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CROP PRODUCTION

Root distribution and its relations with soil chemical attributes and yield of banana under fertigation with and without soil covering

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ABSTRACT. This study evaluated the effects of fertigation, banana biomass as a soil covering under drip and micro-sprinkler irrigation system on the root growth and distribution and their relations with chemical soil attributes, soil water availability, and productivity. This work was conducted in a field with banana 2.5 × 2.0 m spacing and irrigated every two days using a drip and micro-sprinkler irrigation system during the first crop cycle. The experiment followed a random block design with six treatments, two irrigation systems, two fertilization methods of fertigation and side-dressing, as well as two cultivation types with and without soil covering. Roots were collected from each plot using soil monoliths and digitalization allowed the determination of root length density, and diameter at several distances from the plant and at different soil depths. Total root length, density, and distribution by diameter were evaluated based on the treatment interactions with respect to the distance from the plant and the soil depth. Our results showed that the combination of the irrigation system, fertilizer application and soil covering influenced root growth and distribution. In addition, we found that the better soil conditions for root growth were in drip or micro-sprinkler systems with fertigation and cultivated biomass covering.

Keywords: root length density; root distribution; soil depth; effective distance; root diameter; irrigation management.

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Introduction

Drought periods have been increasing in frequency and duration, which has negatively affected irrigated agriculture worldwide. It has become necessary to address water resource scarcity by using irrigation water more efficiently. Banana root systems originate from an underground stem, known as the rhizome, from which the roots extend and ramify continuously until flowering (Carr, 2009). The root system is directly involved in the uptake of water and nutrients from the soil (Kitomi, Itoh, & Uga, 2018) as well as anchoring the plant (Wu, Ma, & Whalen, 2018). Knowing root distribution in the soil profile contributes to defining the best strategies for applying water and fertilizers to improve irrigation and fertilization practices, especially in systems that utilize drip irrigation, fertigation (Donato et al., 2010), and soil water content sensors (Coelho, Silva, & Miranda, 2010).

The method of irrigation significantly affects yield, vegetative quality components, root development, and water use efficiency (WUE) (Pisciotta, Lorenzo, Santalucia, & Barbagallo, 2018). Furthermore, fertigation is the most common method for supplying water and nutrients to the soil (Pérez-Castro et al., 2017) and optimizing fertilizer use efficiency for plant development (Teixeira, Quaggio, & Mellis, 2011; Kapoor, Sandal & Banyal, 2017; Senthilkumar et al., 2017). Fertigation provides better nutrient distribution in the wetted soil volume to improve root growth and yield (Borges, Silva, & Oliveira, 2011a; Sandal & Kapoor, 2015; Santos et al., 2016). Hence, the irrigation system can have a direct effect on root growth and development (Chilundo, Joel, Wesström, Brito, & Messing, 2017). This effect can be pronounced by the irrigation system and fertilization strategy, which acts on the spatial distribution of moisture and nutrients in the soil profile as well as on the development and distribution of the root system (Santos et al., 2016). Thus, ample or limited mobility of nutrients relative to the water distribution within the soil can affect root growth and uptake (Fanish & Muthukrishnan, 2013).

To increase water and nutrient use efficiency in plants to for a more favorable soil environment for root development, the soil surface can be covered with plant residues, such as banana biomass. This technique can maintain soil temperature and humidity, increase nutrient content and organic matter as well as reduce soil nutrient losses due to leaching (Gasparim, Ricieri, Silva, Dallacort, & Gnoatto, 2008; Koshima, Ming, & Marques, 2006; Tindall, Mills, & Radcliffe, 2008). Moreover, irrigation systems can influence the water and nutrient distribution in the soil, which is enhanced by fertigation. Chilundo, Joel, Wesström, Brito, and Messing (2018) verified that the nitrate and ammonium distribution in the soil profile can also be influenced by the individual or interaction effect of the irrigation method, amount, and N fertilizer type. In addition, drip and micro-sprinkler irrigation systems can re-distribute water and nutrient contents in the soil (Koumanov, Hopmans, & Schwankl, 2006). The use of one or the other can significantly influence root distribution, mainly when considering the flow rate and the number of emitters per plant (Santana Junior et al., 2020). Root distribution may also explain the growth and yield of the crop, while generating root indices for water irrigation management and solid or liquid fertilizer application. Studies on banana root distribution under irrigation conditions have been conducted (Sant'Ana, Coelho, Faria, Silva, & Donato, 2012; Santana Junior et al., 2020). However, most have evaluated roots that were influenced by irrigation systems. Coelho, Melo, Pereira, Santos, and Rosa (2016) also evaluated the effect of organic compounds, such as humic acid, on banana root distribution when applied through irrigation, but banana root systems have not yet been evaluated within the soil profile using mulch as a crop biomass for soil covering under fertigation. Fertigation, soil covering, and irrigation systems may interact and influence root development and distribution. Moreover, the micro-sprinkler irrigation system is common in banana cultivations, while the drip irrigation system is less used, but the need to save water causes farmers to use it. Studies on the individual effects of these factors may help to refine management techniques and promote higher efficiency in the use of water and fertilizers, leading to a reduction in costs and, consequently, to increase profitability in irrigated banana production. This study aimed to evaluate the effects on the growth and root distribution of 'BRS Princesa' banana in terms of fertigation, banana biomass as a soil covering, as well as drip and micro-sprinkler irrigation systems relative to the chemical soil attributes, soil water availability, and productivity.

