) and low levels of phosphorus (P) and calcium (Ca^{2+}) (Lynch and Wojciechowski, 2015).

One of the most expensive stages of coffee cultivation is labor (Conab, 2017), especially when cultural treatments and harvesting are conducted manually. In this scenario, mechanization in coffee cultivation is justified to reduce costs, especially in the harvest, making the crops more efficient. However, intensive use of agricultural machinery and equipment in inadequate soil moisture conditions can lead to compaction (Silva et al., 2002; Carmo et al., 2011; Souza et al., 2014). Mechanized operations in coffee plantations are concentrated in small strips along planting rows, forcing the machines to always move in the same place (Cortez et al., 2011), causing differential compaction of this soil. This restricted space, close to the projection of the coffee tree canopy, is where most of its active roots are concentrated, subjecting root growth to soil constraints (Carmo et al., 2011).

The difficulty of expanding the root system has direct and indirect implications for the development of crops, reflecting in the drop in productivity (Fernandes et al., 2012), altering the capacity of water infiltration, aeration, heat transfer, and nutrient movement in the soil profile (Richmond and Rillo, 2006). Soil ability to provide water is a function of retention properties, determined by the quality of soil structure, which results from the interaction between texture, mineralogy, organic matter, and management practices (Silva et al., 2014).

Compaction is a process that varies according to the texture and type of soil management (Fernandes et al., 2012), and is defined as the increase in the soil bulk density as a result of the loads or pressures applied to it. Compaction magnitude is expressed by the increase in the density and resistance of the soil to penetration (Luciano et al., 2012; Lopes et al., 2020), which can be facilitated by the soil water regime. Water acts as a lubricant between soil solid particles, providing, up to a certain content, an increase in the soil susceptibility to compaction, known as critical moisture (θ_{Crit}) of compaction (Martins et al., 2012a).

Combined with critical soil moisture (θ_{Crit}), texture also contributes to the propensity for compaction. Clayey soils are more susceptible to compaction than sandy soils (Naghdi et al., 2020), as sand granules are not susceptible to being compressed, as occurs with clay aggregates. For coffee production systems, where harvesting and cultural treatments are conducted mechanically, there may be short-term compaction due to machine traffic (Oliveira et al., 2010), generating an increase in density directly proportional to the increase in penetration resistance (Sá et al., 2016).

Regarding microporosity, Tormena et al. (2002) found an inverse interaction between microporosity (Mi), total porosity (TP), and bulk density (BD). The first increase in BD came from the decrease in the pore space related to the macropores, since, due to the size of the pores, they are the first to suffer the effects of the tensions exerted by the traffic of machinery and agricultural implements applied to the surface. Thus, macropores (Ma) become smaller and smaller, until they reach the diameters of the micropores, leading to an initial increase in Mi with the consequent increase in BD. Effgen et al. (2012) obtained similar results in coffee plantations in the topsoil layer (0.00-0.20 m) and in a coffee system with mechanized management. Carmo et al. (2011) showed lower macroporosity values, lower Ma/Mi ratio, and increased microporosity values, in the depth of 0.00-0.30 m, four years after planting.

In general, these properties act as indicators of possible constraints to the root growth of crops (Tormena et al., 2002). Based on the above, this study aimed to assess the physical properties of a Red-Yellow Oxisol (Latossolo Vermelho Amarelo) under irrigated and mechanized coffee cultivation in the Alto Paranaíba region, Minas Gerais, assuming that the management system promotes physical constraints in the subsurface for the crop.

MATERIALS AND METHODS

We selected twelve coffee farms in the study area of the macro-region of Alto Paranaíba – Minas Gerais State, considering different types of management: irrigation (drip or central pivot sprinkler), intensity of mechanization, varieties, production, and productivity, all based on consultations with technicians in the region. For the delimitation of properties and cultivation areas, we used information from the Rural Environmental Registry (CAR) (available at https://www.car.gov.br/publico/municipios/downloads). For these areas, we calculated maps with spectral indices from satellite images, testing: Normalized Difference Water Index - NDWI; Moisture Stress Index - MSI; and Normalized Difference Vegetation Index - NDVI, aiming to identify signs of soil constraints for coffee plants. Of the indices calculated, the NDVI showed the best response to plant vigor, which was influenced by the different soil-plant interactions (Ladeia et al., 2019). The variability alters plant vigor, leading to changes in reflectance as a response to biotic and/or abiotic factors. These changes can be linked to certain constraints affecting the coffee plant.

We calculated the NDVIs for the 12 farms. Then, we selected areas with indices between 0.5 and 1 (Supplementary Material 1). Values closer to 0.5 represent coffee plants with low vigor, which may be a physiological response to some kind of constraint. We calculated the NDVI through the difference in reflectance between the NIR (near infrared) and Red bands divided by the sum of the NIR and Red bands according to equation 1, proposed by (Rouse et al., 1974).

$$NDVI = (NIR - Red)/(NIR + Red) \quad \text{(Eq. 1)}$$

Subsequently, we assessed NDVI in the field in the five pre-selected farms, which presented values around 0.5. Of these, only the Chuá farm was selected because it presents the greatest variability of NDVIs within its area in relation to the other farms and its potential association with subsurface constraints (Figure 1). The farm is located in the municipality of Patos de Minas – Minas Gerais State, whose headquarters presents the coordinates 18° 35’ 24” S and 46° 25’ 48” W. The mean elevation of the property is 1,046 m, located in flat to gently undulating terrain (Silva et al., 2003).

The climate, according to the classification system of Alvares et al. (2013), is of the Cwa type, humid subtropical with dry winter and hot summer with annual precipitation around 1,448 mm. Precipitation is concentrated from October to March, and the average annual temperature is 20.4 °C (Alvares et al., 2013). The predominant soil in the area is dystrophic

Red-Yellow Oxisol (Latossolo Vermelho Amarelo distrófico - LVAd) (Santos et al., 2018). Soils have a very clayey texture (clay content >60 %) (Table S1), naturally acidic (pH between 4.3 and 6.0) and dystrophic (V <50 %) (Table S1). Coffee areas are drip-irrigated, fully mechanized, and managed to achieve high coffee productivity (Table S2), following the recommendations for the use of amendments and fertilizers of Ribeiro et al. (1999).

Subsequently, we selected the situations to be assessed at the Chuá Farm, considering again the NDVI, the visual assessment in the field and the management history of the areas. We selected six cultivation areas (BV06, BA08, BV15, CT01a, AR17 and CT01b), with NDVI values between 0.5 and 0.7, which represented areas conducted with drip irrigation system, mechanization and that were in full production. Thus, we searched for areas where the low vegetative vigor of the plants could be associated with subsurface constraints, mainly due to physical conditions. In addition to the areas with low NDVI values, we selected the BA14 and BV09 areas, which presented values from 0.75 to 0.81, which were selected because they presented high vegetative vigor of the plants to contrast with the other chosen cultivation areas.

Soil sampling

We opened two trenches for each selected area (eight) between coffee rows, with an approximate length of 4 m and a depth of 1 m, totaling 16 trenches. In each trench, we considered five collection sites, defined from the position in relation to the plant, the orientation from the irrigation hose, and the slope. The first of these was collected under the canopy of the coffee plants to the projection of the canopy and was conducted both in the rows of plants at the highest altitude of the soil surface, and in the lower line of plants, being called right soil under the tree crown (RSC) and left soil under the tree crown (LSC), respectively. We also collected samples in the position in which the localized traffic of agricultural machinery between the rows is characterized, both in the high and in the low part of the rows, being called left soil under the tree crown (LSC) and left tractor lines (LTL). Finally, we collected samples in the interrows (IR), a region that was not under the influence of plants, irrigation or even machine traffic (Figure 2). We determined sampling positions and depths in each trench by assessing penetration resistance across the entire exposed surface. Using a collection knife tip, we distinguished zones of higher and lower resistance both horizontally and vertically.

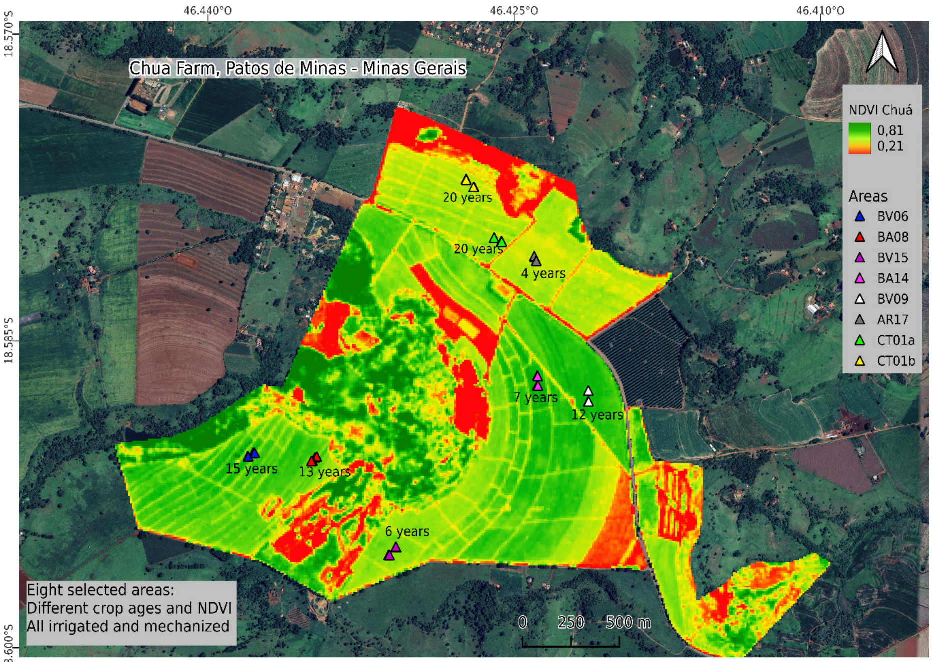

Figure 1. Location of Chuá Farm, delimitation and spatial distribution of the Normalized Difference Vegetation Index (NDVI) of the cultivated areas, Patos de Minas – Minas Gerais State, Brazil.

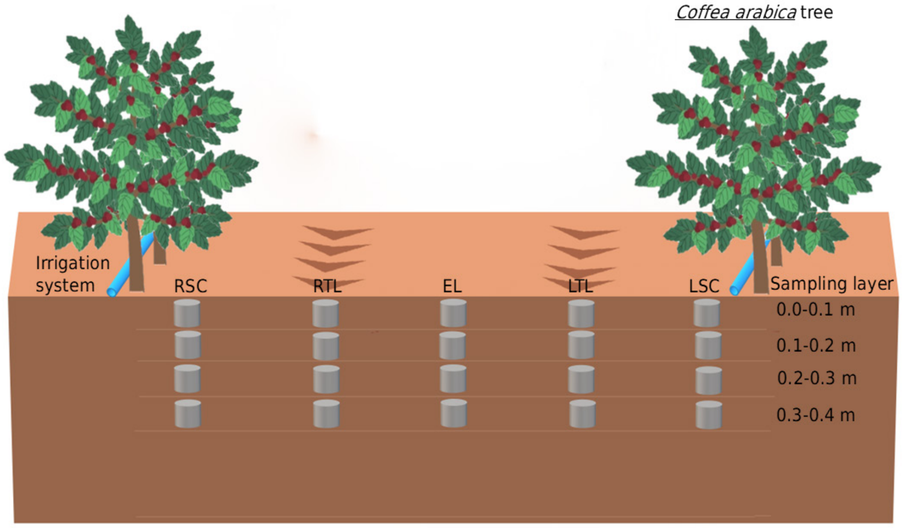

Figure 2. Soil sampling inside the trench. Sampling Position: RSC: Right soil under the tree crown; RTL: Right tractor line; IR: interrow; LTL: left tractor lines; LSC: Left soil under the tree crown.

We identified the tractor lines (LSC and LTL) as the points of greatest resistance to penetration, coinciding with the width of the axes of the machinery used, usually with some intermediate resistance range between the position of the canopy projection and the interrows (IR). The inter-rows are characterized by not receiving irrigation and being under partial passage of machinery, implements and vehicles. We did not consider transition situations in the assessment of the penetration resistance between the wheel track and the interrows for the sample collection.

