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Water Use in Drip- and Microsprinkler-Irrigated Citrus Trees

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Advanced citrus production systems (ACPS) are being evaluated in Florida citrus groves for sustainable, profitable citrus production. The ACPS practices provide tight control over water and nutrient-mediated plant growth and development using irrigation to train the root system into a limited area and fertigate with daily nutrient requirements. Thus, a study was undertaken to (i) compare daily water use using the stem heat balance method on ≤5-yr-old citrus trees using two ACPS irrigation methods (using daily drip and microsprinkler irrigation) and conventional irrigation on two Florida sandy soils; (ii) determine relationships between hourly sap flow and time of day, and daily water use vs. total available soil water in the irrigated zone; and (iii) evaluate the effect of Huanglongbing (HLB) disease on water uptake. The sap flow data suggest that intensive drip and microsprinkler irrigation systems resulted in similar or higher water use than conventional irrigation. Water use was greater ($P \leq 0.01$) with ACPS than conventional microsprinkler practice irrigation in summer 2010, spring 2011, and late summer 2011 at the Entisol site. Water use was 29 to 38% greater using ACPS than conventional irrigation in June 2011 at the Spodosol site, albeit, not significantly different. All irrigation systems showed water contents close to field capacity at both sites, indicating that water was nonlimiting in each irrigation system despite having different irrigation schedules. The high water uptake using intensive irrigation systems is ascribed to frequent irrigation and improved water distribution in the irrigated zone.

Abbreviations: ACPS, advanced citrus production systems; ES, Entisol site; ET_c, crop evapotranspiration; ET_o, reference evapotranspiration; HLB, Huanglongbing; LAI, leaf area index; OHS, open hydroponics system; SHB, stem heat balance; SS, Spodosol site; TASW, total available soil water.

Accurate estimation of plant water use could improve irrigation management (Gutierrez et al., 1994; Morgan et al., 2006), leading to a better understanding of plant-water interactions (Ham et al., 1990). Lysimetry, water balance, and crop evapotranspiration (ET_c) have been used in Florida to estimate citrus water use with microsprinkler irrigation on a field scale without partitioning evaporation and transpiration from the ET component (Obreza and Pitts, 2002; Jia et al., 2007; Morgan et al., 2006; Fares et al., 2008; Barkataky et al., 2012). Estimation of soil water uptake and resulting soil water depletion would allow for a more accurate assessment of citrus water use and soil moisture storage capacity (Morgan et al., 2006).

Reasonably accurate plant water use on a field scale, or ET_c, has been determined with the stem heat balance (SHB) method in citrus (Steppe et al., 2006) and grapevines (Lascano et al., 1992; Heilman et al., 1994). The SHB technique is nonintrusive, responds quickly to plant water flow, can be used over long periods

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of time without damage to the plant, and is simple to use (Devitt et al., 1993; Gutierrez et al., 1994).

Irrigating to meet crop evapotranspiration demands has been shown to have the potential to increase production efficiency (Morgan et al., 2006; Kiggundu et al., 2012). Modifications to current microsprinkler irrigation water recommendations combining an adaptation of the open hydroponics system (OHS) and high tree density on semidwarfing rootstocks are termed ACPS (Morgan et al., 2009; Schumann et al., 2009, 2010; Morgan and Kadyampakeni, 2012). The OHS is an integrated system of drip irrigation, nutrition, and horticultural practices developed in Spain to improve production on gravel based soils with low fertility (Martinez-Valero and Fernandez, 2004; Falivene et al., 2005; Morgan and Kadyampakeni, 2012). According to Stover et al. (2008), OHS provides tight control over water and nutrient-mediated plant growth and development using irrigation to train the root system into a limited area and fertigates with daily nutrient requirements. Advanced citrus production systems combine OHS with higher tree densities on rootstocks that restrict tree size to smaller tree spaces and is being evaluated in Florida citrus groves for sustainable, profitable citrus production in the presence of HLB, also known as citrus greening (Candidatus *Liberibacter asiaticus*) and canker (*Xanthomonas axonopodis*) diseases, with the goal of compressing and enhancing the citrus production cycle so economic payback can be reached in fewer years to offset some of the disease losses (Morgan et al., 2009; Schumann et al., 2009). Early studies on the effect of drip and microsprinkler irrigation on citrus production in Florida showed that drip systems resulted in lower yields than the latter because they irrigated 5 to 10% of the canopy area while microsprinklers covered 28 to 51% of the canopy area (Koo, 1980; Koo and Smajstrla, 1984). Lower citrus yields with drip irrigation do not agree with results from other citrus producing regions with limiting water resources and provided compelling need for this research (Boland et al., 2000; Quinones et al., 2005, 2007).

In the current study, we estimated tree water use using the SHB technique to calculate water use of young citrus trees irrigated with drip and microsprinkler irrigation based on plant sap flow and plant size measurements. Water use through hourly and daily sap flow measurements would help in accurately predicting transpiration and devising ways of minimizing evaporation and percolation losses by synchronizing irrigation applications with peak tree water use. The objectives of the study were to (i) determine tree water use using the SHB method on ≤5-yr-old citrus using three different irrigation methods on Florida Spodosol and Entisol; (ii) determine relationships between hourly sap flow and time of day, and daily water use vs. total available soil water in the irrigated zone; and (iii) evaluate the effect of HLB disease on water uptake.

MATERIALS AND METHODS

Site Conditions

Studies were conducted at two sites: (i) a Spodosol site (SS) at the University of Florida, Southwest Florida Research and Education Center, Immokalee, FL (lat. 26°25′ N, long. 81°25′ W) on Immokalee fine sand (sandy, siliceous, hyperthermic Arenic Alaquods); and (ii) an Entisol site (ES) near the Citrus Research and Education Center, Lake Alfred, FL (lat. 28°5′ N, long. 81°45′ W) on Candler fine sand (hyperthermic, uncoated Lamellic Quartzipsamments). Hamlin orange [*Citrus sinensis* (L.) Osb.] trees on Swingle [*Citrus paradisi Macf.* × *Poncirus trifoliata* (L.) Raf.] rootstock were planted in April 2006 at 3.05 × 6.71 m on 13.5-m-wide beds with drainage swales at the SS. Hamlin orange trees on Swingle were planted at 3.05 × 6.10 m at the ES in December 2008. The soils at ES and SS have similar water and nutrient holding capacities above the spodic horizon present in the Immokalee fine sand (Table 1) and are typical of citrus producing soils in Florida (Obreza and Collins, 2008). The trees at SS were symptomatic for HLB in the second year while those at ES were asymptomatic throughout the study.