Material and methods

Experimental characterization

The type of soil at the experimental area of Cruz das Almas County, Bahia State, Brazil, was a dystrophic cohesive yellow latosol, with a clay loam soil texture class, at an altitude of 225.87 m with geographic coordinates of 12°40′39″ S and 39°06′23″ W. The climate is classified as humid to sub-humid tropical (Aw to Am) according to the Köppen-Geiger classification, with a mean annual rainfall of 1,143 mm. The maximum and minimum monthly temperatures as well as the precipitation are shown in Figure 1, while the initial analyses of the physical-hydraulic and chemical attributes are summarized in Tables 1 and 2.

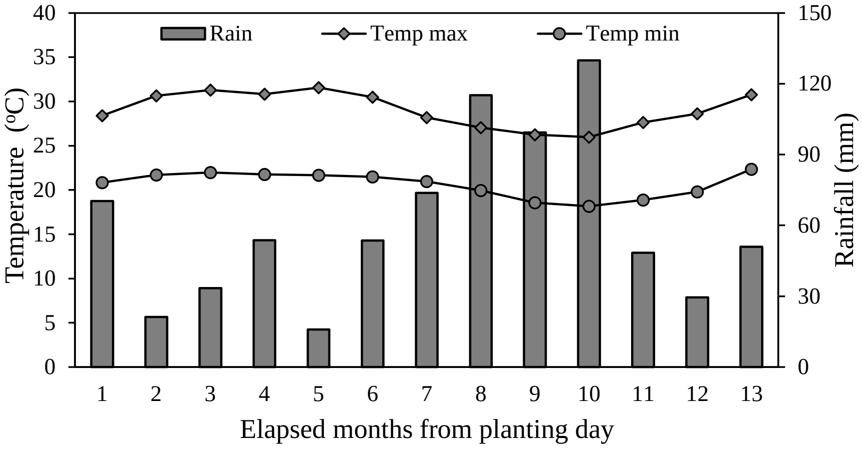

Figure 1. Maximum and minimum temperatures (Temp max and Temp min, respectively) as well as the rainfall (Rain) during the first cycle of the banana crop.

Table 1. Soil bulk density and moisture at the upper and lower limits of water availability within the experimental area of Cruz das Almas County, Bahia State, Brazil, at an altitude of 225.87 m with geographic coordinates of 12°40´39″ S and 39°06´23″ W in the year 2016.

Soil depth (m)	Soil bulk density (mg m^{-3})	Soil moisture at -10 kPa (m^3 m^{-3})	Soil moisture at -1500 kPa (m^3 m^{-3})	Water availability (m^3 m^{-3})
0.00 - 0.20	1.68	0.2600	0.1390	0.121
0.20 - 0.40	1.70	0.2480	0.1500	0.100

Table 2. Soil chemical analysis in the experimental area of Cruz das Almas County, Bahia, Brazil State, at an altitude of 225.87 m with geographic coordinates of 12°40´39″ S and 39°06´23″ W in the year 2016 before initiating the experiment.

Depth (m)	pH under H_2O	$P^{/2}$	$K^{/2}$	$Ca^{/3}$	$Mg^{/3}$	$Na^{/2}$	H+Al	CEC	SB	V	$OM^{/4}$
0.00 – 0.20	6.3	40	0.4	2.4	1,9	0.4	1.5	6.7	5.2	76.6	14.3
0.20 – 0.40	6.1	30	0.6	2.4	2.0	0.3	1.3	6.5	5.1	79.0	14.8

$^{/2}$Extrator Mehlich 1; $^{3/}$Extrator KCl/1 M; $^{4/}$Walkley & Black. CEC: cationic exchange capacity, SB: sum of basis, V: saturation of basis, OM: organic matter.

The analyses of soil chemical attributes were described by Teixeira et al. (2011), where they studied the banana (*Musa spp*.) cultivar BRS Princesa grown at a spacing of 2.0 × 2.5 m (2000 plants ha^{-1}). The cultivar BRS Princesa is new to the market and was developed by Embrapa (Brazilian Agricultural Research Corporation) to generate a cultivar with high tolerance to diseases and high WUE. Seedlings from the laboratory were planted in 0.40 x 0.40 x 0.40 m pits with 100 g of fritted trace elements (FTE), 12 L of manure, and 165 g of simple superphosphate. Phosphorous was split by 60 during planting and 30% during the cycle by fertigation. Potassium chloride and urea were only used in fertigation during the cycle (Borges, Coelho, Costa, & Teixeira, 2011b).

Experimental design and root sampling

We evaluated the root system within the soil profiles of banana plants during the flowering state in the field, where the banana plant, in its first cycle, reduces its root emission during and after the flowering phase (Donato et al., 2010). The experiment followed a randomized block design with six treatments and three replications. Treatments consisted of: T1 – drip irrigation with side dressing fertilization; T2 – micro-sprinkler irrigation with side dressing fertilization; T3 – crop fertigated by drip irrigation with soil covering; T4 – crop fertigated by drip irrigation without soil covering; T5 – crop fertigated by micro-sprinkler irrigation with soil covering, and T6 – crop fertigated by micro-sprinkler irrigation without soil covering.

