Effect of Irrigation Pattern and Timing on Root Density of Young Citrus Trees Infected with Huanglongbing Disease

Davie M. Kadyampakeni^{1,4}, Kelly T. Morgan¹,
Arnold W. Schumann², and Peter Nkedi-Kizza³

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SUMMARY. Citrus (*Citrus* sp.) root length density (RLD) can help in understanding and predicting nutrient and water uptake dynamics. A study was conducted at two sites in Florida to investigate root and water distribution patterns among different irrigation and fertigation systems. The results over the 2 years showed that RLD was highest in the 0- to 15-cm soil depth and decreased with depth for all treatments at both sites. About 64% to 82% of the fibrous roots (<1 mm diameter) were concentrated in the irrigated zones of drip- and microsprinkler-irrigated trees and 18% to 36% were found in the nonirrigated zones at the Spodosol site (SS). At the Entisol site (ES), the RLD (<0.5 mm diameter) in the 0- to 15-cm depth soil for intensive microsprinkler or drip irrigation was 3- to 4-fold (nonirrigated zone) and 4- to 7-fold (irrigated zone) greater at the 0- to 15-cm soil depth than that for conventional irrigation system. The trees at SS were symptomatic for Huanglongbing (HLB; *Candidatus Liberibacter asiaticus*) in the second year, while those at ES were asymptomatic throughout the study. This might have limited the density and extent of root distribution at SS. The water contents remained either close to or slightly above the field capacity. The results showed higher RLD for intensive irrigation and fertigation practices in irrigated zones compared with conventional grower applications suggesting greater water and nutrient uptake potential for the former.

Understanding citrus root distribution is critical for predicting potential pathways of water and nutrient uptake. Studies conducted in Florida over the past 40 years have shown that tree size and yield were intrinsically linked to root density distribution (Castle and Krezdorn, 1975; Eissenstat, 1991; Morgan et al., 2006, 2007). Research has shown that citrus rootstocks with the greater root weight or RLD resulted in greatest water

extraction rates from the soil occupied by the roots (Castle, 1980; Castle and Krezdorn, 1975; Eissenstat, 1991; Morgan et al., 2006, 2007). Coleman (2007) observed that RLD of woody crops was dependent upon tree age, soil depth, and position relative to drip emitter when fertilizers were applied and was greatest at the surface and in proximity to the drip line. Abrisqueta et al. (2008) studied root dynamics of young peach (*Prunus persica*) trees subjected to partial root zone drying and continuous deficit irrigation in Spain. Root length densities were greater in nonlimiting irrigation conditions than those under deficit irrigation where root growth was reduced.

Current citrus fertigation/fertilization practices in Florida are

infrequent and thus, low intensity (Alva et al., 2003, 2006; Koo, 1980). The conditions under which intensive fertigation practices work in Florida citrus producing regions dominated by well-drained sandy soils (Obreza and Collins, 2008) have only recently been investigated (Morgan et al., 2009; Schumann et al., 2009). Intensive fertigation practices are being devised primarily to manage HLB disease and increase yields so growers break-even within a few years of establishing a grove. Graham et al. (2013) found that HLB-infected trees had up to 40% root loss to bacterial infection of roots with potential additional root loss because of the interaction with the root pathogen *Phytophthora nicotianae* depending on grove location.

This study evaluated intensive fertigation practices already in use in citrus production systems in Australia, Chile, South Africa, and Spain (Carrasco et al., 2003; Kruger et al., 2000a, 2000b; Martinez-Valero and Fernandez, 2004) modified for Florida sandy soils. Thus, knowledge of RLD distribution in response to the patterns of water and nutrient application in the citrus root zone may guide the citrus growers and researchers in optimization of irrigation and fertigation practices. Past root density studies in Florida have concentrated on mature trees older than 5 years (Alva and Syvertsen, 1991; Castle and Krezdorn, 1975; Eissenstat, 1991; Mattos et al., 2003; Morgan et al., 2006, 2007). Thus, this study was conducted to determine RLD and water distribution associated with young trees subject to intensive fertigation management with low volume irrigation and the interaction with the damaging effect of HLB on fibrous roots. The objectives of the study were to 1) determine RLD of 1- and 3-year-old citrus trees; 2) compare the distribution of RLD and water as a function of time, distance from the tree, soil depth and fertigation

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¹Southwest Florida Research and Education Center, University of Florida, 2685 SR 29N, Immokalee, FL 34142

²Citrus Research and Education Center, University of Florida, 700 Experiment Station Road, Lake Alfred, FL 33850

³Soil and Water Science Department, University of Florida, 2181 McCarty Hall, P.O. Box 110290, Gainesville, FL 32611

⁴Corresponding author. E-mail: dkadyampakeni@ufl.edu.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.1550	inch/inch ³	cm-cm ⁻³	6.4516
16.3871	inch ³	cm ³	0.0610
1	meq/100 g	cmol·kg ⁻¹	1
1.7300	oz/inch ³	g-cm ⁻³	0.5780

method; and 3) determine differences between the two sites associated with the presence of citrus greening.

