ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.25, n.5, p.312-318, 2021
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v25n5p312-318

Management of trickle irrigation for banana: Hydrodynamic processes and sensor placement at the root zone[1]

Manejo da irrigação localizada para bananeiras: Processos hidrodinâmicos e posicionamento de sensores na zona radicular

Edvaldo B. Santana Junior[2*], Eugênio F. Coelho[3], Marcelo R. dos Santos[4], Alisson J. P. da Silva[5], João B. R. da S. Reis[6] & Bruno L. da S. Pereira[7]

[1] Research developed at Empresa de Pesquisa Agropecuária de Minas Gerais/Estação Experimental de Gorutuba, in northern Minas Gerais State, Brazil
[2] Instituto Federal de Educação, Ciência e Tecnologia do Piauí, Paulistana, PI, Brazil
[3] Embrapa Mandioca e Fruticultura, Cruz das Almas, BA, Brazil
[4] Instituto Federal de Educação, Ciência e Tecnologia Baiano, Guanambi, BA, Brazil
[5] Instituto Federal de Educação, Ciência e Tecnologia Baiano, Governador Mangabeira, BA, Brazil
[6] Empresa de Pesquisa Agropecuária de Minas Gerais, Nova Porteirinha, MG, Brazil
[7] Universidade Federal do Recôncavo da Bahia/Programa de Pós-Graduação em Engenharia Agrícola, Cruz das Almas, BA, Brazil

HIGHLIGHTS:

Microsprinkler flow-rates affect root water extraction and percolation within the wetted volume.
The number of lateral lines and emitters influences hydrodynamic processes under trickle.
Hydrodynamics within the wetted volume shed light on microirrigation sensor placement.

ABSTRACT: Information on soil hydrodynamic processes assists in explaining the soil-water-plant relationship and has practical applications to irrigation management, such as the definition of soil water sensor placement. The objective of this study was to detail the hydrodynamic process in the soil root zone and to define the location for placement of soil water sensor under different configurations of trickle irrigation in banana crops. Three micro-sprinkler emitters with flow rates of 70 (T1), 53 (T2), 35 L h^{-1} (T3), and two drip system, one with one drip line per row of plants (T4), and another with two drip lines per row of plants (T5) were evaluated. The experiment was conducted in a randomized block design with five repetitions. Higher water extraction was found for irrigation systems with higher flow rates for all configurations of trickle irrigation systems. Soil moisture sensors in drip systems should be placed at distances of 0.75 to 0.81 m from the pseudo stem and at depths of 0.33 to 0.44 m. Under micro-sprinkler systems, soil water sensors should be placed at 0.75, 0.77 and 0.83 m from the pseudo stem towards to the emitter and at depths of 0.33, 0.48 and 0.55 m for emitter flow rates of 35, 53 and 70 L h^{-1}, respectively.

Key words: *Musa* spp., drip irrigation, micro-sprinkler irrigation

RESUMO: O conhecimento do processo hidrodinâmico no solo ajuda a explicar a relação entre solo-água-planta com efeitos práticos no manejo da irrigação assim como no posicionamento de sensores de umidade no solo. O estudo foi realizado com o objetivo de detalhar o processo hidrodinâmico na zona radicular e definir a localização para o posicionamento do sensor de umidade do solo sob diferentes configurações de irrigação localizada na cultura da bananeira. Foram avaliados três microaspersores com vazões de 70 (T1), 53 (T2), 35 L h^{-1} (T3) e dois sistemas de gotejamento, (T4) - uma linha de gotejamento por linha de plantas, (T5) - duas linhas de gotejamento por linha de plantas. O experimento seguiu um delineamento em blocos casualizados consistindo de cinco tratamentos com cinco repetições. A extração de água foi maior nos sistemas de irrigação com maiores taxas de vazão para todas as configurações de sistemas de irrigação localizada. Os sensores de umidade do solo em sistemas de gotejamento devem estar a distâncias de 0,75 a 0,81m do pseudocaule e em profundidades de 0,33 a 0,44 m. Em sistemas de microaspersão, os sensores de umidade do solo devem estar a 0,75, 0,77 e 0,83 m do pseudocaule para o emissor e a profundidades de 0,33, 0,48 e 0,55 m para vazões de 35, 53 e 70 L h^{-1}, respectivamente.

Palavras-chave: *Musa* spp., irrigação por gotejamento, irrigação por microaspersão

• Ref. 228782 – Received 16 Sept, 2019
* Corresponding author - E-mail: edvaldobispo@gmail.com
• Accepted 03 Feb, 2021 • Published 05 Mar, 2021
Edited by: Hans Raj Gheyi

Introduction

Water is important for agricultural production and the rational management of water is decisive for plant development and sustainability of water resources. Geronimo et al. (2015) pointed out that an inefficient use of the available water resources may result in water shortage in the future. Information on water distribution in the soil is important and directly affects crop yields (Souza & Matsura, 2004). Thus, it is fundamental for irrigation design and management, including the determination of number of drippers per plant and their position in relation to the plant or plant row (Asawa, 2014; Lopes et al., 2009).