Experimental Design and Irrigation Treatments

A randomized complete block design consisted of three treatments at both sites. Plots consisted of three to four adjacent trees serving as replications and a border tree at each end. The irrigation treatments were applied to the replicate trees independently within a row. The irrigation treatments at SS (Fig. 1) were as follows: (i) conventional microsprinkler irrigation practice (Conventional), irrigated at specific soil water depletions, with the microsprinkler placed at about 15 cm perpendicular to the tree row; (ii) drip open hydroponics system (Drip), irrigated and fertigated daily in small pulses to replace daily ET_c, with two drip lines and integral 2 L h^{-1} pressure-compensating drip emitters (Uniram, Netafim, Fresno, CA) spaced at 30 cm from the tree, each drip line delivering four emitters on each side of the tree; and (iii) microsprinkler open hydroponics system (Restricted Microsprinkler), irrigated daily and fertigated weekly, with the microsprinkler placed at about 15 cm perpendicular to the tree row. The treatments imposed at the ES were similar to the SS except for the modification to Drip that had one drip line placed within the tree row, with one dripper (Netafim, Fresno, CA) placed at 15 cm on each side of the tree. At both sites, microsprinkler irrigation was provided with either a single 40 L h^{-1} Max-14 (Maxijet, Dundee, FL) fill-in blue emitter for Conventional or a 29 L h^{-1} Max-14 fill-in orange emitter for Restricted microsprinkler at each tree (Schumann et al., 2009, 2010). The treatments, due to differences in size of irrigated zones and fertilization methods, applied different amounts of water and fertilizer. Conventional, Restricted Microsprinkler, and Drip applied 460, 430, and 183 kL ha^{-1} yr^{-1} of water and 54, 19, and 9 kg ha^{-1} yr^{-1} of N to achieve standard University of Florida/Institute of Food and Agricultural Sciences recommendations for citrus trees in the first 2 yr at ES. The drip lines were placed differently at the two sites due the differences in row spacing and soil drainage characteristics.

Estimation of Stem Flow

Water uptake was measured using sap flow sensors (Dynamax Inc., Houston, TX) on one branch in each of four trees per treatment (each tree serving as a replicate) at SS from 16 Feb. 2011 to

3 Mar. 2011 and from 3 to 21 June 2011. At the ES, due to limitation in the size of sensors, sap flow measurements on trunks of six trees (with three trees per irrigation method) were taken on Drip and Conventional from 7 to 29 July 2010. From 10 to 22 Mar. 2011, and 23 Aug. to 6 Sept. 2011; sap flow was measured on four trees of each irrigation method (Drip, Conventional, Restricted Microsprinkler) at ES. Before installation of the sensors, measurements were taken of branch and trunk diameters. The sap flow sensors were connected to a data logger (CR 1000, Campbell Scientific Inc., Logan, UT) to record data every hour. Flow data obtained from the logger (in g h^{-1}) were then converted to water flow per unit leaf area per unit time (kg m^{-2} s^{-1}, and to mm d^{-1}). The sap flow measurements were done for >2 wk because that is standard in using the SHB technique (Ham et al., 1990) and for convenience in conducting the experiments at the two sites using the same equipment.

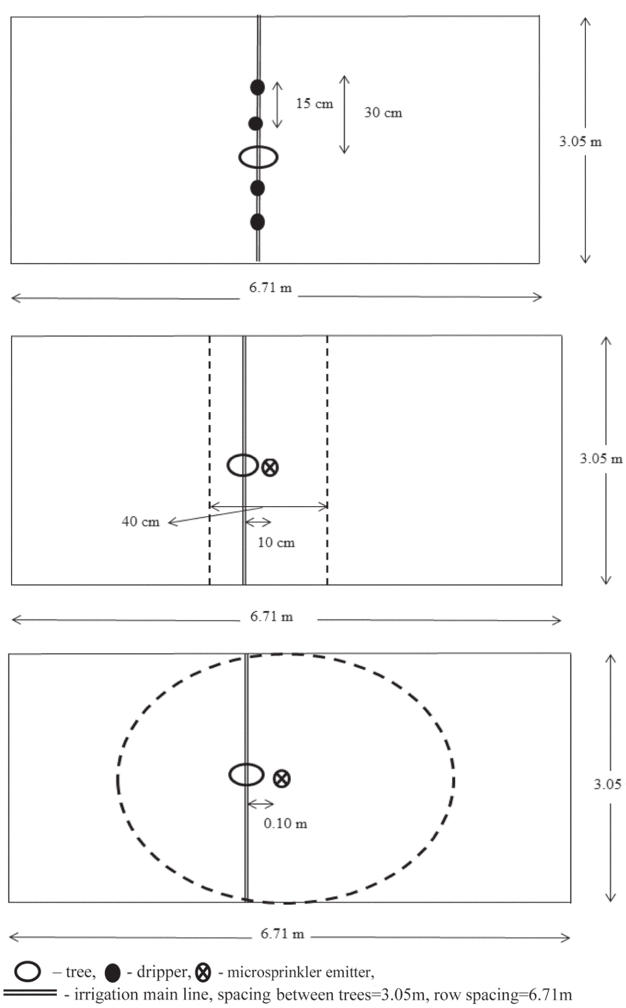

Fig. 1. A schematic field diagram showing the setup of drip irrigation system irrigated and fertigated daily with drip emitters in short pulses (Drip) (top), a modified microsprinkler irrigation system irrigated daily and fertigated weekly with 1-m-wide and 3-m-long wetting pattern microsprinkler (Restricted Microsprinkler) (middle), and conventional microsprinkler irrigation system irrigated with selected allowable soil water depletion between irrigations but fertigated monthly with full-circle microsprinkler (Conventional) (bottom) at the Spodosol site in 2009. The setup for the Entisol site was similar.

Table 1. Selected soil physical and chemical properties for the Spodosol (SS) and Entisol (ES) sites.

Site	Soil depth	pH†	Organic matter‡	Cation exchange capacity	Sand§	Silt	Clay	Bulk density	Saturated hydraulic conductivity	Hydraulic conductivity at field capacity¶	Saturated moisture content	Moisture content at field capacity	Residual moisture content
	cm		%	$cmol_c$ kg^{-1}	—— % ——			g cm^{-3}	—— cm h^{-1} ——		—— cm^3 cm^{-3} ——		
SS	0–15	5.6	0.61	7.63	98.0	1.2	0.8	1.62	15.82	0.37	0.34	0.09	0.013
SS	15–30	5.2	0.41	0.74	97.2	2.7	0.1	1.62	13.97	0.15	0.36	0.10	0.013
SS	30–45	5.8	0.49	0.33	95.0	2.5	2.5	1.59	13.22	0.63	0.39	0.10	0.013
SS	45–60	5.9	0.27	6.85	88.5	1.4	7.1	1.61	14.57	0.35	0.32	0.10	0.013
ES	0–15	5.3	1.96	8.18	95.4	1.4	3.2	1.65	15.53	0.34	0.36	0.07	0.009
ES	15–30	4.9	1.56	1.54	94.8	2.3	2.9	1.64	15.94	0.31	0.33	0.10	0.009
ES	30–45	5.6	1.61	1.40	94.8	2.3	2.9	1.57	14.76	0.77	0.31	0.10	0.009
ES	45–60	5.4	1.28	1.40	95.1	1.8	3.1	1.68	15.73	0.11	0.42	0.09	0.009

† Soil to water ratio = 1:2 (w/v).
‡ Organic matter determined using loss on ignition method (Davies, 1974).
§ Sourced from Grunwald et al. (2007), Fares et al. (2008), and Obreza and Collins (2008).
¶ Hydraulic conductivity at field capacity was determined using equations described in van Genuchten (1980).