Materials and methods

SITE CONDITIONS. The study was conducted at two sites 1) a site at the University of Florida, Southwest Florida Research and Education Center, Immokalee, FL (lat. 26°25'N, long. 81°25'W) with a Spodosol classified as Immokalee fine sand (sandy, siliceous, hyperthermic Arenic Haplaquods) with an excessively drained upper horizon and a low conductivity horizon at less than 1 m from the surface (SS) and 2) a site near the Citrus Research and Education Center, Lake Alfred, FL (lat. 28°5'N, long. 81°45'W) with Candler fine sand (hyperthermic, coated Typic Quartzipsamments) an Entisol excessively drained throughout the profile (ES) (Obreza and Collins, 2008). 'Hamlin' orange (*Citrus sinensis*) trees on 'Swingle' (*Citrus paradisi* × *Poncirus trifoliata*) rootstock were planted in Apr. 2006 at 10 × 22 ft on 13.5-m-wide beds with drainage swales at SS. 'Hamlin' orange trees on 'Swingle' and 'C35' (*Citrus trifoliata* × *C. sinensis* 'Ruby') rootstocks were planted at 10 × 20 ft and 8 × 18 ft, respectively, at ES in Dec. 2008.

The soil characteristics for the two sites are described in Table 1. The pH, bulk density, hydraulic conductivities, and moisture contents at saturation and field capacity are similar for the two sites. The two soils are characterized by low organic matter; however, the soil at the ES has 3- to 4-fold the organic matter at the SS. The cation exchange capacity in the top 0–15 cm is similar for the two soils, but 2- to 5-fold greater for ES than SS in the 15- to 45-cm soil depth due to presence of aluminum/iron coatings, and five times greater at SS at 45- to 60-cm soil depth, due to the spodic soil horizon.

EXPERIMENTAL DESIGN AND IRRIGATION TREATMENTS. Irrigation and fertilizer treatments were as follows: 1) irrigated with selected allowable soil water depletion between irrigations at the two sites but fertigated monthly with 360° microsprinklers (full-circle microsprinkler) wetting a circle 4.5 m in diameter at SS and fertilized with soluble materials four to six times per year at ES (Conventional); 2) irrigated daily and fertigated weekly

Table 1. Selected soil properties for the Spodosol site (SS) and Entisol site (ES) measured at 0- to 15-cm, 15- to 30-cm, 30- to 45-cm, and 45- to 60-cm soil depths.

Site	Soil depth (cm) ^z	Cation					Bulk density (g·cm ⁻³) ^z	Saturated hydraulic conductivity (cm·h ⁻¹)	Hydraulic conductivity at field capacity (cm·h ⁻¹) ^y	Saturated moisture content (cm ³ ·cm ⁻³) ^z	Moisture content at field capacity (cm ³ ·cm ⁻³)
		pH ^y	Organic matter (%) ^x	Cation exchange capacity (cmol·kg ⁻¹) ^w	Sand (%)	Silt (%)	Clay (%)				
SS	0–15	5.6	0.61	7.63	98.0	1.2	0.8	15.82	0.37	0.34	0.09
SS	15–30	5.2	0.41	0.74	97.2	2.7	0.1	13.97	0.15	0.36	0.10
SS	30–45	5.8	0.49	0.33	95.0	2.5	2.5	13.22	0.63	0.39	0.10
SS	45–60	5.9	0.27	6.85	88.5	1.4	7.1	14.57	0.35	0.32	0.10
ES	0–15	5.3	1.96	8.18	95.4	1.4	3.2	15.53	0.34	0.36	0.07
ES	15–30	4.9	1.56	1.54	94.8	2.3	2.9	15.94	0.31	0.33	0.10
ES	30–45	5.6	1.61	1.40	94.8	2.3	2.9	14.76	0.77	0.31	0.10
ES	45–60	5.4	1.28	1.40	95.1	1.8	3.1	15.73	0.11	0.42	0.09

^z1 cm = 0.3937 inch, 1 g·cm⁻³ = 0.5780 oz/inch³, 1 cm³ = 0.0610 inch³.

^ySoil to water ratio = 1:2 (w/v).

^xOrganic matter determined using loss on ignition method (Davies, 1974).

^wSourced from Fares et al. (2008), Obreza and Collins (2008), and University of Florida (2007); 1 cmol·kg⁻¹ = 1 meq/100 g.

^yHydraulic conductivity at field capacity was determined using equations described in van Genuchten (1980).

Fig. 1. A schematic field diagram showing the setup of top—drip irrigation system irrigated and fertigated daily with drip emitters in short pulses (Drip), middle—a modified microsprinkler irrigation system irrigated daily and fertigated weekly with 1-m-wide and 3-m-long wetting pattern microsprinkler (Restricted Microsprinkler), and bottom—conventional microsprinkler irrigation system irrigated with selected allowable soil water depletion between irrigations but fertigated monthly with full-circle microsprinkler (Conventional) at the Spodosol site in 2009. Positions below the dripper within the sampling grid were also sampled and the area between or within the dashed lines was the irrigated zone. All trees were ‘Hamlin’ orange on ‘Swingle’ rootstock. The setup for the Entisol site was similar; 1 m = 3.2808 ft, 1 ft = 0.3048 m, 1 cm = 0.3937 inch.

Fig. 2. Evapotranspiration and rainfall at the Spodosol and Entisol sites from 1 June 2009 to 31 July 2010. A and C are the root sampling dates at the Spodosol site, and B and D are the sampling dates for the Entisol site; 1 cm = 0.3937 inch.

with 1-m-wide and 3-m-long wetting a pattern microsprinkler emitters (Restricted Microsprinkler); and 3) irrigated and fertigated daily with drip emitters in short pulses (Drip). A schematic of the experimental set up is shown in Fig. 1. The SS had one drip line in the first year of the study and two drippers placed on either side of the tree spaced at 15 and 30 cm from the tree, within the tree row. A second drip line with two drippers placed on either side of the tree was added in the second year of the study. The two drip lines were located 30 cm from the tree row. At ES, one drip line was placed within the tree row, with one dripper placed at 15 cm on each side of the tree. All the treatments were laid in a randomized complete block design replicated four times. The trees at SS were symptomatic for HLB in the second year of study (2010), while those of ES were asymptomatic of HLB throughout the study.