Furthermore, the soil profiles were limited by the distance from the plant along the plant row of 1.0 and the depth of 0.80 m. These limits represented half the space between the plants of 2.0 m in one row and the depth with an assumed minimum of roots. This assumption is possible, since irrigation water is calculated according to effective root depth. Root samples were collected in soil volumes of 0.10 m^3 at distances of 0.25, 0.50, 0.75, and 1.00 m from the plant and at depths of 0.10, 0.20, 0.30, 0.40, 0.60, and 0.80 m. These depths corresponded to the center of each sample or half of monolith height.

Irrigation, fertigation, and soil covering

The irrigation systems consisted of: (i) drip irrigation with one lateral line per crop row and three pressure-compensating emitters with a flow rate of 4 L h^{-1} per plant, (ii) micro-sprinkler irrigation with one lateral line between two crop rows with one 64 L h^{-1} emitter positioned between four plants. The calculation of water depths was based on crop evapotranspiration (ETc) (Allen, Pereira, Raes, & Smith, 1998), where, the estimates of crop evapotranspiration used reference evapotranspiration (ETo) and crop coefficient (Kc) as described by Coelho, Donato, Oliveira, and Cruz (2012). Readings soil water contents from a time-domain reflectometer (TDR) before each irrigation event evaluated the need for irrigation. The TDR probes were inserted in the soil profiles at depth of 0.30 and a distance of 0.25 m between a plant and a near dripper as well as between plant and micro-sprinkler (Coelho et al., 2010). The readings of soil water contents were made on a weekly basis across all treatments in one block during the six months after planting. The average readings of each month were used. The soil water availability was calculated from the soil water content data, as shown in Equation 1.

$$SWA = \frac{\theta_{t-\theta_{\wp}}}{\theta_{fc-\theta_{\wp}}} \cdot 100 \qquad (1)$$

where:
SWA is the actual percentage of available water in the soil (%);
θ_t is the moisture given by TDR before irrigation (cm^3 cm^{-3});

θ_{fc} is the soil water content at the upper limit of soil water availability (field capacity), and;
θ_{wp} is the soil water content at the lower limit of soil water availability (cm^3 cm^{-3}).

Furthermore, the fertilizer injection system consisted of a portable injection pump with a flow rate of 60 L h^{-1}. Fertigation was performed on a weekly basis using a venturi as a fertilizer injector, with nitrogen and potassium administered as urea and potassium chloride, respectively. Phosphorous was applied as monoamonic phosphate (46% P_2O_5) every three months. The fertilizer quantity at each fertigation event were calculated based on the need for these nutrients during the vegetative growth and flowering phases of the crop cycle (Borges et al., 2011b). Evaluations of the same soil chemical attributes in Table 2 took place at 0.30 m from the plant pseudo stem within the soil layers of 0 to 0.10 m, 0.10 to 0.20 m, 0.20 to 0.30 m, and 0.30 to 0.40 m across all treatments and replicates during root sampling. The attribute averages within the layers per treatment and replicate were considered between 0 to 0.40 m depth. In addition, the soil covering consisted of the banana crop biomass from a close area. The material included straws, leaf parts, and pseudo stems that covered the soil surface along and between rows. Biomass thickness over the soil surface was approximately 0.10 m, as was observed in the banana plantations. Plot areas with fertigation and soil covering that were irrigated by trickle and micro-sprinkler systems were covered with the biomass, while maintaining bare soil in non-covered treatments was made possible through mechanical weeding.

Total root length, root length density, and root diameter

Roots were collected by the monolith method, separated from the soil according to Böhm (1979), digitized, and processed using the Rootedge software (Kaspar & Ewing, 1997), which resulted in the total root length (TRL) for each distance from the plant and each soil depth. Root length data has used to determine root length density (RLD) in cm cm^{-3}, according to Sant'Ana et al. (2012), and to obtain the effective depth and distance of the root system by considering the different soil profile zones where 80% of the total length was concentrated (Coelho et al., 2016). This was summarized in Equation 2:

$$RLD = \frac{RL}{V_r} \qquad (2)$$

where:
RLD is given in cm cm^{-3};
RL is the root length (cm) of the sample, and;
V_r is the volume of sample (cm^3).

Root diameter was associated with root length to obtain the percentage of root length within a diameter class. The classes and their limits were according to Table 3 (Böhm, 1979).

Table 3. Classes of root diameters (Böhm, 1979).

Classification	Very fine	Fine	Small	Medium	Large	Very large
Diameter (mm)	< 0.5	0.5 – 2.0	2.0 – 5.0	5.0 – 10.0	10.0 – 20.0	> 20.0

Crop productivity and water use efficiency

The crop productivities of all treatments were evaluated and related with the means of total root length. The productivities were based upon the total commercial mean hand weight estimated for 2000 plants (1 ha). Crop water use efficiency (WUE) for each treatment was considered as the ratio between crop productivities (kg) and total crop evapotranspiration (mm) during the cycle (Fanish & Muthukrishnan al., 2013; Jensen, 2007).