Water flow and distribution in irrigated soils differ in the different irrigation systems. Levien (2014) reported that drip irrigation differs from other systems in water flow because of the formation of a wet bulb below each emitter or, when emitters are arranged in rows, a continuous wet strip. Assessments of water distribution in the soil and definitions of root-zones have been carried out using time-domain reflectometry (TDR) (Santos & Martinez, 2013; Silva et al., 2015b; Santos et al., 2017).

Information about positioning of sensors is scarce and relies on root distribution studies (Bassoi et al., 2003; Sant'Ana et al., 2012). The effective root depth and distance (Sant'Ana et al., 2012) combined with the effective root-extraction depth and distance have been recommended as limits for sensor placement in irrigation systems (Santos et al., 2005; Coelho et al., 2007). However, root uptake varies with time and space in the effective root zone (Silva et al., 2018). Thus, the effective root zone for sensor placement also depends upon the crop type, soil type, irrigation system, and age of plants (Coelho et al., 2007). The objective of this study was to detail the hydrodynamic process in the root zone and define the location for placement of soil moisture sensor under different configurations of trickle irrigation in banana crops.

Material and Methods

The study was carried out in 2011 at the Experimental Station of Gorutuba, in northern Minas Gerais State, Brazil (15° 47' S, 43° 18' W, and 516 m of altitude), which belongs to the Empresa de Pesquisa Agropecuária de Minas Gerais (EPAMIG). The region presents a BSwh, hot semi-arid climate with dry winter, according to the Köppen classification (Alvares et al., 2013). The rainfall depth in 2011 was 695 mm, but only March and October presented more than 100 mm per month; the rainfall depth was 10.3 mm during the data collection period (June to September). The soil of the area was classified as a Typic Hapludox; the soil physical and hydraulic attributes is presented in Table 1. The soil water retention curve parameters were: α = 0.6826; n = 1.3345; m = 0.2569, saturation water content = 0.3200 $m^3\ m^{-3}$, and residual water content = 0.2100 $m^3\ m^{-3}$.

The study was conducted using banana crops of the Prata cultivar grown in single plant rows, with spacing of 3.0 × 2.5 m. The experiment was carried out in a randomized block design, with five repetitions and five treatments: T1 - Micro-sprinkler; 70 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows; T2 - Micro-sprinkler; 53 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows; T3 - Micro-sprinkler; 35 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows; T4 - Dripper; 4 L h^{-1} and one lateral line per plant row with on-line emitters spaced 0.7 m apart; and T5 - Dripper; 4 L h^{-1} and two lateral lines per plant row with on-line emitters spaced 0.7 m apart. Irrigation water depths were the same in all treatments, performed on a daily basis, and calculated from daily evaporation data measured by using a Class A pan (EVA), taking into account the pan correction factor (Bernardo et al., 2006), location coefficient (Kl) (Bernardo et al., 2006), and crop coefficient (Kc) (Coelho et al., 2004). The total calculated crop evapotranspiration during the year was 1038 and 593 mm from June to September.

Trenches (1.0 m deep and 1.0 m wide) were opened from the pseudo-stem along the plant row for the drip-irrigation treatments, and from the plant towards the emitter for the micro-sprinkler irrigation treatments. Soil water content (θ) in the root zone of the banana plants were measured at the flowering and beginning of fruit formation stages from June to September. TDR (time-domain reflectometry) probes, containing three 0.1 m long rods (Silva et al., 2015a), which were previously calibrated (Soncela et al., 2013; Batista et al., 2016), were inserted into each trench, at distances of 0.25, 0.50, 0.75, and 1.00 m from the pseudo-stem (r) and at depths of 0.20, 0.40, 0.60, and 1.00 m (z). Each trench wall was considered a two-dimensional plane for the purpose of measuring the hydrodynamic processes.

Soil moisture content (θ) at each distance from the pseudo-stem and soil depth (r_i; z_i) was measured with TDR by using multiplexers and continuously and automatically recorded in a datalogger every 15 min.

The limited number of multiplexers and TDR allowed evaluating the hydrodynamic processes in only one trench of each treatment. Infiltrated water (IW), water extraction (WE), and percolating water (PW) were determined for each treatment by using soil moisture data measured over irrigation cycles. IW (Eq. 1) was determined by the difference between the amount of water stored in the root zone limited by 1.0 m distance from plant (r = 1.0 m) and by 1.0 m soil depth (z = 1.0 m) at the time t+1 and t; t refers to the time immediately after an irrigation, and t+1 refers to the time the irrigation water

Table 1. Soil physical characteristics of the experimental area

Depth (m)	Sand	Silt	Clay	Moisture (kPa) 10	Moisture (kPa) 1500	Soil density (kg dm^{-3})
	(g kg^{-1})			($m^3\ m^{-3}$)		
0-0.20	483	234	283	0.250	0.186	1.70
0.20-0.40	444	263	293	0.296	0.258	1.60
0.40-0.60	456	251	293	0.301	0.253	1.60

reached the zone limited by r = 0.25 m and z = 0.60 m. WE (Eq. 2) was quantified by the difference between the amount of water stored in the root zone at time t+1 and at t+2 (time immediately after the subsequent irrigation).