ROOT SAMPLING. Root samples were collected at 0- to 15-cm and 15- to 30-cm depths because most roots of young citrus trees (≤ 3 years old) are concentrated within 30 cm of the soil surface (Fares and Alva, 2000; Paramasivam et al., 2000; Parsons and Morgan, 2004). Root samples at SS were collected in a 30 $\times$ 45-cm grid in June 2009 and 2010 (Fig. 1).

In 2010, samples were taken at SS from different trees in the same grid locations up to a depth of 45 cm. The samples at ES were collected at four positions in Dec. 2009 and nine positions in July 2010, in a 15 $\times$ 15-cm and 30 $\times$ 30-cm grid in a single quadrant, respectively, at 0- to 15-cm, and 15- to 30-cm soil depths. The root sampling method used in the study provides root length estimate in units such as centimeters per cubic centimeter of soil volume based on volume of the auger (Böhm, 1979; Escamilla et al., 1991; Lopez-Zamora et al., 2002).

Roots were removed from the soil using a 2-mm-diameter sieve and hydrated for 15 min. Hydrated roots were separated into four groups: <0.5, 0.5–1.0, 1.0–3.0, and >3.0 mm using copper wires of known diameter as a size reference (Kimura and Yamasaki, 2001) before root length determination on a 1.0 $\times$ 1.0-cm grid using the line intersection method (Morgan et al., 2007; Tennant, 1975). RLD for each root category was estimated by multiplying the number of horizontal and vertical root intersections by 11/14 and divided by volume of the auger (Mattos, 2000).

ROOT AREA SCANNING METHOD. The scanning method was used for the above four root size groups of

each root sample used for the line intersection method. Image processing software called ImageJ (National Institute of Health, 2009) was used to estimate the surface area covered by the roots on a flatbed scanner (HP4860 Scanjet-G4050; Hewlett-Packard, Palo Alto, CA). We scanned each root sample three times with roots rearranged between scans resulting in different arrangements to get a better estimation of average root length due to inadvertent overlapping of roots on the scanner by calculating the mean of the three scans. RLD for root samples collected in 2010 were estimated using the regression equations developed from root samples in 2009.

ESTIMATION OF SOIL MOISTURE. Volumetric water content was determined gravimetrically for each soil sample (Hillel, 1998). Rainfall data and other climatic variables were collected from Florida Automated Weather Network stations at Southwest Florida Research and Education Center and Citrus Research and Education Center (Fig. 2) (University of Florida, 2013).

STATISTICAL ANALYSIS. The data collected on RLD and water content were analyzed using GLM Mixed Model Type III procedures using SAS (version 9.3 for Windows; SAS Institute, Cary, NC).

Table 2. Means and analysis of variance (ANOVA) for citrus root length density distribution as a function of irrigation method (Conventional, Drip, and Restricted Microsprinkler irrigation systems), soil depth, and distance from the tree at the Spodosol site on 17 June 2009 and 15 June 2010 in irrigated and nonirrigated zones at 0- to 15-cm, 15- to 30-cm, and 30- to 45-cm soil depths. All trees were ‘Hamlin’ orange on ‘Swingle’ rootstock.

		Root diam (mm) ^y							
		<0.5		0.5–1.0		1.0–3.0		>3.0	
		IRR ^x	NI ^x	IRR	NI	IRR	NI	IRR	NI
		17 June 2009							
Irrigation method ^z	Depth (cm) ^y	Root length density (cm·cm ^{−3}) ^y							
Conventional	0–15	0.154	— ^w	0.045	—	0.018	—	0.002	—
Conventional	15–30	0.105	—	0.047	—	0.032	—	0.005	—
Drip	0–15	0.205	0.170	0.065	0.062	0.017	0.027	0.001	0.002
Drip	15–30	0.203	0.078	0.073	0.058	0.052	0.043	0.011	0.003
Restricted Microsprinkler	0–15	0.168	0.136	0.033	0.035	0.008	0.013	0.001	0.001
Restricted Microsprinkler	15–30	0.155	0.055	0.061	0.033	0.031	0.015	0.006	0.001
Source of variation		ANOVA							
Irrigation method		NS		***		***		NS	
Depth		***		NS		***		***	
Position		***		NS		NS		NS	
Irrigation × depth		NS		NS		NS		NS	
Depth × position		NS		NS		NS		NS	
Position × irrigation method		NS		NS		NS		NS	
Irrigation method × depth × position		NS		NS		NS		NS	

		15 June 2010							
		Root diam (mm)							
		<0.5		0.5–1.00		1.0–3.0		>3.0	
		IRR	NI	IRR	NI	IRR	NI	IRR	NI
Irrigation method	Depth (cm)	Root length density (cm·cm ^{−3})							
Conventional	0–15	0.148	—	0.025	—	0.010	—	0.002	—
Conventional	15–30	0.089	—	0.025	—	0.017	—	0.003	—
Conventional	30–45	0.031	—	0.016	—	0.007	—	0.001	—
Drip	0–15	0.318	0.346	0.036	0.054	0.028	0.039	0.005	0.003
Drip	15–30	0.216	0.104	0.064	0.058	0.054	0.036	0.011	0.009
Drip	30–45	0.039	0.028	0.037	0.028	0.014	0.013	0.001	0.001
Restricted Microsprinkler	0–15	0.330	0.206	0.035	0.032	0.024	0.018	0.005	0.001
Restricted Microsprinkler	15–30	0.103	0.061	0.033	0.022	0.013	0.010	0.005	0.002
Restricted Microsprinkler	30–45	0.090	0.022	0.032	0.009	0.015	0.005	0.004	0.001
Source of variation		ANOVA							
Irrigation method		***		***		***		*	
Depth		***		***		***		***	
Position		*		NS		NS		***	
Irrigation × depth		NS		NS		***		*	
Depth × position		NS		NS		NS		NS	
Position × irrigation method		NS		NS		NS		NS	
Irrigation method × depth × position		*		NS		NS		**	