Statistical analysis

A statistical design with randomized blocks with three replicates has used to evaluate the possible effects of fertigation, irrigation system, and soil covering on TRL, on RLD in the entire soil profile, as well as on the soil chemical attributes, soil water availability, crop productivity, and WUE. Another statistical design also followed a randomized block, but in split-split-plot scheme, with three replicates. It evaluated the effects of the same sources of variation on root length and on root length distribution within soil depth and distance from plant. Treatments represented the plots, the distances from plant represented the subplots and the soil depth represented the sub-subplots. Mean clusters of TRL and RLD were analyzed using the Scott-Knott criteria at $p < 0.05$ significance level. Regression analysis was also used to evaluate RLD and root diameters in terms of distance from the plant and soil depth.

Results and discussion

TRL and RLD were successfully determined

The analysis of variance detected effect ($p < 0.05$) of the irrigation system with and without fertigation, both, with and without soil covering on total root length (TRL) and root length density (RLD). TRL and RLD means related to the treatments without soil covering, except in the case of drip irrigation with the side dressing fertilization, were in a group of means smaller than the means of the treatments with soil covering. In addition, TRL and RLD means in the root zone of plants irrigated by micro-sprinklers composed one cluster that differentiated from the ones of treatment with drip irrigation. The mean TRL and RLD within the covered soil profiles under drip irrigation and fertigated conditions was the highest (Table 4), while the larger means were found in the treatments with fertigation and soil covering (T3 and T5). Furthermore, the drip system without fertigation (T1) showed the smallest TRL and RLD means across all treatments, where the mean TRL value increased by approximately 103% under the drip system just by the use of fertigation (T4) and reached a maximum with soil covering in addition to fertigation (T3). Moreover, the means of treatments T3 and T4 were different from the mean of T1 ($p < 0.05$). Finally, the TRL mean under the micro-sprinkler system with fertigation only (T6) and under the same system without fertigation (T2), were in the same cluster of means, which demonstrated no effect of fertigation in this system.

The evaluation of the cluster of means in terms of chemical attributes in treatments between 0 to 0.40 m layer (Table 5) showed that, despite the high variation coefficients in some nutrients with the exception of H+Al and sodium, the soil profile under irrigation systems using fertigation and soil covering (T3 and T5) had larger means of K, Ca, Mg, sum of bases (SB), caution exchange capacity (CEC), and soil organic matter (OM). Moreover, the treatment under the drip irrigation system with soil covering (T3) was also in the cluster of means of larger pH and phosphorous. These results support the larger means of TRL and RLD obtained by T3 and T5 (Table 4).

Table 4. Means of total root length (TRL) and root length density (RLD) of the 'BRS Princesa' banana as a result of the micro irrigation systems combined with fertigation and soil covering.

Treatments	TRL (cm)	RLD (cm cm^{-3})
T1	2741.4 d	0.11 d
T2	4470.1 c	0.16 c
T3	10400.8 a	0.43 a
T4	5575.9 c	0.22 c
T5	9141.6 b	0.37 b
T6	5246.1 c	0.18 c
CV (%)	9.2	8.9

Means followed by the same letters per column belong to the same significance group, according to the Scott-Knott criteria at $p < 0.05$.

Table 5. Means of chemical attributes of the dystrophic cohesive yellow latosol in the 0.0 to 0.4 m soil layer under the ‘BRS Princesa’ banana crop.

Treatments	pH	P	K	Ca	Mg	Na	H+Al	SB	CTC	V	OM
		-mg dm^{-3}-				cmol$_c$ dm^{-3}				%	g kg^{-1}
T1	6.3b	37.8d	0.4c	2.1b	1.2b	0.15d	0.43a	3.9b	4.4b	90a	18b
T2	6.7a	36.0d	0.6b	2.1b	1.5b	0.34a	0.21a	4.5b	4.8b	95a	17b
T3	6.7a	81.7a	0.8a	3.3a	2.1a	0.26b	0.20a	6.5a	6.7a	95a	34a
T4	6.3b	63.8b	0.3d	2.2b	1.5b	0.28b	0.39a	4.3b	4.7b	91a	18b
T5	6.8a	50.8c	0.7b	3.2a	2.1a	0.21c	0.19a	6.1a	6.3a	96a	30a
T6	6.9a	49.8c	0.5c	2.4b	1.7b	0.34a	0.25a	4.9b	5.1b	94a	19b
CV (%)	8.4	55.6	28.0	40.0	34.0	24.8	109.0	33.0	28.0	7.7	46.0

SB: sum of bases; CEC: caution exchange capacity; V: base saturation; OM: soil organic matter. Means followed by the same letters in the column belong to the same significance group by the Scott-Knott criteria at $p < 0.05$.

The soil water availability before an irrigation event as a function of elapsed time was summarized across all treatments (Table 6), where the total water depth applied to the crop by all systems was consistent (1,202 mm). SWA means measured under the micro-sprinkler irrigation system with fertigation and soil covering (T5) was larger than 100% before the irrigation and was also the largest across all treatments. This was followed by the SWA mean under drip irrigation with fertigation and soil covering (T3), where the SWA values in the other treatments varied between 50 to 83% before irrigation. These results showed that the calculated water depth had supplied the root zone suitably. The management allowable soil water depletion from field capacity (100% SWA) for banana was approximately 35% (Doorenbos & Pruitt, 1975; Bernardo, Soares, & Mantovani, 2006), which was verified across most treatments.

