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Root distribution of cactus pear genotypes under different soil water replacement levels[1]

Distribuição radicular de genótipos de palma forrageira sob percentagens de reposição de água no solo

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HIGHLIGHTS:

Very fine root length density increases as soil water replacement levels rise and decreases at greater distance from the base of the plant.
Fine, small and medium-diameter roots are more concentrated near the plant base at a soil water replacement level of 75% of ET_0.
In general, the Miuda genotype shows better root distribution and Gigante a higher root length density.

ABSTRACT: Knowledge of the cactus pear root distribution system can improve management of the plant by defining the areas of soil best suited to fertilizer application and the installation of soil moisture sensors under irrigation. Thus, the aim of the present study was to assess the root distribution of cactus pear genotypes under different water replacement levels. To that end, a field experiment was conducted in a randomized block design, using genetic material from two cactus pear genotypes (*Opuntia fícus-indica* Mill. and *Nopalea cochenillifera* Salm-Dyck) and six water replacement levels based on reference evapotranspiration - ET_0 (T_1, no irrigation; T_2, 15%; T_3, 30%; T_4, 45%; T_5, 60% and T_6, 75% of ET_0), arranged in split-plot, with irrigation treatments allocated to the plots and the genetic material to the sub-plots, and three replicates. The roots of the cultivars were collected for analysis of root length density (RLD) 390 days after planting. The RDL of very fine roots declines as depth and distance from the plant base increases and total, fine, small and medium RDL rise at higher water replacement levels; 75% of ET_0 near the plant base increases RDL; all the root diameter classes are concentrated at a distance of 0-0.20 m from the plant base and depth of 0.10 to 0.25 m; the RDL percentage is higher for the Gigante genotype and Miuda exhibits better root distribution.

Key words: *Opuntia fícus-indica* Mill., *Nopalea cochenillifera* Salm-Dyck., roots, water regime

RESUMO: Com o conhecimento da distribuição do sistema radicular da palma forrageira é possível aprimorar o seu manejo, já que podem ser definidas áreas do solo mais propícias para a aplicação de fertilizantes e a instalação de sensores de umidade do solo em condição irrigada. Assim, objetivou-se avaliar a distribuição radicular de genótipos de palma forrageira sob percentagens de reposição de água no solo. Para isso, desenvolveu-se experimento de campo envolvendo dois materiais genéticos de palma forrageira (Gigante - *Opuntia fícus-indica* Mill. e Miúda - *Nopalea cochenillifera* Salm-Dyck) e seis percentagens de reposição de água no solo, com base na evapotranspiração de referência - ET_0 (T_1, sem irrigação; T_2, 15%; T_3, 30%; T_4, 45%; T_5, 60% e T_6, 75% da ET_0), dispostos no esquema de parcelas subdivididas, ficando os tratamentos de irrigação nas parcelas e os materiais genéticos nas subparcelas, no delineamento em blocos casualizados, com três repetições. Aos 390 dias após o plantio deu-se início à coleta de raízes das cultivares para análise da densidade de comprimento de raízes (DCR). Constatou-se que a DCR muito fina diminui com o aumento da distância da base da planta e profundidade e a DCR total, fina, pequena e média aumentam com maiores reposições de irrigação; 75% da ET_0 próximo à base da planta incrementa a DCR; todas as classes de raízes se concentram entre 0-0,20 m de distância e 0,10 a 0,25 m de profundidade, e a percentagem da DCR é maior no genótipo Gigante e o genótipo Miúda apresenta melhor distribuição.

Palavras-chave: *Opuntia fícus-indica* Mill., *Nopalea cochenillifera* Salm-Dyck., raízes, regime hídrico

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Introduction

The Brazilian semiarid region limits large-scale agricultural production due to the irregular spatiotemporal distribution of rainfall, with average annual rainfall below 800 mm and high evapotranspiration rates, which vary between 5.5 and 7.5 mm per day (Santos et al., 2017a). Under these conditions, the cactus pear is a viable option for agricultural production in the region (Pinheiro et al., 2014; Silva et al., 2015).

However, most of the cactus pears in the region are grown with few formal agricultural practices, preventing them from reaching their production potential (Silva et al., 2012; Donato et al., 2014; Leite et al., 2014). This is due to lack of knowledge and consolidated research on management practices, particularly regarding irrigation conditions in relation to the root system of the plant.