^aConventional = A microsprinkler irrigation system irrigated with selected allowable soil water depletion between irrigations but fertigated monthly with full-circle microsprinkler; Drip = Drip irrigation system irrigated and fertigated daily with drip emitters in short pulses; Restricted Microsprinkler = A modified microsprinkler irrigation system irrigated daily and fertigated weekly with 1-m-wide and 3-m-long wetting pattern microsprinkler; 1 m = 3.2808 ft.

^y1 cm = 0.3937 inch, 1 mm = 0.0394 inch, 1 cm·cm⁻³ = 6.4516 inch³/inch³.

^xIRR = irrigated zone, NI = nonirrigated zone.

^wFor conventional practices, all the sampled positions were irrigated.

NS = Nonsignificant at $P < 0.05$; *, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

Results and discussion

COMPARISON OF ROOT DENSITIES BY SITE. At the SS, root density increased with depth in both irrigated and nonirrigated zones across the 2 years. About 50% to 70% of the fibrous roots (<0.5 mm) in the irrigated zone

were concentrated in the top 0- to 15-cm soil depth with the remaining fibrous roots in the 15- to 30-cm soil depth in all treatments (Table 2; Figs. 3–5). However, 51% to 92% of the larger roots (>0.5 mm diameter) in the irrigated zone were concentrated

in 15- to 30-cm soil depth. In 2009, nearly all the fibrous roots (<0.5 mm) in the nonirrigated zone were found in the top 0- to 15-cm layer probably because of the rains in summer that provided adequate moisture in the top layer. In 2010, 55% to 72% of

Fig. 3. Lateral root length density distribution of <0.5-mm-, 0.5- to 1-mm-, 1- to 3-mm-, and >3-mm-diameter roots of 'Hamlin' orange on 'Swingle' rootstock at the Spodosol site in June 2009 using conventional microsprinkler irrigation system irrigated with selected allowable soil water depletion between irrigations but fertigated monthly with full-circle microsprinkler (Conventional) at the Spodosol site in 2009 in the 0- to 30-cm soil depth layer. All contour units are $\text{cm}\cdot\text{cm}^{-3}$; 1 mm = 0.0394 inch, 1 cm = 0.3937 inch, $1\text{ cm}\cdot\text{cm}^{-3} = 6.4516\text{ inch}^3/\text{inch}^3$.

fibrous roots concentrated in the top layer (0- to 15-cm soil depth), while larger roots (0.5 to 1.0 mm diameter) were distributed evenly in the 0- to 15-cm (26% to 39%), 15- to 30-cm (20% to 47%), and 30- to 45-cm (14% to 32%) soil depths (Table 3). Roots with diameters between 1 and 3 mm were concentrated in the 15- to 30-cm soil depth for Conventional and Drip and in the 0- to 15-cm soil depth for Restricted Microsprinkler in both the irrigated and nonirrigated zones. Woody roots (>3 mm) contributed <3% of total RLD in both years. These results showed greater root densities for Drip and Restricted Microsprinkler than those reported by Morgan et al. (2007) on 2- to 5-year-old 'Hamlin' and 'Valencia' orange trees because trees in that study received infrequent irrigation and fertilization via conventional practice irrigated by full circle pattern emitters with a 4.5-m diameter.

In 2009, 46% to 82% of the fibrous and small roots (<1 mm diameter) were concentrated in the top

0- to 15-cm soil depth for the Drip and Restricted Microsprinkler irrigation systems, while only 34% to 41% of such roots were found at this layer in the Conventional treatment ($P \leq 0.001$) at ES. As at SS, 1- to 3-mm-diameter roots were concentrated in the 15- to 30-cm layer (60% to 77%) in all irrigation methods. In Summer 2010, the trees had increased in size and developed dense fibrous roots (<0.5 mm diameter) with 61% to 85% of such roots found in the 0- to 15-cm soil layer and the rest in the 15- to 30-cm soil depth. About 60% to 80% of the larger root sizes (>0.5 mm) were found in 15- to 30-cm soil depth in the irrigated and nonirrigated zones. Other researchers (Basso et al., 2003; Nappi et al., 1985) also reported similar results. The greater fibrous RLD in the ES compared with SS confirms that HLB damages fibrous roots on young trees (actually even before aboveground symptoms are apparent in 3- to 4-year-old trees) in agreement with Graham et al. (2013).

ROOT DISTRIBUTION PATTERNS OF DRIP- AND MICROSPRINKLER-IRRIGATED TREES. Overall, fibrous roots accounted for $\geq 80\%$ of the RLD at both 0- to 15- and 15- to 30-cm depths, while woody roots (>3 mm) contributed <3% of the total RLD. Root samples collected at SS in June 2009 showed that lateral RLD distribution for the Conventional treatment decreased ($P \leq 0.001$) 5-fold from near the tree (within 15 cm) to 45 cm away from the tree row (Figs. 3-5). About 64% to 82% of the fibrous roots were concentrated in the irrigated zones of Drip and Restricted Microsprinkler and 18% to 36% were found in the nonirrigated zones. Roots in the 15- to 30-cm depth in the nonirrigated zones close to the dripper or the irrigated zone of Restricted Microsprinkler had greater RLD than the irrigated zones of the Conventional irrigation, probably due to the high Florida summer rainfall.