We collected the deformed samples for chemical analysis by combining the RSC and LSC positions to form soil under the tree crown samples (SC). We also collected and homogenized RTL and LTL samples to form tractor lines samples (TL), as well as composite samples from the interrows (IR). For these samples, we considered depths of 0.00-0.20, 0.20-0.40 and 0.40-1.00 m, delimited according to the preliminary assessment of resistance to manual penetration with the tip of the collection knife.

We also collected undisturbed samples for the assessment of physical properties using rings of 0.05 m in diameter and 0.05 m in length, for each of the RSC, LSC, LSC, LTL and IR positions, but at the layers of 0.00-0.10, 0.10-0.20, 0.20-0.30 and 0.30-0.40 m. Thus, we obtained 20 undisturbed samples and 9 deformed samples per trench.

Physical analysis

We determined bulk density (Bd) and particle density (Pd) using the ring and volumetric balloon methods, respectively (Teixeira et al., 2017), allowing the estimation of total porosity (TP), according to equation 2.

$$\mathrm{TP} = (1 - \mathrm{Bd}/\mathrm{Pd}) \qquad \text{(Eq. 2)}$$

We determined the microporosity (Mi) in undisturbed samples by balancing samples on a tension table at 6 kPa, and the macroporosity was obtained by the difference between TP and Mi (Teixeira et al., 2017). We performed the hydraulic conductivity of the soil in saturated medium (K0) using rings, with a stabilization time of 60 min and a water column height of 2.5 cm with a constant load, and water volume measured in calibrated beakers according to Teixeira et al. (2017). We obtained the tensions for the soil water retention curve (SWRC) by balancing undisturbed samples at pressures 1, 6, and 10 kPa in a tension table, and, in deformed samples, the pressures of 100, 300, and 1500 kPa were determined in Richard's chambers. However, due to the amount of SWRC's generated, we proceeded with the statistical analysis of the moisture contents retained in each of the tensions, since 160 total curves would be generated. We assessed the penetration resistance (PR), measured in the TE-096 digital benchtop penetrometer of the Soil Physics Laboratory, at the central point of each undeformed sample in samples with balanced humidity at 10 kPa, a tension that characterizes the humidity in the field capacity (FC).

Statistical analysis

We submitted the results obtained to multivariate principal component analysis (PCA) in order to identify those properties that would further explain the total variance. Initially, we conducted the analyses with two groups of properties: physical and chemical, separately, obtaining the set of properties, in descending order of their contribution to the total variation of the data (Silva et al., 2010). After this selection, we formed a new group of properties composed of physical+chemical properties, being again submitted to PCA, always considering properties with eigenvalues above 1. Subsequently, each one of the 12 properties selected in the final PCA, in the case: Ca^{2+}, Mg^{2+}, Coarse Sand (CS), Fine Sand (FS), Clay, PD, Mean PR, Maximum PR, TP and Moisture (θ) at pressures of 100 and 300 kPa were analyzed in univariate form, considering three situations. For those properties obtained in deformed samples, we considered ANOVA, a factorial of 8 × 3 × 3, involving the eight cultivation areas (BV06, BA08, BV15, BA14, BV09, CT01a, AR17 and CT01b), the three collection positions (soil under the tree crown – SC, tractor lines – TL and interrows -IR) and three layers (0.00-0.20, 0.20-0.40 and 0.40-1.00 m). We assessed the properties of the undisturbed samples as an 8 × 5 × 4 factorial, eight cultivation areas (BV06, BA08, BV15, BA14, BV09, CT01a, AR17 and CT01b), five collection positions (right soil under the tree crown - RSC, left soil under the tree crown - LSC, right tractor lines - RTL, left tractor lines - LTL and interrows - IR) and four layers (0.00-0.10, 0.10-0.20, 0.20-0.30 and 0.30 to 0.40 m). In all the situations analyzed, we considered a completely randomized design, with constraints on randomization and two replications. All significant and non-significant interactions, by the F test in the ANOVAs, were unfolded, considering up to 5 % probability. In cases where the effects were significant by the F test, we compared the means by the Tukey test at 5 %. We performed the unfolding of the triple interactions as follows: areas in the position and depth of collections (A/Pos × Depth); depth in the cultivation areas and collection position (Depth/A × Pos) and; collection position in the cultivation and depth areas (Pos/A × Depth), and the last interaction that takes the collection position as the main factor is the most relevant for this study. For the PCAs and ANOVAs and their developments, we used the software (Statistica, v.13.0, 2023), and for Tukey's comparisons, we used an Excel spreadsheet.

RESULTS

Principal Component Analysis

Table 1 presents the results obtained by the PCA for the dataset of the physical+chemical properties, considering those variables selected by the PCA procedures applied separately to the chemical and physical properties. The three main components explained 81.16 % of the total variance associated with the areas studied (Table 1). Principal component 1 (PC1) explained 40.24 % and involved the properties mean resistance penetration (RPmean), maximum resistance penetration (RPmax), minimum resistance penetration (RPmin), total porosity (TP), volumetric moisture at 100 kPa tension (θ 100 kPa) and volumetric moisture at 300 kPa tension (θ 300 kPa) with eigenvalues ≥0.70, while component 2 (PC2) explained 28.75 %, in this case, involving the properties coarse sand, fine sand and clay with the highest scores (0.96, 0.92 and -0.96, respectively). The third component (PC3) presented a percentage of 11.99 % associated with variability between areas, and the properties Ca^{2+} and Mg^{2+} presented scores above 0.70 (0.77 and 0.75, respectively).

Table 1. Eigenvalues, explained variance, accumulated variance and correlation of variables in principal component analysis involving a combination of physico-chemical properties of a Red-Yellow Oxisol (Latossolo Vermelho Amarelo) under coffee cultivation, in the municipality of Patos de Minas-MG, Brazil, with eigenvalues >1

Core Component	CP1	CP2	CP3
Eigenvalue	4.85	3.44	1.43
Explained variance (%)	40.42	28.74	11.99
Accumulated variance (%)	40.42	69.17	81.16
Property		**Correlation** [(1)]	
Ca^{2+}	-0.60	0.09	0.76*
Mg^{2+}	-0.60	0.19	0.74*
Coarse sand	0.15	0.95*	-0.09
Fine sand	0.20	0.91*	-0.10
Clay	-0.08	-0.96*	-0.06
PD	0.34	0.75*	-0.02
Mean PR	-0.88*	0.22	-0.12
Maximum PR	-0.84*	0.19	-0.21
Minimum PR	-0.76*	0.13	-0.09
Total porosity	0.73*	-0.17	0.19
θ 100 kPa	-0.82*	0.02	-0.29
θ 300 kPa	-0.78*	-0.13	-0.26

(1) Considered in the interpretation of the principal component; * scores ≥0.7. Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; PD: particle density; RP: resistance to penetration; θ: volumetric moisture; kPa: tension in kilopascal.

The graphic dispersion of the eight areas, five collection positions, and at the layers of 0.00-0.10, 0.10-0.20, 0.20-0.30 and 0.30-0.40 m assessed of the studied properties for the first two principal components corresponds to figures 3a, 3b, 3c and 3d, respectively, and considers the physical+chemical properties with scores ≥0.7 (Figure 3). We separated the results obtained by layer to facilitate their visualization, keeping the same scores for each component. Thus, all figures show the same percentages of explained variability for the studied situations in principal components 1 and 2. The axis corresponding to PC1 explained 40.42 % of the total variation of the samples, while PC2 explained 28.75 %.

The graphic dispersion of the cultivation areas and collection positions at the layers of 0.00-0.10 m (Figure 3a), considering PC1 as a reference, points to the proximity of the eight areas in terms of the LSC, IR and LTL collection positions, most of them occupying the two quadrants (upper and lower) on the right side. On the other hand, the RSC and LSC collection positions occur in opposite quadrants, i.e., farther away from the other positions, but close to each other. Some areas have the IR collection position graphically dispersed intermediately between the LSC and LTL positions and the RSC and LSC positions. The dispersion in relation to PC2 indicated greater proximity between areas BA14, BV09, CT01a, CT01b and AR17 for all collection positions, with a greater number of cases being distributed close to and/or below PC2 in the left and right quadrants (Figure 3a). Areas BV06 and BA08 are close to each other in all collection positions and distant from areas BA14, BV09, CT01a, CT01b and AR17, with BV15 being intermediate between the two groups of these areas. The dispersion of the areas in relation to CP1, the properties associated with the distribution of the areas and collection positions are: mean PR, maximum PR, minimum PR, PT, θ 100 kPa and θ 300 kPa. In the second case, dispersion in relation to PC2, the properties PD, CS, FS and Clay were the ones that most contributed to the separation of the areas (Figure 3a).

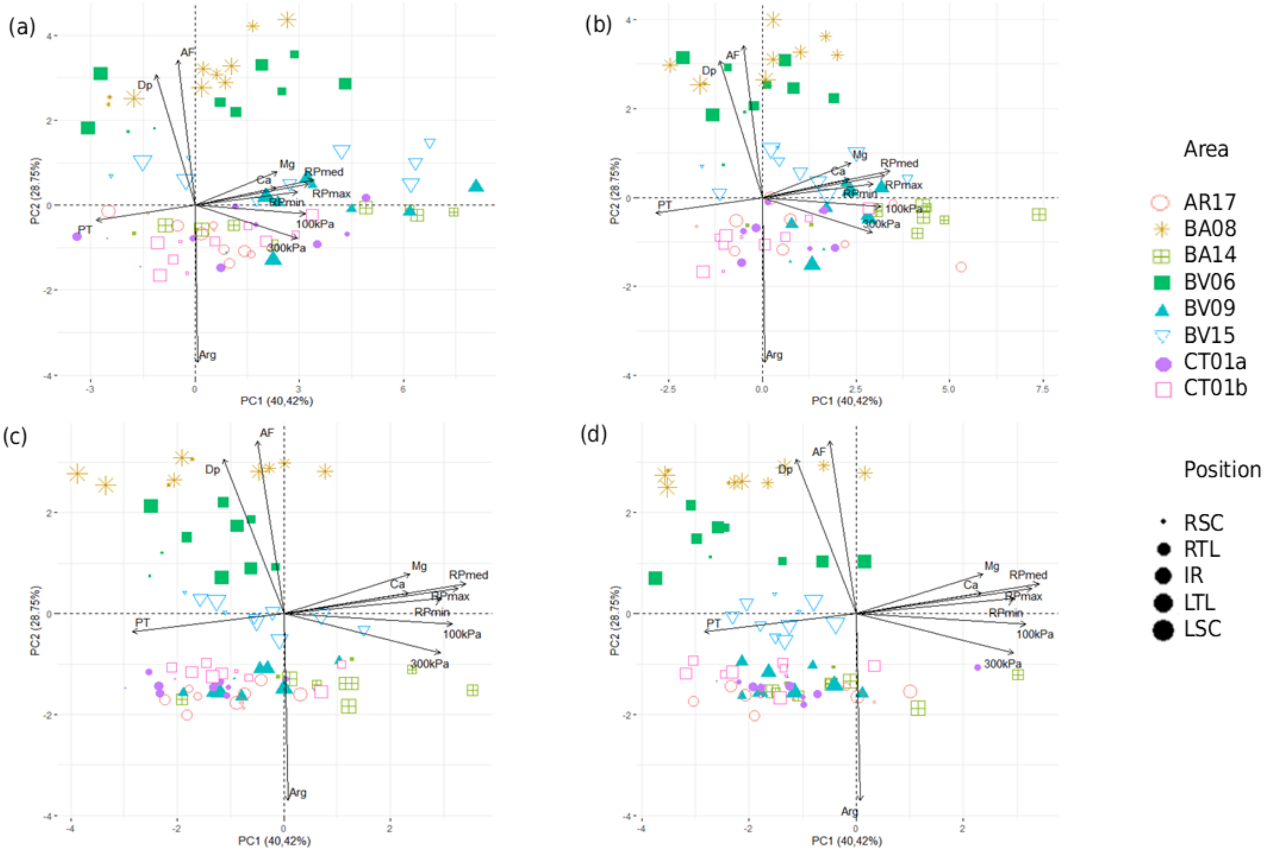

Figure 3. Graphical dispersion of the principal component analysis results for physicochemical properties, areas and collection positions at layers (a): 0.00-0.10 m; (b): 0.10-0.20 m; (c): 0.20-0.30 m and (d): 0.30-0.40 m in a dystrophic Red-Yellow Oxisol (Latossolo Vermelho Amarelo distrófico) in the municipality of Patos de Minas, Minas Gerais, Brazil. Particle density (PD), fine sand (FS), total porosity (TP), clay, mean penetration resistance (PRmean), maximum penetration resistance (PRmax), Minimum penetration resistance (PRmin), moisture on a volumetric basis at 300 kPa (θ 300 kPa) and moisture on a volumetric basis at 100 kPa (θ 100 kPa).