$$IW = \int_{z_i=0}^{z_i=1m} \int_{r_i=0.25m}^{r_i=1m} \left[\theta_{t+1}(r_i, z_i) - \theta_t(r_i, z_i)\right] drdz \quad (1)$$

$$WE = \int_{z_i=0}^{z_i=1m} \int_{r_i=0.25m}^{r_i=1m} \left[\theta_{t+1}(r_i, z_i) - \theta_{t+2}(r_i, z_i)\right] drdz \quad (2)$$

where:

θ_t (r_i, z_i) - soil moisture content at (r_i, z_i) and at time t, m^3 m^{-3};

θ_{t+1} (r_i, z_i) - soil moisture content at (r_i, z_i) and at time t+1, m^3 m^{-3}; and,

θ_{t+2} (r_i, z_i) - moisture content at (r, z) and at time t+2, m^3 m^{-3}.

The integrals were solved numerically by using the trapezium rule.

Water extraction (WE) included soil evaporation, deep percolation (PW), and root extraction. Deep percolation was assumed as the water in the soil layer below the effective rooting depth between two irrigation events. Effective rooting depth was assumed as that with 80% of total root length (Kanber et al., 1996), which was 0.40 m based upon the results of Sant'Ana et al. (2012). Thus, deep percolation was assumed as the difference between water content stored in the soil layer limited by depths 0.40 and 1.00 m at time t (immediately before an irrigation event) and at time t+2 (time before the next irrigation event). The water stored (WS) in the layer at any time (t_i) limited by depths 0.40 and 1.00 m was given by Eq. 3.

$$WS_{ti} = \int_{z_i=0}^{z_i=1m} \int_{r_i=0.25m}^{r_i=1m} \left[\theta_{t_i}(r_i, z_i)\right] drdz - \int_{z_i=0}^{z_i=0.40m} \int_{r_i=0.25m}^{r_i=1m} \left[\theta_{t_i}(r_i, z_i)\right] drdz \quad (3)$$

Root distribution was evaluated by using the monolith method, using monoliths of 0.1 × 0.1 × 0.1 m (Bohm, 1979). The samples were collected at the distances of 0.25, 0.50, 0.75, and 1.0 m, and depths of 0.1, 0.2, 0.4, 0.6, and 0.8 m. The roots were separated from the soil by washing and digitalized as TIFF (Tagged Image File Format). The files were then processed in the software Rootedge to determine total root length at each position (r_i,z_i). The individual root length data were processed to obtain the effective root distance and depth according to Sant'Ana et al. (2012). Root distribution in depth and distance from the plant was evaluated in a randomized block statistical design using a split-split plot arrangement, with five treatments, five depths, and four distances from the plant.

Water extraction was related to soil water availability (AW) that was obtained in each point (ri, zi) of the trench, using the soil moisture content $\theta_{(ri,\ zi)}$ (Eq. 4).

$$AW_{(r_i, z_i)} = \left(\frac{\theta_{(r_i, z_i)} - \theta_{pwp}}{\theta_{cc} - \theta_{pwp}}\right)100 \quad (4)$$

where:

$AW_{(ri,\ zi)}$ - percentage of available water at a point (ri, zi) in the soil profile;

$\theta_{(ri,\ zi)}$ - moisture content at the monitoring position (ri, zi), m^3 m^{-3};

θ_{cc} - moisture content at field capacity, m^3 m^{-3}; and,

θ_{pwp} - water content at permanent wilting point (m^3 m^{-3}).

θ_{cc} and θ_{pwp} - constants of the soil water contents at -10 and -1500 kPa, respectively (Table 1).

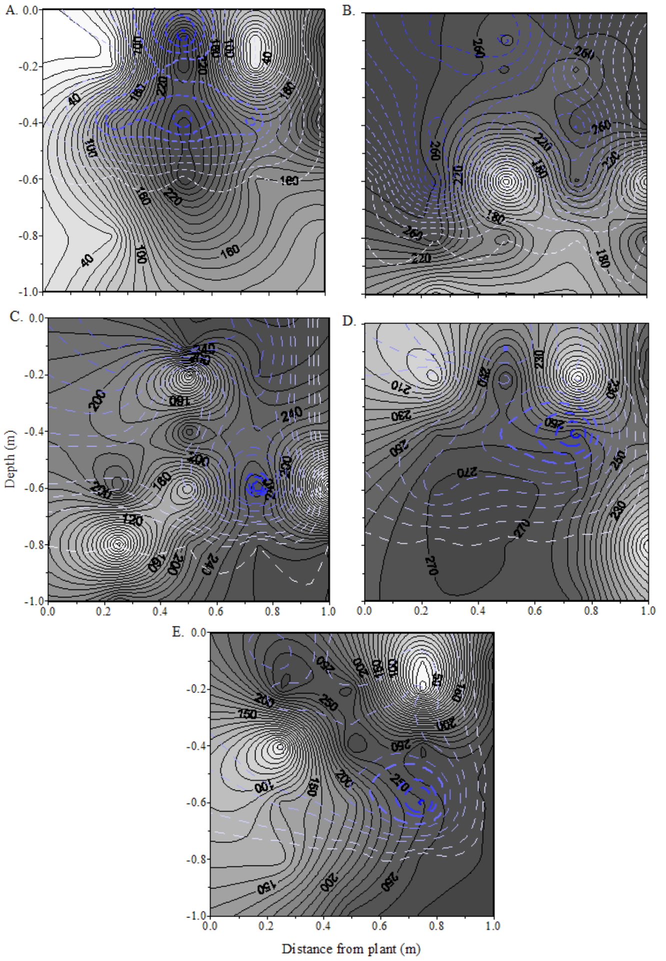
This study considered the suitable location in the root zone for placing soil moisture sensors as the intersection between the zones of effective root distribution and effective water extraction. The effective rooting zone was assumed as that with at least 80% of total root length found in the trench. The effective water uptake zone was assumed as that with at least 80% of total water extraction in the trench (Santos et al., 2005).