Interaction between genetic factors and soil characteristics plays a vital role in the root distribution pattern of crops (Sant'ana et al., 2012; Santos et al., 2014; Segura et al., 2015). Knowledge of the root distribution system is important in sustainable irrigation management, since nutrients and water are not evenly distributed in the soil.

Knowing the effective depth of the root system is not sufficient to make inferences on their water absorption area (Coelho et al., 2005). As such, information on root length density (RLD) is important because it plays a decisive role in water and nutrient uptake, and is a good indicator of the impact of crop practices on root development in the soil (Hassan et al., 2019).

In light of the above, the aim of the present study was to assess the root distribution of cactus pear genotypes under different soil water replacement percentages.

Material and Methods

The experiment was conducted on a rural property in the Pitarana district of the municipality of Montalvânia, located in the semiarid region of Minas Gerais state, Brazil (14° 19' 21.73" S and 44° 28' 39.45" W, 492 m a.s.l.), between September 2017 and November 2018. Climate in the region is classified as Aw according to Köppen's classification system (Alvares et al., 2013).

Soil in the study area is classified as Oxisol and the land was previously cultivated with forage, followed by bean, corn and watermelon, after which it remained fallow for six years. Before the experiment, soil samples were collected at depths of 0-0.2 m and 0.2-0.4 m for hydro-physical characterization with a water retention curve at potentials of 6, 10, 33, 100, 500 and 1500 kPa, and chemical characterization, according to the methodology of Teixeira et al. (2017) (Table 1).

The field experiment was conducted in September 2017, with six water replacement levels, based on reference evapotranspiration (ET_0) (T_1, no irrigation (0%); T_2, 15%; T_3, 30%; T_4, 45%; T_5, 60% and T_6, 75% of ET_0), and two cactus pear genotypes ('Gigante' - *Opuntia fícus-indica* Mill. and 'Miuda' - *Nopalea cochenillifera* Salm-Dyck). Planting was performed with 50% of the cladode buried in the soil, in a split-plot arrangement, with irrigation treatments in the plots and genotypes in the subplots, and three replicates. Each experimental unit consisted of 3.25-meter-long double rows, with plants spaced 0.25 m apart, 0.5 m between individual rows and 1.5 m between double rows, totaling 26 plants, with the seven center plants considered the study area. The total area was 234 m^2 and study area 126 m^2, with a population density of 40,000 plants ha^{-1}.

Before the experiment, the soil was prepared by plowing and harrowing, and a hoe was used to open 0.20 m-deep furrows for placement of the cladodes. Based on soil chemical analysis, organic fertilizer was used at planting, with 20 t ha^{-1} of sheep manure, as well as chemical fertilization with 75 kg ha^{-1} of N, 100 kg ha^{-1} of P_2O_5 and 75 kg ha^{-1} of K_2O, with P supplied via 4-30-10 formulation and N and K_2O using urea and KCl, respectively, according to Donato et al. (2017). Crop treatments were applied throughout the experiment, including manual weeding for weed control.

The crop remained unirrigated until 60 days after planting (DAP), when treatment application began, with weekly irrigation using depths based on ET_0, in accordance with the Hargreaves-Samani equation (1985), with modifications (Allen et al., 2006). Maximum and minimum temperature, relative air humidity and rainfall (Figures 1A and B) were obtained from a weather station 6 m from the experimental area. The ET_0 data were recorded daily and the values obtained over seven days were added to calculate irrigation time for that week, in accordance with Mantovani et al. (2009).

The water used in the experiment was obtained from the Carinhanha River, with electrical conductivity (ECw) of 0.03 dS m^{-1}. Drip irrigation was performed via 13 mm-diameter lateral lines of linear low-density polyethylene (LLDPE) tubing equipped with self-compensating on-line drippers (50 to 400 kPa of pressure) spaced 0.40 m apart with flow rates of

Table 1. Hydro-physical and chemical characterization of soil in the experimental area

Hydro-physical characteristics						
Depth (m)	Texture ($dag\ kg^{-1}$) Sand	Silt	Clay	Retention curve*	R^2	ρ_s ($g\ cm^{-3}$)
0-0.2	13	36	51	$\theta = 0.2255 + \frac{(0.5850 - 0.2255)}{[1 + (0.1056 * \tau)^{1.6220}]^{0.3835}}$	0.99	1.36
0.2-0.4	-	-	-	$\theta = 0.2534 + \frac{(0.5950 - 0.2534)}{[1 + (0.0813 * \tau)^{1.7832}]^{0.4392}}$	0.99	1.40

