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Root spatial distribution in coffee plants of different ages under conservation management system

Érika Andressa da Silva[1]*, Sérgio Henrique Godinho Silva[2], Geraldo César de Oliveira[3] and Carla Eloize Carducci[4]

[1]Department of Soil Science, Federal University of Lavras, DCS-UFLA, Lavras, MG, Brazil.
[2]Federal University of Vales Jequitinhonha and Mucuri, Brazil.
[3]Federal University of Lavras, DCS-UFLA, Lavras, MG, Brazil.
[4]Federal University of Santa Catarina, Curitibanos campi (UFSC), 89520-000 Curitibanos, SC, Brazil.

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Root system growth and soil structure are interdependent and the threshold of separation between both of them is complex. However, by the evaluation of soil pore space, it is possible to characterize the root system growth environment. The aim of this study was to evaluate the effect of conservation management system over time on pore distribution and on root system development of coffee plantation in Cerrado Oxisol, located in the state of Minas Gerais, Brazil. Two coffee plantation areas were sampled (3 or 6 years old). Trenches were dug lengthwise along the planting row to expose the root system and the vertical profiles were divided into 0.05 × 0.05 m grid cells (0.70 × 1.50 m grid), totaling 420 sample sites. Digital images were taken and using the computer software Safira, it was measured layers along the soil profile, which was spaced 0.10 m apart. Disturbed and undisturbed soil cores the length, the surface area and the volume of the root system were sampled at 0.20 to 0.34, 0.80 to 0.94, and 1.50 to 1.64 m depths layers, in order to determine particle size, total porosity, and pore size distribution. The 3-years coffee stand had the greatest volume of macropores and the largest number of absorbent roots, besides a noticeable root system growth below 1 m depth. The 6-years old coffee stand presented pores reconfiguration due to increase in the intermediate-sized pores and to the uniform root distribution in both horizontal and vertical directions up to 0.9 m depth.

Key words: Gibbsitic Oxisol, pore system, 2D images, geostatistics, root system distribution.

INTRODUCTION

Soil pore space results from mineral particles organization into water-stable aggregates. During soil structural organization, there are alterations in pore distribution and configuration, which interfere with root system distribution and plant growth (Carducci et al., 2013, 2014a, b, 2016; Silva et al., 2014).

Among several reasons, soil structural organization may be related to the use of soil conditioners, such as

*Corresponding author. E-mail: ec.carducci@ufsc.br. Tel: +55 48 3721 6274.

Table 1. Particle size distribution of a very clayey Rhodic Haplustox at different depth under soil conservation management system.

Depth (m)	3-years (1)			6-years (2)		
	Clay	Silt	Sand	Clay	Silt	Sand
	g kg^{-1}					
0.20-0.34	869	65	66	819	24	157
0.80-0.94	895	59	46	848	25	127
1.50-1.64	904	57	39	886	25	89

(1)3 years-old; (2) 6 years-old.

agricultural gypsum associated with soil organic matter, which influences the formation of organo-mineral complexes, especially calcium and organic radicals derived from the decomposition of plant residues (Silva et al., 2013, 2014).

Based on this premise, some coffee growers in Minas Gerais have adopted a soil management system which consists of periodically mowed grass cultivation (*Brachiaria decumbens*) between planting rows as a permanent source of organic matter, associated with the building of fertility in deep soil layers, which is possible due to the adoption of a deep, fertilized planting furrow and to the gypsum application on soil surface. This management improves physical and chemical soil conditions, as well as increases root system depth (van Raij, 2008; Serafim et al., 2013a, b, c; Silva, 2012; Carducci et al., 2014b; Silva et al., 2014).

Cerrado Biome, one of the main coffee-producing regions of Brazil, has faced prolonged and more frequent dry spells. The region has the highest proportion of oxidic Latosols (Oxisols). Although, these soils present good physical quality, they have bimodal pore size distribution, that is, this soil has high values of macro and microporosity, but with low proportion of intermediate diameter pores, which hold the readily available soil water to plant roots (Oliveira et al., 2004; Carducci et al., 2013).

Thus, the adoption of water conservation practices might mitigate soil water deficit in Cerrado, which is partly possible due to the increase in intermediate pores in Latosols (Barbosa et al., 2014) and to plant root system development, especially in plants younger than 3-years (Carducci et al., 2016), which improves the use of deep water stored in the soil. This practice is possible and was confirmed by other authors (Silva et al., 2014; Santos et al., 2014; Serafim et al., 2013a, b, c).

The increment of intermediate sized pores and the increase in effective root zone depth in oxidic Latosols contributed to increase coffee production. However, the adoption of new management practices able of altering the pore distribution and promote root growth must be preceded by scientific studies. Thus, the aim of this study was to evaluate the effect of conservation management system over time on pore distribution and on root system development of coffee plantation in Cerrado Oxisol located in the state of Minas Gerais, Brazil.

MATERIALS AND METHODS

Study area description

The study was carried out in two coffee plantations near São Roque de Minas, in the upper São Francisco river basin, Minas Gerais, Brazil. The soil studied is a very clayey Rhodic Haplustox (*Latossolo Vermelho* in the Brazilian System of Soil Classification-Embrapa, 2013; Santos et al., 2013), with ca. 86% clay, from which 55% is gibbsite, and 25% is kaolinite, according to thermal analyses (Carducci et al., 2014a, b) (Table 1). Two plantations were sampled: a young stand (3 years-old, planted in November, 2008) stand, at 20°15'45" S and 46°8'17" W, at 850 m asl, and an old stand (6 years-old, planted November, 2005), at 20°11'35"S and 46°22'07" E, at 841 m asl. Both plantations were planted and conducted according to the soil conservation management system described subsequently.