We adapted the approach for determining sap flow measurements from individual plants from Ham et al. (1990) and Lascano et al. (1992). Mean transpiration, T_1 in kg m^{-2} s^{-1} (= mm s^{-1}), was computed by normalizing the stem flow data on a population per land area basis as:

$$T_1 = \sum\left(\frac{f_i}{x_i}\right) * \frac{\text{LAI}}{n} \qquad (i = 1, 2,..,n) \qquad [1]$$

where f_i is measured stem flow, kg s^{-1}, x_i is the leaf area, m^2, of plant i, and LAI is the leaf areas index of the plot. The transpiration was converted to mm d^{-1} by dividing T_1 by the density of water (1000 kg m^{-3}) and multiplying with 86,400 s (1 d = 86,400 s). Accordingly, we assumed small hydraulic capacitance for young citrus trees and that stem flow measurement for individual trees would provide a good estimate of transpiration (Ham and Heilman, 1990). Reference evapotranspiration (ET_o) using the Penman–Monteith equation and rainfall were estimated from the Florida Automated Weather Network stations (http://fawn.ifas.ufl.edu/) located at SS and ES (Fig. 2).

Tree Measurements

Leaf area was determined using a portable leaf area meter (Model LI-3000A LI-COR, Lincoln, NB). Leaf area index (LAI) of each tree for each plot was measured using a SunScan canopy analysis system (Dynamax Inc., Houston, TX) during a sunny day. The LAI measurements were taken in two directions: the northwest-southeast and northeast-southwest directions around a tree and were averaged as an estimate of the tree LAI. A calibration curve relating the total leaf area (LA) and LAI was developed for subsequent seasons (LA = 0.24*LAI, r^2 = 0.82 at SS and LA = 0.35*LAI, r^2 = 84 at ES). Tree canopy volumes were estimated using the formula for a prolate spheroid: (4/3)(π)(tree height/2)(mean canopy radius), by measuring the canopy width in the east-west and north-south directions and canopy height (Obreza and Rouse, 1993). Trunk diameter was estimated from averaging the diameter in the east-west and north-south directions and then calculating the area using the formula πr^2, where r is the trunk radius.

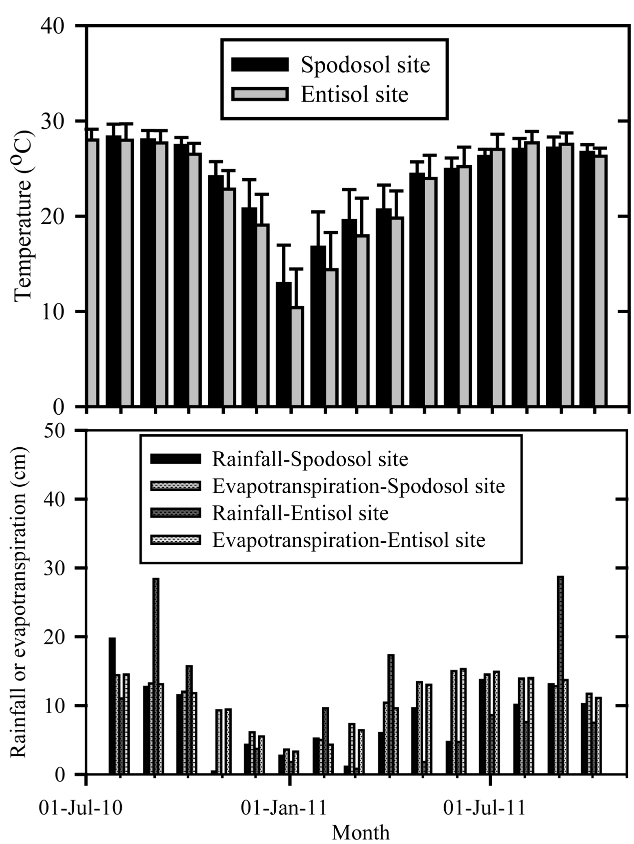

Fig. 2. Average daily temperature (top) and monthly rainfall and evapotranspiration (bottom) for the Spodosol and Entisol sites (1 July 2010 to 1 October 2011). Error bars denote one standard deviation.

Estimation of Soil Moisture in the Irrigated Zone by Using Soil Moisture Sensors

Soil water sensors were used to measure soil moisture on Candler (VG400, Vegetronix, Sandy, UT) and Immokalee fine sand (RS485, Portland, OR), using the capacitance method and an automated logging system (Morgan et al., 1999) of estimating volumetric water content to determine treatment effects on soil water status in the irrigated zone at periods ranging from 13 to 21 d. Soil moisture was measured every 30 min at 10- and 45-cm depths at ES and 10-, 20-, 30-, 40-, and 50-cm depths at SS. The sensors were installed at the selected depths because most roots of young citrus trees are concentrated within 30 cm of the soil surface (Fares and Alva, 2000a, 2000b; Paramasivam et al., 2000; Parsons and Morgan, 2004). Volumetric water content was expressed as a percentage (Hillel, 1998). Changes in soil moisture storage (ΔS) between depths z_1 and z_2, z_2, and z_3, and so on (dz) were determined using the formula adapted from Fares and Alva (2000b):

$$\Delta S = \int_{z_1}^{z_2} \theta(z, t_1)\,dz - \int_{z_1}^{z_2} \theta(z, t_2)\,dz \qquad [2]$$

where θ_1 and θ_2 are the moisture contents (cm^3 cm^{-3}) at depths z_1 and z_2.

The total available soil water (TASW expressed as a percentage) was determined as:

$$\text{TASW} = \left(\frac{\theta - \theta_r}{\theta_{FC} - \theta_r}\right) x100 \qquad [3]$$

where θ is the moisture content (cm^3 cm^{-3}) at a particular depth; θ_r is the residual moisture content (cm^3 cm^{-3}) corresponding to the permanent wilting point; θ_{FC} is the moisture content at field capacity (cm^3 cm^{-3}).

Data Analysis

The study used PROC GLM procedures (SAS Institute, Cary, NC) to compare treatments and employed regression analysis to develop relationships between hourly sap flow vs. time of day and daily water use vs. TASW. Means were separated using the Tukey's procedure (SAS Institute, 2011).

RESULTS AND DISCUSSION

Tree Characteristics

The trunk cross-sectional area, canopy volume, leaf area, and LAI were similar among the treatments at SS in February 2011 and June 2011 (Fig. 3). In July 2010, trunk cross-sectional area and canopy volume at ES did not differ between Drip and Conventional but leaf area and LAI were greater ($P \leq 0.05$) for the former than the latter (Fig. 3). In March and August 2011, leaf areas, trunk cross-sectional area, canopy volumes, and LAI were similar for all irrigation systems at ES (Fig. 3). In spring 2011 at ES, trees irrigated using Conventional showed smaller trunk cross-sectional area, canopy volume, leaf area, and LAI compared with the ACPS irrigation methods (Fig. 3).