The average soil moisture content data collected on the bi dimensional plane of each treatment from June to September was used to evaluate the infiltrated water (IW), extracted water (WE), percolated water, and available water. Analysis of variance was performed for root data, focusing on root distribution.

Results and Discussion

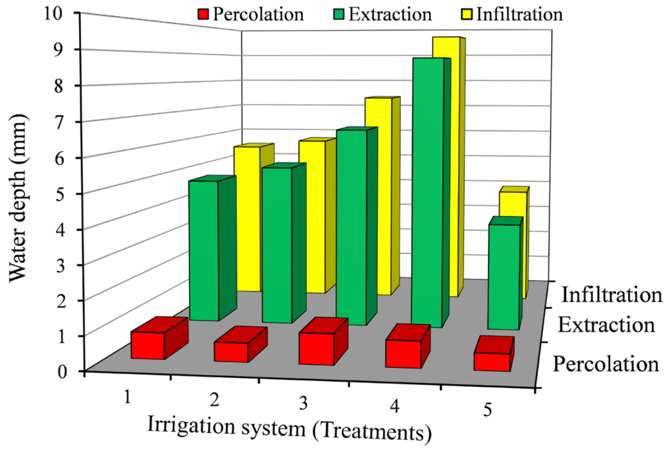
The use of one-drip lateral lines per plant row resulted in higher water depths than two lateral lines per plant row. This larger water depth is a result of a smaller wetted area under the soil surface when using one lateral line, considering that the same volume of water was applied using two lateral lines per plant row. Available water contents were above the upper limit, which corresponds to the field capacity of the soil (Figure 1). The highest water availability in the soil irrigated by one-drip lateral line is due to the area and volume watered by the drippers, which were spaced 0.70 m apart. The use of two lateral lines resulted in a greater total wetted area per plant. A single lateral line per plant row wetted an area that corresponded to half the area and soil volume watered when using two lateral lines with drippers under the same conditions and applying the same amount of water. Micro-sprinklers provided larger wetted areas than drippers (Figure 1).

Both irrigation systems (micro-sprinkler and drip) showed losses by percolation (Figure 2). The losses found for the one-drip lateral line per plant row were higher than those found for two-drip lateral lines per plant row. The micro-sprinkler irrigation showed lower percolation losses for flow rates of 35 and 53 L h^{-1} than for the rate of 70 L h^{-1}. Water extraction from the system (WE), which includes percolation, evaporation, and water uptake by roots, were affected by the irrigation system and its configurations, i.e., flow rates of emitters and number of lateral lines (drip system). The highest water extraction rates occurred under higher flow rates of micro-sprinklers and drip irrigation with one lateral line per plant row (Figure 2). Micro-sprinklers applied lower



(A) T1 - Micro-sprinkler, 70 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows;
(B) T2 - Micro-sprinkler, 53 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows;
(C) T3 - Micro-sprinkler, 35 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows;
(D) T4 - Dripper, 4 L h^{-1} and one lateral line per plant row with on-line emitters spaced 0.7 m apart;
(E) T5 - Dripper, 4 L h^{-1} and two lateral lines per plant row with on-line emitters spaced 0.7 m apart

Figure 1. Available water (dark lines) and uptake (blue lines) for micro-sprinkler irrigation treatments: T1 (A), T2 (B), T3 (C), with water emitters at 1.0 m from plant, and drip irrigation treatments: T4 (D) and T5 (E), with drippers as water emitters



1 - Micro-sprinkler, 70 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows;
2 - Micro-sprinkler, 53 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows;
3 - Micro-sprinkler, 35 L h^{-1} and one emitter for four plants located in one lateral line between two plant rows;
4 - Dripper, 4 L h^{-1} and one lateral line per plant row with on-line emitters spaced 0.7 m apart;
5 - Dripper, 4 L h^{-1} and two lateral lines per plant row with on-line emitters spaced 0.7 m apart

Figure 2. Infiltration, extraction, and percolation water depth in profiles of soils irrigated by micro-sprinkler (1, 2, 3) and drip (4 and 5) systems

water depths than drippers due to their larger wetted area and unevenly water distribution. The one-drip line waters a smaller area than two lateral lines, which results in a higher water depth. According to Silva et al. (2009), increasing the number of the drip emitters in lateral lines results in larger root zone distribution, larger water extraction, smaller losses by percolation flow, and higher water application efficiency in banana crops. This difference is even greater when compared with micro-sprinklers.