The fields were managed by using soil conservation practices for coffee cultivation. Planting was carried out in a narrow row, with spacing of 2.5 m between plants and 0.65 m between rows; one plowing and two harrowing were carried out to prepare the land, followed by application of dolomitic limestone (4 mg ha^{-1}) and agricultural gypsum (1.92 mg ha^{-1}) in the total area. Furrows of 0.60 m depth and 0.50 m width were made with a subsoiler coupled to a rotary tiller, which enabled homogeneous distribution of liming and fertilizers to 0.40 m depth.

It was applied 8 mg ha^{-1} (2 kg m^{-1}) of dolomitic limestone and basic fertilizer in the furrow. Afterwards, *B. decumbens* (*Syn*.Urochloa) was planted between rows as cover crop and mowed periodically (Serafim et al., 2013a, b, c; Silva et al., 2013). After the grass had been established, coffee seedlings were planted. Three months later, 7 kg m^{-1} of agricultural gypsum was applied on soil surface of the coffee rows, followed by hilling around the base of the plants (Serafim et al., 2011, 2013a, b, c).

In order to designate the treatment types, terms were chosen according to the age of the coffee plants in each field. According to Nutman (1933a, b, 1934), who published the most comprehensive study about the root system of Arabic coffee, the main morphological and physiological characteristics of the root system complete their development between 5 and 6 years after planting. After this period, the coffee plant is considered adult, and its roots renew constantly; however, it maintains the typical conformation to the end of life cycle.

Soil sampling and physical characterization

Three random trenches were dug lengthwise along the plant row and three replications of disturbed and undisturbed soil cores were sampled from 0.20 to 0.34, 0.80 to 0.94, and 1.50 to 1.64 m depth layers. The choice of depths was based on the cultural profile method (Tavares Filho et al., 1999), which detects morphological alterations caused by the management system. The disturbed samples were used to determine soil particle size by the pipette method (Embrapa, 2011).

Undisturbed soil cores were collected in volumetric rings (80 cm^3) in the middle of the spacing between plants (0.65 m), using a Uhland-type sampler in order to obtain the water retention curve. Samples were subjected to the following matric potentials of water in the soil: -2, -4, -6, and -10 kPa, using Buchner funnels and -33, -100, -500, and -1500 kPa in the porous plate, with the saturated soil samples placed in pressure chambers. After samples stabilization in each of thematric potential (Ψ_m), they were weighed and kept in incubators at 105 to 110°C for 48 h, to determine the soil bulk density (BD) and the corresponding water content (θ). Macroporosity was calculated by the difference between total porosity (TP = (1 - Ds / Dp)) and microporosity (water retained at Ψ_m -6 kPa) (Embrapa, 2011).

In order to better discriminate the soil pore diameter, information from the water retention curve was used, by using the Bouma equation (1991), which considers cylindrical-shaped pores:

$$D = 4\,\sigma\,\mathrm{Cos}\,\theta/\Psi_m$$

where D is the pore diameter (µm); σ is the water surface tension (73.43 kPa uM at 20°C); θ is the contact angle between the meniscus and the capillary tube wall (considered 0), and Ψ_m the matric potential (kPa). The Mesopores (intermediate-sized pores) were classified according to Barbosa et al. (2014).

After reaching equilibrium at the matric potential of -6 kPa (considered as the field capacity for Latosols - Oxisols) (Ferreira and Marcos, 1983; Silva et al., 2014), some samples were weighted and used to determine the soil resistance to penetration (RP), by using a bench top electronic penetrograph (Tormena et al., 1998; Lima et al., 2012).

Assessment of the root system of the coffee plants

For the study of the root system distribution in the 3 and 6-years old stand, three 0.70 × 1.50 × 1.50 m trenches were dug lengthwise the planting row. The vertical trench wall stood in the projection of the coffee canopy at 0.10 m distance from the plant stem. Considering the spacing between plants of 0.65 m, the trench was arranged in order to have a coffee plant in its center. Subsequently, the soil was scarified at 0.03 m to expose the roots, and a grid (0.05 × 0.05 m cells) with the same dimensions as the trench, which consisted of 420 sample units, as detailed by Carducci et al. (2014a, 2015a). The following variables were analyzed: volume (mm³), surface area (mm²), length (mm), and root diameter (mm), by using the computer software Safira (Jorge and Silva, 2010), as described in Carducci et al. (2015a).

Statistical analyses

The experiments consisted of complete randomized split-plot design, in both stand age, in which the plot referred to the age of the plantation and the subplot referred to the depth. After the data normality generated by the Shapiro-Wilk method was checked, analysis of variance was carried out, and the means were compared by the Scott-Knott test at 5% of probability, using the computer statistical analysis system Sisvar (Ferreira, 2011).

Data on volume, surface area and root length were subjected to the frequency distribution test and the classes were defined by the Stunges formula:

$$K = 1 + 3.22 \times \log n$$

where K is the number of classes and n is the total number of individuals in the population (420 sample units [grid with 0.70 m wide × 1.50 m long, subdivided into 0.05 × 0.05 m cells]).

Roots were classified in three different diameters: 1, fine or absorbent roots (Ø≤1 mm); 2, intermediate or support for the absorbent roots (1<Ø≤3 mm); 3, thick or permanent roots (Ø>3 mm), according to Rena and Guimarães (2000) and Motta et al. (2006).

The surface maps of the root spatial distribution in all soil profiles for both stand ages was carried out by interpolation through the inverse square of the distance method (ISD), using the ArcGIS 9.3 software (ESRI, 2009).