Hourly Sap Flow

At SS, hourly sap flow ranged from 0.12 to 0.19 mm h^{-1} between 900 and 1000 HR, peaking to 0.21 mm h^{-1} from 1100 to 1500 HR, declining steadily to 0.03 mm h^{-1} at 2100 HR in spring 2011 using Drip only. We noted very low sap flow measurements in spring 2011 for Restricted Microsprinkler and Conventional,

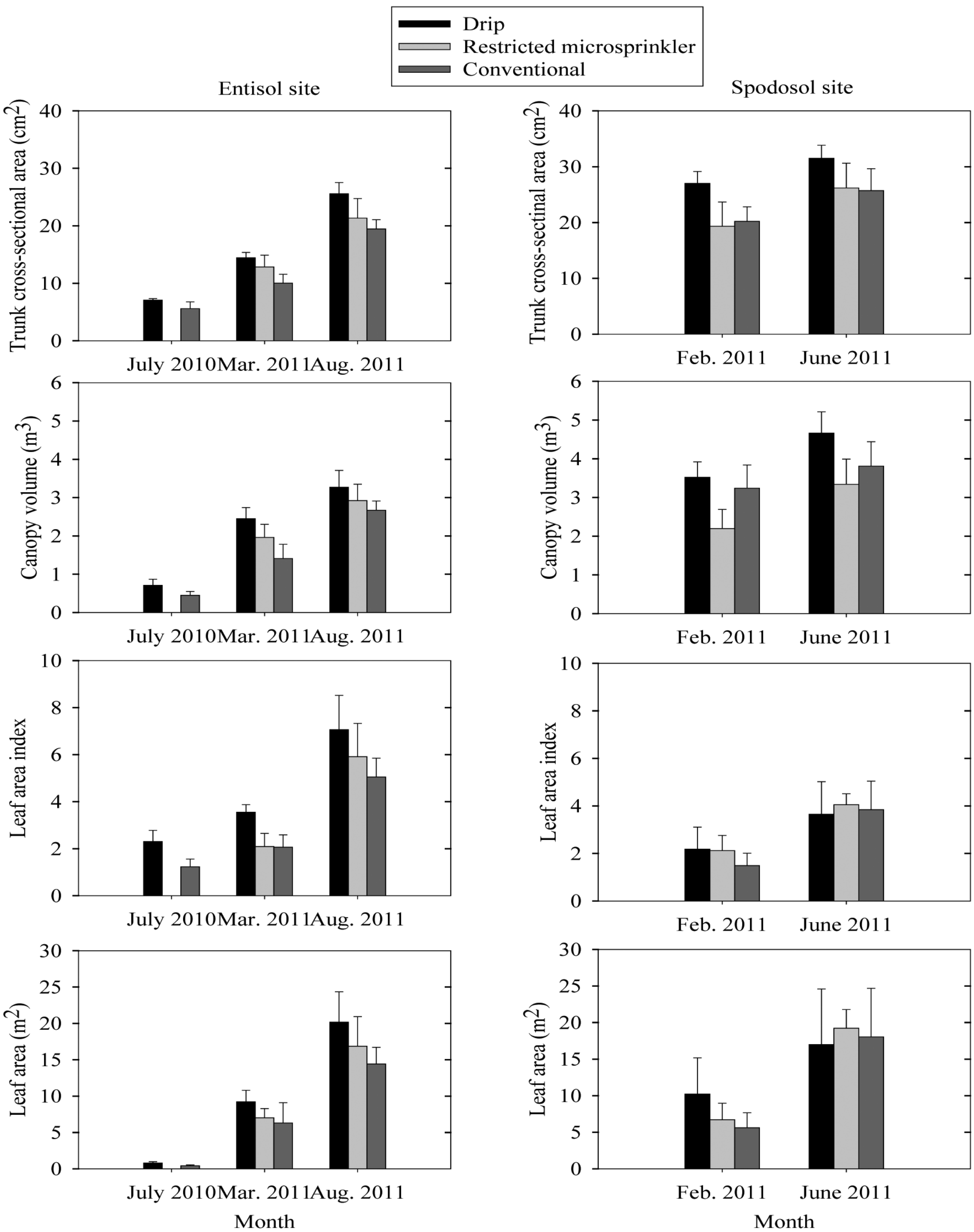

Fig. 3. Tree characteristics for trees sampled at the Entisol and Spodosol sites. Error bars denote one standard deviation.

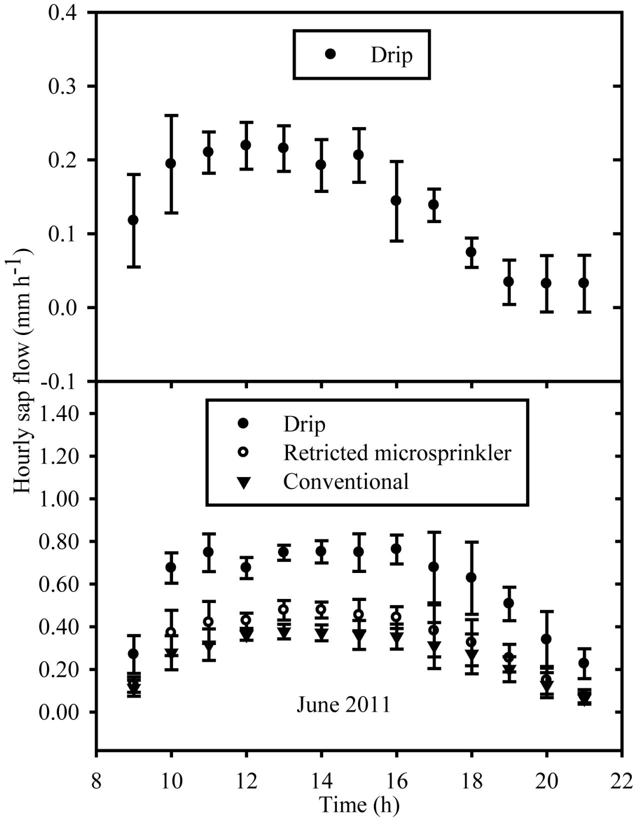

Fig. 4. Average hourly sap flow at Spodosol site in February and June 2011. Error bars denote one standard deviation.

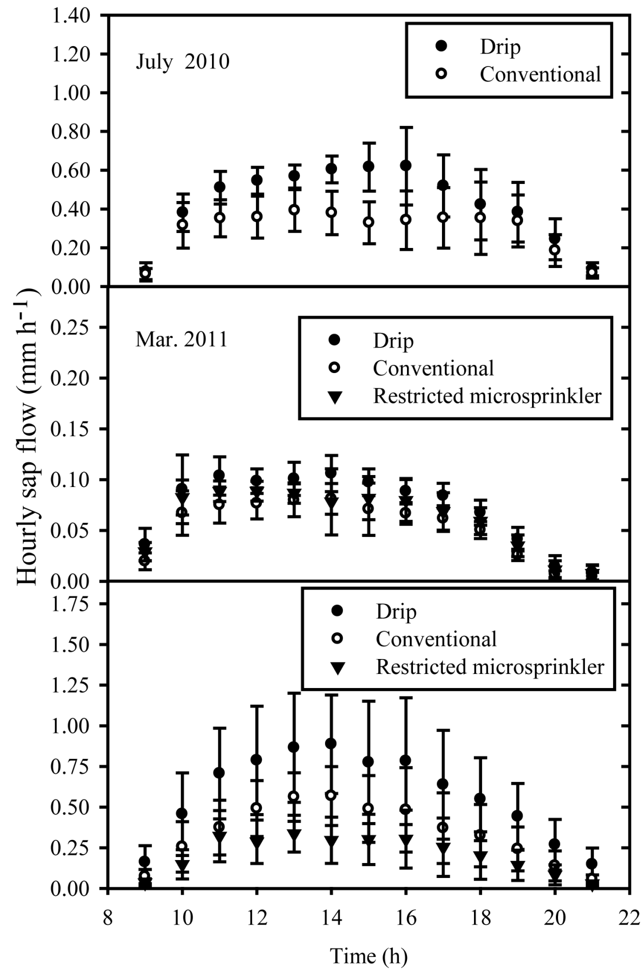

Fig. 5. Average hourly sap flow at Entisol site in July 2010, March 2011, and August to September 2011. Error bars denote one standard deviation.

