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EFFECT OF IRRIGATION ON ROOT DEVELOPMENT OF COFFEE PLANTS

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1 ABSTRACT

Increasing the development and deepening of the root system in coffee crops ensures higher water and nutrient uptakes as a result of improved soil utilization, ultimately leading to greater crop yields and longevity. The aim of this study was to evaluate the effect of irrigation levels on the root system of drip-irrigated coffee plants in western Bahia State (BA), Brazil. The experiment was carried out on *Café do Rio Branco* farm, located in Barreiras - BA, using adult plants (approximately 3.5 years old) of coffee variety Catuaí Vermelho IAC 144. The experiment was set up as a randomized block design with three treatments corresponding to the irrigation depths of 75, 100 and 150% as determined using Irriplus software. After the fourth harvest, the coffee root system was assessed to determine root length density (RLD) and root weight density (RWD) in different sampled layers. A greater concentration of roots (RLD and RWD) was observed in the surface layer (0-20 cm) and under the lateral line (at 30 and 70 cm from the orthotropic branch). The irrigation depth of 75% provided the highest concentration of roots (RLD and RWD) in the 0-10 cm layer.

Keywords: Drip irrigation, *Coffea arabica* L, root system.

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EFEITO DA IRRIGAÇÃO NO DESENVOLVIMENTO RADICULAR DO CAFEEIRO

2 RESUMO

Um maior desenvolvimento e aprofundamento do sistema radicular garante ao cafezal um aumento da absorção de água e nutrientes devido a maior exploração do solo, com isto maior produtividade e longevidade da lavoura. O objetivo deste trabalho foi avaliar os efeitos de

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diferentes lâminas de irrigação sobre o sistema radicular do cafeeiro irrigado por gotejamento na região Oeste da Bahia. Realizou-se o trabalho na fazenda Café do Rio Branco, localizada em Barreiras - BA em cafeeiros adultos, aproximadamente 3,5 anos de idade, da variedade Catuaí Vermelho IAC 144. O experimento ocorreu no delineamento em blocos casualizados, composto de 3 tratamentos, correspondentes à 75, 100 e 150% da lâmina de irrigação determinada pelo software Irriplus. Após a quarta safra, procedeu-se às avaliações do sistema radicular do cafeeiro, onde foi determinada a densidade de comprimento radicular - DCR e a densidade radicular – DR em diferentes camadas amostradas. Observou-se maior concentração de raízes, DCR e DR, na camada superficial (0-20 cm) e sob a linha lateral (30 e 70 cm de distância do ramo ortotrópico). A lâmina de irrigação correspondente a 75% proporcionou maior concentração de raízes (DCR e DR) na camada de 0 a 10 cm.

Palavras - chaves: Irrigação localizada, *Coffea arábica* L, sistema radicular

3 INTRODUCTION

Brazil is the largest coffee growing country in the world, representing, in 2017, around 29,09% of the global production (FAOSTAT, 2019). According to data from the National Supply Company (BRASIL, 2019), coffee plantations under production in Brazil currently occupy 2.15 million hectares, and in 2018 they generated 61.6 million bags of processed coffee, 77.01% of which originated from the species *Coffea arabica* L.

Water determines the success of coffee farming, since it influences the phenology of the plant and, consequently, its productivity, product quality and commercial viability (SILVA et al., 2019). The root system of the coffee varies depending on species, genotype, plant age, season, crop density, biotic stresses, texture, and soil structure (PARTELLI et al., 2014; RONCHI et al., 2015)

Although the root system of coffee has its development characteristics linked primarily to the plant genetics, other factors can also modify its spatial distribution; e.g., amount of water present in the soil (BARRETO et al., 2006) and nutrient availability to plants (VICENTE et al., 2017). The water availability provided by irrigation can influence the primary and secondary development of the root system in the various soil layers (SOUZA et al., 2018).

Drip irrigation is becoming a common technique to improve coffee growing as it provides a more controlled of the production environment and prevents production losses stemming from water deficiencies (SAKAI et al., 2015).

The objective of this study is to examine the effects of drip irrigation on the root system development of coffee plants in the environmental conditions of west Bahia State, Brazil.