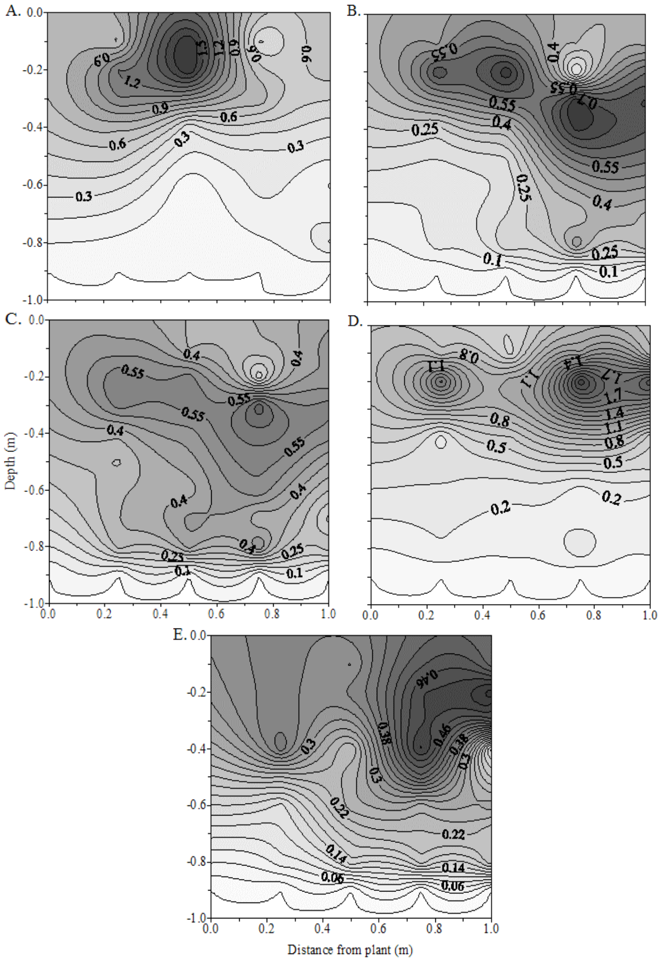
Regions of higher water extraction in the root zone of the banana plants overlapped zones in the soil where water was more readily available (Figure 1). This result was also reported by Silva et al. (2009) and Carvalho (2011) and confirmed what was expected, since zones with the highest water availability are those in which plants can uptake water more easily, as long as water-uptake roots are present. Additionally, Silva et al. (2013) concluded that available soil water distribution in the root zone affects the water extraction rate by the plant, deep percolation, and irrigation efficiency when the same volume of water is applied by micro-sprinklers with different flow rates on the lateral line. After irrigation, treatment 1 exhibited average available water content of 57.20%, at the distance of r = 0.25 m. The highest water extraction rates occurred up to the depth of 0.4 m, where water is more readily available (Figure 1), and the effective rooting depth occurred up to 0.36 m (Figure 3A and Figure 4A).

The remaining treatments exhibited higher soil available water contents, water extraction at depths higher than 0.40 m, and effective rooting depths, which were 0.48, 0.55, 0.33, and 0.44 m, for treatments T2, T3, T4, and T5, respectively (Figure 3 and Figure 4A).

The effective distances of roots were 0.75, 0.79, 0.83, 0.82, and 0.81 m, for treatments T1, T2, T3, T4, and T5, respectively (Figure 3 and Figure 4B). These results are consistent with those found by Calheiros (1992), Borges et al. (2008), Silva et al. (2009), and Sant'Ana et al. (2012).

Available soil water distribution affects water extraction zones, as seen in treatment T1, whose average available water content at the distance of 0.25 m from the plant after irrigation was 57.20% and the percentage of total extracted water from the effective rooting zone was 23.37%. Regarding the distance from the plant of 0.50 m, where the average available water content increased 269%, the percentage of total extracted water from the effective rooting zone was 37.41%.