because the statuses of sensors reportedly ranged from 5 to 7 showing faulty readings that were identified late in the study, and the data are not presented here (Fig. 4). In summer 2011, the hourly sap flow for Drip and Restricted Microsprinkler were respectively 85 to 142% and 19 to 33% greater than Conventional between 1000 and 1800 HR when sap flow was highest (Fig. 4). Overall, the trees at SS had greater trunk cross-sectional areas, canopy volumes, and leaf areas than at ES, resulting in greater sap flow at the former site (Fig. 3) probably because the trees at SS were 2.5 yr older than those at ES.

Hourly sap flow values in summer 2010 were not statistically different between Drip and Conventional at ES. However, sap flow for Drip was greater than Conventional by 17 to 60% between 900 and 1400 HR, 81 to 87% around 1500 to 1600 HR, and 13 to 47% at the time interval of 1700 to 2100 HR. This represents about 0.05 to 0.29 mm h^{-1} greater sap flow using drip irrigation than the conventional microsprinkler practice due to frequent irrigation (Fig. 5). The spring 2011 results showed that Drip resulted in higher sap flow than the Conventional. For example, Drip sap flow was 26 to 112% greater than that of Conventional. Restricted microsprinkler showed sap flow values that were largely between 9 and 68% more than Conventional between 900 and 2100 HR, except at around 1400 HR when sap flow was 4% below that of Conventional (Fig. 5). The frequent, daily irrigation in small pulses using Drip or daily irrigation using Restricted Microsprinkler might have resulted in increased sap flow.

The relationship between hourly sap flow and time of day was described by third-order polynomial models and explained between 78 and 99% of the variation in sap flow between 900 and 2100 HR (Table 2). Such models could provide important information for irrigation decision support for improving citrus irrigation scheduling to match with peak water use during the day. Thus, irrigation events could be slated just before 900 HR to coincide with the cycle of elevated sap flow in the citrus trees.

Water Use Per Day

In spring 2011, the estimated daily water use at SS averaged 4.01 ± 1.56 mm d^{-1}, accounting for 135% of the reference evapotranspiration (ET_o) (Fig. 6). Water use increased in June 2011, with Drip, Restricted Microsprinkler, and Conventional treatments averaging 117, 109, and 85% of the ET_o (Fig. 6). Drip and Restricted Microsprinkler showed similar water use that was greater ($P \leq 0.05$) than that of Conventional. The greater water use with Drip and Restricted Microsprinkler irrigation is ascribed to the frequent, daily irrigation as opposed to irrigation with allowable soil water depletion between events associated with Conventional irrigation (Morgan et al., 2006). At the ES, from days of the year 190 to 209, water uptake for Drip and Conventional treatments averaged 97 and 87% of ET_o

Table 2. Regression analysis of hourly sap flow (Y, mm h^{-1}) with time of day (T, h) using the third-order polynomial model $Y = Y_o + aT + bT^2 + cT^3$.†

Site	Irrigation method	Season/Year	Y_o	a	b	c	R^2	RMSE	P
				Regression coefficients					
			mm h^{-1}	mm h^{-2}	mm h^{-3}	mm h^{-4}		mm h^{-2}	
Entisol	Drip	summer 2010	–8.073	1.547	-0.080	0.00120	0.961	0.0065	***
Entisol	Conventional	summer 2010	-3.303	0.631	-0.029	0.00033	0.782	0.0129	**
Entisol	Pooled	summer 2010	–5.689	1.089	-0.055	0.00076	0.925	0.0078	***
Entisol	Drip	spring 2011	-0.729	0.153	-0.009	0.00015	0.944	0.0001	***
Entisol	Conventional	spring 2011	-0.705	0.146	-0.009	0.00015	0.945	0.0001	***
Entisol	Restricted microsprinkler	spring 2011	-0.617	0.131	-0.008	0.00013	0.911	0.0001	***
Entisol	Pooled	spring 2011	-0.684	0.143	-0.008	0.00014	0.938	0.0001	***
Entisol	Drip	summer 2011	–7.748	1.553	-0.089	0.00160	0.990	0.0010	***
Entisol	Conventional	summer 2011	-3.806	0.773	-0.045	0.00080	0.994	0.0002	***
Entisol	Restricted microsprinkler	summer 2011	–5.330	1.056	-0.060	0.00106	0.989	0.0005	***
Entisol	Pooled	summer 2011	–5.628	1.127	-0.065	0.00114	0.994	0.0003	***
Spodosol	Drip	spring 2011	-2.028	0.455	-0.029	0.00059	0.966	0.0003	***
Spodosol	Drip	summer 2011	-3.474	0.715	-0.037	0.00052	0.889	0.0056	***
Spodosol	Conventional	summer 2011	-2.397	0.482	-0.026	0.00041	0.977	0.0004	***
Spodosol	Restricted microsprinkler	summer 2011	-3.250	0.660	-0.036	0.00060	0.962	0.0010	***
Spodosol	Pooled	summer 2011	-3.040	0.619	-0.033	0.00051	0.942	0.0017	***

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Regression coefficients are a, b, and c.

in summer 2010 (Fig. 7). In spring 2011, due to lower temperature at ES, water uptake for Drip, Restricted Microsprinkler, and Conventional treatments accounted for 59, 58, and 42% of the ET_o between days of the year 70 and 82 (Fig. 7). The water use in late summer 2011 followed the order Drip > Restricted Microsprinkler > Conventional, representing significant differences between the irrigation methods ($P \leq 0.01$; Fig. 7).

The daily water use vs. TASW at various depths was described by multiple linear regression models for each site (Table 3). Significant relationships between daily water use and TASW were observed for Conventional in spring 2011 ($R^2 = 0.50$, RMSE = 0.270 mm d^{-1}), Restricted Microsprinkler in late summer 2011 ($R^2 = 0.59$, RMSE = 0.622 mm d^{-1}) at ES, Drip in spring 2011 ($R^2 = 0.93$, RMSE = 0.234 mm d^{-1}), and Conventional ($R^2 = 0.60$, RMSE = 0.572 mm d^{-1}) at SS. Though not all irrigation treatments showed these trends by season, the significant relationships established should provide the basis for improving soil water management in citrus irrigation systems.