RESULTS AND DISCUSSION

Characterization of the soil physical properties

In both stand ages, it was verified that soils were very clayey in all the profile. Clayey Oxisols generally have low bulk density (BD) and resistance to penetration, as observed in the present study (Table 2).

The soil layer at 1.50 to 1.64 m depth (Bw horizon) is a reference that reflects the intrinsic structural condition of very clayey Oxisols (Ferreira et al., 1999; Severiano et al., 2011a, b). The bulk density (BD) and resistance to penetration (RP) values at other depths confirm the good physical condition of the soil, partly due to the initial effects of the tillage adopted, and to the maintenance of soil organic matter in this management system (Serafim et al., 2013a, b, c; Silva et al., 2012, 2013).

Thus, in order to detect the influence of conservation management practices over time and sampling depth on the pore diameter distribution, factor analysis was carried out with a view towards possible interactions between both factors. The interaction was not observed for all pore diameter classes. However, differences between the conservation management practices over time for some pore diameter classes were detected, as presented in Tables 3 and 4.

The Oxisol under 3-years coffee stand showed higher pore volume in the diameter classes >147 µm (Ψm -2 kPa) and 2.9 to 0.6 6 µm (referring to the Ψm between -100 and -500 kPa), while in the condition of 6 years coffee stand, higher pores volume was observed in the classes of 147 to 9 µm (referring to Ψm between -4 and -33 kPa), and these classes present inter-aggregated pores (macropores and intermediate pores), which suggests a more homogeneous arrangement of the pores with better distribution between intermediate pores (Carducci et al., 2015b), as the management system is consolidated (Table 3)

For the diameter classes < 0.2 µm (Ψ_m -1500 kPa), high volume of micropores was observed (intra-aggregate pores) in both plantations, which means that strong water retention in these gibbsitic Oxisol makes the water unavailable to plants, as previously reported by Carducci et al. (2011).

In both stand ages, the soil at 0.20 to 0.34 m and 0.80 to 0.94 m depth, in comparison with the soil at 1.50 to

Table 2. Rhodic Haplustox physics attributes under 3- and 6-yrs old coffee stand in different depth.

Depth (m)	3-years	
	PR[ns(1)] (MPa)	**Bd*[(2)] (Mg dm^{-3})**
0.20-0.34	0.26[a] (±0.02)	0.78[b] (±0.05)
0.80-0.94	0.20[a] (±0.003)	0.91[a] (±0.005)
1.50-1.64	0.37[a] (±0.07)	0.96[a] (±0.03)
	6-years	
	PR[ns] (Mpa)	**Bd[ns] (Mg dm^{-3})**
0.20-0.34	0.19[a(±0.03)]	0.95[a(± 0.05)]
0.80-0.94	0.14[a(±0.04)]	1.04[a(±0.01)]
1.50-1.64	0.13[a(±0.04)]	1.03[a(± 0.03)]

[(1)]PR: Penetration resistance on -6 kPa potential matric. [(2)]Bd: Bulk density. ns: Non significant, *significant ($p < 0.05$). Means followed by the same letter in the columns do not differ by the Scott Knott test at 5%. Between parenthesis: mean standard error (n=3).

Table 3. Means values of pores diameter distribution in Rhodic Haplustox under 3- and 6-years old coffee stand.

Stand	Pores diameter distribution (µm)						
	> 147**	**147 - 73***	**49 - 29****	**29 - 9***	**2.9 - 0.6****	**< 0.2[ns]**	**TP[ns]**
Age	cm^3 cm^{-3}						
3-years	0.130[a(±0.01)]	0.063[b(±0.009)]	0.031[b(±0.004)]	0.038[b(±0.003)]	0.020[a(±0.001)]	0.259[a(±0.02)]	0.62[a(±0.01)]
6-years	0.087[b(±0.006)]	0.092[a(±0.006)]	0.048[a(±0.01)]	0.050[a(±0.002)]	0.008[b(±0.001)]	0.260[a(±0.007)]	0.61[a(±0.01)]

Means followed by the same letter in the column do not differ by the Scott-Knott test at 5% probability. ns: Non significant; *significant ($p < 0.05$); ** significant ($p < 0.01$). TP: total porosity. Between parenthesis: mean standard error (n = 3).

Table 4. Means values of pores diameter distribution at different depth under soil conservation management system.

Depth (m)	Pore diameter distribution (µm)						
	>147***	**147-73****	**49-29****	**29 -9***	**2.9-0.6***	**< 0.2[ns]**	**TP***
	cm^3 cm^{-3}						
0.20-0.34	0.128[a(±0.01)]	0.087[a(±0.006)]	0.041[a(±0.004)]	0.051[a(±0.004)]	0.015[a(±0.003)]	0.231[a(±0.02)]	0.63[a(±0.01)]
0.80-0.94	0.118[a(±0.01)]	0.093[a(±0.006)]	0.046[a(±0.003)]	0.044[a(±0.001)]	0.016[a(±0.002)]	0.241[a(±0.006)]	0.63[a(±0.01)]
1.50-1.64	0.080[b(±0.008)]	0.052[b(±0.01)]	0.031[b(±0.005)]	0.037[b(±0.004)]	0.010[b(±0.002)]	0.306[a(±0.01)]	0.58[b(±0.01)]

Means followed by the same letter in the column do not differ by the Scott-Knott test at 5% probability. Ns: Non significant; *Significant ($p < 0.05$); **Significant ($p < 0.01$). TP: Total porosity. Between parenthesis: mean standard error (n = 3).