Chemical characteristics (Proof 0-0.20 m)													
pH[1]	MO[2] ($dag\ kg^{-1}$)	P[3] ($mg\ dm^{-3}$)	K[3]	Na[3] ($cmol_c\ dm^{-3}$)	Mg[4]	Al[4]	H + Al[5]	B[6] ($mg\ dm^{-3}$)	Cu[3]	Fe[3]	Mn[3]	Zn[3]	S[7]
6.3	2.4	9.1	362	0.2	1.7	0.0	1.6	0.3	2.4	20.9	61.7	5.3	0.0

[1]pH in water; [2]Colorimetry; [3]Extractor: Mehlich-1; [4]Extractor: KCl 1 mol L^{-1}; [5]pH SMP; [6]Extractor: $BaCl_2$; 7Extractor: $Ca(H_2PO_4)^2$ 500 mg L^{-1} of P in HOAc 2 mol L^{-1}; θ - Volumetric water content ($cm^3\ cm^{-3}$); τ - Matric potential (-kPa)

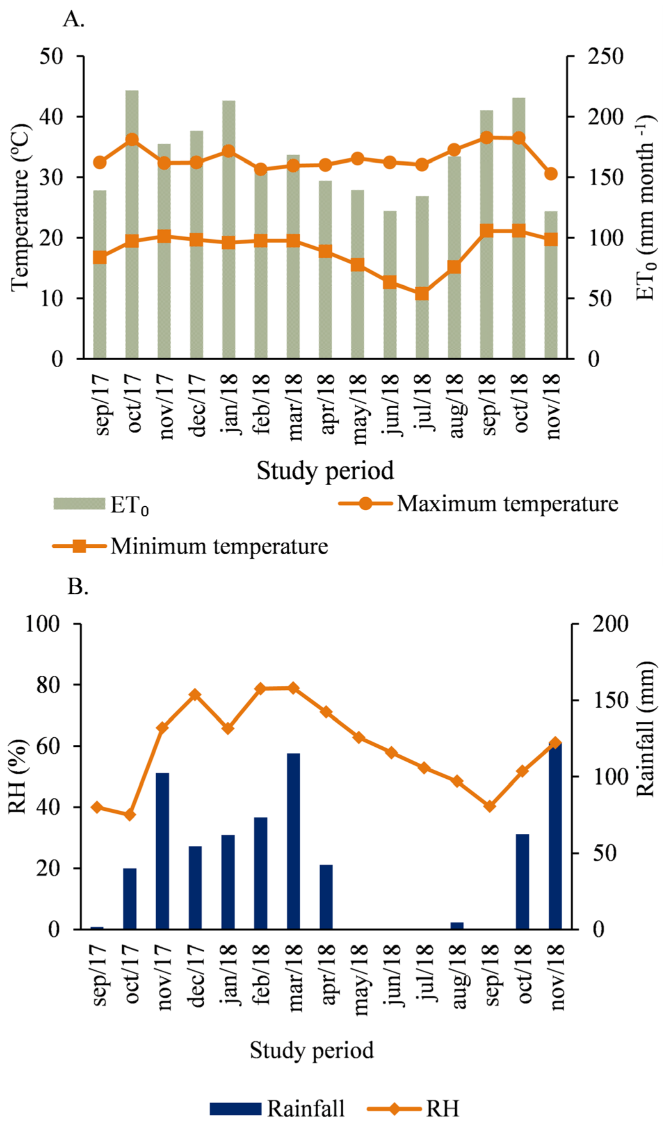


Figure 1. Maximum and minimum temperature and reference evapotranspiration (ET_0) (A), rainfall and relative air humidity (RH) (B) during the experiment

2, 4, 6, 8 and 10 L h^{-1}, corresponding to 15; 30; 45; 60 and 75% of ET_0, respectively. Water accumulation under the different conditions was monitored using the oven method (Mantovani et al., 2009), based on the difference in weight of a soil sample before and after oven drying, followed by analysis of soil water content with a water retention curve (Table 2).

Beginning at 390 DAP, root samples of the Gigante and Miuda genotypes were collected from one plant per plot in order to assess root distribution, totaling 36 plants sampled throughout the experiment.