Table 6. Water availability in the soil with 'BRS Princesa' banana cultivation as a function of elapsed time across all treatments. (T1 – drip system with side dressing fertilization and without soil covering; T2 – micro-sprinkler system with side dressing fertilization and without soil covering; T3 – drip system with soil covering and fertigation; T4 – drip system with fertigation and without soil covering; T5 – micro-sprinkler system with soil covering and fertigation; and T6 – micro-sprinkler system with fertigation and without soil covering). The productivity and WUE across all treatments (Table 7) were found not be significantly changed in TRL or RLD, where the differences among the cluster means of these variables indicated that root growth did not affect productivity and WUE.

Treatment	Month					
	1	2	3	4	5	6
T1	62.56 b	61.91 b	61.45 b	62.79 c	56.66 b	53.4 c
T2	47.34 b	60.17 b	59.52 b	52.88 c	49.28 b	62.98 c
T3	103.92 a	98.12 a	103.07 a	92.1 b	90.64 a	90.14 b
T4	83.46 b	82.02 b	70.36 b	78.43 c	50.54 b	52.65 c
T5	123.43 a	115.03 a	118.83 a	123.62 a	117.67 a	118.79 a
T6	72.79 b	69.93 b	64.14 b	62.55 c	51.69 b	58.54 c
CV (%)	22.29					

Root length density distribution

The treatments with biomass covering and fertigation (T3 and T5) corresponded to larger RLD means across all depths (Figure 2). Regression analyses of RLD and soil depth (Figure 2a) indicated a reduction in RLD as the soil depth increased through quadratic and linear models of the treatments with drip irrigation (T1, T3, and T4). However, these models did not explain RLD as a function of depth in the micro-sprinkler system (Figure 2b). In addition, the RLD reduction rate was constant relative to the soil depth under drip irrigation with fertigation and soil covering (Figure 2a). The rate of reduction of RLD did not change until 0.40 m depth in the T1 and T4 treatments, where the reduction in RLD was minimized below this depth.

The evaluation of RLD at different distances from the plant demonstrated that RLD was higher in treatments with fertigation and biomass covering (T3 and T5) in both irrigation systems and across all distances from the plant (Figure 3). Mean RLD values as a function of the distance from the plant (Figure 3) led to quadratic and linear fittings, where the linear fittings were regarded as micro-sprinkler systems (T2, T5) and the drip system with fertigation on bare soil (T4). The RLD reduction rate in terms of the distance from the plant was constant across all distances for these treatments. RLD decreased at the same rate until 0.50 and 0.60 m depths with distance from plant the treatments T1, T3, and T6.

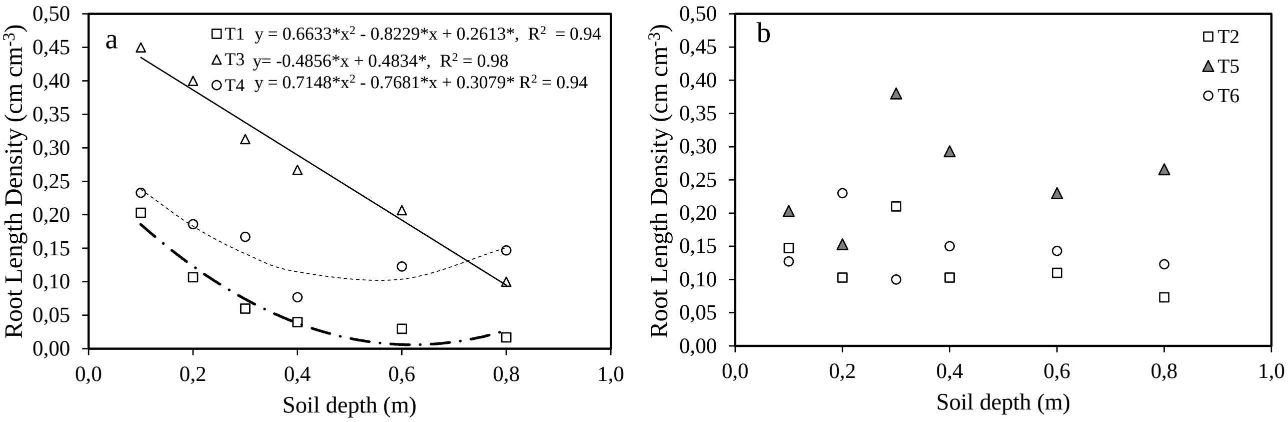

Figure 2. Root length density of 'BRS Princesa' banana as a function of soil depth for (a) the drip irrigation system and (b) the micro-sprinkler irrigation system, which included fertigation and soil covering. (T1 – drip system with side dressing fertilization and without soil covering; T2 – micro-sprinkler system with side dressing fertilization and without soil covering; T3 – drip system with soil covering and fertigation; T4 – drip system with fertigation and without soil covering; T5 – micro-sprinkler system with soil covering and fertigation; and T6 – micro-sprinkler system with fertigation and without soil covering). *significant at $p < 0.05$.