1.64 m depth, showed higher intermediate and inter-aggregate pore volume, especially of the class >147 µm. However, it presented lower pore volume in relation to potential under -1500 kPa (pores < 0.2 µm), which means that there was higher volume of pores with larger diameter at shallow depths (Table 4).

Soil tillage in the row, carried out due to the coffee planting, significantly altered the soil pore distribution, confirming what was observed by Carducci et al. (2013) regarding the pores bimodality of the these Oxisols.

Since intermediate diameter pores are important for roots penetration, aeration and retention of readily available water (Carducci et al., 2015b), a study was carried out with soil pore classes between 73 to 49 µm (referring to Ψ_m from -4 to -6 kPa) and from 9 to 2.9 µm (referring to Ψ_m from -33 to -100 kPa) (Table 5) due to significant interaction between field and sampling depth.

For the diameter classes referring to these intervals, the highest values were found in the 6-years stand age, and were more noticeable at 0.80 to 0.94 m depth. At this

Table 5. Means values of pores diameter (cm^3 cm^{-3}) of intermediate class (73-49 e 9-2,9 µm) at different depth under 3 and 6-yrs old coffee stand with soil conservation management system.

Depth (m)	3-years	6-years
	73 - 49* (µm)	
0.20-0.34	$0.041^{bA(\pm 0.007)}$	$0.053^{aB(\pm 0.003)}$
0.80-0.94	$0.056^{bA(\pm 0.004)}$	$0.104^{aA(\pm 0.007)}$
1.50-1.64	$0.044^{aA(\pm 0.006)}$	$0.043^{aB(\pm 0.006)}$
	9 - 2.9**(µm)	
0.20-0.34	$0.015^{aA(\pm 0.0006)}$	$0.019^{aB(\pm 0.003)}$
0.80-0.94	$0.018^{bA(\pm 0.0009)}$	$0.044^{aA(\pm 0.001)}$
1.50-1.64	$0.016^{aA(\pm 0.001)}$	$0.013^{aB(\pm 0.002)}$

Means followed by the same capital letter in the column and small letter on the line do not differ by the Scott-Knott test at 5% probability; *Significant ($p < 0.05$); **Significant ($p < 0.01$). Between parenthesis: mean standard error (n = 3).

depth, the highest water uptake by plants was observed, as verified by Santos et al. (2014), when monitoring the spatial distribution of soil moisture at the same depths and experimental area. Sampling depth was not significant in the 3-years coffee stand, which could be related to the plants at younger stage (3 years age), being insufficient to cause alterations in these pore diameter classes.

It is suggested that subsoil tillage at 0.60 m depth allowed sharp increase in macroporosity along the soil profile (Table 4). Since with the increase in the implantation time, new soil structure reorganization occurred.

This fact was promoted by the joint action of climatic processes and conservation practices carried out in this management system, which caused the inter-aggregate pores go from the largest c diameter pore class to the intermediate class (Tables 3 and 5). This alteration is positive since intermediate diameter pores are responsible for the greater water availability to plants, which may minimize hydric stress during dry spell periods, a typical phenomenon in the Brazilian Cerrado region.

Root classification of the coffee plants

By the frequency distribution tests, roots were clustered into three different classes (Figures 1 and 2). It was verified that the 3-years coffee stand presented greater number of roots with lower surface area (< 77 mm²) and lower volume (< 35 mm³), besides being short (< 21 mm) along the whole soil profile.

It is important to highlight that roots growth had excellent performance in 3-years stand age, since they reached depth greater than 1 m, showed typical conformity of a mature plant, and had greater root concentration near the trunk, decreasing the number of roots and the depth gradually in areas close to the periphery of the canopy projection of the coffee plant (Rena and Guimarães, 2000).

Figures 1 and 2 show a great number of the roots with small area and volume (fine roots) in all the soil profile. Since fine roots are the most efficient in water absorption and nutrient uptake (Jesus et al., 2006), this may suggest positive plant response to edaphological conditions caused by management practices.

In both stand age, a great number of fine roots with lower volume (<35 mm³) was observed along the soil profile, which may be related to the compatibility between the root diameter with some pore diameter classes. This fact is relevant when considering the suggestions of Carducci et al. (2014b) on porosity studies carried out with X-ray CT scan on the 6-years stand age, in which the soil fine macropores (Ø = 1 mm), as well as the large mesopores (Ø = 0.2 mm), favored the development of fine roots (Ø ≤ 1 mm).

From the classification of roots by diameter (Rena and Guimarães, 2000), it was observed that in the 3-years coffee stand a greater number of fine roots (Ø ≤ 1 mm) at the 0.60 to 0.90 m depth layer and intermediate roots (1< Ø ≤ 3 mm) predominated at 0.60 m depth. On the other hand, in the 6-years coffee stand there was a higher concentration of roots with a diameter range of 1 < Ø < 2 mm at 0.90 to 1.20 m depth and the 2 < Ø ≤ 3 mm diameter class at the 0.60 to 0.90 depth layer, and fewer fine roots along the profile (Table 6).

Pore distribution 3D images and coffee root system 2D images were evaluated in the same experimental study area by Carducci et al. (2015a), who also observed the presence of fine roots in layers below 0.80 m depth, especially in younger coffee plants (3 years old), a fact that has not been reported yet in the scientific literature on coffee crop management (Tables 6 and 7).