Effective rooting depths (Figure 3) and distances from the plant matched the effective water extraction zone (Figure 1), as also reported by Carvalho (2011). Eighty percent of roots in treatment T1 were up to 0.36 m deep and 0.75 m away from the plant, whereas 80% of the total water extraction occurred up to 0.33 m deep and 0.77 m away from the pseudo-stem, denoting that most absorbing roots were at the effective depth of water extraction. The effective depth of water extraction in treatment T5 was 0.60 m from the soil surface, which did not match the



(A) T1 - Micro-sprinkler, 70 L h-1 and one emitter for four plants located in one lateral line between two plant rows;
(B) T2 - Micro-sprinkler, 53 L h-1 and one emitter for four plants located in one lateral line between two plant rows;
(C) T3 - Micro-sprinkler, 35 L h-1 and one emitter for four plants located in one lateral line between two plant rows;
(D) T4 - Dripper, 4 L h-1 and one lateral line per plant row with on-line emitters spaced 0.7 m apart;
(E) T5 - Dripper, 4 L h-1 and two lateral lines per plant row with on-line emitters spaced 0.7 m apart

Figure 3. Root length density in the profiles of soils irrigated by micro-sprinkler: T1 (A), T2 (B) and T3 (C), and drip: T4 (D) and T5 (E) at the end of the crop cycle

effective rooting depth measured at 0.44 m. In this case, the effective distance of water extraction, was found at 0.86 m from the pseudo-stem of the banana trees, which somewhat relates to the effective distance of the root system, 0.81 m.

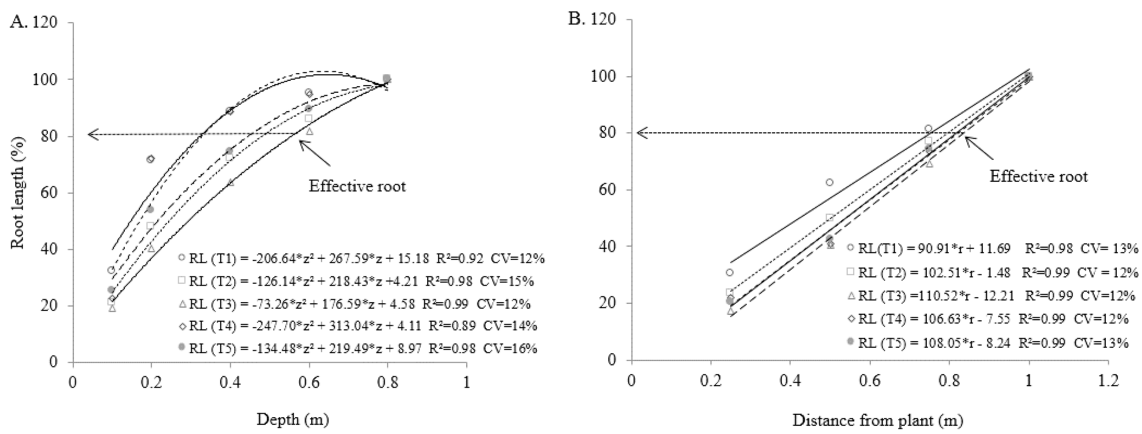
The optimal soil moisture sensor positioning was determined by the intersection between the effective zones of higher water extraction and the soil region with 80% of total roots.

The depths and distances from the plants for an adequate positioning of sensors in the soil irrigated with drip and micro-sprinkler irrigation systems are shown in Table 2. The ideal regions of sensor placement found was up to 0.75 m, from the pseudo-stem and up to 0.33 m deep, towards the micro-sprinkler for treatment T1; up to 0.80 m from pseudo-stem and up to 0.48 m deep for treatment 2; and up to 0.83 m from pseudo-stem towards the micro-sprinkler, and up to 0.55 m deep for treatment 3. These results are in agreement with those proposed by Silva et al. (2018), who applied the concept of Time Stable Representative Proposition (TSRP) and found two patterns of water uptake for banana crops as a function of the developmental stages: one characterizes the initial and vegetative growth stage, when the effective water extraction occurs up to the distance of 0.70 m from the plant, and the other characterizes the flowering and fruit growth stages, when the effective extraction occurs up to 0.90 m from

Table 2. Distances from plant and soil depth for placement water content or potential sensors in the root zone of banana crops

Treatment	Depth	Distance from plant
	(m)	
T1	0-0.33	0-0.75
T2	0-0.48	0-0.77
T3	0-0.55	0-0.83
T4	0-0.33	0-0.75
T5	0-0.44	0-0.81

T1 - Micro-sprinkler, 70 L h-1 and one emitter for four plants located in one lateral line between two plant rows; T2 - Micro-sprinkler, 53 L h-1 and one emitter for four plants located in one lateral line between two plant rows; T3 - Micro-sprinkler, 35 L h-1 and one emitter for four plants located in one lateral line between two plant rows; T4 - Dripper, 4 L h-1 and one lateral line per plant row with on-line emitters spaced 0.7 m apart; T5 - Dripper, 4 L h-1 and two lateral lines per plant row with on-line emitters spaced 0.7 m apart



T1 - Micro-sprinkler, 70 L h-1 and one emitter for four plants located in one lateral line between two plant rows;
T2 - Micro-sprinkler, 53 L h-1 and one emitter for four plants located in one lateral line between two plant rows;
T3 - Micro-sprinkler, 35 L h-1 and one emitter for four plants located in one lateral line between two plant rows;
T4 - Dripper, 4 L h-1 and one lateral line per plant row with on-line emitters spaced 0.7 m apart;
T5 - Dripper, 4 L h-1 and two lateral lines per plant row with on-line emitters spaced 0.7 m apart
* - Significant at $p \leq 0.05$ by F test

Figure 4. Percentage of total length as a function of depth (A) and of distance from the plant (B) for irrigated systems: micro-sprinkler (T1, T2 and T3) and drip (T4 and T5)

the plant. Moreover, Silva et al. (2012) reported that effective water extraction in banana crops is up to the distance of 0.70, 0.80, and 1.00 m from the plants for one micro-sprinkler at 32 L h^{-1} for four plants, at 60 L h^{-1} for four plants, and at 60 L h^{-1} for two plants, respectively.