4 MATERIAL AND METHODS

4.1 Experimental field

The trial was developed on *Café do Rio Branco* farm, in Barreiras - BA, Brazil (11°48’ S, 45°35’ W, 735 m altitude), from November 2004 to May 2008, using adult plants (approximately 3.5 years old) of coffee variety Catuaí Vermelho IAC 144.

The soils were classified as “sandy clay loam” (0-40 cm) and “sandy clay” (40-60 cm) types (Table 1).

Table 1. Physical and water-related properties of soil in the experimental areas in Barreiras - BA, Brazil. 2004/2008.

Depth (cm)	**0-20**	**20-40**	**40-60**
FC* (m^3 m^{-3})	0.265	0.260	0.283
PWP** (m^3 m^{-3})^2	0.175	0.179	0.174
Clay	32	34	40
Silt	2	3	3
Sand	66	63	57
Classification	Sandy clay loam	Sandy clay loam	Sandy clay

* Soil field capacity and ** Permanent wilting point. Textural classification according to the Brazilian Soil Science Society (LEMOS; SANTOS, 1996).

4.2 Irrigation management and climate

A watering frequency of two to three days was adopted in the management of the irrigation depth, with the water requirement calculated based on the estimate of the crop evapotranspiration (ET_c), thus forming the treatments. The water requirement of the coffee plant was determined using the fitting coefficients relative to the reference evapotranspiration (ET_o). The net irrigation depth was calculated based on the water balance, considering the water input from irrigation and its output.

Evapotranspiration in the crop was estimated using the following Equations 1 and 2 (ALLEN et al., 2006; ALLEN; PEREIRA, 2009).

$$ET_c = ET_o \, x \, K_c \qquad (1)$$

$$K_c = (K_{cb} x K_s) + K_e \qquad (2)$$

Where, ET_c is crop evapotranspiration (mm d^{-1}); ET_o is reference evapotranspiration (mm d^{-1}); K_c = crop coefficient; K_{cb} = basal crop coefficient; K_e = soil evaporation coefficient; K_s = stress coefficient.

The K_c values of coffee are influenced by characteristics of the crop developmental stage and general soil-climatic conditions. A K_{cb} value of 0.9 was adopted for the calculations (ALLEN et al., 2006).

The irrigation frequency and the total amount of water (irrigation + precipitation) varied across the treatments (Table 2).

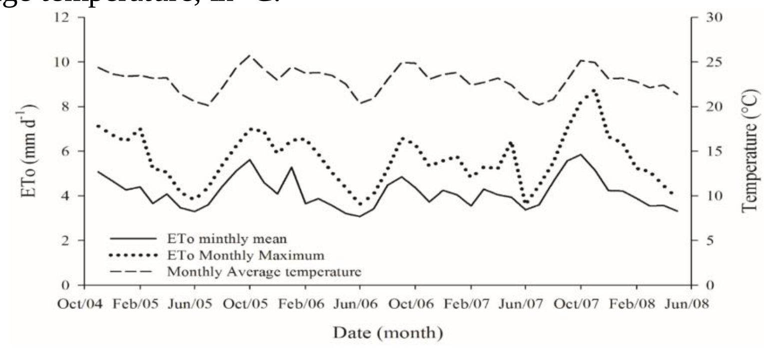
Table 2. Rainfall and applied irrigation during the seasons from 2004 to 2008.

Season	Irrigation (% ETc)	Rainfall (mm)	Irrigation (mm)	Rainfall and irrigation (mm)
	75	320.8	100.9 (24)[a]	421.7
2004	100	320.8	134.5 (24)	455.3
	150	320.8	201.8 (24)	522.6
	75	1074.7	811.7 (236)	1886.4
2005	100	1074.7	1082.6 (236)	2157.3
	150	1074.7	1623.8 (236)	2698.5
	75	1210.3	483.4 (180)	1693.7
2006	100	1210.3	645.1 (180)	1855.4
	150	1210.3	967.7 (180)	2178
	75	587.8	688.8 (209)	1276.6
2007	100	587.8	918.9 (209)	1506.7
	150	587.8	1378.4 (209)	1966.2
	75	521.9	184.1 (67)	706.0
2008	100	521.9	246.6 (67)	768.5
	150	521.9	369.9 (67)	891.8

[a] Values in parentheses are the number of irrigation events.