Daily Water Use of Huanglongbing Infected and Noninfected Trees

Daily water use per unit canopy volume and leaf area were determined for both sites (Table 4). Mixed results were observed in February and March 2011 where HLB infected trees under drip irrigation at SS used more water by 2.8-fold per unit canopy volume and 3.4-fold per unit leaf area than the smaller noninfected trees at ES under the same irrigation system. However, similar water use patterns were observed in summer 2011. Another study conducted parallel to this study showed that non-HLB infected trees at ES had 1.5- to 4-fold greater root density than HLB infected trees at SS (Kadyampakeni et al., 2014). Graham et al. (2013) also found that HLB infected trees experience a reduction in root mass that should limit water uptake. Thus, less water use at SS than ES was expected. However, the results

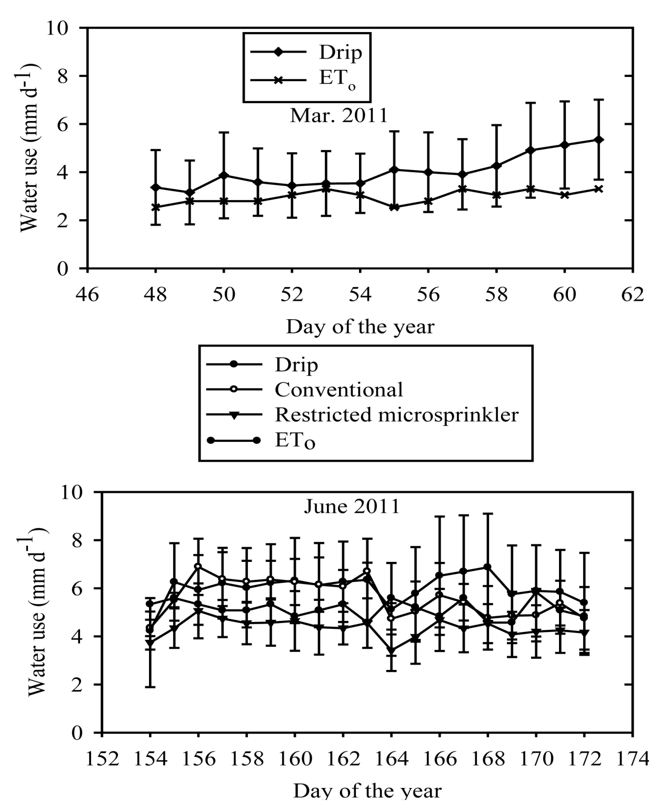

Fig. 6. Daily sap flow at the Spodosol site in spring and summer 2011 using Drip, Conventional, and Restricted Microsprinkler. Error bars denote one standard deviation.

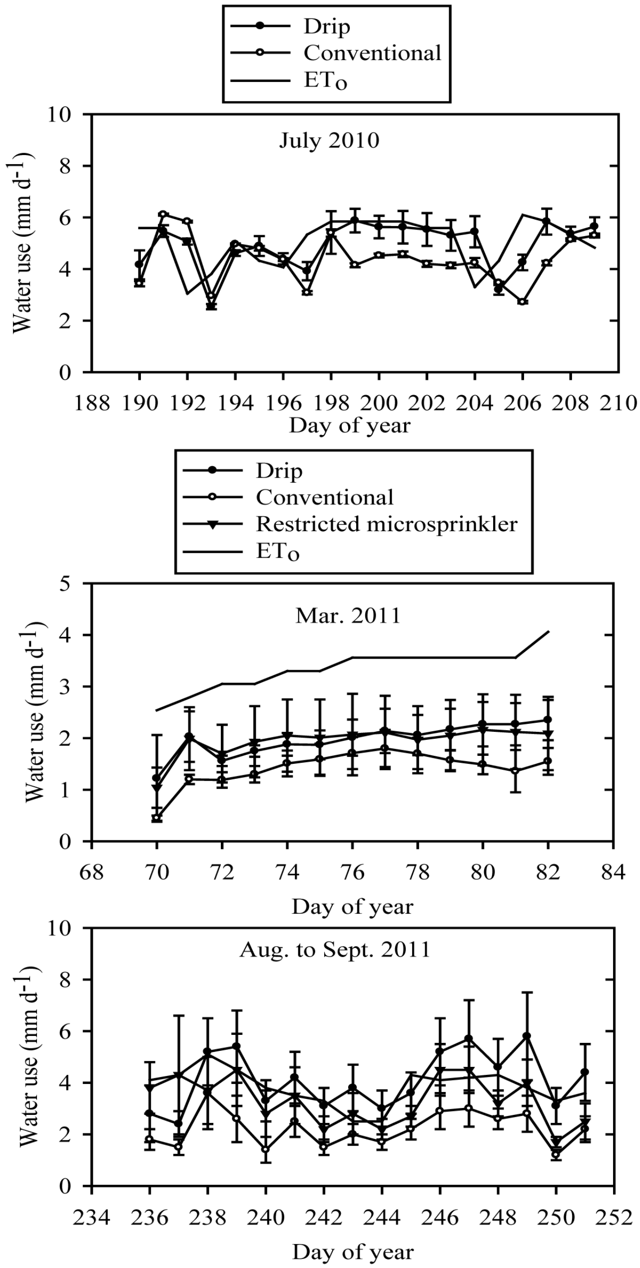

Fig. 7. Daily water use at the Entisol site in summer 2010 and spring and late summer 2011. Error bars denote one standard deviation.

showed that though trees at SS had less root length density than ES (Kadyampakeni et al., 2014), they used similar or more water per unit leaf area or canopy volume at SS indicating that water use may not be limited by HLB infection as long as the tree has sufficient leaf mass and canopy volume.

Sensor-Based Soil Moisture Distribution in the Irrigated Zone

The soil moisture distribution pattern evaluated with automated capacitance sensors showed that there was ample soil moisture in the root zone in all the treatments in July 2010 at ES. Daily soil moisture at 10- and 45-cm soil depths averaged between 6 and 13% (Fig. 8) using the three irrigation systems in summer 2010 and late summer 2011 at ES. Soil moisture decreased with depth probably because of the frequent rainfall that kept the top 10-cm layer wet throughout the study period. Lower average soil moisture content at 10 cm than 45 cm suggests water removals either through tree uptake, soil evaporation, or downward drainage. Daily soil moisture at ES averaged 7.3 to 11.3% at 10-cm depth and 7.6 to 12.3% at 45-cm depth using the three irrigation treatments in March 2011.