The dispersion of the collection areas and positions at the layer of 0.10-0.20 m (Figure 3b) was very similar to that presented at the layer of 0.00-0.10 m (Figure 3a), with a tendency towards greater proximity between areas and collection positions when considering PC1, and the same behavior was not observed in relation to PC2. At layers of 0.20-0.30 m (Figure 3c) and 0.30-0.40 m (Figure 3d), the dispersion of the studied situations (areas and collection positions) in relation to PC1 tended to be closer, being located largely in the upper and lower left quadrants. The studied situations and their distribution can be associated, in the first case (left-side quadrants) with TP and, in the second case (right-side quadrants) with the properties: mean PR, maximum PR, minimum PR, TP, θ 100 kPa and θ 300 kPa. On the other hand, in relation to PC2, the dispersion of areas and collection positions at layers 0.20-0.30 and 0.30-0.40 m was similar to that observed at depths 0.00-0.10 and 0.10-0.20 m.

Analysis of variance of triple interactions

According to the results of the PCAs performed, the results of the univariate analyses for the properties selected in the PCA are presented, considering the appropriate ANOVA for each of them. As already mentioned, all interactions were unfolded, regardless of whether they were significant or not, but only the results of the unfolding of the triple significant interactions will be presented by the F test ($p<0.05$), choosing to present the results individually, considering each of the properties. Still, considering the fulfillment of the objectives of this study, the presentation of results and their discussion for the chemical variables Ca^{2+} and Mg^{2+} and even the maximum (PRmax) and minimum (PRmin) penetration resistance will not be performed, since the initial are outside the scope of the article and the latter because they terminate by being addressed when discussing the mean penetration resistance (PRmean). However, the results and comparisons made are presented in the Supplementary Material.

Total porosity

Comparisons between collection positions, in the same area and layer, showed that TP was higher ($p<0.05$) in the BV15, BA14 and CT01 cultivation areas, at the layer of 0.00-0.10 m, RSC and LSC positions, and the LSC and LTL positions presented the lowest means ($p<0.05$) (Table 2). With the exception of BV15, the lowest TP values ($p<0.05$) occurred in IL, which, in most cases, presented intermediate values between soil under the tree crowns (RSC and LSC) and tractor lines (LSC and LTL). In the case of BV15, the means did not differ from the LSC and LTL positions ($p>0.05$) (Table 2). At the layer of 0.10-0.20 m, BA14 had the same behavior observed at 0.00-0.10 m, as well as CT01a, with RSC and LSC positions, presenting higher values ($p<0.05$), intermediate values in IR and lower means ($p<0.05$) in LSC and LTL. The AR17 did not show differences in TP for any of the positions at the layer of 0.00-0.10 m ($p>0.05$). At the layer of 0.10-0.20 m, the LSC, RSC, LTL, and LSC positions did not differ from each other ($p>0.05$), but, in IR, the PT was lower than in the others ($p<0.05$).

Total porosity (TP), when the areas were compared at the same sampling position and layer, showed significant differences at 0.00-0.10 m (LSC), 0.20-0.30 m (LSC, IR, LTL and LSC) and 0.20-0.30 m (RSC, LSC and LSC) and at 0.30-0.40 m (IR). At 0.00-0.10 m, AR17, BA08 and CT01b, the highest values ($p<0.05$) were observed among the cultivated areas, but they did not differ statistically from BV06, BV15, CT01a and BV09 ($p>0.05$). The exception was BA14 with the lowest mean (0.49 m^3 m^{-3}) in the LSC position (Table 2), also not differing from BV06, BV15, CT01a and BV09 ($p>0.05$). In the LSC, IR and LTL positions, at 0.10-0.20 m, the mean values and the differences or not ($p<0.05$) of TP for the different cultivation areas showed varied behavior. However, BA14 was characterized by presenting the lowest ($p<0.05$) TP in all the positions mentioned. No differences were observed among the eight cultivation areas ($p>0.05$) in LSC, at the layers 0.10-0.20 and 0.20-0.30 m, RSC and LTL at 0.20-0.30 m and IR at 0.30-0.40 m. At layers of 0.20-0.30 m, for IR, significant differences were observed between BA14 and CT01a, BV15 and CT01b, with these cultivated areas being the ones with the highest means ($p<0.05$) of PT, while in BA14 the lowest values ($p<0.05$; 0.53 m^3 m^{-3}) were observed.

Among layers, in the same cultivation area and sampling position, TP showed a direct relationship with its increase, i.e., as depths increased, TP also increased, sometimes with similarities or statistically significant differences. This behavior was evident in most of the situations assessed, with the exception for BV09 and CT01a in LSC, BA08 and AR17 in LSC, and AR17 in LSC, which did not have statistically significant differences among layers ($p>0.05$) (Table 2).

Total porosity (TP) showed an inverse relationship with PRmean. In the BA14 and CT01a areas, which have the highest pore volume in the RSC and LSC, they responded with the lowest values of PRmean, as well as the lowest contents of θ at tensions of 100 and 300 kPa in these positions, measured compared in the layer of 0.00-0.10 m in the direction of position at the same level of area and layer.

Mean penetration resistance in undisturbed specimens

Table 3 shows the PRmean values obtained in undisturbed samples from the different study situations. For the sampling positions at the layer of 0.00-0.10 m, the comparisons in the same cultivation area showed the highest ($p<0.05$) values of PRmean in the LSC and LTL positions in BV06, BA08, BA14 and CT01a, compared to IR, RSC and LSC. However, no significant difference was observed in BV15 and in the LTL, IR and LSC positions ($p>0.05$), but, in relation to CRS and LSC, whose mean values were 0.84 and 0.97 MPa, respectively, these were the lowest observed ($p<0.05$). The BV09, still at 0.00-0.10 m, presented an PRmean of 3.67 MPa in LTL, which was statistically higher than 1.49 and 1.33 MPa in RSC and LSC, but, IR and LSC did not differ from the other positions ($p>0.05$).

Table 2. Means of total porosity of a Red-Yellow Oxisol (Latossolo Vermelho Amarelo) in the harvesting positions under the plant (right soil under the tree crowns – RSC and left soil under the tree crowns – LSC), at the place of tractor lines (left soil under the tree crown – LSC and left tractor lines – LTL) and in the plants interrows (IR) in coffee cultivation areas at Chuá Farm, Patos de Minas, Minas Gerais

Cultivation area	Sampling position				
	Right soil under the tree crown	Right tractor lines	Interrow	Left tractor lines	Left soil under the tree crown
	m^3 m^{-3}				
	Layer of 0.00-0.10 m				
BV06	0.60	0.58AB	0.57β	0.57	0.63
BA08	0.61	0.59A	0.58	0.59	0.59α
BV15	0.65b	0.58ABabβ	0.56bβ	0.56bβ	0.66A
BA14	0.63A	0.49Bbβ	0.56ab	0.51bβ	0.62A
BV09	0.60	0.56Abα	0.53β	0.56αβ	0.58
CT01a	0.67A	0.57Abbα	0.61ab	0.56bβ	0.64ab
AR17	0.64A	0.60Aa	0.57aαβ	0.61A	0.66aα
CT01b	0.62	0.59A	0.61	0.59	0.63
	Layer of 0.10-0.20 m				
BV06	0.59	0.61AB	0.55ABCβ	0.59A	0.60A
BA08	0.60	0.54AB	0.63A	0.60A	0.58Aα
BV15	0.64	0.61Abαβ	0.62Abαβ	0.62Aαβ	0.59A
BA14	0.59A	0.52Babβ	0.53Bcab	0.47Bb β	0.55Aab
BV09	0.57	0.56Abα	0.57ABCαβ	0.54Abβ	0.57A
CT01a	0.64	0.59Abα	0.63A	0.59Aαβ	0.62A
AR17	0.65A	0.58Abab	0.51Cbβ	0.60Aa	0.65Aaα
CT01b	0.63	0.64A	0.60AB	0.61A	0.68A
	Layer of 0.20-0.30 m				
BV06	0.58A	0.56AB	0.62αβ	0.56A	0.56A
BA08	0.62A	0.60AB	0.59	0.63A	0.65Aα
BV15	0.65A	0.65Aαβ	0.66α	0.65Aα	0.62A
BA14	0.57A	0.58Bαβ	0.54	0.57Aαβ	0.56A
BV09	0.60A	0.62Abα	0.62α	0.62Aαβ	0.59A
CT01a	0.66A	0.64Aα	0.67	0.65Aα	0.65A
AR17	0.58A	0.64AB	0.63α	0.62A	0.60Aα
CT01b	0.61A	0.62A	0.66 546	0.66A	0.61A
	Layer of 0.30-0.40 m				
BV06	0.60	0.60	0.66Aα	0.60	0.59
BA08	0.64	0.60	0.59A	0.62	0.65α
BV15	0.64	0.67α	0.68Aα	0.67α	0.61
BA14	0.59	0.62α	0.56A	0.62α	0.55
BV09	0.62	0.63α	0.64Aα	0.64α	0.60
CT01a	0.66	0.65α	0.61A	0.64αβ	0.63
AR17	0.59	0.62	0.64Aα	0.65	0.58α
CT01b	0.64	0.67	0.67A	0.66	0.65

Means followed by capital letters compare the areas at the same layer and sampling position (e.g., red hatching); lowercase letters compare the positions in the same area and layer (e.g., dark green hatching); and letters of the Greek alphabet compare the layers in the same cultivation area and sampling position (e.g., light green crosshatching); when letters are similar, the means do not differ from each other by the Tukey test at 5 % probability.

Table 3. Mean Penetration Resistance (MPa) of a Red-Yellow Oxisol (Latossolo Vermelho Amarelo) in the sampling positions under the plant (right soil under the tree crowns – RSC and low – LSC), at the tractor lines (left soil under the tree crown – LSC and left tractor lines – LTL) and in the plants interrows (IR) in coffee cultivation areas at Chuá Farm, Patos de Minas, Minas Gerais

Cultivation area	Sampling position				
	Right soil under the tree crown	Right tractor lines	Interrow	Left tractor lines	Left soil under the tree crown
	MPa				
	Layer 0.00-0.01 m				
BV06	0.99b	2.77ABaα	1.79ABCab	2.60ABaα	0.83b
BA08	0.51b	1.93Ba	1.46BCab	2.53ABaα	1.22ab
BV15	0.84b	2.68ABaα	3.13Aaα	3.33Aaα	0.97b
BA14	1.11b	3.55Aaα	1.51BCb	3.51Aaα	1.38bβ
BV09	1.34b	2.46ABabα	2.49ABabα	3.67Aaα	1.94b
CT01a	0.71b	2.24ABabα	0.81Cb	2.93Aaα	0.94b
AR17	1.01	1.34Bαβ	1.40BC	1.36B	0.68
CT01b	1.17	1.84B	0.96C	2.03B	0.98
	Layer 0.10-0.20 m				
BV06	0.99	1.33β	1.41	1.50αβ	1.15A
BA08	1.16	1.41	1.31	1.47αβ	1.24A
BV15	0.90	1.69αβ	1.10β	1.94β	1.16A
BA14	1.3 b	2.53abαβ	2.19ab	2.74aα	2.82Aaα
BV09	1,67	1.63αβ	0.99β	1.81β	1.61A
CT01a	0.99	1.43αβ	0.64	1.53β	1.11A
AR17	1.43	2.15α	1.27	1.24	1.16A
CT01b	1.03	1.06	1.03	1.40	0.92A
	Layer 0.20-0.30 m				
BV06	0.81	1.21β	1.03	0.75β	0.75
BA08	1.35	1.49	1.19	1.40αβ	0.51
BV15	0.99	1.48αβ	1.14β	1.14β	1.18
BA14	1.26	1.69β	1.15	1.44β	1.44β
BV09	0.84	1.09β	0.82β	0.94β	1.00
CT01a	0.55	1.28αβ	0.81	0.71β	0.84
AR17	0.75	0.73β	0.69	1.17	1.11
CT01b	1.29	1.40	0.70	0.99	0.98
	Layer 0.30-0.40 m				
BV06	0.55	0.67β	0.6	0.76β	0.77
BA08	0.83	1.33	0.93	0.83β	0.43
BV15	0.98	0.84β	0.65β	0.86β	1.07
BA14	0.68	0.67β	1.51	0.75β	1.13β
BV09	0.83	0.72β	0.93β	0.73β	1.06
CT01a	0.66	0.68β	1.34	0.75β	0.67
AR17	0.94	1.06αβ	0.54	0.64	1.51
CT01b	0.85	0.94	0.75	1.12	0.91

Means followed by capital letters compare the areas at the same layer and sampling position (e.g., red hatching); lowercase letters compare the positions in the same area and layer (e.g., dark green hatching); and letters of the Greek alphabet compare the layers in the same cultivation area and sampling position (e.g., light green crosshatching); when letters are similar, the means do not differ from each other by the Tukey test at 5 % probability.