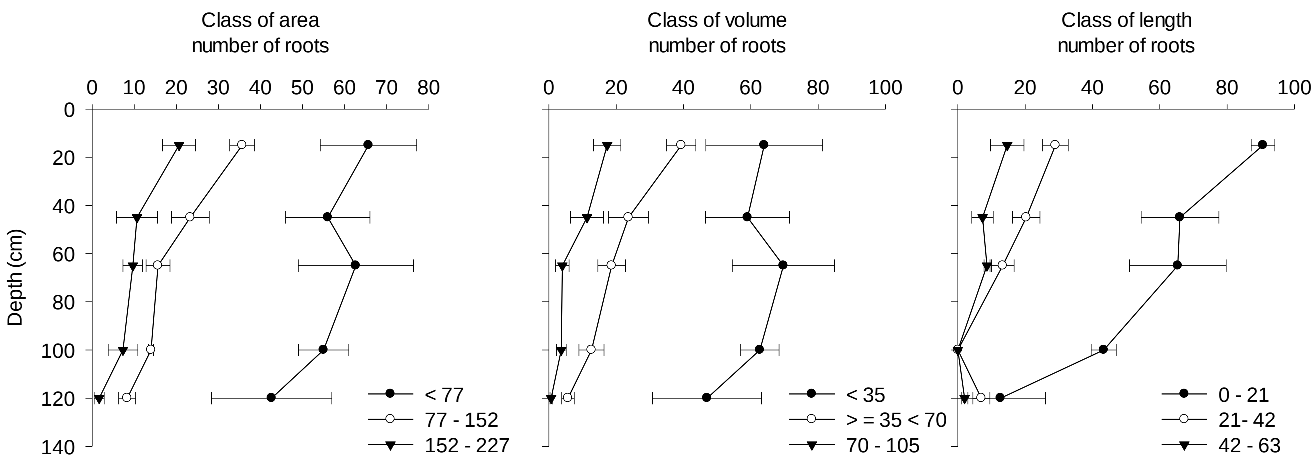

Figure 1. Distribution in classes of the variables: superficial area (mm^2), volume (mm^3) and length (mm) of roots in 3-yrs tillage under conservation system. The Error bars are mean standard error.

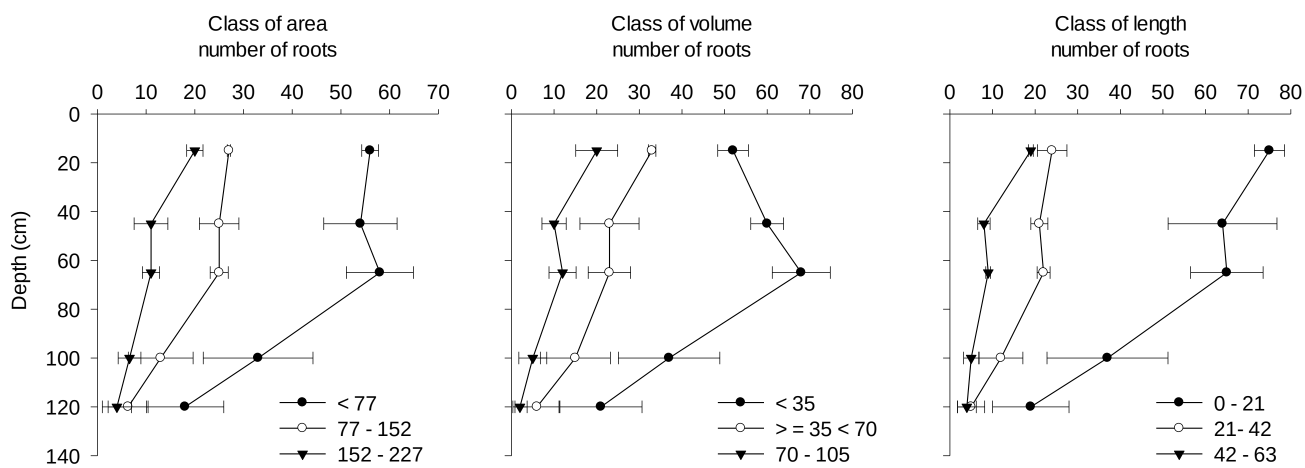

Figure 2. Distribution in classes of the variables: superficial area (mm^2), volume (mm^3) and length (mm) of roots in 6-yrs tillage under conservation system. The Error bars are mean standard error.

Table 6. Mean values of diameter roots class to 3-yrs old coffee stand under soil conservation system.

Depth (m)	Ø ≤ 1	1>Ø < 2	2 > Ø ≤ 3	Ø > 3
0-0.30	$0^{cB(\pm0.3)}$	$74^{aA(\pm3)}$	$55^{aA(\pm6)}$	$34^{bA(\pm10)}$
0.30-0.60	$4^{bB(\pm2)}$	$52^{aA(\pm7)}$	$55^{aA(\pm9)}$	$12^{bB(\pm5)}$
0.60-0.90	$44^{aA(\pm9)}$	$34^{aB(\pm5)}$	$13^{bB(\pm4)}$	$3^{bB(\pm1)}$
0.90-1.20	$20^{aB(\pm11)}$	$40^{aB(\pm2)}$	$14^{aB(\pm3)}$	$3^{aB(\pm0.5)}$
1.20-1.50	$15^{aB(\pm10)}$	$27^{aB(\pm6)}$	$9^{aB(\pm2)}$	$1^{aB(\pm0.3)}$

Means followed by the same capital letter in the column and small letter on the line do not differ by the Scott-Knott test ($p < 0.05$). Ø (mm). Between parenthesis: mean standard error (n=3). Average roots number refers to 0.21 m^2.

In the same study, the authors attributed their results to the higher volume of pores with diameter <2 mm detected by X-ray CT scan. These pores are related to good root system development (Tables 3 and 4). The Pearson's correlation tests showed that the root distribution was associated with the pore distribution of the gibbsitic

Table 7. Mean values of roots diameter class to 6-yrs old coffee stand under soil conservation management system.