Reference evapotranspiration (monthly mean and maximum) and monthly average temperatures recorded between November 2004 and May 2008 are presented in Figure 1. In this period, the accumulated ETo was 5,444 mm (average 4.20 mm d^{-1} and 1,485 mm $year^{-1}$). The highest average ETo occurred in October 2007 (5.85 mm d^{-1}), while in November 2007 the maximum daily ETo was 8.76 mm. The average temperature in the studied period was 22.9 ºC, with the highest monthly average (25.7 ºC) occurring in October 2005.

Figure 1. Reference evapotranspiration (monthly mean and maximum), in mm d^{-1}, and monthly average temperature, in ºC.



The total irrigation depths applied during the analyzed period (November 2004 to May 2008) were 2,271; 3,028 and 4,541 mm for respective treatments of 75, 100, and 150%. The average irrigation depth of the four harvests, corresponding to treatment 100%, was 826 mm $year^{-1}$.

Accumulated precipitation in this period was 3,715. Although the precipitation rate in the region is higher than 1,000 mm, the concentration of rainfall in the months from October-November to March-April, coupled with the sandy soils, make it impossible to grow coffee in rainfed regions.

4.3 Description of treatments

The experiment was carried out with adult coffee plants spaced 3.80 × 0.5 m apart (5,263 plants ha^{-1}). It was set up as a randomized block design with three replicates where the plots consisted of 20 plants, with the 10 central plants considered usable.

Table 3 describes the treatments corresponding to the irrigation depths and also information on the emitters used.

Table 3. Percentage of irrigation depths, flow, distance between emitters, manufacturer and model of emitters used in the drip-irrigation experiment.

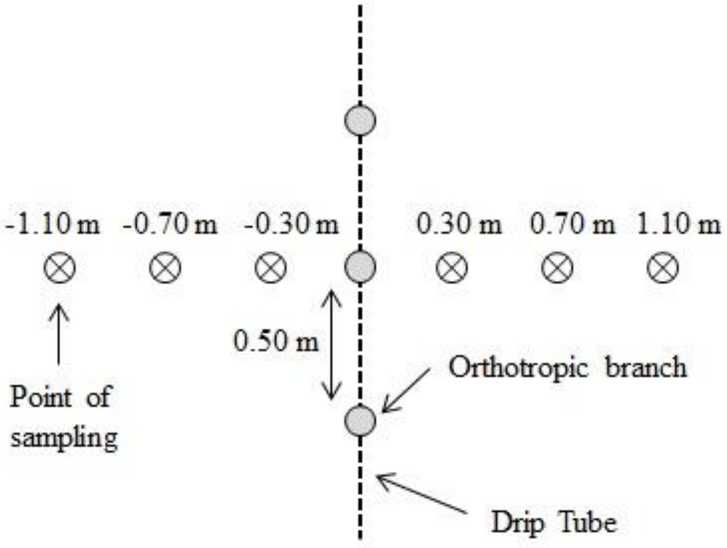
Treatment	Irrigation depth (%)	Flow ($L\ h^{-1}$)	Space between emitters (m)	Manufacturer	Model
1	75	1.35	0.60	Plastro	Hydro PC
2	100	2.20	0.75	Rain Bird	Drip Line
3	150	2.20	0.50	Plastro	Super Tif

The irrigation management was based on Treatment 2 of this experiment; i.e., the depth corresponding to 100%. Christiansen's uniformity coefficient of the irrigation system was 93.9%.

4.4 Analysis of the coffee root system

For the sampling of the root system, a tube auger (Fig. 2) 72 mm wide × 1.30 m long was used (QUANQI et al., 2010; GUAN et al., 2015). Sampling points were established at 0.30, 0.70, and 1.10 m from the main orthotropic branch, from both sides of the plant and perpendicularly to the planting row (Figure 2). Samples were harvested from the 0-0.10, 0.10-0.20, 0.30-0.40, 0.50-0.60, 0.70-0.80, and 0.90-1.00-m layers, from one plant in each plot of the treatments, in three replicates. Sampling took place in October 2008; i.e., 43 months after the treatments were applied.

Figure 2. Sampling positions in relation to the planting row and the lateral line (drip tube) for the evaluation of the coffee root system.