Table 2. Irrigation depths (ID), rainfall (RAIN) and gross irrigation depth during the first production cycle of 'Gigante' and 'Miuda' genotypes

Water replacement ($\% ET_0$)	ID	RAIN	Gross irrigation depth
	(mm)		
0	0	680.9	680.9
15	177.9	680.9	858.8
30	355.8	680.9	1036.7
45	533.7	680.9	1214.6
60	711.6	680.9	1392.5
75	889.5	680.9	1570.4

The roots were collected using a modified 10 cm-long auger with an internal diameter of 7 cm. Samples were collected perpendicular to the vertical line of drippers, at four depths (0-0.10; 0.10-0.20; 0.20-0.30 and 0.30-0.40 m) and four distances from the plant base (0.10; 0.20; 0.30 and 0.40 m), totaling 576 samples throughout the experiment. The volume of each sample was 384.84 cm^3, corresponding to the auger volume.

After collection, the samples were placed in plastic bags and sent to the laboratory, where they were washed with water to remove the soil. Next, impurities (organic matter and plant residue) were removed from the roots, which were then digitized and converted into Tagged Image File Format - TIFF, as described by Santos et al. (2017b).

After the dark edges caused by digitization were removed, the TIFF files were processed in the Rootedge application (Kaspar & Ewing, 1997) to determine the geometric characteristics (length and diameter) of the roots. The sum of the root lengths (Lr) in the sample volume (Vr) was used to calculate root length density (RLD) (Eq. 1) (Santos et al., 2016).

$$RLD = \frac{Lr}{Vr} \quad (1)$$

where:

RLD - root length density, cm cm^{-3};
Lr - root length, cm; and,
Vr - sample volume, cm^3.

RLD was classified as a function of root diameter, according to the classes proposed by Bohm (1979): very fine (< 0.5 mm); fine (0.5-2.0 mm); small (2.0-5.0 mm) and medium (5.0-10 mm). This information was used to determine the percentage of roots of the Miuda and Gigante genotypes for the different classes and respective water replacement levels.

The data on very fine, fine, small, medium and total RLD were submitted to the Shapiro-Wilk test, followed by nonparametric statistical analysis for non-normal data using the Wilcoxon test (Mann-Whitney), at $p \leq 0.05$ for the genotypes. Given the lack of a significant difference between the genotypes, a 6 x 4 x 4 factorial scheme was adopted, consisting of six soil water replacement levels, four distances from the plant base and four soil depths. Regression analysis was applied for the factors water replacement, distance and depth. The regression model that best represented the biological phenomenon involved was selected, exhibiting the highest coefficient of determination (R^2) and significant regression parameters according to the Student's t-test ($p \leq 0.05$).

Results and Discussion

Nonparametric analysis of variance indicated that the genotypes did not influence root distribution for the different root classes (Table 3).

Although the results showed no difference between the genotypes, Gigante differs from Miuda in its large size, erect stem, larger leaf area in the upper section of the plant, and cladode weighing around 1.0 kg and up to 0.5 m long (Silva et al., 2017).

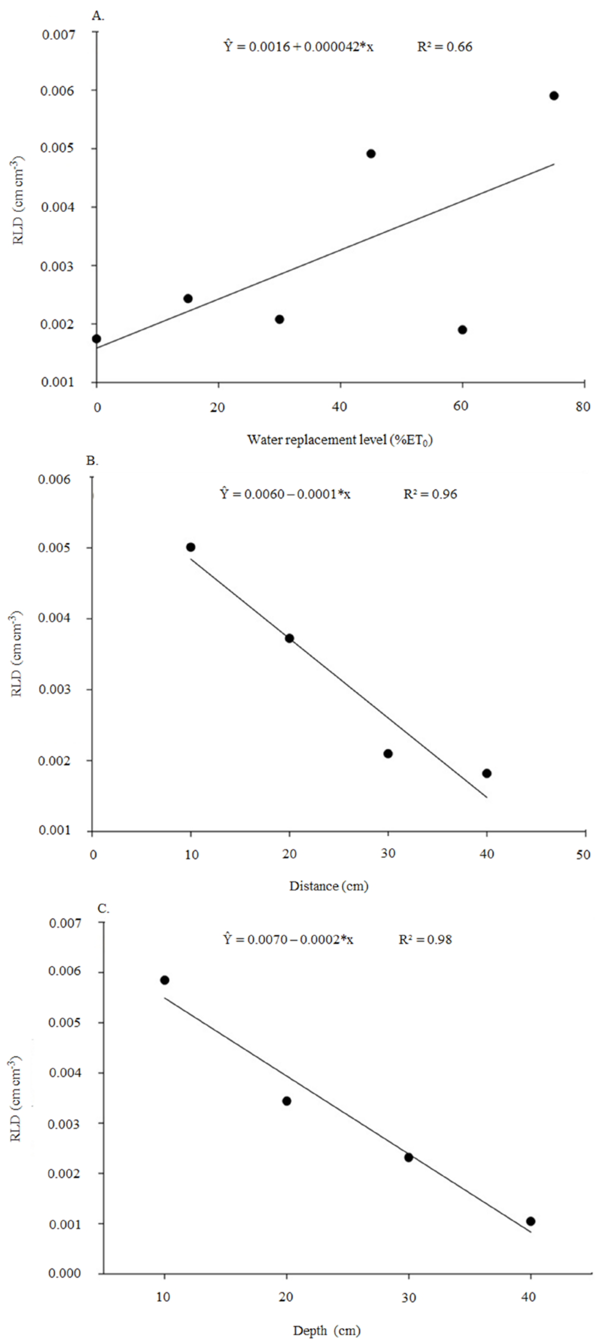
Table 3. Wilcoxon test for the root length density (RLD, cm cm^{-3}) of the Gigante and Miuda genotypes in the different root classes