The Drip soil moisture varied between 7.5 and 10.0% in the top 30 cm and remained between 5 and 6.5% at 40- and 50-cm depths in February and March 2011 at SS. The Conventional soil moisture contents ranged between 8 and 13% in the top 20 cm, and between 6 and 7% in the bottom 30- to 50-cm soil depth layers from February to March 2011. In June 2011, the moisture contents for Drip ranged from 7.5 to 12.0% in the top 30 cm and between 6.5 and 7.7% at 40- and 50-cm soil depths. The soil water at SS using Restricted Microsprinkler ranged from 8.5 to 14% and around 6 to 8% in the 40- to 50-cm soil depths in February, March, and June 2011 (Fig. 9). In June 2011, the soil moisture varied from 10 to 20% in the top 20 cm and ranged from 6 to 13% in the lower 30- to 50-cm soil depth using Conventional irrigation (Fig. 9). The lower soil moisture contents in the lower 30- to 50-cm depth suggest that root water extraction in the top 30 cm resulted in less water percolating to lower soil depth layers. This might hold because the Immokalee fine sand has a shallow water table that limits root development to the top 30 cm (Obreza and Pitts, 2002; Bauer et al., 2004).

Implications of the Results on Irrigation Management and Water Use

The experiments compared the performance of Conventional irrigation with Drip and Restricted Microsprinkler ACPS where 4 to 20% of the root zone was irrigated. Advanced citrus production systems irrigation, despite irrigating in a limited area of the root zone, had similar or greater water use than Conventional. Frequent irrigation (pulsed with drip or irrigated once a day with restricted microsprinklers) increased soil water availability and promoted root length density in the irrigated zone which in turn increased water uptake. The root density of the Conventional treatment was about 25 to 50% of that observed in the irrigated zone of ACPS (Kadyampakeni, 2012; Kadyampakeni et al., 2014). These results are in agreement with past studies in citrus which have shown good correlation between root density and water use (Castle and Krezdorn, 1977; Grieve, 1989; Morgan et al., 2006), though such studies used less frequent irrigation practices compared with the ACPS practices explored in this study. In this study, the soil moisture distribution patterns in all the irrigation methods were similar and maintained soil moisture close to or above field capacity largely in the range of 7 and 15%, suggesting that soil moisture was nonlimiting (Fig. 8 and 9). More than 60% of the roots for ACPS irrigation were found in the 0- to 15-cm depth layer while a large portion of roots for Conventional irrigation were concentrated in the lower depth (15- to 30-, and 30- to 45-cm depths), where soil water content was below 5% (Kadyampakeni, 2012). This might explain, in

Table 3. Multiple regression analysis of daily water use (Y, mm d^{-1}) with respect to total available soil water (D, %) at selected soil depths (Di, i = 1, 2 at 10- and 45-cm soil depths at Entisol site, and i = 1, 2, 3, 4, 5 at 10-, 20-, 30-, 40-, and 50-cm soil depths at the Spodosol site.†

Site	Irrigation method	Season/Year	Regression coefficients Y_o	a	b	c	d	e	R^2	RMSE	P
			mm d^{-1}							mm d^{-1}	
Entisol	Drip	summer 2010	5.629	0.003	-0.011	‡	‡	‡	0.035	0.949	NS§
Entisol	Conventional	summer 2010	3.973	-0.007	0.014	‡	‡	‡	0.110	0.934	NS
Entisol	Pooled	summer 2010	5.179	-0.001	-0.004	‡	‡	‡	0.010	0.878	NS
Entisol	Drip	spring 2011	2.693	-0.003	-0.003	‡	‡	‡	0.167	0.317	NS
Entisol	Conventional	spring 2011	0.430	-0.002	0.011	‡	‡	‡	0.496	0.270	*
Entisol	Restricted microsprinkler	Spring 2011	1.650	0.004	-0.003	‡	‡	‡	0.250	0.280	NS
Entisol	Pooled	spring 2011	1.320	-0.004	0.010	‡	‡	‡	0.295	0.278	NS
Entisol	Drip	summer 2011	3.211	-0.022	0.048	‡	‡	‡	0.219	1.037	NS
Entisol	Conventional	summer 2011	4.621	-0.012	-0.001	‡	‡	‡	0.346	0.623	NS
Entisol	Restricted microsprinkler	summer 2011	3.623	-0.027	0.053	‡	‡	‡	0.591	0.622	*
Entisol	Pooled	summer 2011	2.880	-0.022	0.043	‡	‡	‡	0.402	0.648	NS
Spodosol	Drip	spring 2011	61.822	-0.874	0.315	-0.363	1.729	-1.399	0.928	0.234	***
Spodosol	Drip	summer 2011	−53.866	-0.141	0.620	-0.235	-1.235	1.476	0.391	0.546	NS
Spodosol	Conventional	summer 2011	1.054	-0.196	0.769	-1.449	1.555	-0.591	0.602	0.572	*
Spodosol	Restricted microsprinkler	summer 2011	2.651	-0.067	0.074	-0.114	-0.013	0.020	0.398	0.342	NS
Spodosol	Pooled	Summer 2011	12.677	0.042	-0.142	0.118	-0.251	0.139	0.245	0.518	NS

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

† The models are $Y = Y_o + aD_1 + bD_2$ at Entisol site and $Y = Y_o + aD_1 + bD_2 + cD_3 + dD_4 + eD_5$ at the Spodosol site; a, b, c, d, and e are regression coefficients.

‡ Not applicable.

§ NS, nonsignificant.

part, the higher water uptake with ACPS than Conventional irrigation. The results somewhat differ from the work of Fernandez et al. (2003) who showed that in olive trees irrigated at 100% ET_c daily by localized irrigation, water use was markedly curtailed, as compared with the values recorded when the whole root zone was wetted. They explained that water lost by transpiration was restricted under regulated deficit irrigation due to a portion of roots having been left in drying soil. However, orange trees in our studies under ACPS developed dense root systems in the irrigated zones. Also, the rains in Florida (Fig. 2) tend to supply ample water even in nonirrigated zones in summer (Obreza and Pitts, 2002), thus enhancing water availability in the root zone. These results strongly indicate that despite the predominant sandy soil characteristic of Florida and low water retention, water use might be increased with ACPS irrigation without subjecting the tree to water stress. Similar to observations in summer 2010, we noted that water use in summer and late summer 2011 also showed consistently high readings between 1000 and 1800 HR, probably due to increased irradiance and temperature compared with the rest of day.

CONCLUSIONS

There were largely no differences in hourly sap flow and daily water use between Conventional and ACPS irrigation methods at

Table 4. Canopy size, leaf area, and water use for the Entisol and Spodosol sites.