Upon being removed, samples of soil and root were placed on a 2-mm sieve where the two materials were separated with the aid of water jets.

Roots were then preserved in a 50% alcohol solution and classified according to their diameter into coarse (> 3 mm), medium or absorbing-root supporter (1 to 3 mm), and fine or absorbing (< 1 mm) (RENA; DAMATTA, 2002). Afterwards, roots were placed on transparency sheets for the processing of the images obtained from a scanner into JPG files with a 300-dpi resolution, and processed to obtain the root length and diameter in Quaantroot software.

Subsequently, the dry matter was determined on an analytical scale after the material was dried in an oven at 60 ºC for sufficient time to obtain a constant root mass.

Root length density was determined using the Equation 3.

$$RLD = \frac{L_R}{V_A} \quad (3)$$

Where, RLD is root length density (cm cm^{-3}); L_R is total root length in the sample (cm); V_A is total volume of the soil sample (cm^{-3}).

Root weight density was calculated using the Equation 4.

$$RWD = \frac{M_R}{V_R} \quad (4)$$

Where: RWD is root weight density (g cm^{-3}); M_R is root dry matter (g); V_R is total volume of the soil sample (dm^{-3})

Root density isolines were developed in the SigmaPlot 11.0. computer program, using the experimental mean.

4.5 Statistical analyses

In the analysis of the root length density (RLD) and root weight density (RWD) data, a split-plot arrangement was adopted in which the irrigation depths constituted the treatments in the plot and sampling depth and distance were the sub-plot treatments.

In the analysis of variance, the F test was applied at the 5% probability level. Means were compared by Tukey's test at the 5% probability level. R statistical software was used for statistical analyses.

5 RESULTS AND DISCUSSION

No separate effect of irrigation depths ($p<0.05$) was observed on RLD or RWD for either fine/absorbing roots or medium/supporting roots. Although the coffee plants has the capacity to lengthen its root system under conditions of water restriction (CARDUCCI et al., 2014; SILVA et al., 2016), the irrigation depth of 75% was not sufficient to provide the greatest development of the root system. The soil aeration is an important parameter for the development of the root system (CARDUCCI et al., 2015). However, excess water, the irrigation depth of 150%, was also not sufficient to cause soil aeration problems (sandy soil) to cause reduction in root development.

A separate effect of sampling distance was detected on RLD and RWD for both root classes, as can be seen by the means in Table 4. A higher concentration of roots was observed at the distances of 30 and 70 cm under the drip tube; i.e., in the wet and fertigated zone. As observed by Barreto et al. (2006), where there was a tendency to maintain root volume in the region close to the emitters. These findings are similar to those observed in six-year-old coffee crops, where a larger root volume was present on the side where fertilizer is commonly applied (RENA; DAMATTA, 2002).

The greater development of the root system under the drip tube was possibly due to the maintenance of soil moisture near the wet bulb (SOUZA et al., 2018) and by fertigation (PARTELLI et al., 2014; RONCHI et al., 2015) and higher accumulation of nutrients (RAMOS et al., 2013).

Table 4. Root length density (RLD) and root weight density (RWD) of fine and medium roots for the sampled distances.

Distance (cm)	RLD (cm cm^{-3})	Distance (cm)	RWD (g dm^{-3})
Fine roots			
70	4.18 A	70	0.83 A
30	3.44 AB	30	0.80 A
–70	2.71 B	–70	0.55 B
–30	2.55 B	–30	0.50 B
110	0.99 C	110	0.22 C
–110	0.60 C	–110	0.17 C
Medium roots			
30	0.0737 A	30	0.2778 A
70	0.0699 AB	70	0.2678 A
–70	0.0435 BC	–30	0.2076 A
–30	0.0417 BC	–70	0.0913 B
110	0.0219 C	110	0.0625 B
–110	0.0192 C	–110	0.0375 B

Means followed by common letters for RLD and RWD within the root classes do not differ at the 5% probability level by Tukey's test.

A separate effect of sampled layer ($p<0.05$) was also detected on RLD and RWD for fine and medium roots (Table 5). As expected, the surface layers (0-10 and 10-20 cm) contained the greatest concentrations of roots (RLD and RWD) for both root classes.