Diameter (mm)	Genotype	Median	p
<0.05	Gigante	0.0044	0.8636
	Miuda	0.0025	
0.5-2.0	Gigante	0.0484	0.9369
	Miuda	0.0467	
2.0-5.0	Gigante	0.0237	0.5628
	Miuda	0.0224	
5.0-10	Gigante	0.0021	0.7705
	Miuda	0.0018	
Total roots	Gigante	0.1143	0.7193
	Miuda	0.0962	

There were no interactions between water replacement level (WRL), distance from the base of the plant (DIST) and depth and WRL x PROF for any of the root classes; however, interactions were observed between DIST x depth for small (2.0-5.0 mm) and medium-diameter roots (5.0-10 mm) and between PR x DIST for fine roots (0.5-2.0 mm). An isolated effect was observed for WRL, DIST and depth in all the RLD classes, with the exception of WRL for medium-diameter roots (Table 4).

The RLD of very fine roots (< 0.5) was influenced by water replacement levels, with an increase of 1% of ET_0 resulting in a 0.000042 cm cm^{-3} increase in RLD. However, this is only valid for the percentage range studied, that is, 0 to 75% of ET_0, totaling 0.00315 cm cm^{-3} (Figure 1A). With respect to interaction between distance from the plant base and soil depth, RLD declined as water replacement levels increased (Figures 2B and C) for very fine roots, with a 0.0001 and 0.002 cm cm^{-3} decrease in RLD for every 1 cm increase in distance and depth, respectively.

In regard to water replacement levels, plants under water stress show greater root growth (Taiz & Zeiger, 2017), with a decline in leaf area due to the altered root-shoot ratio, as well as a change in preferred sinks, which is dependent on drought intensity. The highest very fine RLD values were recorded in soil layers closer to the surface and the plant base. This can be explained by the greater availability of water in this region, which reduced the development of roots in deeper soil layers. The search for water is more intense in finer roots when there is less water available in the soil (Santos et al., 2016). Santos et al. (2017b) studied the root systems of cactus pears and reported a higher concentration of roots up to 0.2 m from the plant.



* - Significant at $p \leq 0.05$ according to the Student's t-test

Figure 2. Root length density (RLD) as a function of water replacement levels (%ET_0) (A), distance (B) and depth (C) for very fine roots (< 0.5 mm) in cactus pears

Table 4. Summary of analysis of variance for root length density in different root diameter classes for cactus pears grown under different water replacement levels, distances from the plant base and soil depths, 390 days after planting

SV	DF	Mean square				
		< 0.5 mm	0.5-2.0 mm	2.0-5.0 mm	5.0-10 mm	Total roots
Block	2	0.00035**	0.03646**	0.00432**	0.00006^{ns}	0.04224**
WRL	5	0.00015*	0.05130**	0.00390**	0.00008^{ns}	0.05407**
DIST	3	0.00016*	0.09981**	0.03071**	0.00080**	0.19220**
Depth	3	0.00030**	0.07214**	0.00530**	0.00020**	0.07738**
WRL*DIST	15	0.00005^{ns}	0.00643*	0.00107*	0.00010**	0.00791*
WRL*Depth	15	0.00004^{ns}	0.00290^{ns}	0.00073^{ns}	0.00004^{ns}	0.00411^{ns}
DIST*Depth	9	0.00005^{ns}	0.00525^{ns}	0.00235**	0.00025**	0.01242**
WRL*DIST*Depth	45	0.00003^{ns}	0.00294^{ns}	0.00055^{ns}	0.00004^{ns}	0.00279^{ns}
Residual	478	0.00005	0.00324	0.00057	0.00004	0.00379
CV (%)		229.25	104.89	112.81	302.81	75.71