Depth (m)	Ø ≤ 1	1> Ø < 2	2 > Ø ≤ 3	Ø > 3
0-0.30	$0^{bA(\pm0.3)}$	$77^{aA(\pm1.5)}$	$52^{aA(\pm5)}$	$26^{bA(\pm5)}$
0.30-0.60	$1^{bA(\pm0.8)}$	$65^{aA(\pm4)}$	$25^{bB(\pm9)}$	$10^{bA(\pm8)}$
0.60-0.90	$19^{bA(\pm18)}$	$54^{aA(\pm11)}$	$28^{bB(\pm10)}$	$8^{bA(\pm5)}$
0.90-1.20	$7^{aA(\pm6)}$	$33^{aB(\pm14)}$	$17^{aB(\pm10)}$	$3^{aA(\pm2)}$
1.20-1.50	$4^{aA(\pm3)}$	$17^{aB(\pm9)}$	$7^{aB(\pm5)}$	$2^{aA(\pm2)}$

Means followed by the same capital letter in the column and small letter on the line do not differ by the Scott-Knott test ($p<0.05$). Ø (mm). Between parenthesis: mean standard error (n=3). Average roots number refers to 0.21 m^2.

Oxisol under the same management system.

The occurrence of dry spells and prolonged drought periods are common in the study area. Thus, the presence of deep fine or absorption roots is positive, since the water content will be almost always available to coffee plants in these layers, as reported by Silva (2012) and Santos et al. (2014), which may minimize the hydric stress and increase yield.

Spatial distribution of coffee root system

In order to simplify the visualization of regions with and without roots, a surface map was made for the root spatial distribution of both stand ages (3- and 6-years old) (Figure 3).

Greater root growth at depth (roots presence detectable at 1.45 m depth) and root concentration in the upper soil layer, with an irregular profile distribution in the profile horizontal direction occurred in the 3-years coffee stand. This result was due to the conservation practices that influenced the increase in organic matter, the fertility building, the erosion control, and boosted the root growth at depth, favored rapid plant establishment during its first years of planting.

The root distribution was relatively uniform in the vertical direction until 0.90 m depth and reached 0.70 m horizontally in the 6-years stand age. Therefore, it had good soil exploration and root growth in both directions, which allows greater water absorption and nutrients uptake. Thus, it is evident that the development of the root system in all the soil profile over the time analyzed for the management practices employed in the area.

It was observed that root system growth stabilization, which was verified by a clear homogeneous occupancy of the area at depth (Figure 4) in the 6-years stand age. The plant evaluated in the 3-years stand age revealed root growth at depth, but lower lateral root branching, differently from the plant in the 6-years stand age, which showed horizontal branching along the profile, up to approximately 0.90 m depth. It should be mentioned that coffee plants are considered physiologically mature at the age of three years; however, their root system completes its development only at the age of 5 to 6 years.

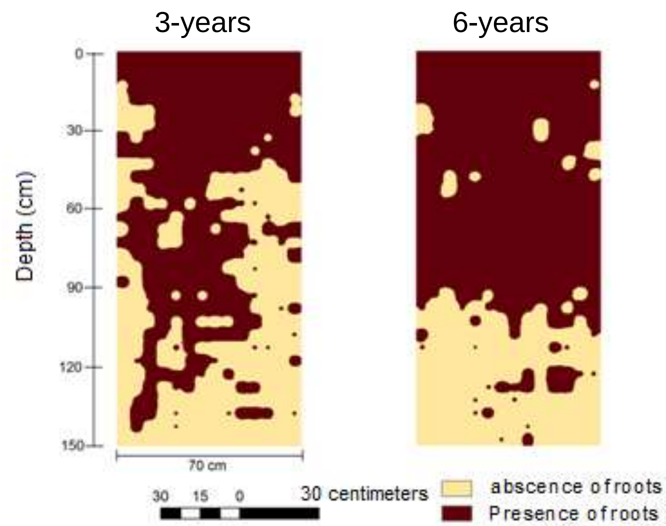

Figure 3. Spatial distribution of roots system in Rhodic Haplustox under 3- and 6-yrs old coffee stand.

In both stand ages, the percentage of the area occupied by roots follows a decreasing trend, according to the soil depth (Figure 4), which is explained by the reduction in the number of intermediate roots 1< Ø < 2 mm; 2 < Ø ≤ 3 mm (Tables 5 and 6), along the soil profile. It was observed that the 3-years coffee stand compared with the 6-years coffee stand presented higher percentage of area occupied by the roots at deeper layers (from 0.90 to 1.20 and 1.20 to 1.50 m), while the 6-years coffee stand presented most of the area occupied by the roots down through the 0.90 m layer.

Ramos et al. (2013), using the same experimental area, verified that even at 0.80 m depth, Ca^{2+} concentration was approximately 2 $mmol_c$ dm^{-3}, which according to Ritchey et al. (1980) is sufficient to normalize root growth and ensure rooting of coffee plants at depth.