At the other soil layers (also for AR17 and CT01b at 0.00-0.10 m), the comparisons between the sampling positions for the same cultivation area were not significant (p>0.05), with the only exception being the differences observed in PRmean in BA14, in this case by 0.10-0.20 m. In BA14, LSC and LTL presented the highest means (p<0.05), with the lowest means (p<0.05) observed in RSC, while LSC and IR presented intermediate values (2.52 and 2.18 MPa), with no significant differences between them (Table 3).

In the comparison between cultivation areas in each position and layer, we observed statistical differences between PRmean (Table 3) at the layer of 0.00-0.10 m in the LSC, IR and LTL sampling positions, and 0.10-0.20 m in LSC. In the other situations, the interactions were not significant (p<0.05). At 0.00-0.10 m and in the LSC sampling position, BA14 presented the highest (p<0.05) values of PRmean (3.55 MPa), followed by the intermediate values of the areas BA06 (2.76 MPa), BV15 (2.67 MPa), BV09 (2.46 MPa) and CT01a (2.23 MPa), while BV08 (1.93 MPa), CT09b (1.84 MPa) and AR17 (1.34 MPa) presented the lowest values (p<0.05). At 0.00-0.10 m, BV15 presented the highest (p<0.05) values of PRmean in IR (3.13 MPa), followed by the intermediate values of the cultivation areas BV09 (2.49 MPa), BV06 (1.79 MPa), BA14 (1.51 MPa), BA08 (1.46 MPa), AR17 (1.40 MPa), with the lowest being CT01b (0.96 MPa) and CT01a (0.81 MPa) (p<0.05). In the LTL position and also at 0.00-0.10 m, the highest values (p<0.05) of PRmean were observed in the BV09, BA14, BV15 and CT01a cultivation areas (3.67, 3.51, 3.32, and 2.93 MPa, respectively), intermediate in BV06 and BA08, and the lowest values in CT01b and AR17 (p<0.05). On the other hand, in the LSC sampling position, at a depth of 0.10-0.20 m, no significant differences were found between the sampling areas.

When assessing the depth in the cultivation areas and sampling position, the results obtained from PRmean (Tables 3) did not indicate significant differences (p>0.05) in RSC. In LSC, on the other hand, we found that BA14 was the only cultivation area that presented statistical differences, with higher values of PRmean (2.82 MPa). In LSC and LTL, the interaction of attributes was significant for a greater number of cultivation areas. We found the highest PRmean values (p<0.05) at 0.00-0.10 m, and at 0.10-0.20 and 0.20-0.30 m, we observed values that are statistically similar to each other or are higher at 0.10-0.20 m. At layers of 0.20-0.30 and 0.30-0.40 m, PRmean values are lower (p<0.05) than at depths of 0.00-0.10 and 0.10-0.20 m. The interaction was not significant for all areas studied and the previously reported common behavior of the attribute occurred with BA1, BV09 and CT01a. BV06, BV15 and BA08 and AR17.

The LTL sampling position showed a behavior similar to LSC, and PRmean was the attribute that presented the highest number of significant interactions regarding the cultivation area, which did not occur in AR17 and CT01b. In the other areas, we found that the PRmean values were higher in 0.00-0.10 m (p<0.05), and in 0.10-0.20 or 0.20-0.30 m the property showed similar behavior (p>0.05) to the highest and lowest PRmean values at 0.00-0.10 or at 0.30-0.40 m. However, the lowest values (p<0.05) of PRmean at 0.30-0.40 m are common to all areas.

Mean moisture content on a volumetric basis (θ) at pressures of 100 kPa and 300 kPa

The mean moisture content on a volumetric basis (θ) at the tensions of 100 kPa and 300 kPa in the different study situations are presented in Tables 4 and 5, respectively. The comparison between sampling positions, assessed in each cultivation area and sampling depth, showed significant differences in 0.00-0.10 and 0.10-0.20 m, both for (θ) at the tensions of 100 kPa (Table 4) and 300 kPa (Table 5). In both cases, we observed that the differences occurred for the same cultivation areas, both in the first (BV15, BA14, CT01a and CT01b) and in the second depth (BA08 and AR17). BV06 was the only exception with significant differences of 0.00-0.10 m, in this case for θ100 kPa (Table 4).

Table 4. Mean moisture content on a volumetric basis (θ) at 100 kPa tension of a Red-Yellow Oxisol (Latossolo Vermelho Amarelo) in the sampling positions under the plant (right soil under the tree crowns - RSC and left soil under the tree crowns - LSC), at the tractor lines (left soil under the tree crown - LSC and left tractor lines - LTL) and in the plants interrows (IR) in coffee growing areas at Chuá Farm, Patos de Minas- MG

Cultivation area	Sampling position				
	Right soil under the tree crown	Right tractor lines	Interrow	Left tractor lines	Left soil under the tree crown
	$m^3\ m^{-3}$				
			Layer 0.00-0.10 m		
BV06	0.30ab	0.35A	0.32ab	0.36aα	0.27b
BA08	0.31	0.34αβ	0.32	0.34	0.33α
BV15	0.32b	0.38ab	0.38abα	0.40A	0.33ab
BA14	0.31b	0.40A	0.34ab	0.38abαβ	0.32b
BV09	0.32	0.35	0.36α	0.35αβ	0.34
CT01a	0.29b	0.36A	0.32ab	0.37A	0.30ab
AR17	0.29	0.32	0.32	0.30	0.28
CT01b	0.31A	0.36A	0.32A	0.37A	0.30A
			Layer 0.10-0.20 m		
BV06	0.31	0.32	0.33AB	0.34ABαβ	0.29C
BA08	0.32b	0.39aα	0.28Bb	0.34ABab	0.33ABCabα
BV15	0.33	0.35	0.33ABαβ	0.34AB	0.39A
BA14	0.35	0.37	0.37A	0.41Aα	0.37AB
BV09	0.35	0.35	0.34ABα	0.37ABα	0.35ABC
CT01a	0.32	0.34	0.30AB	0.35AB	0.32ABC
AR17	0.29b	0.33ab	0.36ABa	0.31Bab	0.29Cb
CT01b	0.30	0.33	0.31AB	0.35AB	0.29BC
			Layer 0.20-0.30 m		
BV06	0.29	0.31	0.3	0.31αβ	0.28
BA08	0.29	0.31β	0.32	0.29	0.27α
BV15	0.31	0.35	0.31αβ	0.35	0.33
BA14	0.34	0.36	0.34	0.37αβ	0.34
BV09	0.31	0.31	0.33α	0.31αβ	0.32
CT01a	0.29	0.33	0.32	0.31	0.31
AR17	0.32	0.29	0.30	0.31	0.31
CT01b	0.32	0.35	0.31	0.31	0.33
			Layer 0.30-0.40 m		
BV06	0.27	0.28	0.27B	0.28β	0.30
BA08	0.28	0.31β	0.32AB	0.30	0.28α
BV15	0.32	0.32	0.30Bβ	0.33	0.33
BA14	0.33	0.33	0.33AB	0.33β	0.34
BV09	0.30	0.30	0.32ABα	0.30β	0.32
CT01a	0.30	0.32	0.38A	0.33	0.32
AR17	0.32	0.31	0.30B	0.28	0.32
CT01b	0.31	0.30	0.30AB	0.31	0.30

Means followed by capital letters compare the areas at the same layer and sampling position (e.g., red hatching); lowercase letters compare the positions in the same area and layer h (e.g., dark green hatching); and letters of the Greek alphabet compare the layers in the same cultivation area and sampling position (e.g., light green crosshatching); when letters are similar, the means do not differ from each other by the Tukey test at 5 % probability.

Table 5. Mean moisture content on a volumetric basis (θ) at 300 kPa tension of a Red-Yellow Oxisol (Latossolo Vermelho Amarelo) in the sampling positions under the plant (right soil under the tree crowns - RSC and left soil under the tree crowns - LSC), at the tractor lines (left soil under the tree crown - LSC and left tractor lines - LTL) and in the plants interrows (IR) in coffee growing areas at Chuá Farm, Patos de Minas- MG

Cultivation area	Sampling position				
	Right soil under the tree crown	Right tractor lines	Interrow	Left tractor lines	Left soil under the tree crown
	$m^3 m^{-3}$				
Layer 0.00-0.10 m					
BV06	0.26	0.29AB	0.28	0.31A	0.24
BA08	0.26	0.29B	0.28	0.29A	0.28
BV15	0.29A	0.34ABa	0.35aα	0.35Aa	0.29A
BA14	0.28b	0.37Aaα	0.30ab	0.35Aabα	0.29b
BV09	0.29	0.29AB	0.34	0.29A	0.30
CT01a	0.27A	0.33ABa	0.30A	0.34Aa	0.29A
AR17	0.28	0.31AB	0.31αβ	0.30A	0.26
CT01b	0.29ab	0.35ABaα	0.30ab	0.35Aaα	0.28ab
Layer 0.10-0.20 m					
BV06	0.27	0.27	0.29 AB	0.29B	0.26 B
BA08	0.27ab	0.33A	0.25Bb	0.28Bab	0.28ABab
BV15	0.30	0.32	0.31ABαβ	0.31AB	0.35A
BA14	0.31	0.35αβ	0.32AB	0.38Aα	0.34AB
BV09	0.31	0.29	0.31AB	0.31AB	0.30AB
CT01a	0.30	0.31	0.29AB	0.32AB	0.31AB
AR17	0.27b	0.32ab	0.35Aaα	0.30ABab	0.27ABb
CT01b	0.28	0.31αβ	0.29AB	0.34ABαβ	0.27AB
Layer 0.20-0.30 m					
BV06	0.26	0.29	0.28	0,28	0.25
BA08	0.26	0.29	0.28	0,26	0.24
BV15	0.29	0.32	0.29β	0,32	0.31
BA14	0.29	0.32αβ	0.30	0,33αβ	0.29
BV09	0.26	0.29	0.30	0.29	0.29
CT01a	0.27	0.31	0.28	0.29	0.29
AR17	0.30	0.28	0.27β	0,3	0.29
CT01b	0.30	0.32αβ	0.29	0.30αβ	0.31
Layer 0.30-0.40 m					
BV06	0.25	0.26	0.25	0.26	0.27
BA08	0.25	0.28	0.28	0.27	0.25
BV15	0.29	0.30	0.28β	0.30	0.31
BA14	0.28	0.29β	0.29	0.29β	0.29
BV09	0.26	0.28	0.29	0.27	0.28
CT01a	0.28	0.30	0.33	0.31	0.23
AR17	0.29	0.30	0.26β	0.27	0.30
CT01b	0.29	0.28β	0.27	0.29β	0.28

Means followed by capital letters compare the areas at the same layer and sampling position (e.g., red hatching); lowercase letters compare the positions in the same area and layer (e.g., dark green hatching); and letters of the Greek alphabet compare the layers in the same cultivation area and sampling position (e.g., light green crosshatching); when letters are similar, the means do not differ from each other by the Tukey test at 5 % probability.