In the second year (2010), fibrous roots samples collected at SS contributed more than 77% of RLD,

Fig. 4. Lateral root length density distribution of <0.5-mm-, 0.5- to 1-mm-, 1- to 3-mm-, and >3-mm-diameter roots of 'Hamlin' orange on 'Swingle' rootstock at the Spodosol site in June 2009 using drip irrigation system irrigated and fertigated daily with drip emitters in short pulses (Drip) in the 0- to 30-cm soil depth layer. All contour units are $\text{cm}\cdot\text{cm}^{-3}$; 1 mm = 0.0394 inch, 1 cm = 0.3937 inch, 1 $\text{cm}\cdot\text{cm}^{-3}$ = 6.4516 $\text{inch}/\text{inch}^3$.

while woody roots (>3 mm) accounted for less than 2% of total RLD. The results showed that $\approx 49\%$, 36%, and 15% of roots were distributed in the 0- to 15-, 15- to 30-, and 30- to 45-cm soil depths, respectively, for Conventional irrigation system. The RLD distributions were significantly greater in irrigated zones of Restricted Microsprinkler and Drip than those in the Conventional irrigation systems across the 2 years at SS (Table 2). Positions below the dripper or in the irrigated zone of Restricted Microsprinkler showed 53% to 81% greater RLD (<0.5 mm diameter) than that in nonirrigated zones ($P \leq 0.001$) at 0- to 15- and 15- to 30-cm soil depths in 2009 and 2010. The RLD (<0.5 mm diameter) in 0- to 15-cm depth for Drip and Restricted Microsprinkler irrigation were 3- to 4-fold (nonirrigated zone) and 4- to 7-fold (irrigated zone) greater than that for Conventional irrigation. Zhang et al. (1996, 1998) also reported that RLD of fibrous roots was significantly greater near the drip emitter and at 0- to 15-cm depth soil. At the 15- to

30-cm soil depth, RLD was up to two times greater in the irrigated zone of Drip-Swingle and Drip-C35 than that of the Conventional irrigated trees. However, RLD for larger roots (>0.5 mm diameter) for Drip and Restricted Microsprinkler irrigation showed similar distribution patterns between irrigated and nonirrigated zones in 2009 but greater density in the latter in 2010 ($P \leq 0.001$). At ES, fibrous roots (<0.5 mm) accounted for >87% and >64% of the total RLD at 0- to 15- and 15- to 30-cm soil depth, respectively, across all irrigation methods. The distribution of woody roots (>3 mm diameter) was <2%. Overall, RLD found at ES was greater for drip- than microsprinkler-irrigated citrus, in accord with results from grapevines (Basso et al., 2003; Stevens and Douglas, 1994).

COMPARISON OF ROOT DENSITIES FOR DRIP IRRIGATION. Fibrous root densities at 0- to 15- and 15- to 30-cm soil depths for Drip-Swingle and Drip-C35 at ES were up to 4-fold greater ($P \leq 0.001$) than the RLD for Drip at SS in the irrigated and

nonirrigated zones, respectively. Lower fibrous RLD at the SS compared with RLD at ES was probably due to interaction of HLB that infected the grove at the SS. Citrus greening-infected trees were found to have 30% to 37% less fibrous roots compared with nonsymptomatic trees (Graham et al., 2013). Tree roots at the SS may also be limited by poor aeration and the presence of an impervious hard pan within 1 m from the soil surface, which impairs drainage and impedes further root proliferation.

The RLD of larger roots (0.5 to 3 mm diameter) were similar between the two sites at 0- to 15-cm soil depth since the trees were less than 5 years old. Because of their young age, woody roots at ES were nonexistent or very few. For example, no woody roots were found in irrigated and nonirrigated zones of Drip-Swingle (0- to 15-cm soil depth) and in the nonirrigated zone at 0- to 15- and 15- to 30-cm soil depths for Drip-C35. The drip-irrigated treatments showed high RLD of about $1.0 \text{ cm}\cdot\text{cm}^{-3}$ in the irrigated zone that decreased to

Fig. 5. Lateral root length density distribution of <0.5-mm-, 0.5- to 1-mm-, 1- to 3-mm-, and >3-mm-diameter roots of ‘Hamlin’ orange on ‘Swingle’ rootstock at the Spodosol site in June 2009 using a modified microsprinkler irrigation system irrigated daily and fertigated weekly with a 1-m-wide and 3-m-long wetting pattern microsprinkler (Restricted Microsprinkler) in the 0- to 30-cm soil depth layer. All contour units are $\text{cm}\cdot\text{cm}^{-3}$; 1 mm = 0.0394 inch, 1 m = 3.2808 ft, 1 cm = 0.3937 inch, $1 \text{ cm}\cdot\text{cm}^{-3} = 6.4516 \text{ inch}^3/\text{inch}^3$.

0.20 $\text{cm}\cdot\text{cm}^{-3}$ in the nonirrigated zone at ES. The high RLDs in the nonirrigated zones for the Drip and Restricted Microsprinkler fertigation methods were not expected. We ascribe the presence of roots in the nonirrigated zone to the high rainfall in Florida (Fig. 2), which increased the amount of available water including the nonirrigated zone thus promoting root growth and development. For example, there were unusually high rains in Dec. 2009, Jan. 2010, Feb. 2010, Mar. 2010, and Apr. 2010 ranging from 65% to 235% at SS and 43% to 278% at ES greater than 10-year average of these months (calculated from 1 Jan. 2000 to 31 Dec. 2010) that might have supplied water in the dry months in the nonirrigated zones. Obreza and Pitts (2002) also observed similar phenomena on RLD distribution between the irrigated and nonirrigated zones of southwestern Florida. The results show $\text{RLD} < 1.3 \text{ cm}\cdot\text{cm}^{-3}$, consistent with findings of other researchers in citrus (Mattos et al., 2003), apple [*Malus domestica* (De Silva et al.,

1999)], and somewhat lower than the RLD reported by Coleman (2007) in other woody species.