Furthermore, the chemical improvement promoted by liming and fertilizers, in addition to the 7 kg m^{-1} of agricultural gypsum applied to the surface associated with the increase of organic residues on the soil surface (Caires et al., 2001) from the grasses grown inter-row

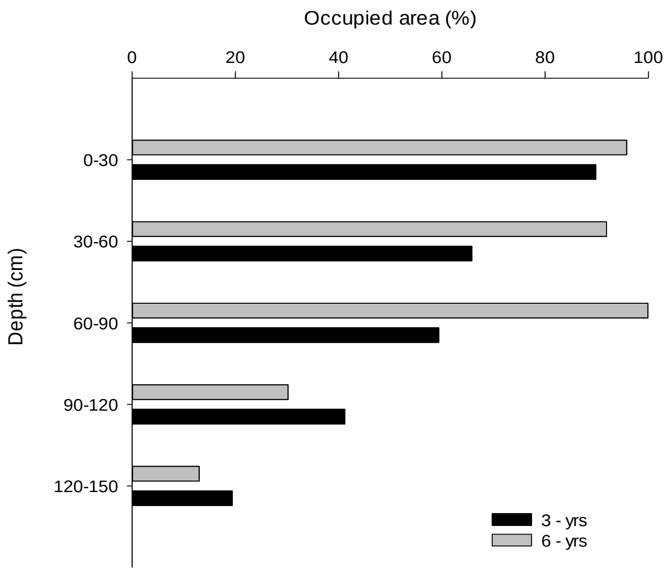

Figure 4. Area occupied by the coffee plant roots along the profile of a Rhodic Haplustox.

(*Brachiaria* species), as well as the coffee itself, should have acted jointly for the construction and maintenance of soil fertility, as well as for the Al^{3+} toxicity reduction, which is primarily responsible for root growth retardation (Carvalho-Pupatto et al., 2003), justifying the uniform growth of the coffee plant roots in the 6-years coffee stand to 0.9 m depth (Figure 4).

Conclusions

Management practices that adopt deep tillage promoted beneficial alteration in the soil pore configuration, which is associated with the use of agricultural inputs, such as gypsum, limestone, together with a balanced fertilization program, and the increase in organic matter, provided the deep root system development of the coffee plants.

During the first years, there was significant amount of inter-aggregate soil pores. However, there was pores reconfiguration with the adoption of management practices over time, which increased the amount of intermediate diameter pores. Coffee plants at the age of three years in the absence of chemical and physical soil limitations had their root system deeper than 1 m. Six years later, there was uniform distribution of roots, both laterally and along the soil profile, reaching up to 0.90 m depth, which evidences the effect of management practices over time on the stabilization of the root network along the gibbsitic Oxisol profile.

Conflict of Interests

The authors have not declared any conflict of interests.

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REFERENCES

Barbosa SM, Oliveira G C, Carducci CE, Silva BM (2014). Potencialidade de uso de zeólitas na atenuação do déficit hídrico em Latossolo do cerrado. Sem: Ciênc. Agric. 35:2357-2368.

Bouma J (1991). Influence of soil macroporosity on environmental quality. Adv. Agron. 46:2-37.

Caires EF, Feldhaus IC, Blum J (2001). Crescimento radicular e nutrição da cevada em função da calagem e aplicação de gesso. Bragantia 60:213–223.

Carducci CE, Oliveira GC, Curi N, Heck R J, Rossoni DF (2014b). Scaling of pores in 3D images of Latosols (Oxisols) with contrasting mineralogy under conservation management system. Soil Res. 52:231-243.

Carducci CE, Oliveira GC, Curi N, Heck RJ, Rossoni DF, Carvalho TS, Costa AL (2015a). Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol. Soil Till. Res. 145:171-180.

Carducci CE, Oliveira GC, Lima JM, Rossoni DF, Souza AL, Oliveira LM (2014a). Distribuição espacial das raízes de cafeeiro e dos poros de dois Latossolos sob manejo conservacionista. R. Bras. Eng. Agríc. Amb. 18:270-278.

Carducci CE, Oliveira GC, Oliveira LM, Barbosa SM, Silva ÉA (2015b). Retenção de água do solo sob sistema conservacionista de manejo com diferentes doses de gesso. Rev. Ciênc. Agrar. 58:284-291.

Carducci CE, Oliveira GC, Severiano EC, Zeviani WM (2011). Modelagem da curva de retenção de água de Latossolos utilizando a equação duplo van Genuchten. R. Bras. Cienc. Solo 35:77-86.

Carducci CE, Oliveira GC, Zeviani WM, Lima VMP, Serafim ME (2013). Bimodal pore distribution on soils under conservation management system for coffee crop. Eng. Agríc. 33:291-302.

Carducci CE, Zinn YL, Rossoni DF, Heckd RJ, Oliveira GC (2016). Visual analysis and X-ray computed tomography for assessing the spatial variability of soil structure in a cultivated Oxisol. Soil Till. Res. 1:12-24.

Carvalho-Pupatto JG, Büll LT, Crusciol CAA, Mauad M, Silva RH (2003). Efeito de escória de alto forno no crescimento radicular e na produtividade de arroz. Pesqui. Agropecu. Bras. 38:1323-1328.

Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) (2013). Centro Nacional de Pesquisas de Solos. Sistema Brasileiro de Classificação de Solos. 3.ed. Rio de Janeiro 353 p.

Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) (2011). Centro Nacional de Pesquisa de Solos. Manual de métodos de análise de solo. 2. ed. revista. Rio de Janeiro 225 p.

Environmental Systems Research Institute (ESRI) (2009). ArcGIS. Professional GIS for the desktop. versão 9.3.1. CA.

Ferreira DF (2011). SISVAR 5.0. Sisvar: a computer statistical analysis system. Cienc. Agrotec. 35:1039-1042.

Ferreira MM, Fernandes B, Curi N (1999). Influência da mineralogia da fração argila nas propriedades físicas de Latossolos da região sudeste do Brasil. R. Bras. Ci. Solo 23:515-524.

Ferreira MM, Marcos ZZ (1983). Estimativa da capacidade de campo de Latossolo Roxo Distrófico e Regossolo através do ponto de inflexão da curva característica de umidade. Ci. Prátic. 7:96-101.