In both moisture levels (θ 100 kPa and θ 300 kPa) (Tables 4 and 5), we found that the LSC and/or LTL sampling positions were those with higher ($p<0.05$) values in relation to the other positions. The LSC presented the highest numerical and statistical values ($p<0.05$), and in the others it was similar to LTL ($p>0.05$). When this behavior was not observed, we found that IR was the one with the highest values of θ 100 kPa (Table 4) and θ 300 kPa (Table 5), and this was associated with ART17, both at 0.00-0.10 and 0.10-0.20 m. IR was statistically similar to LSC and/or LTL, especially θ 300 kPa (Table 5). This variable showed some areas with lower IR values ($p<0.05$) than LSC and LTL. Finally, the sampling positions RSC and LSC were the ones with the lowest values of θ 100 kPa (Table 4) and θ 300 kPa (Table 5), practically for all areas and depths in which the interaction was significant, sometimes being similar to each other ($p>0.05$), or RSC with the lowest values, or LSC ($p<0.05$).

When we assessed the cultivation areas in the same sampling position and layer (Tables 4 and 5), we found differences in the sampling positions LSC, LTL, IR, and LSC. In the LSC position, these differences occurred only for θ 300 kPa and at 0.10-0.20 m (Table 5), while in the other situations, for both properties (Tables 4 and 5), they only occurred at layers of 0.10-0.20 and 0.20-0.30 m. The BA14 cultivation area was the one with the highest ($p<0.05$) θ content at the 100 kPa tension in the IR and LTL positions in the 0.10-0.20 m layer (Table 4) being statistically different from the other areas (BV06, BV15, BV09, CT01a and CT01b), which did not show differences ($p>0.05$) among them, but greater than BA08 in IR and AR17 in LTL. When assessing θ 300 kPa (Table 5), BA14 in LSC and LTL, at 0.00-0.10 m, and also LTL at 0.10-0.20 m, was the cultivation area with the highest and lowest ($p<0.05$) volumetric moistures, while the other areas presented intermediate values, all being statistically similar.

The IR and LSC sampling positions did not correspond to LSC and LTL, either in θ 100 kPa (Table 4) or θ 300 kPa (Table 5), nor in the extreme cases, i.e., the highest and lowest values ($p<0.05$) of volumetric moisture, as observed for the other cases. In LSC, BV15 was the area with the highest ($p<0.05$) values of θ 100 kPa and θ 300 kPa at 0.10-0.20 m, with the lowest occurring with AR17 and BV06 ($p<0.05$), respectively. In IR too, only for θ 300 kPa (Table 5) and 0.10-0.20 m, two extreme values were observed with significant differences, but without coincidence of the cultivation areas with the other situations commented. In this case, AR17 was the cultivation area with the highest values and BA08 with the lowest ($p<0.05$), with the other situations being statistically similar.

Sampling layer showed significant differences for a few cultivation areas and positions, even though there was not much correspondence among them, both for θ 100 kPa (Table 4) and θ 300 kPa (Table 5). In most situations, an inverse relationship can be attributed to the layer, i.e., with the increase in depth, a decrease in the volume of water in the soil was observed [θ 100 kPa (Table 4): BV15 in IR and LTL in BV06; θ 300 kPa (Table 5): BA14 in LSC, BV15 in IR, and BA14 and CT01b in LTL]. This decrease is more evident in relation to the layers 0.20-0.30 m and 0.30-0.40 m, and in the first (0.00-0.10 m), the highest values do not always occur, as these are observed in the second layer (0.10-0.20 m; BA14 and BA09 in LTL; BA08 in LSC for θ 100 kPa and AR17 in IR for θ 300 kPa).

Coarse sand, fine sand and clay contents

We obtained the results of the granulometric classes (CS, FS and Clay) from samples composed of the sampling positions LSC+LTL and RSC+LSC, which led to the soil under the tree crown (SC) and tractor lines (TL), being complemented by IR. We also altered the layers in relation to the properties discussed up to this item, being considered 0.00-0.20, 0.20-0.40 and 0.40-1.00 m (Table 6). Thus, we performed statistical analyses considering this condition.

Table 6. Means of coarse sand, fine sand and clay of an Oxisol, in g kg^{-1}, in the sampling positions under the plant (right soil under the tree crowns – RSC and left soil under the tree crown – LSC), at the tractor lines (left soil under the tree crown – LSC and left tractor lines – LTL) and in the plants interrows (IR) in coffee growing areas at Chuá Farm, Patos de Minas - MG

Cultivation area	Coarse sand			Fine sand			Clay		
	Soil under the tree crown	Tractor lines	Interrow	Soil under the tree crown	Tractor lines	Interrow	Soil under the tree crown	Tractor lines	Interrow
	g kg^{-1}								
	Layer 0.00-0.20 m								
BV06	1.50Aα	1.60Aα	1.60Aα	1.20Aα	1.20Aα	1.10Aα	4.10C	4.00Cβ	4.00Cβ
BA08	1.60Aα	1.80Aα	1.70Aα	1.20A	1.20A	1.10A	3.70C	2.70C	3.30C
BV15	1.30Aaα	1.00Bbα	1.20Baα	1.00Aaα	0.80Bb	0.90Aabα	5.60Bβ	6.10Bβ	6.30B
BA14	0.70Bα	0.65Cα	0.60Cα	0.50Bα	0.40Cα	0.30B	7.10Aβ	6.50Aβ	6.80ABβ
BV09	0.30BC	0.40CD	0.40C	0.20C	0.40Cα	0.30B	7.70Aa	6.70Abβ	6.20Bbβ
CT01a	0.30C	0.30CD	0.30C	0.30B	0.30C	0.30B	8.00Aa	7.40Aaβ	6.50Bbβ
AR17	0.30C	0.20B	0.30C	0.30B	0.30C	0.30B	7.30A	7.50Aα	7.80A
CT01b	0.40BC	0.30CB	0.40C	0.30B	0.30C	0.30B	8.00A	7.10Aβ	7.80A
	Layer 0.20-0.40 m								
BV06	1.40Aα	1.20Aβ	1.30Aβ	0.90Aβ	1.00Aα	1.10Aα	4.70C	4.90Cα	5.40Bα
BA08	1.50Aα	1.50Aβ	1.40Aβ	1.00A	1.10A	1.10A	3.50C	3.40D	3.90C
BV15	0.80Bβ	0.80Bα	0.80Bβ	1.00Aα	0.90A	0.80Bα	6.40Bα	7.00Bα	6.10B
BA14	0.30Cβ	0.30Cβ	0.30Cβ	0.30Bβ	0.20Bβ	0.20C	8.10Aα	8.40Aα	8.30Aα
BV09	0.30C	0.20C	0.20C	0.20B	0.20Bα	0.20C	8.20A	8.20ABα	8.20Aα
CT01a	0.20C	0.30C	0.20C	0.30B	0.20B	0.20C	8.30A	8.40Aα	8.60Aα
AR17	0.20C	0.20C	0.20C	0.30B	0.30B	0.30C	8.20Aa	8.30ABaα	8.60Aa
CT01b	0.30C	0.30C	0.30C	0.30B	0.30B	0.40C	8.00A	8.00ABα	7.30AB
	Layer 0.40-1.00 m								
BV06	1.10Aβ	1.10Aβ	1.20Aβ	0.80Aβ	0.80ABβ	0.90Aβ	5.00B	5.20Bα	5.50Bα
BA08	1.30Aβ	1.50Aαβ	1.40Aβ	1.00A	1.10A	0.90A	3.70B	3.60C	3.90C
BV15	0.50Bγ	0.50Bβ	0.50Bγ	0.70Bβ	0.70B	0.60Bβ	7.00Aα	7.40Aα	7.10B
BA14	0.20Bβ	0.30Bβ	0.25Bβ	0.30Cβ	0.10Cβ	0.20B	8.10Aα	8.30Aα	8.50Aα
BV09	0.20B	0.20B	0.30B	0.20C	0.20Cα	0.20B	8.10A	8.30Aα	8.30Aα
CT01a	0.30B	0.20B	0.20B	0.20C	0.20C	0.20B	8.20A	8.40Aα	8.30Aα
AR17	0.20B	0.20B	0.20B	0.30C	0.30C	0.20B	8.20A	8.50Aα	8.60A
CT01b	0.30B	0.30B	0.40B	0.30C	0.30C	0.30B	8.10A	8.40Aα	7.90A

Means followed by capital letters compare the areas at the same layer and sampling position (e.g., red hatching); lowercase letters compare the positions in the same area and layer (e.g., dark green hatching); and letters of the Greek alphabet compare the layers in the same cultivation area and sampling position (e.g., light green crosshatching); when letters are similar, the means do not differ from each other by the Tukey test at 5 % probability.

The CS variable in BV15 and 0.00-0.20 m showed the highest values ($p<0.05$) in the soil under the tree crown (SC), in the case 1.30 g kg^{-1}, while in IR and TL, the values of 0.12 and 1.10 g kg^{-1} were similar to each other ($p>0.05$) (Table 6). We observed similar results for FS in this same cultivation area, but with the third layer (0.40-1.00 m) presenting intermediate values (1.00 g kg^{-1} in SC; 0.90 g kg^{-1} in IR; and 0.82 g kg^{-1} in TL). Regarding the clay, the comparisons showed similar behavior for BV09 and CT01a at 0.00-0.20 m. We observed that the two cultivation areas presented the highest ($p<0.05$) clay contents in SC (7.70 and 8.00 g kg^{-1}, respectively), while in TL were observed 0.67 and 7.40 g kg^{-1} and, in IR, the lowest ($p<0.05$) contents, 6.20 and 6.50 g kg^{-1}, respectively. In the AR17 cultivation area and at 0.20-0.40 m, no significant differences between sampling positions were observed between depths ($p>0.05$).

Assessment of granulometric classes (CS, FS and clay) showed significant differences when the interaction of the cultivation areas in the same sampling position and layer was assessed (Table 6). The BA08 and BV06 cultivation areas were similar and statistically superior (CS and FS, $p<0.05$), (Clay – inverse relationship in relation to CS and FS), in terms of the contents of these fractions, in relation to the other areas, regardless of the sampling positions (SC, TL and IR) or layer (0.00-0.20, 0.20-0.40 and 0.40-1.00 m). After, there is BV15, which presented similar levels ($p>0.05$) compared to BA08 and BV06, but without a common behavior between layers and particle size classes. However, this similarity ($p>0.05$) occurred in seven of the 27 situations, which may be important for association with other results.

The other areas (BA14, BV09, CT01a, AR17 and CT01b) did not show significant differences ($p>0.05$) among themselves, being usually smaller ($p<0.05$) than the three areas already mentioned. There were few cases regarding the similarity between BV15 and the other areas, such as for CS in TL and 0.00-0.10 m, FS in IR and 0.40-1.00 m and ARG in IR and 0.40-1.00 m. However, we also observed that CT01a and AR17 had the lowest levels of CS at 0.00-0.20 m, as well as with FS in SC and 0.00-0.10 m for BV09 (Table 6).

The CS contents were higher ($p<0.05$) in the BV06, BA08, BV09 and BA14 areas by 0.00-0.20 m, either in SC, TL or IR, and in relation to 0.20-0.40 m, the contents were similar (SC: BV06 and BA08; TL: BV15, $p>0.05$) to 0.00-0.20 m, or lower ($p<0.05$; SC: BV15 and BA14; TL: BV06, BA08 and BA14; IR: BV06, BA08, BV09 and BA14, $p>0.05$) at this layer (Table 6). However, in relation to 0.40-1.00 m, all areas presented lower CS ($p<0.05$) than the first two layers. The behavior observed for CS was also observed in FS, but not with the same areas, but in BV06, BV15 and BA14 in SC; BV06, BA14 and BV09 in TL; Similarities ($p>0.05$) and differences ($p<0.05$) of means are repeated, but, with lower FS values at layer, especially in the latter (0.40-1.00 m), but there are cases of statistical similarities between the means of the first two depths.

Clay mean contents showed a direct relationship with the layer, increasing ($p<0.05$) with it, different from that observed for CS and FS. This granulometric fraction presented a higher number of significant differences in TL (except BA08) (Table 6). In this case, the first layer (0.00-0.20 m) presented the lowest ($p<0.05$) contents, compared to 0.20-0.40 m and 0.40-1.00 m, which were statistically similar ($p>0.05$). The only exception to this clay behavior was in AR17, which did not show significant differences between layers.