LATERAL SOIL MOISTURE DISTRIBUTION. Results at SS showed higher water contents in the 15- to 30-cm soil depth layer in 2009 and moisture contents in the decreasing order of 30–45 cm > 15–30 cm > 0–15 cm in 2010 (Table 4; Fig. 6). The significantly lower soil moisture contents point to the decreasing RLD with depth suggesting that most of the water in the upper soil layers were depleted by root uptake, surface evaporation, or drainage. Our own results (Kadyampakeni, 2012) and those of Zhang et al. (1996) showed that tree uptake should be greater in the 0- to 15-cm soil layer than lower horizons due to higher root density in the range of 55% to 67% on length basis and 70% to 75% on weight basis in the top 15 cm. Davenport et al. (2008) also observed that soil moisture distribution for drip-irrigated vineyards was adequate in the 0- to 45-cm depth and within 20- to 40-cm radius, either diagonal or perpendicular

to the drip line. Our observations are also in agreement with Goldberg et al. (1971) who found that soil moisture resulting from drip irrigation was two-dimensional, with moisture contents high along and beneath the row and decreasing laterally. Thus, the effect of shorter irrigation intervals, as was the case with Drip and Restricted Microsprinkler, with proportionally smaller amounts of water applied in a single irrigation, is to reduce the variations in moisture content in the root zone and establish a continuously higher moisture regime. The irrigated and nonirrigated zones were similar in both years owing to high rainfall at SS totaling 518 and 218 mm in May/June of 2009 and 2010, respectively. The rains in May/June 2009 were 49% greater than a 10-year average for these months, while the rains in May/June 2010 were very similar to the 10-year average. Thus, even the nonirrigated zones of all treatments remained wet. Obreza and Pitts (2002) also found that availability of moisture in the root zone may promote root development even

Fig. 6. Lateral soil moisture distribution at the Spodosol Site in June 2009 (0- to 30-cm depth) and June 2010 (0- to 45-cm depth) using drip irrigation system irrigated and fertigated daily with drip emitters in short pulses (Drip), a modified microsprinkler irrigation system irrigated daily and fertigated weekly with a 1-m-wide and 3-m-long wetting pattern microsprinkler (Restricted Microsprinkler), and conventional microsprinkler irrigation system irrigated with selected allowable soil water depletion between irrigations but fertigated monthly with full-circle microsprinkler (Conventional). All trees were 'Hamlin' orange on 'Swingle' rootstock. All contour units are $\text{cm}^3\text{cm}^{-3}$; 1 cm = 0.3937 inch; 1 m = 3.2808 ft, 1 $\text{cm}^3 = 0.0610 \text{ inch}^3$.

in the nonirrigated zones. The moisture contents in 2009 were collected just within 30% to 50% soil moisture depletion, while the soil samples in 2010 were determined after an irrigation event and were all above field capacity. Additionally in 2010, another drip line was placed on each side of the tree at Immokalee due to the increase in tree size resulting in eight drippers on either side of the tree. The sampling was limited to one quadrant assuming uniform root distribution on the within-row bed in the northwest or northeast of the tree sampled.

In stark contrast to observations at SS, the soil moisture contents in samples collected at ES in Dec. 2009 and June 2010 decreased with depth in all treatments with soil moisture

contents well above field capacity at both sampling times (Fig. 7, Table 5). Also, there were no differences between irrigated and nonirrigated zones owing to the 89 mm of rain in Dec. 2009 (which was 175% greater than the 10-year average rainfall for the month of December) and 322 mm in June and July 2010 (which represented 46% less rainfall than a 10-year average for the months of June and July), which might have accounted for high soil moisture availability in the nonirrigated zone. Also, low evapotranspiration coupled with low temperatures in December at ES suggest minimal losses due to evaporation in the 0- to 15-cm soil layer. The significantly higher root density in the irrigated than nonirrigated zones suggest that water uptake might have been

greater in the former than the latter because root water uptake is intrinsically related to root density (Tinker and Nye, 2000). The fact that water contents were mostly greater than field capacity moisture content suggests that more water was available for uptake. Miller (1967) pointed out that the actual amount of plant available moisture in the active soil layer can be considerably greater than the range between standard field capacity and wilting point. Furthermore, Goldberg et al. (1971) noted that if a part of the drainable water remains in the root zone for a time sufficient for its absorption by the roots, it will add to the actual amount of available water. Drip irrigation in small pulses or daily applications with restricted microsprinklers provide for tree consumptive

Table 3. Means and analysis of variance (ANOVA) for citrus root length density distribution as a function of irrigation method (Conventional, Drip, and Restricted Microsprinkler irrigation systems), soil depth, and distance from the tree at the Entisol site on 22 Dec. 2009 and 28 July 2010 in irrigated and nonirrigated zones at 0- to 15-cm and 15- to 30-cm soil depths.