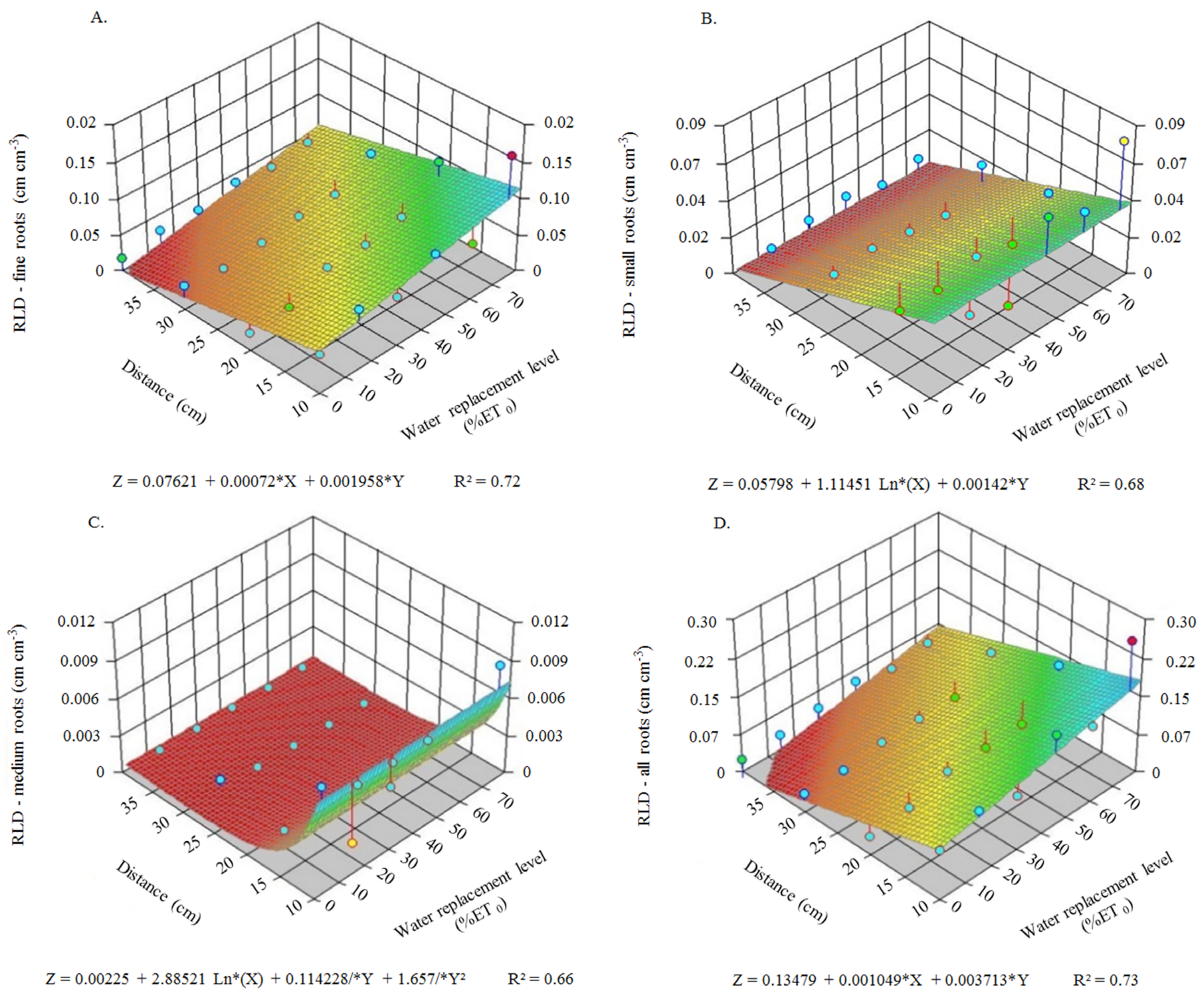
SV - Source of variation; DF - Degrees of freedom; WRP - Water replacement percentages, % ET_0; DIST - Distance from the base of the plant, cm; Depth - in cm; CV - Coefficient of variation; **, *, ns - Significant at $p \leq 0.1$ and $p \leq 0.05$, and non-significant according to the F-test, respectively. Data converted into $\sqrt{X + 0.5}$

For the conditions studied here, there is a dependent relationship between water replacement levels and distance that affects the RLD of fine (Figure 3A), small (Figure 3B) medium (Figure 3C) and all root diameters (Figure 3D).