The roots up to 20 cm depth are the main responsible for the water absorption in the coffee tree, according to the classic definition of absorbent roots with diameter less than 1.0 mm (RENA; DAMATTA, 2002).

Table 5. Root length density (RLD) and root weight density (RWD) of fine and medium roots for the sampled layers.

Layer (cm)	RLD (cm cm^{-3})	Distance (cm)	RWD (g dm^{-3})
Fine roots			
0-10	8.81 A	10	1.80 A
10-20	2.69 B	20	0.57 B
30-40	0.86 C	40	0.23 C
50-60	0.82 C	60	0.20 C
90-100	0.64 C	100	0.15 C
70-80	0.63 C	80	0.14 C
Medium roots			
0-10	0.1030 A	10	0.3717 A
10-20	0.0508 B	20	0.2115 B
30-40	0.0347 B	40	0.1191 BC
50-60	0.0329 B	60	0.1005 BC
90-100	0.0243 B	100	0.0895 BC
70-80	0.0242 B	80	0.0520 C

Means followed by common letters for RLD and RWD within the root classes do not differ at the 5% probability level by Tukey's test.

Values of the orders of 7.1 and 10.4 cm cm^{-3} have been reported for the 0-20-cm layer in seed- and cutting-propagated coffee plants variety Conilon under different doses of potassium and nitrogen in fertigation, respectively (PARTELLI et al., 2006; VICENTE et al., 2017). The authors also observed this reduction of root density with depth.

In other studies, percentages higher than 55% of roots were found in the 0-20-cm soil layer, when root length was assessed (MOTTA et al., 2006; PARTELLI et al., 2014; COVRE et al., 2015).

Approximately 80% of the active absorbing roots in Arabica coffee were found within the depth of 20 cm (VICENTE et al., 2017). Several authors observed a higher concentration of coffee roots in the uppermost layers (COVRE et al., 2015; VICENTE et al., 2017; DARDENGO et al. 2018).

A proposition to justify this root up to 20 cm depth is the characteristic of the drip irrigation system, since it is characterized by the irrigation of a fraction of the cultivated area, under high frequency and low volume, which maintains the soil of the zone close to the maximum water retention capacity (field capacity), associated with the practice of fertigation.

A significant interaction effect ($p<0.05$) between distance and sampled layer was detected on RLD and RWD. Tables 6 and 7 contain the mean values of RLD (Table 8) and RWD (Table 8) for the different sampled distances and layers.

Table 6. Root length density (cm cm^{-3}) of fine and medium roots for the sampled distances and layers

Layer (cm)	Distance (cm)					
	–110	–70	–30	30	70	110
Fine roots						
0-10	1.46 D a	11.37 BC a	9.13 C a	12.51 BC a	15.36 A a	3.08 D ab
10-20	0.79 C a	1.96 C b	2.16 BC b	4.35 ABC b	6.08 AB b	0.85 C ab
30-40	0.33 A a	0.81 A b	1.14 A b	0.9 A c	1.35 A c	0.67 A b
50-60	0.39 A a	0.69 A b	0.99 A b	1.12 A c	1.24 A c	0.47 A b
70-80	0.44 A a	0.55 A b	0.7 A b	1.18 A c	0.49 A c	0.46 A b
90-100	0.24 A a	0.89 A b	1.18 A b	0.6 A c	0.59 A c	0.41 A b
Medium roots						
0-10	0.04 B a	0.1 AB ab	0.12 AB ab	0.16 AB ab	0.17 AB a	0.03 B a
10-20	0.04 A a	0.05 A ab	0.03 A b	0.08 A b	0.08 A b	0.03 A a
30-40	0.01 B a	0.01 B b	0.02 AB b	0.09 AB ab	0.06 AB b	0.03 AB a
50-60	0.00 A a	0.01 A b	0.05 A ab	0.06 A b	0.04 A b	0.03 A a
70-80	0.01 A a	0.05 A ab	0.03 A b	0.02 A b	0.03 A b	0.00 A a
90-100	0.01 A a	0.04 A ab	0.01 A b	0.03 A b	0.04 A b	0.01 A a

Means followed by common uppercase (row) and lowercase (column) letters within the same root class do not differ at the 5% probability level by Tukey's test.