		Root diam (mm) ^y							
		<0.5		0.5–1.0		1.0–3.0		>3.0	
		22 Dec. 2009							
		IRR ^x	NI ^x	IRR	NI	IRR	NI	IRR	NI
Irrigation method ^z	Depth (cm) ^y	Root length density (cm·cm ^{−3}) ^y							
Drip-Swingle	0–15	0.777	0.404	0.041	0.072	0.029	0.017	0.000	0.000
Drip-Swingle	15–30	0.407	0.261	0.048	0.061	0.044	0.044	0.003	0.003
Conventional	0–15	0.113	— ^w	0.026	—	0.013	—	0.002	—
Conventional	15–30	0.220	—	0.038	—	0.026	—	0.000	—
Restricted Microsprinkler	0–15	0.428	0.351	0.079	0.054	0.015	0.012	0.000	0.004
Restricted Microsprinkler	15–30	0.124	0.109	0.037	0.029	0.040	0.013	0.000	0.000
Drip-C35	0–15	0.811	0.347	0.044	0.060	0.003	0.031	0.002	0.000
Drip-C35	15–30	0.323	0.077	0.019	0.008	0.010	0.005	0.002	0.000
Source of variation		ANOVA							
Irrigation method		**		***		***		NS	
Depth		***		NS		***		***	
Position		***		NS		NS		NS	
Irrigation method × depth		NS		NS		NS		NS	
Depth × position		NS		NS		NS		NS	
Position × irrigation method		NS		NS		NS		NS	
Irrigation method × depth × position		NS		NS		NS		NS	

		28 July 2010							
		Root diam (mm)							
		<0.5		0.5–1.0		1.0–3.0		>3.0	
		IRR	NI	IRR	NI	IRR	NI	IRR	NI
Irrigation method	Depth (cm)	Root length density (cm·cm ^{−3})							
Drip-Swingle	0–15	1.172	0.885	0.033	0.036	0.026	0.019	0.010	0.000
Drip-Swingle	15–30	0.543	0.185	0.030	0.027	0.040	0.016	0.007	0.001
Conventional	0–15	0.184	—	0.016	—	0.011	—	0.001	—
Conventional	15–30	0.120	—	0.043	—	0.023	—	0.002	—
Restricted Microsprinkler	0–15	0.564	0.487	0.026	0.038	0.023	0.019	0.004	0.002
Restricted Microsprinkler	15–30	0.218	0.083	0.022	0.027	0.018	0.029	0.006	0.000
Drip-C35	0–15	1.195	0.582	0.008	0.017	0.010	0.017	0.004	0.005
Drip-C35	15–30	0.293	0.165	0.012	0.017	0.008	0.016	0.000	0.001
Source of variation		ANOVA							
Irrigation method		***		**		NS		NS	
Depth		***		NS		NS		NS	
Position		***		NS		NS		**	
Irrigation method × depth		***		**		NS		NS	
Depth × position		*		NS		NS		NS	
Position × irrigation method		NS		NS		NS		NS	
Irrigation method × depth × position		NS		NS		NS		NS	

^zDrip-Swingle = Drip irrigation system installed for 'Hamlin' orange on 'Swingle' rootstock irrigated and fertigated daily with drip emitters in short pulses; Conventional = Conventional microsprinkler irrigation system used by Florida citrus growers irrigated with selected allowable soil water depletion between irrigations but fertilized with granular fertilizer four to six times per year ('Hamlin' orange/'Swingle'); Restricted Microsprinkler = A microsprinkler irrigation system irrigated daily and fertigated weekly with a 1-m-wide and 3-m-long wetting a pattern microsprinkler ('Hamlin' orange/'Swingle'); Drip-C35 = Drip irrigation system installed for 'Hamlin' orange on 'C35' rootstock irrigated and fertigated daily with drip emitters in short pulses; 1 m = 3.2808 ft.

^y1 cm = 0.3937 inch, 1 mm = 0.0394 inch, 1 cm·cm⁻³ = 6.4516 inch/inch³

^xIRR = irrigated zone, NI = nonirrigated zone.

^wFor conventional practices, all the sampled positions were irrigated.

NS = Nonsignificant at $P < 0.05$; *, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

water use at a higher level, (i.e., more efficacious) than weekly irrigation by conventional means. Water distribution in the irrigated zones was within 10 to 30 cm from the drippers as reported by other researchers (Badr

and Abuarab, 2013; Davenport et al., 2008).

Conclusion

This study demonstrated that RLDs in the irrigated zones were

greater for intensive irrigation and fertigation managed young citrus trees compared with less intensive conventional grower practices. These results were not known before this study and could provide useful information in

Table 4. Means and analysis of variance (ANOVA) for lateral soil moisture distribution using Conventional, Drip, and Restricted Microsprinkler irrigation systems at the Spodosol site in June 2009 and 2010 in irrigated and nonirrigated zones at 0- to 15-cm, 15- to 30-cm, and 30- to 45-cm soil depths. All trees were ‘Hamlin’ orange on ‘Swingle’ rootstock.

Irrigation method ^z	Depth (cm) ^y	2009		2010	
		Irrigated	Nonirrigated	Irrigated	Nonirrigated
		Soil moisture content [mean $\pm$ SD ($\text{cm}^3\text{cm}^{-3}$)] ^x			
Conv.	0–15	0.024 $\pm$ 0.015	— ^w	0.082 $\pm$ 0.041	—
Conv.	15–30	0.037 $\pm$ 0.017	—	0.106 $\pm$ 0.061	—
Conv.	30–45	—	—	0.117 $\pm$ 0.069	—
Drip	0–15	0.023 $\pm$ 0.012	0.015 $\pm$ 0.014	0.106 $\pm$ 0.051	0.088 $\pm$ 0.047
Drip	15–30	0.029 $\pm$ 0.008	0.033 $\pm$ 0.021	0.127 $\pm$ 0.046	0.114 $\pm$ 0.050
Drip	30–45	—	—	0.140 $\pm$ 0.045	0.123 $\pm$ 0.054
RM	0–15	0.018 $\pm$ 0.013	0.018 $\pm$ 0.008	0.096 $\pm$ 0.065	0.076 $\pm$ 0.041
RM	15–30	0.028 $\pm$ 0.015	0.046 $\pm$ 0.031	0.102 $\pm$ 0.048	0.105 $\pm$ 0.046
RM	30–45	—	—	0.135 $\pm$ 0.049	0.130 $\pm$ 0.051
Source of variation		ANOVA			
Irrigation method		***		***	
Depth		***		***	
Position		*		NS	

^zConv. = Conventional microsprinkler practice, Drip = Drip irrigation system, RM = Restricted Microsprinkler irrigation system.