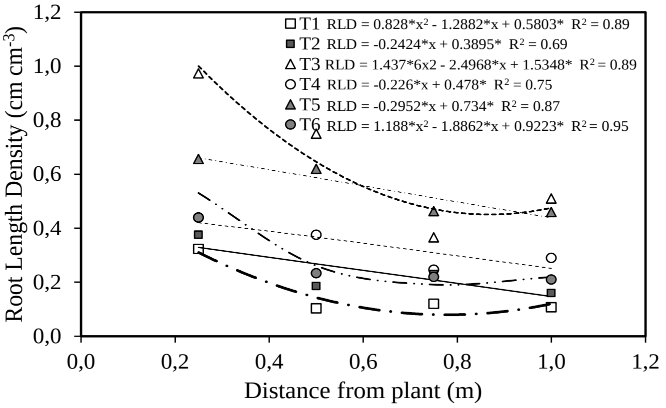

Figure 3. Root length density (RLD) as a function of plant distance across all treatments. (T1 – drip system with side dressing fertilization and without soil covering; T2 – micro-sprinkler system with side dressing fertilization and without soil covering; T3 – drip system with soil covering and fertigation; T4 – drip system with fertigation and without soil covering; T5 – micro-sprinkler system with soil covering and fertigation; and T6 – micro-sprinkler system with fertigation and without soil covering). *significant at $p < 0.05$.

Root diameter distribution

The soil profile (Figure 4 and Table 3) in T5 and T6 contained roots of diameter up to 24 and 60% of TRL within the very fine and fine diameter classes, respectively, in the layer of 0.10 to 0.80 m (Figure 4a). A total of 27 and 57% of TRL were within the very fine and fine diameter classes, respectively, and at distances of 0.25 to 1.00 m from the plant (Figure 4b). Furthermore, the percentage of fine or very fine roots (MMF) decreased, except in the case of the micro-sprinkler systems, with soil depth and, except in the case of T2 and T5, with distance from the plant (Figure 5), where the maximum percentage of fine and very fine roots under drip irrigation occurred at 0.10 depth and 0.25 m from the plant.

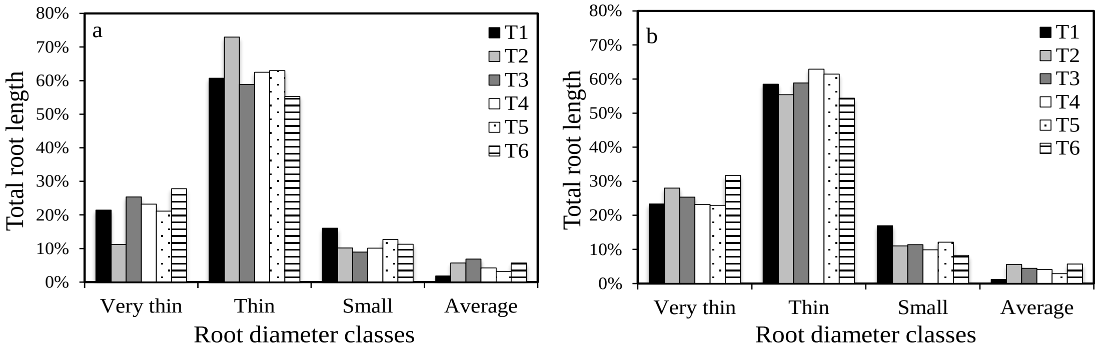

Figure 4. Percentage of total root length distributed across diameter classes in terms of soil depth (a) and distance from the plant (b) in drip and micro-sprinkler systems with and without soil biomass covering. (T1 – drip system with side dressing fertilization and without soil covering; T2 – micro-sprinkler system with side dressing fertilization and without soil covering; T3 – drip system with soil covering and fertigation; T4 – drip system with fertigation and without soil covering; T5 – micro-sprinkler system with soil covering and fertigation; and T6 – micro-sprinkler system with fertigation and without soil covering).

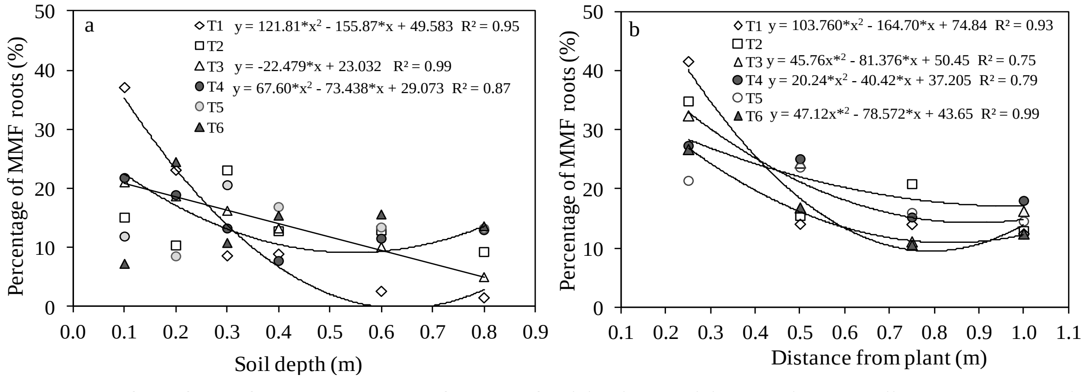

Figure 5. Percentage of very fine or fine roots (MMF) as a function of soil depth (a) and distance (b) across all treatments. (T1 – drip system with side dressing fertilization and without soil covering; T2 – micro-sprinkler system with side dressing fertilization, without soil covering; T3 – drip system with soil covering and fertigation; T4 – drip system with fertigation and without soil covering; T5 – micro-sprinkler system with soil covering and fertigation; and T6 – micro-sprinkler system with fertigation and without soil covering.) *significant at $p < 0.05$.