Jesus MAS, Carvalho SP, SOARES AM (2006). Comparação entre sistemas radiculares de mudas de coffea arabica obtidas por estaquia e por sementes. Coffee Sci. 1:14-20.

Jorge LAC, Silva DJCB (2010). SAFIRA: Manual de utilização. São Carlos: Embrapa CPDIA. 29 p.

Lima VMP, Oliveira GC, Serafim ME, Curi N, Evangelista AR (2012). Intervalo hídrico ótimo como indicador de melhoria da qualidade

estrutural de Latossolo degradado. R. Bras. Cienc. Solo 36:71-78.
Motta ACV, Nick JA, Yorinori GT, Serrat BM (2006). Distribuição horizontal e vertical da fertilidade do solo e das raízes de cafeeiro (Coffea arabica L.) cultivar Catuaí. Acta Sci. Agron. 28:455-463.
Nutman FJ (1933a). The root system of C. arabica. Pt. II. The effect of some soil conditions in modifying the normal root-system. Emp. J. Exp. Agric.1:285-296.
Nutman FJ (1934). The root system of C. arabica. Pt. III. The spatial distribution of the absorbing area of the root. Emp. J. Exp. Agric. 2:294-302.
Nutman FJ (1933b). The root system of C. arabica. Pt. I. Root-systems in typical soils of British East Africa. Emp. J. Exp. Agric. 1:271-284.
Oliveira GC, Dias Junior MS, Resck DVS, CURI N (2004). Caracterização química e físico-hídrica de um Latossolo Vermelho após vinte anos de Manejo e cultivo do solo. R. Bras. Cienc. Solo 28:327-336.
Ramos BZ, Toledo JPVF, Lima JM, Serafim ME, Bastos ARR, Guimarães PTG, Coscione, AR (2013). Doses de gesso em cafeeiro: influência nos teores de cálcio, magnésio, potássio e pH na solução de um Latossolo Vermelho distrófico. R. Bras. Cienc. Solo 37:1018-1026.
Rena AB, Guimarães PTG (2000). Sistema radicular do cafeeiro: estrutura, distribuição, atividade e fatores que o influenciam. Belo Horizonte: EPAMIG. 80 p.
Ritchey KD, Souza DMG, Lobato E, Correa O (1980). Calcium leaching to increase rooting depth in a Brazilian Savannah Oxisol. Agron. J. 72:40-44.
Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Cunha TJF, Oliveira JB (2013). Sistema brasileiro de classificação de solos. 3. ed. Embrapa 353 p.
Santos WJR, Silva BM, Oliveira GC, Volpato MML, Lima JM, Curi N, Marques JJ (2014). Soil moisture in the root zone and its relation to plant vigor assessed by remote sensing at management scale. Geoderma 221:91-95.
Serafim ME, Oliveira GC, Curi N, LIMA JM, Guimarães PTG, LIMA VMP (2013b). Potencialidades e limitações de uso de Latossolos e Cambissolos sob sistema conservacionista em lavouras cafeeiras. Biosci. J. 29:1640-1652.
Serafim ME, Oliveira GC, Lima JM, Silva BM, Zeviani WM, Lima VMP (2013c). Disponibilidade hídrica e distinção de ambientes para cultivo de cafeeiros. R. Bras. Eng. Agríc. Amb. 17:362-370.
Serafim ME, Oliveira GC, Oliveira AS, Lima JM, Guimarães TG, Costa JC (2011). Sistema conservacionista e de manejo intensivo do solo no cultivo de cafeeiros na região do alto são francisco, MG: um estudo de caso. Biosci. J. 27:964-977.
Serafim ME, Oliveira GC, Vitorino ACT, Silva, BM, Carducci CE (2013a). Qualidade física e intervalo hídrico ótimo em Latossolo e Cambissolo, cultivados com cafeeiro sob manejo conservacionista do solo. R. Bras. Cienc. Solo 37:733-742.
Severiano EC, Oliveira GC, Dias Junior MDS, Costa KAP, Silva, FG, Ferreira Filho SM (2011a). Structural changes in Latosols of the Cerrado region: I – Relationships between soil physical properties and least limiting. R. Bras. Cienc. Solo 35:773-782.
Severiano EC, Oliveira GC, Dias Junior MS, Costa KAP, Benites VDM, Ferreira Filho SM (2011b). Structural changes in Latosols of the Cerrado region : ii – Soil compressive behavior and modeling of additional compaction. R. Bras. Cienc. Solo 35:783-791.
Silva BM (2012). Dinâmica espaço-temporal da água no solo cultivado com cafeeiro nas condições climáticas do Alto São Francísco – MG. Universidade Federal de Lavras (UFLA).
Silva BM, Silva ÉA, Oliveira GC, Ferreira MM, Serafim ME (2014). Plant-available soil water capacity: Estimation methods and implications. R. Bras. Cienc. Solo 38:464-475.
Silva EA, Oliveira GC, Carducci, CE, Silva BM, Oliveira LM, Costa JC (2013). Increasing doses of agricultural gypsum, aggregate stability and organic carbon in Cerrado Latosol under coffee crop. R. Ciênc. Agrár. 56:25-32.
Tavares Filho J, Ralisch R, Guimarães MF, Medina CC, Balbino LC, Neves CSVJ (1999). Método do perfil cultural para avaliação do estado físico de solos em condições tropicais. R. Bras. Cienc. Solo 23:393-399.
Tormena CA, Silva AP, Libardi PL (1998). Caracterização do intervalo hídrico ótimo de um latossolo roxo sob plantio direto. R. Bras. Cienc. Solo 22:573-581.
Van Raij B (2008). Gesso na agricultura. Instituto Agronômico, Campinas 233 p.