These results may be used with confidence, since the sensor placement region in the soil recommended in this study are within the limits reported by Silva et al. (2009), who determined positioning of sensors for banana crops irrigated by micro-sprinklers under sub-humid climate and recommend the range of 0.10 and 0.80 m from the pseudo-stem, up to the depth of 0.25 m. Moreover, the recommended range of distance and depth are within the limits reported by Coelho et al. (2010), who proposed an ideal zone to placing sensors in soils with banana crops irrigated by four drippers per plant of 0.50 m from pseudo-stem and up to 0.35 m deep. Regarding the percent distribution of water extraction relative to soil depth, two patterns of soil water extraction distribution were also found by Silva et al. (2018): the first characterizes the initial and vegetative growth stages, when the effective water extraction occurs up to depth of 0.30 m, and the second characterizes the flowering and fruit growth stages, when the effective water extraction reaches the depth of 0.40 m.

Conclusions

1. Water extraction and percolation in the soil profile decreased as the flow rate of the emitter was increased from 35 to 70 L h^{-1} in the micro-sprinkler system.

2. Water extraction in the soil profile and percolation decreased as the wetted area was increased, i.e., when using two-drip lateral lines per plant row in the drip system.

3. The effective distances and depths of water extraction are related to the effective rooting distances and depth of banana plants, in both micro-sprinkler and drip irrigation systems.

4. In drip systems, soil moisture sensors should be at distances of 0.75 to 0.81 m from the pseudo stem and at depths of 0.33 to 0.44 m. In micro-sprinkler systems, soil water sensors should be at 0.75, 0.77, and 0.83 m from the pseudo stem towards to the emitter and at depths of 0.33, 0.48, and 0.55 m for emitter flow rates of 35, 53, and 70 L h^{-1}, respectively.

Literature Cited

Alvares, C. A. Stape, J. L.; Sentelhas, P. C.; Gonçalves, J. L. de M.; Sparovek, G. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, Stuttgart, v.22, p.711-728, 2013. https://doi.org/10.1127/0941-2948/2013/0507

Asawa, G. L. Irrigation and water resources engineering, New Age International (P) Limited Publishers, New Delhi, 2014. 624p.

Bassoi, L. H.; Hopmans, J. W.; Jorge, L. A. de C.; Alencar, C. M. de; Silva, J. A. M. e. Grapevine root distribution in drip and sprinkler irrigation. Scientia Agrícola, v.60, p.377-387, 2003. https://doi.org/10.1590/S0103-90162003000200024

Batista, L. dos S.; Coelho, E. F.; Pereira, F. A. de C.; Silva, M. G. da; Gonçalves, A. de A.; Gomez Filho, R. R. Calibração de sondas artesanal de uso com TDR para avaliação da umidade do solo. Revista Brasileira de Agricultura Irrigada, v.10, p.522-532, 2016. https://doi.org/10.7127/rbai.v10n200388

Bernardo, S.; Soares, A. A.; Mantovani, E. C. Manual de irrigação. 8 ed. Viçosa: Ed. UFV. 625p, 2006.

Bohm, W. Methods of studing root systems. New York: Springer-Verlag, 1979. 190p. https://doi.org/10.1007/978-3-642-67282-8

Borges, A. L.; Souza, L. da S.; Peixoto, C. A. B.; Santos Júnior, J. L. C. dos. Distribuição do sistema radicular da bananeira prata-anã em duas freqüências de fertirrigação com uréia. Revista Brasileira de Fruticultura, v.30, p.259-262, 2008. https://doi.org/10.1590/S0100-29452008000100048

Calheiros, R. O. Sistema radicular de quatro culturas em solo Glei pouco húmico da região de Londrina. Revista Brasileira de Ciência do Solo, v.16, p.299-307, 1992.

Carvalho, G. C. Variáveis de crescimento, produção e da relação solo-água-planta no mamoneiro sunrise solo sob configurações de sistemas de irrigação localizada. Cruz das Almas: UFRB, 2011. 92p. Tese Doutorado

Coelho, E. F.; Costa, E. L.; Teixeira, A. H. C. Irrigação. In: Borges, A. L., Souza, L. S. (Org.). O cultivo da bananeira. 1 ed. Cruz das Almas: Embrapa Mandioca e Fruticultura, v.1, p.132-145, 2004.