DISCUSSION

Principal component analysis

Soil is a complex system that has a large number of properties. Relating the occurrence and behavior of these properties to agriculture increases the complexity of analyses through univariate statistical methods (Silva et al., 2015). Principal component analysis proved useful in classifying soil properties to identify those that best described their variability. The inverse correlation between TP and PRmean, PRmax, θ 100 kPa and θ 300 kPa indicates that while the value of one variable increases, the value of the other decreases (Carvalho, 2012). The contrast between PRmean and TP can be taken as a general measure of soil compaction, since it is characterized, among others, by an increase in PR and a decrease in pore volume (Cortez et al., 2011), results also observed by Lima et al. (2013).

Dispersion graphic presented in figure 2 indicates that PD, FS and Clay are mostly explained by CP2, while the other properties are explained by CP1. There is an overlap between the BV06 and BA08 areas, which may be due to the similarity that the soils of these areas have in terms of granulometry. This fact can be associated with the sloping relief where these two areas are located, since there is greater clay eluviation (Thompson and Troeh, 2021).

In general, the eight areas have the same behavior when compared to the soil sampling positions. LSC, LTL and IR are located in the same quadrant, indicating similarity in the values of PRmean, PRmax, PRmin, θ 100 kPa and θ 300 kPa (Figure 2), which can be explained by the constant traffic of machinery for cultural treatments, especially LSC and LTL (Santinato et al., 2018). These values are higher when compared with the RSC and LSC positions, which showed an inverse relationship with TP.

When analyzing the layer 0.10-0.20 m (Figure 2b), we observed a similar behavior with the first layer (0.00-0.10 m, Figure 2a). The LSC, LTL, and IR sampling positions showed the same similarity in terms of quadrant location, which is far from the RSC and LSC positions. The distance between these two groups tends to decrease in comparison to figure 3a, because, with the increase in depth, the TP tends to have less change with the influence of the traffic of machines and implements and possible compaction (Martins et al., 2012b; Maia, 2016; Masola, 2020).

Decreased penetration resistance and moisture content (θ) at the 100 and 300 kPa tensions, at the layer 0.20-0.30 m (Figure 2c), can be explained, again, by the low influence of machinery traffic at this layer, which is lower when compared to the 0.00-0.10 and 0.10 to 0.20 m layers, and the higher the moisture content, the lower the PR (Oyola-Guzmán, 2016). Management practices, in this case mechanization, alter the interaggregated space through the effect of external and internal forces that act together, reorganizing them into a denser structure (Bertollo and Levien, 2019).

Total porosity showed similar values in the five sampling positions at the layer of 0.20-0.30 m, with the same trend when analyzing the layer of 0.30-0.40 m (Figure 2c). It is noteworthy that the graphical dispersion of the areas in relation to CP2 for the four layers (Figures 2) showed the same distribution, indicating that the intrinsic characteristics of the soil, such as PD, FS and clay, did not show great variability, as observed by Burak et al. (2012). Areas BV06 and BA08 were grouped according to the highest coarse and fine sand contents, while the BV09, BA14, AR17, CT01a and CT01b areas had the lowest sand contents, and the BV15 as an intermediate between the two mentioned groups.

Physical properties

The smallest TP values (0.017 and 0.005 $m^3 m^{-3}$) were observed in the LSC and LTL positions in the BA14 area, coinciding with higher PRmean values. These TP levels likely limit soil aeration during wetter seasons, as they are much lower than the ideal aeration porosity for optimal root growth (0.10 $m^3 m^{-3}$) reported for most plants (Tormena et al., 1998; Pagliai et al., 2003) and specific coffee cultivars, such as Rubi (0.152–0.163 $m^3 m^{-3}$) (Goularte, 2014) and conilon (0.12–0.13 $m^3 m^{-3}$) (Souza et al., 2016). However, this value is only a reference as soil gas diffusion rate depends on the l and density of the root system, soil temperature, tortuosity of the pore space, among others (van Lier, 2020), and the determination of the minimum limits of aeration porosity for coffee is complex.

In contrast to the LSC and LTL positions, in general, for RSC and LSC, macropore volumes were close to the above values (0.15 and 0.14 $m^3 m^{-3}$), concluding that in the positions that comprise the soil under the tree crown area, there is no risk of root loss due to suffocation. In this sense, Feng et al. (2002) comment that, for clayey soils, values of 0.1 $m^3 m^{-3}$ begin to cause inhibition to the adequate supply of O_2 to the plants, requiring volumes greater than 0.1 of aeration porosity.

In the BA14 area, we observed a high (>0.8) normalized difference vegetation index (NDVI) and good development of the coffee plant, although this area presents low porosity of aeration in the wheel tracks. The decrease in the porosity of aeration in the wheel tracks can be explained by the pressure exerted by the machinery traffic in the cultural management in the area. At the RSC and LSC positions, the aeration porosity (0.15 and 0.14 $m^3 m^{-3}$) did not compromise the gas exchange of the roots. On the other hand, despite the decrease in TP, they were the positions that presented the highest θ content at the 100 and 300 kPa tensions, confirming the inverse relationship shown in the PCA between TP and the other physical attributes of CP1.

The changes caused to the soil structure, such as the reduction of TP, and the differences between the positions in relation to this parameter, smaller in LSC and LTL, can cause the collapse of pores of larger sizes. Initially, there is a decrease in pore size, consequently increasing the micropore volume, promoting water retention at higher tensions (Gontijo et al., 2008). This condition can be associated with the fact that the areas with the lowest TP values are precisely those that retain the most water (θ) at tensions of 100 and 300 kPa. We observed the same pattern in the BA14 area in the 0.10-0.20 m layer.

For the AR17 area, there were no significant differences ($p<0.05$) between the TP values in the positions assessed at any of the layers. These results indicate that this property was not appropriate for quantifying and assessing the effect of crop management on soil structure (Martins et al., 2012b), which may be due to the short establishment time of the cultivar in this area. The AR17 area was installed in November 2017, about 3.5 years before the soil samples were collected. Soil preparation for planting included subsoiling the area and plowing and grading the total area. Thus, the short period was not yet enough for the first modifications in the structure to appear, although the numbers already show a trend of decrease in the TP in the area's wheel tracks, which, as observed by Machado et al. (1981) may begin after the fourth year post-planting.

The BA08 area has a slope of around 8 %, and the CS and FS content (Table 6) is substantially higher in the first layers of 0.00-0.10 and 0.10-0.20 m compared to the BA14, BV09, CT01a, AR17 and CT01b areas, which may be responsible for the highest values in the TP due to the presence of sand-sized particles (2.0 to 0.053 mm). Coarser soil particles, such as those of sand size or larger, hinders compaction by impeding the efficient rearrangement of particles (Naderi-Boldaji and Keller, 2016).

In the CT01b area (implanted in 2001), we observed petroplinthite and plinthite features, with diameters ranging from 0.5 to 2 cm. This generated a "gravelly" texture in the layers, distributed continuously or fragmented, through which small amounts of soil permeate (Ker and Schaefer, 1995). The condition of a coarser particle in the profile, generated by the small ferruginous concretions, leads to a similar effect of the BA08 area. This area is also old, planted in 2008, and has a well-developed coffee root system, with accumulation of organic matter (OM) in the layers of 0.00-0.20 and 0.20-0.40 m of 8.75 and 7.96 %, determined from the COT content (5.08 and 4.62 dag kg^{-1}) in the LSC and LTL positions. Organic matter acts as a buffer for soil particles, which contributes to hindering or mitigating compaction (Naderi-Boldaji and Keller, 2016).

The BA14 differs from the previously mentioned areas with the lowest TP value. This decrease, in addition to being attributed to machine traffic in LSC and LTL, may have the contribution of other elements, such as the low sand content (11 % for both positions and in the 0.00-0.20 m layer and 5.3 % in the 0.20-0.40 m layer), although it presents OM contents of 9.53 and 4.39 % for the 0.00-0.20 and 0.20-0.04 m layers, respectively. Sousa et al. (2011) found OM values of 4.21 % in the 0.00-0.20 m layer and 3.36 % in the 0.20-0.40 m layer, in Oxisol cultivated in the state of Goiás under the influence of the Cerrado, verifying the inverse relationship between OM and soil depth. It is noteworthy that, in the NDVI calculated in the pre-selection stage of the areas (Figure 1), we chose BA14 because it presents one of the high vigor indices (NDVI ≥0.8). For the BA14 area, the NDVI contradicted the physical quality data, which showed the lowest TP and the highest PRmean values when compared to the other areas, inferring that in the LSC and LTL positions, BA14 presents compaction (Maia, 2016), also demonstrated by the aeration porosity values of these layers.

The BA14 area also showed high production in the 2020/2021 harvest, with a yield of 82.56 bags ha^{-1}, averaging in the biennium (2019/2020 and 2020/2021 harvests), a mean production of 41.28 bags ha^{-1} (Table 1S). The Yellow Bourbon cultivar present in the BV14 area is recognized for the high quality of the beverage and the early maturation of the fruits (Fazuoli et al., 2007), as well as having a less aggressive root system, being used successfully when there is irrigation. In general, the root system was contained in the projection of the plant canopy, with a large superficial presence of fine roots, not advancing to the row of wheel tracks. We also observed that the roots were shallower compared to AR17, CT01a, and CT01b. Although the area with the Arara variety (AR17) was the youngest to be planted and had the smallest coffee, the root system of this one explored a greater soil volume than the Bourbon varieties.

As the roots of the Bourbon cultivars were more superficial, and the demand for water and nutrients was met via drip irrigation and broadcast fertilization, the shallower root system was more efficient in taking advantage of irrigation and fertilization, as its absorption area was closer compared to the other cultivars. This hypothesis is valid for the BA14 and BV09 areas with clayey soil, which are in flat terrain. The other cultivars of Bourbon are in areas with some slope, and with a greater presence of sands, a fact that favors the surface and subsurface runoff of water, as well as soil particle erosion and nutrient runoff. This helps to understand why, despite presenting, according to the analyses conducted, worse physical quality of the soil, the plants presented high vigor and good productivity. Another factor that may explain the high NDVI rates is crop renewal management. The BA14 plot was skeletonized in 2019, providing renewal of leaves and productive branches, improving the appearance of leaves and their vegetative development.

The PRmean results in the comparison of the areas at the same level of position and depth showed for the BA14 area the highest values of the two properties among all the RSC at the layers of 0.00-0.10 and 0.10-0.20 m and among the LTLs in the 0.20-0.30 m layer. In contrast, AR17 had the lowest means at the same positions and depths among the eight areas. According to Palma et al. (2013), changes in soil resistance to penetration were observed in the traffic line of mechanized coffee cultivation up to a depth of 0.15 m. Bergamin et al. (2010) reported changes in soil RP in the no-tillage system up to 0.10 m depth subjected to machine traffic.

Areas BA14 and AR17 are located at an altitude of 1080 m, on flat sites, at a distance of 645 m from each other, with similar clay contents in the 0.20-0.40 and 0.40-1.00 m layers (≥80 %). However, they differed in TP values, and the highest means for the AR17 area were 0.6 $m^3 m^{-3}$ up to a depth of 0.40 m and 0.54 $m^3 m^{-3}$ for the BA14 area, showing a reduction in macroporosity with values of 0.15 $m^3 m^{-3}$ for AR17 and 0.06 $m^3 m^{-3}$ for BA14, consequently increasing microporosity. These differences, mainly the reduction of macropores, were due to the collapse of the soil structure by the effect of the load applied in the mechanized operations in the LSC and LTL positions, when compared with the RSC and LSC, corroborating the data obtained by Palma et al. (2013), Carmo et al. (2011), Gontijo et al. (2008), Yavuzcan et al. (2005) and Lipiec and Hatano (2003). The low macroporosity values of the BA14 area are lower than what would be ideal for soil aeration porosity (0.1 $m^3 m^{-3}$).