Table 7. Root weight density (g dm^{-3}) of fine and medium roots for the sampled distances and layers

Layer (cm)	Distance (cm)					
	–110	–70	–30	30	70	110
Fine roots						
0-10	0.52 C a	2.02 B a	1.82 B a	2.74 A a	3.07 A a	0.61 C a
10-20	0.19 C a	0.36 C b	0.55 BC b	1.13 AB b	1.01 ABC b	0.19 C a
30-40	0.11 A a	0.16 A b	0.31 A b	0.33 A c	0.32 A c	0.16 A a
50-60	0.09 A a	0.16 A b	0.26 A b	0.23 A c	0.33 A c	0.13 A a
70-80	0.08 A a	0.12 A b	0.15 A b	0.26 A c	0.11 A c	0.12 A a
90-100	0.06 A a	0.17 A b	0.24 A b	0.13 A c	0.14 A c	0.14 A a
Medium roots						
0-10	0.05 B a	0.19 B a	0.54 A ab	0.81 A a	0.56 A ab	0.08 B a
10-20	0.10 A a	0.15 A a	0.29 A ab	0.33 A b	0.32 A ab	0.08 A a
30-40	0.02 A a	0.03 A a	0.13 A b	0.20 A b	0.30 A ab	0.04 A a
50-60	0.00 A a	0.04 A a	0.15 A b	0.14 A b	0.20 A b	0.08 A a
70-80	0.03 A a	0.04 A a	0.07 A b	0.06 A b	0.1 A b	0.02 A a
90-100	0.02 A a	0.11 A a	0.06 A b	0.13 A b	0.14 A b	0.08 A a

Means followed by common uppercase (row) and lowercase (column) letters within the same root class do not differ at the 5% probability level by Tukey's test.

By analyzing the values described in Tables 6 and 7 along with Tables 4 and 5, a higher concentration of roots is confirmed in the surface layers and in the areas near the drip tubes.

Tables 8 and 9 contain the mean RLD (Table 8) and RWD (Table 9) according to the irrigation depths and sampled layers. A significant interaction effect ($p<0.05$) between treatments (irrigation depth) and sampled layer was observed on both variables.

Table 8. Root length density (cm cm^{-3}) of fine roots in the sampled layers as a function of irrigation depths

Layer (cm)	Irrigation depth (%)		
	75	100	150
0-10	10.73 A a	8.39 B a	7.34 B a
10-20	2.61 A b	2.91 A b	2.58 A b
30-40	0.95 A c	0.92 A c	0.74 A c
50-60	0.80 A c	0.80 A c	0.85 A c
70-80	0.69 A c	0.44 A c	0.78 A c
90-100	0.85 A c	0.52 A c	0.57 A c

Means followed by common uppercase (row) and lowercase (column) letters do not differ at the 5% probability level by Tukey's test.

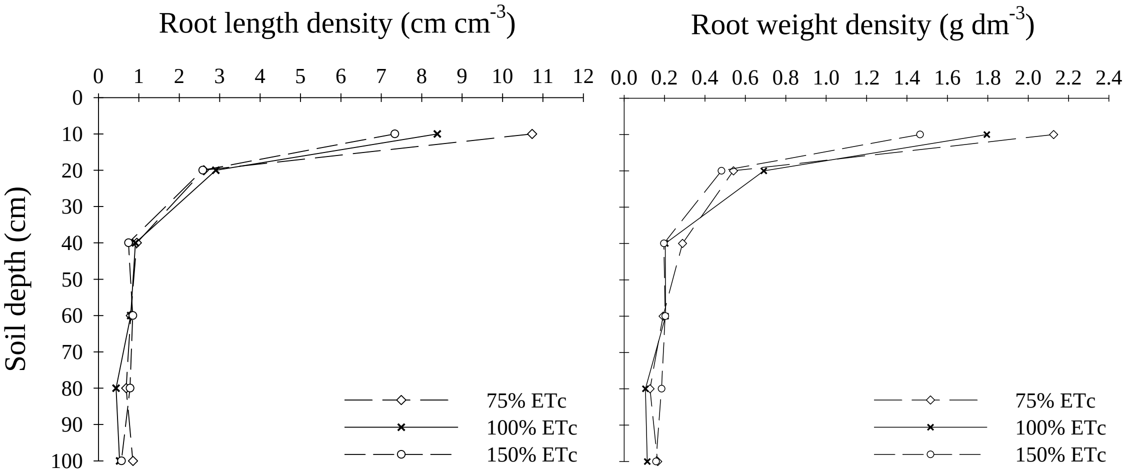
Table 9. Root weight density (g dm^{-3}) of fine roots in the sampled layers as a function of irrigation depths