^y1 cm = 0.3937 inch.

^xSoil moisture expressed as volumetric moisture content; 1 $\text{cm}^3 = 0.0610 \text{ inch}^3$.

^wNot applicable.

NS = Nonsignificant at $P < 0.05$; *, ***, Significant at $P < 0.05$ and $P < 0.001$, respectively.

Fig. 7. Lateral soil moisture distribution at the Entisol Site in the 0- to 30-cm depth layer in July 2010 using drip irrigation system installed for ‘Hamlin’ orange on ‘Swingle’ rootstock irrigated and fertigated daily with drip emitters in short pulses (Drip-Swingle), conventional microsprinkler irrigation system used by Florida citrus growers irrigated with selected allowable soil water depletion between irrigations but fertilized with granular fertilizer four to six times per year (Conventional), a microsprinkler irrigation system irrigated daily and fertigated weekly with a 1-m-wide and 3-m-long wetting pattern microsprinkler (Restricted Microsprinkler), and drip irrigation system installed for ‘Hamlin’ orange on ‘C35’ rootstock irrigated and fertigated daily with drip emitters in short pulses (Drip-C35). All contour units are $\text{cm}^3\text{cm}^{-3}$; 1 cm = 0.3937 inch; 1 m = 3.2808 ft, 1 $\text{cm}^3 = 0.0610 \text{ inch}^3$.

Table 5. Means and analysis of variance (ANOVA) for lateral soil moisture distribution using Conventional, Drip, and Restricted Microsprinkler irrigation systems at the Entisol site in Dec. 2009 and July 2010 in irrigated and nonirrigated zones at 0- to 15- and 15- to 30-cm soil depths.

Irrigation method ^z	Depth (cm) ^y	2009		2010	
		Irrigated	Nonirrigated	Irrigated	Nonirrigated
		Soil moisture content [mean ± sd (cm ³ .cm ⁻³)] ^x			
Conv.	0–15	0.079 ± 0.033	— ^w	0.069 ± 0.046	—
Conv.	15–30	0.057 ± 0.018	—	0.057 ± 0.019	—
Drip-Swingle	0–15	0.072 ± 0.008	0.067 ± 0.010	0.057 ± 0.029	0.056 ± 0.021
Drip-Swingle	15–30	0.065 ± 0.017	0.079 ± 0.043	0.046 ± 0.021	0.054 ± 0.021
Drip-C35	0–15	0.084 ± 0.019	0.075 ± 0.018	0.080 ± 0.027	0.070 ± 0.027
Drip-C35	15–30	0.081 ± 0.014	0.078 ± 0.011	0.074 ± 0.021	0.065 ± 0.021
RM	0–15	0.088 ± 0.012	0.085 ± 0.009	0.085 ± 0.027	0.094 ± 0.044
RM	15–30	0.084 ± 0.010	0.082 ± 0.012	0.074 ± 0.024	0.078 ± 0.023
Source of variation		ANOVA			
Irrigation method		**		***	
Depth		NS		**	
Position		NS		NS	

^aDrip-Swingle = Drip irrigation system with ‘Hamlin’ orange on ‘Swingle’ rootstock; Conv. = Conventional microsprinkler irrigation practice (‘Hamlin’ orange/‘Swingle’); Drip-C35 = Drip irrigation system with ‘Hamlin’ orange on ‘C35’ rootstock; RM = Restricted Microsprinkler irrigation system (‘Hamlin’ orange/‘Swingle’).

^y1 cm = 0.3937 inch.

^xSoil moisture expressed as volumetric moisture content; 1 cm³ = 0.0610 inch³.

^wNot applicable.

NS = Nonsignificant at $P < 0.05$; **, ***Significant at $P < 0.01$ and $P < 0.001$, respectively.

models for estimating water use and nutrient uptake in young citrus trees (<6 years old). About 64% to 82% of the fibrous roots were concentrated in the irrigated zones of Drip and Restricted Microsprinkler and 18% to 36% was found in the nonirrigated zones at SS. At ES, the RLD of fibrous roots (<0.5 mm diameter) for trees grown with intensively managed irrigation systems were 3- to 7-fold greater at 0- to 15-cm soil depth than that for conventional irrigation management. Further, higher RLD was observed in the 0- to 15-cm soil depth and decreased with depth for all treatments at both sites. Fibrous root densities at 0- to 15-cm soil depth for Drip at the ES were up to 4-fold greater than the RLD for Drip at SS in the irrigated and nonirrigated zones due to greater number of drip emitters and as a result of HLB disease pressure. Results showed significant differences in soil moisture between Drip, the Restricted Microsprinkler, and Conventional irrigation methods. Laterally, there were no differences between irrigated and nonirrigated zones even in the irrigation methods where water application was limited to positions above or near the root zone due to the heavy rains associated with the summer months in Florida. Thus, use of intensive irrigation and fertigation management should help in promoting citrus root development, water and nutrient uptake, and improved management of

HLB-infected trees without limiting tree production on Florida’s Spodosols and Entisols.

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