It is noteworthy that superficially the root system of the coffee plant becomes limited to the soil under the tree crown due to the availability of water by the drip irrigation system. Vicente et al. (2017) showed that the highest concentration of roots was observed in the superficial layers and under the dripper, where fertilizers were applied by fertigation. Other studies evidenced that conilon coffee plants (*Coffea canephora*) under drip showed 74.5 and 64.5 % (sandy to medium texture) and 75.4 and 70.2 % (sandy to clayey texture) of the volume and surface area of the root, respectively, concentrated up to a depth of 0.30 m (Souza et al., 2021) and even the highest values of PRmean and lower values of TP. This condition does not depend on the cultivation time, since the observed behavior occurred in all crops (BV06, BA08, BV15, BA14, BV09, CT01a and CT01b), except for the youngest RA17.

Lower PRmean values of the AR17 area in most of the sampling positions can be explained by the fact that the area was planted in 2017, when the soil was turned into the pre-planting treatments. This condition led the aggregates to a phase of accommodation, which persisted four years later, without showing a marked effect on the increase in penetration resistance and decrease in total porosity. According to Machado et al. (1981), these changes become evident from the fourth year and worsen after the eighth consecutive year of planting, although it is possible to perceive in the numerical means a tendency in the alteration of the values of these physical soil properties.

Martins (2009) indicates that among the physical properties, PR was not appropriate for quantifying the effect of management on soil structure, probably due to the short time of crop establishment. We expect that over time, there will be a greater change in the physical properties when coffee is managed with mechanization (Carmo et al., 2011), a fact observed in area AR17.

We observed higher PRmean values in the BV14 area. Gontijo et al. (2008) highlight that places where there is less pore space tend to have lower volumetric water content at low tensions and higher content (θ) at tensions higher than 6 kPa, providing an increase in water retention, increasing residual moisture. This fact is explained by the increase in the surface matrix potential caused by soil compression, which increases the contact points between the particles and, consequently, water adsorption (Assouline et al., 1997).

With the highest amount of micropores at the LSC and LTL positions in relation to the locations not altered by the compaction process (RSC, LSC and IR positions), according to Resende et al. (2007), soil compaction could be beneficial in terms of water retention in the case of Oxisol with a “coffee powder” structure. Within certain limits, this condition would transform part of the macropores into micropores, favoring greater water retention. Therefore, it is possible to explain the direct relationship between PRmean and water contents (θ) at tensions of 100 and 300 kPa. However, when discussing the benefit of water retention at higher tensions, it is important to analyze the other properties, such as macropore volumes and aeration porosity, which, in the case of LSC and LTL positions, in their majority, are inconsistent with the needs of the crops.

When observing the textural analysis data, the areas BA08, BV06 and BV15 showed the highest sand contents in the general profile, differing from the other areas (BA14, BV09, CT01a, AR17 and CT01b). Area BA08 was sandier in relation to the BV06 and BV15, when the positions and depths were compared, and in turn, with the lower clay contents (Table 6), an inverse relationship was observed in the PCA for PC2. According to the altitude data, the BA08 and BV06 areas are at the lowest altitudes and have the highest slopes, especially the BA08, which has a slope close to 8 %.

The higher sand content and lower clay content may be attributed to the effects of relief and intense precipitation events, which lead to the erosion of finer particles, as well as to the site’s geology. According to surveys by Codemig and CPRM (2013), areas BA08, BV06, and BV15 are in transition zones with geological domains of more acidic rocks, while the remaining areas are found in regions with soils developed from mafic magmatism. However, it is important to note that soil texture is not a determining factor in the soil compaction effect.

The textural properties alone are not sufficient to identify soil compaction. While areas with higher sand content show lower PRmean values compared to the BA14 area, suggesting that texture can influence soil compression, this effect does not directly determine compaction. In fact, the PRmean values in these areas do not differ significantly ($p<0.05$) from those in other areas with high clay content (>70 %), such as BV09, CT01a, CT01b, and AR17. This indicates that factors other than texture are more influential in soil compaction and the propagation of its impacts.

The low water storage capacity in these areas can be explained by their granulometry, since BA08 and BV06 were classified as clayey loam and very clayey texture, respectively, a condition that can cause water stress in the plant in times of low precipitation. Sales et al. (2016) showed low water storage capacity in an Oxisol compared to an Ultisol, with higher levels at 0.01 and 0.03 MPa tensions, corroborating the influence of texture on soil water storage and their water retention curves.

This study is based on the premise that soil compaction is a restrictive factor in productivity, but, water deficit, at certain times of the year, is also a clearly important factor in coffee production due to its direct relationship with the ripening of the grains (Alves, 2008; Molina et al., 2020). On the other hand, the presence of compaction requires a more complex management from an operational point of view. However, it can be mitigated by adding higher water and fertilizer contents. This situation creates more favorable conditions for the plant with less effort in the search for these elements by the roots, in contrast to increasing production costs and the environmental effect due to the high water expenditure.

Final remarks

Machine traffic causes changes in the physical soil properties, as evidenced by the variations in the values of the TP and PRmean indicators compared among the sampling positions. The AR17 area, with 3.5 years of planting until the date of the study, did not show significant differences in the values of TP and PRmean in the different sampling positions, therefore, the period between planting and the fourth year of crop establishment can be considered adequate to conduct practices aimed at reducing and/or mitigating for a longer period the effect of machine traffic. After the fourth year, the management of the effects of compaction is operationally complex and costly and has consequences.

CONCLUSIONS

Physical constraints in the Oxisol under mechanized coffee cultivation occurred in a doubly localized manner: superficially (<0.20 m) and in the sampling positions of the right tractor lines (RTL) Left tractor lines (LTL), as indicated by total porosity (TP) and mean soil penetration resistance (PRmean), characterizing soil compaction No significant impediments to root development were observed at depths below 0.20 m, as the differences between sampling sites were negligible regardless of the assessed property.

Among the physical properties evaluated, total porosity and mean penetration resistance were the most effective in demonstrating the existence of compaction in the RTL and LTL positions in the coffee plantation. Principal component analysis (PCA) revealed that, in addition to TP and PRmean, other important soil quality indicators included volumetric moisture content at 100 and 300 kPa tensions, particle density, and granulometric fractions (clay, fine sand, and coarse sand). These properties showed significant variations across layers and sampling positions, influencing the soil susceptibility to compaction and water retention characteristics. Volumetric moisture content at 100 and 300 kPa tensions was higher in compacted areas, indicating increased water retention capacity. However, this may lead to reduced aeration porosity, potentially affecting root respiration and nutrient uptake, particularly in the RTL and LTL positions.

The youngest plantation (AR17, 3.5 years old) did not show significant variations in TP and PRmean across sampling positions, suggesting that the initial years post-planting may offer a window of opportunity for implementing soil conservation practices before compaction effects become pronounced. The relationship between soil physical properties and coffee plant vigor (as measured by NDVI) was not consistently strong across all areas, highlighting the complex nature of plant-soil interactions in coffee cultivation systems.

While not primary indicators in the PCA, other physical properties such as maximum and minimum penetration resistance, macroporosity, and soil hydraulic properties provided valuable complementary information on soil structure and function. These properties should be considered in comprehensive assessments of soil quality in mechanized coffee plantations.

Observed changes in soil physical properties, particularly in the RTL and LTL positions, emphasize the need for site-specific management strategies to mitigate compaction and maintain soil health in mechanized coffee cultivation systems. This study underscores the importance of considering a wide range of soil physical properties when assessing soil quality and developing sustainable management practices for coffee plantations in the Cerrado region.

SUPPLEMENTARY MATERIALS

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-49-e0240111/1806-9657-rbcs-49-e0240111-suppl01.pdf

DATA AVAILABILITY

The data will be provided upon request.

FUNDING

This study was partially financed by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Finance Code 001. The National Council for Scientific and Technological Development - Brazil (CNPq) supported the productivity grant of author TSO (#314012/2021-4).

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to the staff of Soil and Plant Nutrition Consultancy, Rodrigo de Oliveira Lima for their valuable assistance. We also extend our heartfelt thanks to the owner of Chuá Farm, Group DB - Décio Bruxel and his sons, for their generous support during field trips and for granting access to the coffee plantation areas for soil sampling. Their cooperation was instrumental in the successful completion of this research.

AUTHOR CONTRIBUTIONS

Conceptualization: Katherine Martinez Escobar (equal), Laís Maria Rodrigues Silva (equal) and Teogenes Senna de Oliveira (equal).

Data acquisition: Katherine Martinez Escobar (equal), Keise Duarte Bacelar de Morais (equal) and Laís Maria Rodrigues Silva (equal).

Data analyses: Júlio César Lima Neves (equal), Katherine Martinez Escobar (equal) and Laís Maria Rodrigues Silva (equal).

Supervision: Júlio César Lima Neves (equal) and Teogenes Senna de Oliveira (equal).

Writing- original draft: Katherine Martinez Escobar (lead).

Writing- review and edition: Júlio César Lima Neves (equal), Katherine Martinez Escobar (equal), Keise Duarte Bacelar de Morais (equal), Laís Maria Rodrigues Silva (equal) and Teogenes Senna de Oliveira (equal).

REFERENCES

Alcântara E, Ferreira MM. Efeitos de métodos de controle de plantas daninhas na cultura do cafeeiro (*Coffea arabica* L.) sobre a qualidade física do solo. Rev Bras Cienc Solo. 2020;24:711-21. https://doi.org/10.1590/S0100-06832000000400003

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Z. 2013;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Alves JD. Morfologia do cafeeiro. In: Carvalho CHS, editor. Cultivares de café: Origem, características e recomendações. Brasília, DF: Embrapa Café; 2008. p. 35-56.

Assouline S, Tessier D, Tavares-Filho J. Effect of compaction on soil physical and hydraulic properties: Experimental results and modeling. Soil Sci Soc Am J. 1997;61:390-8. https://doi.org/10.2136/sssaj1997.03615995006100020005x

Azevedo AS. As cafeiculturas do Cerrado Mineiro e do Sul de Minas no escopo das singularidades institucionais [dissertation]. Lavras, MG: Universidade Federal de Lavras; 2018.

Bergamin AC, Vitorino ACT, Franchini JC, Souza CMAD, Souza FRD. Compactação em um Latossolo Vermelho distroférrico e suas relações com o crescimento radicular do milho. Rev Bras Cienc Solo. 2010;34:681-91. https://doi.org/10.1590/S0100-06832010000300009

Bertollo AM, Levien R. Compactação do solo em Sistema de Plantio Direto na palha. Pesq Agropec Gaúcha. 2019;25:208-18. https://doi.org/10.36812/pag.2019253208-218

Burak DL, Passos RR, Andrade FV. Variabilidade espacial de atributos químicos do solo sob cafeeiro Conilon: Relação com textura, matéria orgânica e relevo. Bragantia. 2012;71:538-47. https://doi.org/10.1590/S0006-87052012000400012

Carmo DL, Nannetti DC, Dias Júnior MS, Espírito Santo DJ, Nannetti AN, Lacerda TM. Physical properties of a Red-Yellow Latosol under three different systems of coffee management in the state of minas gerais. Rev Bras Cienc Solo. 2011;35:991-8. https://doi.org/10.1590/S0100-06832011000300033

Carvalho LCC. Variabilidade espacial de atributos físicos do solo e características agronômicas da cultura do café [dissertation]. Lavras, MG: Universidade Federal de Lavras; 2012.

Companhia de Desenvolvimento Econômico de Minas Gerais - Codemig, Serviço Geológico do Brasil - CPRM. Mapa geológico do Estado de Minas Gerais. Escala 1:1000.000. Belo Horizonte, MG: Codemig, CPRM; 2013.

Companhia Nacional de Abastecimento - Conab. A Cultura do café: Análise dos custos de produção e da rentabilidade nos anos-safra 2008 a 2017. Brasília, DF: Conab; 2017. (Compêndio de estudos Conab, 12).