The proportion of fine roots (0.5 and 2 mm) increased and the water replacement level rose and decreased at a greater distance from the plant (Figure 3A), which was also observed for very fine roots (RLD < 0.5 mm) (Figures 2A and B). Small (RLD between 2 and 5 mm) and medium-diameter roots (RLD between 5 and 10 mm) exhibited the same RLD at all the water replacement levels because these roots are not as responsible for water and nutrient uptake as their fine and very fine counterparts, meaning it is less important for them to remain in wet areas of the soil. However, RLD declined with an increase in distance from the plant (Figures 3B and C) due to the clayey soil in the experimental area (Table 1) in which localized irrigation distributes water across a larger radius of the soil surface, and the closer to the emitter, the greater the water content. All the root diameter classes (Figure 3D) behaved similarly to fine roots due to the large number of fine and small roots.

For the genotypes assessed and all root diameter classes, there was a greater concentration of roots at a distance of 0 to 0.2 m from the plant and depth of 0.1 to 0.25 m, with root length declining from 0.16 to 0.06 cm cm^{-3} for the Gigante genotype (Figure 4A) and 0.15 to 0.05 cm cm^{-3} for Miuda (Figure 4B) across the soil profile for all treatments, as distance from and the plant base and depth increased. However, Miuda exhibited better root distribution (Figure 4B), despite the fact that the roots were concentrated near the emitter, located 0.25 m from the base of the plant. Thus, it is suggested that the ideal location for water and nutrients is up to 0.25 m from the plant or emitter and up to 0.40 m deep, since the cactus pear root system is most effective within this range. These distances could result in higher yield and better water use efficiency, the latter being an indicator of plant water absorption potential and the location of sensors to monitor water content or soil matric potential for rational water management (Borges et al., 2008; Coelho et al., 2010; Sant'ana et al., 2012; Silva et al., 2013).

Similar results were reported for the Gigante genotype in the municipality of Guanambi, Bahia state (BA), Brazil, whereby the greatest root concentration was observed at a



* - Significant at p ≤ 0.05 according to the Student's t-test

Figure 3. Root length density (RLD) as a function of distance from the plant and water replacement levels for the root diameter classes 0.5-2.0 mm (fine) (A); 2.0-5.0 mm (small) (B); 5.0-10 mm (medium), (C); and all classes (D)