Layer (cm)	Irrigation depth (%)		
	75	100	150
0-10	2.13 A a	1.80 B a	1.46 C a
10-20	0.54 A bc	0.69 A b	0.48 A b
30-40	0.29 A bc	0.20 A c	0.20 A b
50-60	0.19 A bc	0.21 A c	0.20 A b
70-80	0.13 A c	0.11 A c	0.19 A b
90-100	0.17 A c	0.11 A c	0.16 A b

Means followed by common uppercase (row) and lowercase (column) letters do not differ at the 5% probability level by Tukey's test.

As described in Tables 8 and 9 and also depicted in Figure 3, the treatments with the lowest irrigation depths led to the largest concentrations ($p<0.05$) of roots (RLD and RWD) in the 0-10-cm layer. These results indicate that plants receiving less water had to generate more roots to offset the water deficit.

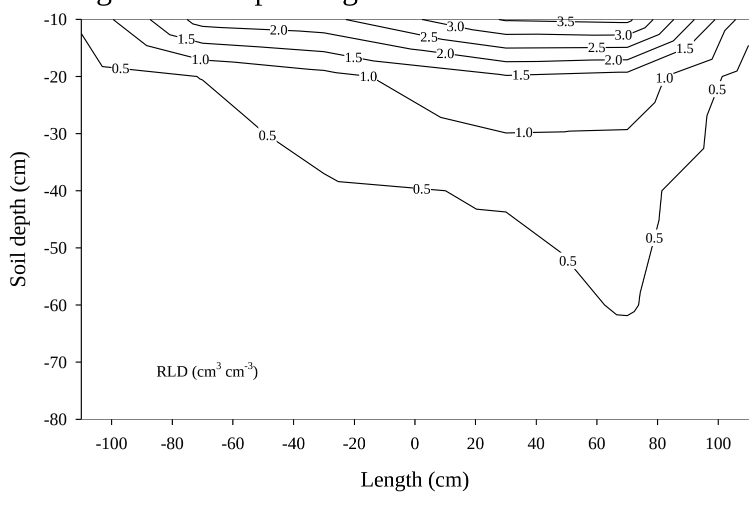
Figure 3. Root length density (cm cm^{-3}) and root weight density (g cm^{-3}) of fine roots in the sampled layers as a function of irrigation depths.



In adequate conditions of water supply, root growth in coffee is usually lower than under moderate water stress. Under stress, the plant produces more abscisic acid, lessening the effect of ethylene, an inhibitor of root length growth (RENA; GUIMARÃES, 2000). Furthermore, high wet-bulb water contents should interfere with aeration, which is an important factor for root respiration. According to those authors, excess water hinders the passage of ethylene through the soil pores; as a result, it concentrates at sufficient levels to slow root development.

Figure 4 illustrates the density distribution of root length (RLD) in the direction orthogonal to the planting row. A greater expansion of the root system was observed both in terms of distance and depth under the drip tube, which can be confirmed by the RLD values. However, the figure also indicates excellent root expansion of the coffee plant up to a distance of –50 cm on the side without the drip tube.

Figure 4. Density distribution of root length (cm cm^{-3}; fine roots) of coffee plants in the direction orthogonal to the planting row.



The root distribution results as a function of drip irrigation presented here reinforce the recommendation of fertigation as an appropriate alternative for fertilizer application to the soil, since a larger number of roots will receive the nutrients in a short time span, improving their uptake.

6 CONCLUSION

There is a greater concentration in the root layer (0-20 cm) under the drip line.

The reduction in the irrigation depth gives a higher root concentration in the 0-10 cm layer, making the plants that receive less water produce more roots to compensate the water deficit.

The largest root length is observed in the soil surface depth range, decreasing as the depth increased.

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