Cortez JW, Alves ADS, Moura MRD, Olszevski N, Nagahama HJ. Atributos físicos do Argissolo Amarelo do semiárido nordestino sob sistemas de preparo. Rev Bras Cienc Solo. 2011;35:1207-16. https://doi.org/10.1590/S0100-06832011000400014

Effgen TAM, Passos RR, Andrade FV, Lima JSS, Reis EF, Borges EN. Propriedades físicas do solo em função de manejos em lavouras de cafeeiro conilon. Rev Ceres. 2012;59:414-21. https://doi.org/10.1590/S0034-737X2012000300018

Fazuoli LC, Silvarolla MB, Salva TJG, Guerreiro Filho O, Medina Filho HP, Gonçalves W. Cultivares de café arábica do IAC, um patrimônio da cafeicultura brasileira. In: Anais do 33º Congresso Brasileiro de Pesquisas Cafeeiras; 23 a 26 de outubro, 2007; Lavras. Lavras, MG: CBPC; 2007.

Feng G, Wu L, Letey J. Evaluating aeration criteria by simultaneous measurement of oxygen diffusion rate and soil-water regime: Soil Sci. 2002;167:495-503. https://doi.org/10.1097/00010694-200208000-00001

Fernandes AL, Santinato F, Santinato R. Utilização da subsolagem na redução da compactação do solo para produção de café cultivado no cerrado mineiro. Encicl Biosf. 2012;8:1648-56.

Geoportal do Café [internet]. Portal do café de minas [cited 2023 Nov 11]. Available from: https://portaldocafedeminas.emater.mg.gov.br/#o-que-e.

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

Gontijo I, Dias Junior MS, Guimarães PTG, Araujo-Junior CF. Atributos físico-hídricos de um Latossolo de Cerrado em diferentes posições de amostragem na lavoura cafeeira. Rev Bras Cienc Solo. 2008;32:2227-34. https://doi.org/10.1590/S0100-06832008000600002

Goularte GD. Porosidade de aeração e relações hídricas na produtividade do cafeeiro irrigado em Latossolo Roxo, no sul de Minas Gerais [dissertation]. Curitiba, PR: Universidade Federal do Paraná; 2014.

Ker JC, Schaefer CER. Roteiro da excursão pedológica Viçosa - Sete Lagoas. Viçosa, MG: Universidade Federal de Viçosa, Departamento de Solos, Sociedade Brasileira de Ciência do Solo; Rio de Janeiro: Embrapa-CNPS; 1995.

Ladeia CA, Santos JRE, Sousa DS, Freire DS, Castro ITP, Ferreira GFP, Castro ITP, Ferreira GFP, Neves MC, Scipioni CA, Lemos OL. Sensor ativo como ferramenta de estimativa de nitrogênio e clorofila em variedades de café. In: X Simpósio de Pesquisa dos Cafés do Brasil; 8 a 11 de outubro de 2019, Vitória. Vitória, ES: SPCB; 2019.

Lima RP, Silva AR, Raminelli JA. Importância de atributos físicos do solo na identificação da compactação. Rev Verde Agroecol Des Sust. 2013;8:93-7.

Lipiec J, Hatano R. Quantification of compaction effects on soil physical properties and crop growth. Geoderma. 2003;116:107-36. https://doi.org/10.1016/S0016-7061(03)00097-1

Lopes AGC, Correia TPS, Brito GR, Faria APFA, Silva PRA. Desempenho operacional e custo da subsolagem com e sem rodado duplo no trator agrícola. Energ Agric. 2020;35:317-29. https://doi.org/10.17224/EnergAgric.2020v35n3p317-329

Luciano RV, Albuquerque JA, Costa A, Batistella B, Warmling MT. Physical attributes related to soil compaction under native vegetation of Southern Brazil. Rev Bras Cienc Solo. 2012;36:1733-44. https://doi.org/10.1590/S0100-06832012000600007

Lynch JP, Wojciechowski T. Opportunities and challenges in the subsoil: pathways to deeper rooted crops. J Exp Bot. 2015;66:2199-210. https://doi.org/10.1093/jxb/eru508

Machado JA, Souza DMP, Brum ACR. Efeito de anos de cultivo convencional em propriedades fisicas do solo. Rev Bras Cienc Solo. 1981;5:187-9.

Maia IC. Compactação do solo causada pelo trafego de maquinas agrícolas [supervised internship report]. Fortaleza, CE: Universidade Federal do Ceará; 2016.

Martins P. Avaliação da sustentabilidade da estrutura de um Cambissolo sob difetentes sistemas de uso da terra na Amazônia Ocidental [thesis]. Lavras: Universidade Federal de Lavras; 2009.

Martins PCC, Dias Junior MS, Andrade MLC, Guimarães PTG. Compactação causada pelas operações mecanizadas em um Latossolo Vermelho-Amarelo cultivado com cafeeiros ao longo do tempo. Cienc Agrotec. 2012a;36:391-8. https://doi.org/10.1590/S1413-70542012000400002

Martins PCC, Dias Junior MS, Ajayi AE, Moreira FMS. Sustentabilidade estrutural de um cambissolo sob diferentes sistemas de uso. Rev Bras Cienc Solo. 2012b;36:1724-32. https://doi.org/10.1590/S0100-06832012000600006

Masola MJ. Propagación lateral de la compactación por tránsito de la maquinaria agrícola: ¿afecta la calidad del suelo, el intercambio gaseoso y la productividad de los cultivos? [thesis]. Esperanza, Santa Fé: Universidad Nacional del Litoral; 2020.

Molina PCP, Martínez MJG, Ceballos GO, Cabrera CRC, Pérez JC. Fenómenos meteorológicos y su efecto sobre la producción de café en la Zona Central de Veracruz. UVserva. 2020;9:47-58.

Naderi-Boldaji M, Keller T. Degree of soil compactness is highly correlated with the soil physical quality index S. Soil Till Res. 2016;159:41-6. https://doi.org/10.1016/j.still.2016.01.010

Naghdi R, Solgi A, Labelle ER, Nikooy M. Combined effects of soil texture and machine operating trail gradient on changes in forest soil physical properties during ground-based skidding. Pedosphere. 2020;30:508-16. https://doi.org/10.1016/S1002-0160(17)60428-4

Oliveira VS, Rolim MM, Vasconcelos RFB, Costa YDJ, Pedrosa EMR. Compaction of a Ultisol submitted to different managements. Rev Bras Eng Agric Ambient. 2010;14:914-20. https://doi.org/10.1590/S1415-43662010000900002

Oyola-Guzmán RD. Determinación de la resistencia a la penetración de un suelo cohesivo en diferentes condiciones de hidratación y compactación. Rev Arq Ing. 2016;10:1-10.

Pagliai M, Marsili A, Servadio P, Vignozzi N, Pellegrini S. Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power. Soil Till Res. 2003;73:119-29. https://doi.org/10.1016/S0167-1987(03)00105-3

Palma MAZ, Volpato CES, Silva FC, Souza P, Silva JA. Resistência do solo à penetração em cafezais cultivados com sistema mecanizado e manual. Coffee Sci. 2013;8:364-70.

Resende M, Curi N, Rezende S, Corrêa GF. Pedologia: Base para distinção de ambientes. 5. ed. Lavras: Editora UFLA; 2007.

Ribeiro AC, Guimarães PTG, Avarez V VH. Recomendações para o uso de corretivos e fertilizantes em Minas Gerais - 5ª Aproximação. Viçosa, MG: Comissão de fertilidade do solo do estado de Minas Gerais; 1999.

Richmond P, Rillo S. Evaluación del efecto de la compactación por el rodado de maquinarias sobre algunas propiedades físicas del suelo y el cultivo de trigo en siembra directa. Cono Sur: Instituto de la Potasa y el Fósforo; 2006. p. 22-5. (Informaciones Agronómicas, 32).

Rouse JW, Haas RH, Schell JA, Deering DW. Monitoring vegetation systems in the Great Plains with ERTS. In: Freden SC, Mercanti EP, Becker MA, editors. Third Earth Resources Technology Satellite-1 Symposium: Section A. Washington, DC: NASA; 1974. p. 309-18.

Sá MAC, Santos Junior JDG, Franz CAB, Rein TA. Soil physical quality and sugarcane yield with the use of inter-row chiseling. Pesq Agropec Bras. 2016;51:1610-22. https://doi.org/10.1590/S0100-204X2016000900061

Sales RP, Portugal AF, Moreira JAA, Kondo MK, Pegoraro RF. Qualidade física de um Latossolo sob plantio direto e preparo convencional no semiárido. Rev Cienc Agron. 2016;47:429-38. https://doi.org/10.5935/1806-6690.20160052

Santinato F, Cantarella H, Santinato R, Eckhardt CF, Gonçalves VA, Silva CD, Arceda EUD. Sistema radicular do cafeeiro em lavouras irrigadas mecanizadas das cultivares Catuaí, Acauã Novo e Apoatã. In: 44º Congresso Brasileiro de Pesquisas Cafeeiras, 23 a 26 de outubro, 2018, Franca, SP. Franca, SP: CBPC; 2018.

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

Silva BM, Silva EAD, Oliveira GCD, Ferreira MM, Serafim ME. Plant-available soil water capacity: estimation methods and implications. Rev Bras Cienc Solo. 2014;38:464-75. https://doi.org/10.1590/S0100-06832014000200011

Silva AL, Faria MA, Reis RP. Viabilidade técnico-econômica do uso do sistema de irrigação por gotejamento na cultura do cafeeiro. Rev Bras Eng Agríc Ambient. 2003;7:37-44. https://doi.org/10.1590/S1415-43662003000100007

Silva ENS, Montanari R, Panosso AR, Correa AR, Tomaz PK, Ferraudo AS. Variabilidade de atributos físicos e químicos do solo e produção de feijoeiro cultivado em sistema de cultivo minimo com irrigação. Rev Bras Cienc Solo. 2015;39:598-607. https://doi.org/10.1590/01000683rbcs20140429

Silva SA, Lima JSS, Xavier AC, Teixeira MM. Variabilidade espacial de atributos químicos de um Latossolo Vermelho-Amarelo húmico cultivado com café. Rev Bras Cienc Solo. 2010;34:15-22. https://doi.org/10.1590/S0100-06832010000100002

Silva VR, Reinert DJ, Reichert JM, Soares JM. Fatores controladores da compressibilidade de um Argissolo Vermelho-Amarelo distrófico arênico e de um Latossolo Vermelho distrófico típico. I-estado inicial de compactação. Rev Bras Cienc Solo. 2002;26:1-8. https://doi.org/10.1590/S0100-06832002000100001

Souza GS, Dan ML, Araújo JBS. Qualidade física do solo sob cafeeiro conilon consorciado e em monocultivo. Coffee Sci. 2016;11:180-6.

Souza GSD, Souza ZMD, Silva RBD, Barbosa RS, Araújo FS. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. Rev Bras Cienc Solo. 2014;38:135-46. https://doi.org/10.1590/S0100-06832014000100013

Souza JM, Reis EF, Bonomo R, Garcia GO, Pereira LR. Caracterización del sistema radicular Conilon café bajo riego por goteo. Idesia. 2021;39:117-24. https://doi.org/10.4067/S0718-34292021000300117

Statistica. Statistica, 13.0. Get the software safely and easily. Software Informer. [internet]; 2023. Available from: https://statistica.software.informer.com/13.0/.

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.

Thompson LM, Troeh FR. Los suelos y su fertilidad. 4. ed. Barcelona: Editorial Reverté; 2021.

Tormena CA, Barbosa MC, Costa ACS, Gonçalves ACA. Densidade, porosidade e resistência à penetração em Latossolo cultivado sob diferentes sistemas de preparo do solo. Sci Agric. 2002;59:795-801. https://doi.org/10.1590/S0103-90162002000400026

Tormena CA, Silva AP, Libardi PL. Caracterização do intervalo hídrico ótimo de um Latossolo Roxo sob plantio direto. Rev Bras Cienc Solo. 1998;22:573-81. https://doi.org/10.1590/S0100-06831998000400002

Van Lier QJ. Física do solo baseada em processos. Piracicaba, SP: Edição do autor; 2020.

Vicente MR, Mantovani EC, Fernandes ALT, Neves JCL, Figueredo EM, Delazari FT. Spacial distribution of fertigated coffee root system. Cienc Agrotec. 2017;41:72-80. https://doi.org/10.1590/1413-70542016411021316

Yavuzcan HG, Matthies D, Auernhammer H. Vulnerability of Bavarian silty loam soil to compaction under heavy wheel traffic: impacts of tillage method and soil water content. Soil Till Res. 2005;84:200-15. https://doi.org/10.1016/j.still.2004.11.003