Total root length and root length density

The use of fertigation was effective in increasing total root length (TRL) and root length density (RDL) in the drip irrigation system (Table 4), where the positive effects of fertigation on root growth were verified in apple (Neilsen, Parchomchuk, Neilsen, & Zebarth, 2000) and tomato (Rimcharoen & Wonprasaid, 2016), where the benefits of fertigation included nutrient distribution within the soil profile (Mahgoub, Mohamed, El Sikhary, & Ali, 2017). The more relevant role of increasing the TRL and RLD in the drip irrigation systems compared to those under the micro-sprinkler irrigation (Table 4) should be due to the smaller soil wetted volume under drip irrigation, which also had a larger concentration of nutrients and a higher soil moisture within the root system. These results are in line with the ones of Sant'Ana et al. (2012), who found superiority of the RLD of banana under drip irrigation over to micro-sprinkler and sprinkler systems, with the use of fertigation. The treatments with side dressing fertilization (T1 and T2) resulted in lower values of TRL and RLD, possibly because of the lower availability of nutrients in the soil solution for the roots due to the fewer fertilization events.

The combination of fertigation and soil covering contributed positively with the total root length (TRL) and root length density (RLD), regardless of the irrigation systems (Table 4). The increases of TRL and RLD may be explained by the larger contents of P, K, Ca, Mg, SB, OM, and CEC in the 0 to 0.40 m soil layer under fertigation (Table 5). This result is probably due to the use of biomass covering that was present in both treatments and was also observed in other studies (McIntyre et al., 2001; Tiquia, Lloyd, Herms, Hoitink, & Michel Jr., 2002). The OM in the root zone increased in both the drip or micro-sprinkler systems with fertigation and biomass covering more than in treatments without soil covering (Table 5), which was likely due to the continuous decomposition of biomass covering that was enhanced by the nutrients from fertigation (Štursová & Baldrian, 2011). In addition, SWA of approximately 100% under the drip and micro-sprinkler irrigation systems with fertigation and biomass covering (Table 6), associated with the chemical attributes (Table 5), may have favored nutrient availability and lower soil mechanical resistance in root development. The SWA of approximately 100% in these treatments should have also contributed to maintaining soil temperatures without daily fluctuations, which favored root growth as verified by previous studies (Gasparim et al., 2008; Koshima et al., 2006; Tindall et al., 2008; Kosterna, 2014). Furthermore, the soil surface covered with biomass (T5 and T3) prevented evaporation and limited water loss to mainly favor root extraction. SWA in T5 was above 100% throughout the crop season (Table 6), indicating that the biomass covering under this irrigation system was more effective than that of the drip system. Biomass covering stores water after irrigation and may have supplied water at shallower soil layers between two irrigation events, while reducing soil evaporation. The differences among the clusters of either productivity or WUE means (Table 7) and of RLD means (Table 4) justified the non-significant differences in the fitting of these variables (Figure 6).

Root length density (RLD) showed differences when using soil covering with or without fertigation in both irrigation systems. The productivity and WUE (Table 7) differed between two clusters of means, one with means of T2, T5, T6, i.e., all treatments with micro-sprinkler systems and T3 (drip system with fertigation and soil covering). The other cluster was composed of means of treatments T1 and T4, that is, the drip irrigation systems without and with fertigation. Treatments like T3 and T2 were in the same cluster of productivity means while they were in different ones for TRL or RLD means (Table 4). The same trend has observed for T1 and T4. These differences explain the non-linearity of productivity and total root length or root length density. Root growth was dependent on the irrigation system, type of fertilization method, and soil covering, as was hypothesized.

Table 7. Means of productivity and water use efficiency of 'BRS Princesa' banana across all treatments. (T1 – drip system with side dressing fertilization and without soil covering; T2 –micro-sprinkler system with side dressing fertilization and without soil covering; T3 – drip system with soil covering and fertigation; T4 – drip system with fertigation and without soil covering; T5 – micro-sprinkler system with soil covering and fertigation; and T6 – micro-sprinkler system with fertigation and without soil covering).

Treatments	Productivity (t ha^{-1})	Water use efficiency (kg mm^{-1})
T1	21.087 b	17.20 b
T2	31.322 a	26.56 a
T3	30.512 a	24.85 a
T4	22.529 b	18.30 b
T5	32.586 a	27.73 a
T6	31.412 a	26.62 a
CV (%)	16.2	16.9

Means followed by the same letters in the column belong to the same significance group, according to the Scott-Knott criteria at $p < 0.05$.