Coelho, E. F.; Santos, D. B. dos; Azevedo, C. A. V. de. Sensor placement for soil water monitoring in lemon irrigated by micro sprinkler. Revista Brasileira de Engenharia Agrícola e Ambiental, v.11, p.46-52, 2007. https://doi.org/10.1590/S1415-43662007000100006

Coelho, E. F.; Silva, A. J. P. da; Miranda, J. H. de. Definição do posicionamento de sensores para monitoramento da água no solo em bananeira irrigada por diferentes sistemas de irrigação localizada. Engenharia Agrícola, v.30, p.608-618, 2010. https://doi.org/10.1590/S0100-69162010000400005

Geronimo, J. A.; Henriques, P. D.; Carvalho, M. L. da S. Impactes do preço da água na agricultura no Perímetro Irrigado do Vale de Caxito. Revista de Economia e Sociologia Rural, v.53, p.699-714, 2015. https://doi.org/10.1590/1234-56781806-9479005304008

Kanber, R.; Köksal, H.; Önder, S.; Eylen, M. Effects of different irrigation methods on yield, evapotranspiration and root development of young orange trees. Turkish Journal of Agriculture and Forestry, Ankara, v.20, p.163-172, 1996.

Levien, S. L. A. Simulação de formação de faixa molhada na irrigação por gotejamento superficial em solo franco. Irriga, v.1, p.47-54, 2014. https://doi.org/10.15809/irriga.2014v1n1p47

Lopes, L. do N.; Martins, E.; Santoro, B. de L.; Souza, C. F. Caracterização da distribuição da água no solo para irrigação por gotejamento. Irriga, v.14, p.564-577, 2009. https://doi.org/10.15809/irriga.2009v14n4p564-577

Sant'Ana, J. A. do V.; Coelho, E. F.; Faria, M. A. de; Silva, E. L. da; Donato, S. L. R. Distribuição de raízes de bananeira 'Prata-Anã' no segundo ciclo de produção sob três sistemas de irrigação. Revista Brasileira de Fruticultura, v.34, p.124-133, 2012. https://doi.org/10.1590/S0100-29452012000100018

Santos, D. B. dos; Coelho, E. F.; Azevedo, C. A. V. de. Absorção de água pelas raízes do limoeiro sob distintas frequências de irrigação. Revista Brasileira de Engenharia Agrícola Ambiental, v.9, p.327-333, 2005. https://doi.org/10.1590/S1415-43662005000300006

Santos, M. R.; Coelho, E. F.; Donato, S. L. R.; Rodrigues, M. G. V. Distribuição de raízes e extração de água da bananeira 'BRS Princesa' sob diferentes configurações de irrigação. Engenharia na Agricultura, v.24, p.513-522, 2017. https://doi.org/10.13083/reveng.v24i6.701

Santos, M. R. dos; Martinez, M. A. Soil water distribution and extraction by 'Tommy Atkins' mango (*Mangifera indica* L.) trees under different irrigation regimes. Idesia, v.31, p.7-16, 2013. https://doi.org/10.4067/S0718-34292013000300002

Silva, A. J. P. da; Coelho, E. F.; Coelho Filho, M. A. Water extraction variability in the banana root zone affects the reliability of water balance. Scientia Agricola, v.72, p.1-10, 2015a. https://doi.org/10.1590/0103-9016-2014-0003

Silva, A. J. P. da; Coelho, E. F.; Coelho Filho, M. A.; Souza, J. L. Water extraction and implications on soil moisture sensor placement in the root zone of banana. Scientia Agricola, v.75, p.95-101, 2018. https://doi.org/10.1590/1678-992x-2016-0339

Silva, A. J. P. da; Coelho, E. F.; Miranda, J. H. de. Sensor placement for irrigation scheduling in banana using micro-sprinkler system. Water Resources and Irrigation Management v.1, p.15-23, 2012.

Silva, A. J. P. da; Coelho, E. F.; Miranda, J. H. de. Efficiency of water application of irrigation systems based on micro-sprinkling in banana plantations. Scientia Agricola, v.70, p.139-146, 2013. https://doi.org/10.1590/S0103-90162013000300001

Silva, A. J. P. da; Coelho, E. F., Miranda, J. H. de; Workman, S. R. Estimating water application efficiency for drip irrigation emitter patterns on banana. Pesquisa Agropecuária Brasileira, v.44, p.730-737, 2009. https://doi.org/10.1590/S0100-204X2009000700013

Silva, J. R. L.; Montenegro, A. A. de A.; Monteiro, A. L. N.; Silva Junior, V. de P. e. Modelagem da dinâmica de umidade do solo em diferentes condições de cobertura no semiárido pernambucano. Revista Brasileira de Ciências Agrárias, v.10, p.293-303, 2015b. https://doi.org/10.5039/agraria.v10i2a4219

Soncela, R.; Sampaio, S. C.; Vilas Boas, M. A; Tavares, M. H. F., Smanhoto, A. Construction and calibration of TDR probes for volumetric water contente estimation in a Distrofic Red Latossol. Engenharia Agrícola, v.34, p.919-928, 2013. https://doi.org/10.1590/S0100-69162013000500004

Souza, C. F.; Matsura, E. E. Distribuição da água no solo para o dimensionamento da irrigação por gotejamento. Revista Brasileira de Engenharia Agrícola e Ambiental, v.8, p.7-15, 2004. https://doi.org/10.1590/S1415-43662004000100002