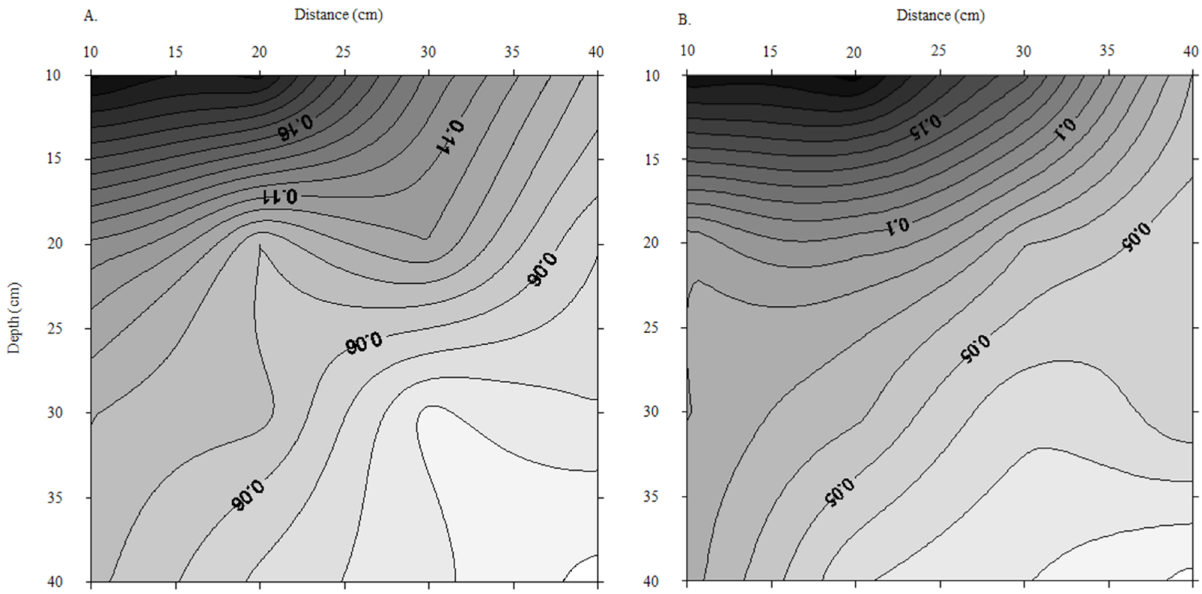


Figure 4. Isolines of root length density (RLD) as a function of depth and distance in the Gigante (A) and Miúda (B) cactus pear genotypes

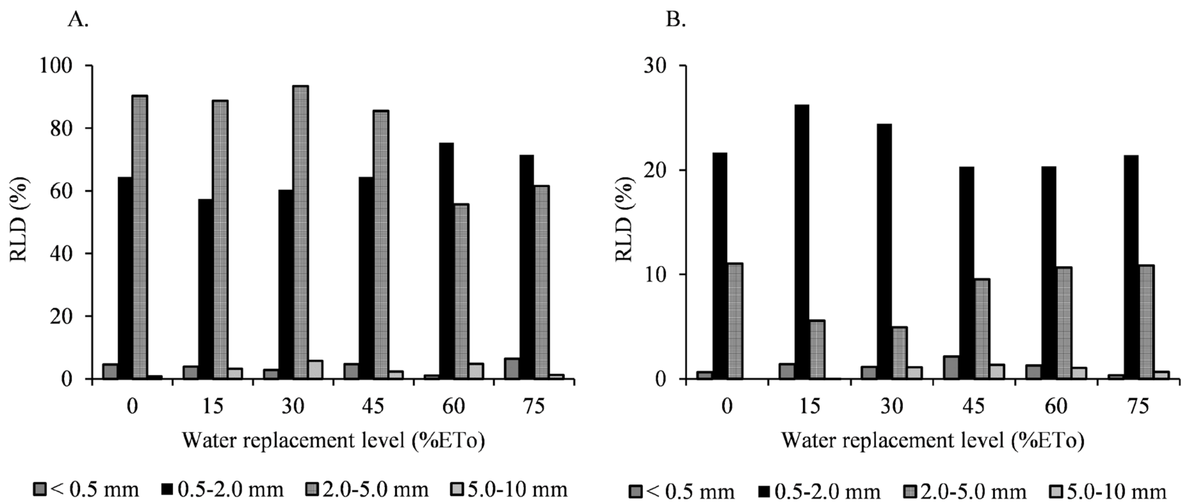


Figure 5. Percentage root length density (RLD) in the Gigante (A) and Miuda (B) genotypes for the different root classes as a function of water replacement level

depth of 0.10 to 0.20 m and distance of 0.15 m from the center of the row, under larger irrigation depths and shorter irrigation intervals (Santos et al., 2017b). Edvan et al. (2013) studied the same genotype and found that the roots were concentrated close to the plant at a distance of 40 cm and depth of 10 cm regardless of harvesting time, and can reach up to 40 cm deep during the rainy season.

The total RLD percentage for all the root diameter classes and water replacement levels is shown in Figure 5.

The proportion of small roots was higher for the first four irrigation depths in the Gigante genotype (Figure 5A), whereas fine roots obtained higher percentages for Miuda (Figure 5B). The average percentage of fine and small roots for all the water replacement levels was 65.59 and 79.20% for Gigante and 22.40 and 8.77% for Miuda, respectively, indicating a difference in root distribution characteristics between the two genotypes. While the concentration of roots is not a decisive factor in the behavior of growth, yield and drought tolerance, it does affect the architecture and distribution of roots across the soil profile (Vasconcelos & Garcia, 2005).

Conclusions

1. Depth and distance from the plant base of up to 0.4 m reduce very fine root length density, whereas higher water replacement levels increase total, fine, small and medium root length density.

2. Water replacement of up to 75% of ET_0 increases root length density near the plant base.

3. All the root diameter classes were concentrated primarily 0 to 0.20 m from the plant base and at a depth of 0.10 to 0.25 m.

4. The Gigante genotype exhibits a higher root length density and Miuda better root distribution.

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