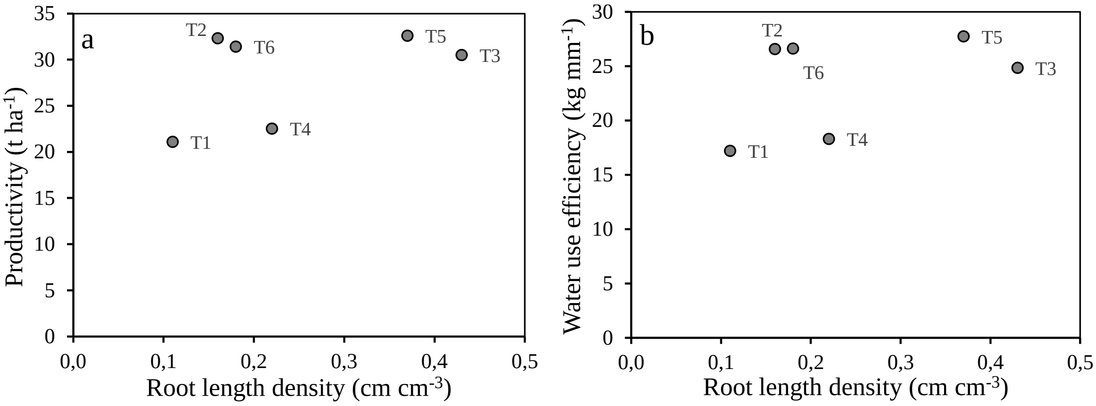

Figure 6. Productivity (a) and water use efficiency (b) of treatments as a function of root length density.

Root length density distribution

The higher mean RLD in the soil profile in T3 and T5 (Figure 3) was due to the deeper movement of water and nutrients from the emitters, which was enhanced by the small evaporation loss due to the biomass covering. In addition, the soil profile under drip irrigation with fertigation and biomass covering (T3) showed a linear decrease in RLD with soil depth (Figure 2a), which might be explained by the gradual decrease in soil water content with depth under the drip irrigation. The means of RLD did not change significantly with soil depth under the micro-sprinkler irrigation below 0.30 m soil depth (Figure 2b), since this system wets a larger area with more uniform soil moisture distribution compared to the drip system, as noted by Sant'Ana et al. (2012).

The larger means of RLD across all distances from the plant along the crop row observed in treatments with fertigation and biomass covering (Figure 3) highlighted the need for soil covering to improve the cultivation of banana crops. RLD decreased with distance from the plant along the crop row across all treatments (Figure 3). This is expected, since the root distribution patterns of plants establishes root concentration closer to the stem, especially under drip irrigation (Pisciotta et al., 2018). In addition, the non-uniform water distribution in the soil wetted volume under both the drip and micro-sprinkler irrigation systems influences root distribution through the different distances from the plant. Fertigated drip system with biomass covering (T3) resulted in the largest reduction rates in RLD as a function of distance from the plant (Figure 3) across the other treatments. The drippers were located near the plant at a distance of 0.50 m from both sides along the crop row in treatments T1, T3, and T4. These locations contributed to the soil water distribution up to a distance of 1.0 m from the plants according to the soil physical attributes, while the micro-sprinklers were located in the middle of two crop rows at 1.25 m from the plant and provided larger water depths nearer to that area than to the plant. This non-uniform water distribution was the reason for the lower rates of RLD at any distance from the plants under the micro-sprinkler systems (Figure 3).

Root diameter distribution

The results shown in Figure 4a and b highlighted that the classes of the very thin diameter (smaller than 0.5 mm) and the thin diameter (between 0.5 to 2.0 mm) were the most representative of the root system and this result was in agreement with previous studies (Lecompte, Pagès, & Ozier-Lafontaine, 2005; Carr, 2009; Sant’Ana et al., 2012). The distribution of fine and very fine roots, as a function of distance from the plant (Figure 5), demonstrated the presence of these root classes across distances between plants and treatments. Furthermore, there was a reduction in fine and very fine roots up to 0.50 m from the plants across all treatments, except for T5. The smaller variation rate in the percentage of fine and very fine root classes in treatments T1, T2, T5, and T6 (Figure 5) reflected a better distribution of those roots in the soil, which contributed to the water and nutrient uptake efficiency of the root system. The inherent soil moisture and nutrient distribution in the micro-sprinkler system (Table 5) influenced by both fertigation and soil biomass covering also contributed to a better distribution of fine and very fine roots within the depth of the soil. These distributions may have enhanced nutrient uptake and favored higher productivity and WUE (Table 7) in T5 and T6. Hence, the results of the present study demonstrated that the fertigation applied by drip and micro-sprinkler irrigation systems, as well as the use of biomass soil covering, contributed significantly to the changes in root distribution patterns and banana root growth.

Conclusion

Drip and micro-sprinkler irrigation systems with fertigation, as well as the use of biomass soil coverings, provided better conditions for root growth and distribution within the soil. Fine roots and very fine roots were the most illustrative among the root diameters until a depth of 0.50 and a distance of 0.50 m from the plant. Furthermore, the irrigation system, with or without fertigation as well as with fertigation and soil covering influenced the chemical and hydraulic soil attributes, which also influenced the root length and distribution within the soil. TRL or RLD was not linearly related to productivity and WUE during the first cycle of banana BRS Princesa.

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