Irrigation method	Site	Mo/Yr	Canopy volume	Leaf area	Water use per tree per day	Water use per unit canopy volume	Water use per unit leaf area
			m^3	m^2	kg d^{-1}	kg m^{-3} d^{-1}	kg m^{-2} d^{-1}
Conventional	Entisol	Mar. 2011	2.81 ± 0.73b†	6.31 ± 2.78a	3.13 ± 0.65a	1.33 ± 0.19a	0.60 ± 0.29a
Drip	Entisol	Mar. 2011	4.89 ± 0.58a	9.23 ± 1.57a	4.86 ± 0.78b	0.96 ± 0.18a	0.52 ± 0.17a
Restricted Microsprinkler	Entisol	Mar. 2011	3.91 ± 0.67ab	7.01 ± 1.28a	4.39 ± 1.97b	1.36 ± 0.74a	0.89 ± 0.62a
Conventional	Entisol	Aug. 2011	5.33 ± 0.48a	14.42 ± 2.29a	20.54 ± 7.77a	4.44 ± 2.09a	1.73 ± 0.97a
Drip	Entisol	Aug. 2011	6.53 ± 0.88a	20.16 ± 4.18a	44.69 ± 35.04a	3.76 ± 0.16a	1.17 ± 0.05a
Restricted Microsprinkler	Entisol	Aug. 2011	5.84 ± 0.85a	16.87 ± 4.06a	30.05 ± 6.12a	3.21 ± 2.81a	1.10 ± 0.95a
Drip	Spodosol	Feb. 2011	3.52 ± 0.40	10.22 ± 4.96	15.82 ± 7.43	2.71 ± 1.16	1.75 ± 0.78
Conventional	Spodosol	June 2011	7.61 ± 1.25a	17.78 ± 7.84a	22.90 ± 8.3b	3.06 ± 0.76a	1.19 ± 0.17a
Drip	Spodosol	June 2011	9.32 ± 1.10a	28.48 ± 6.86a	53.8 ± 25.6a	4.52 ± 1.66a	1.44 ± 0.37a
Restricted Microsprinkler	Spodosol	June 2011	6.67 ± 1.30a	11.94 ± 8.12a	25.2 ± 12.0ab	3.08 ± 1.42a	2.22 ± 0.92a

† Mean ± 1 standard deviation, means followed by the same letter in the same column during a particular month are not significantly different at P = 0.05 using Tukey's Test.

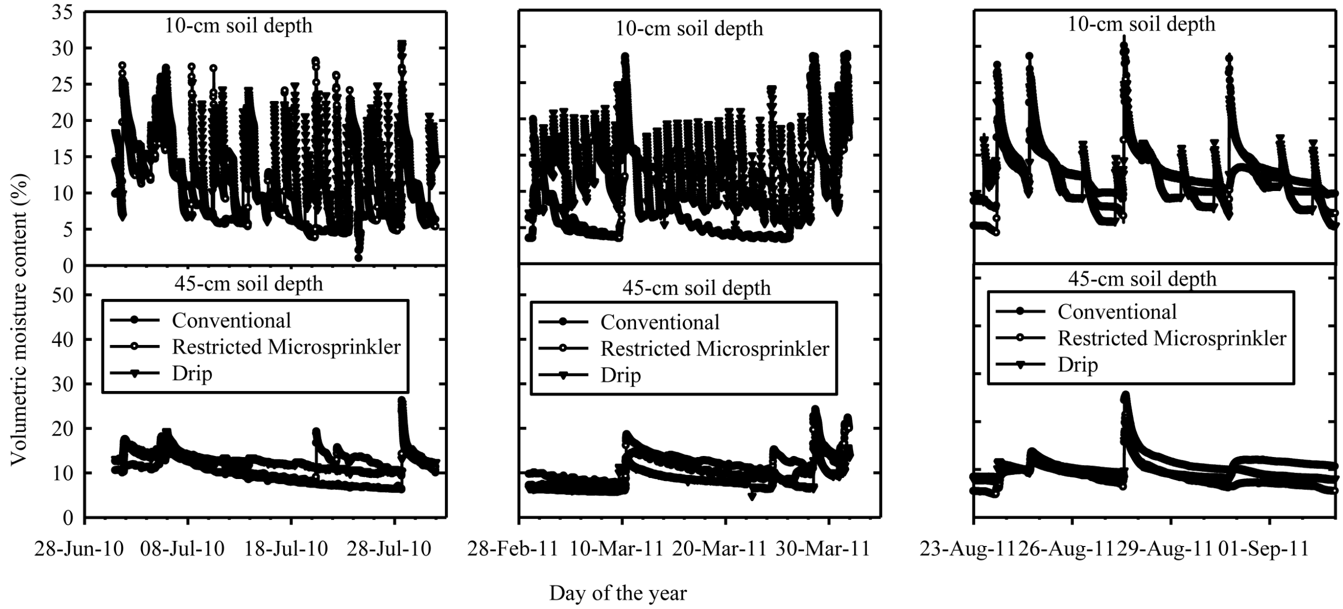

Fig. 8. Soil moisture distribution in summer 2010, spring 2011, and late summer 2011 at the Entisol site.

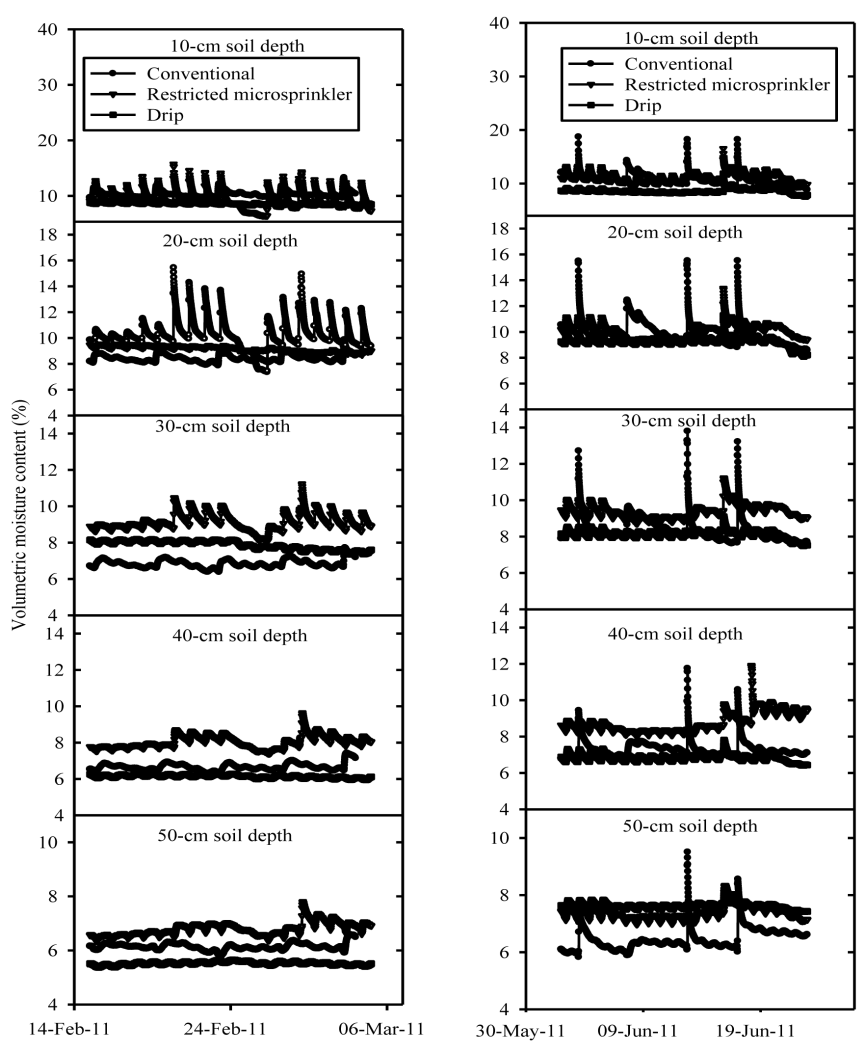

Fig. 9. Soil moisture distribution for Drip, Restricted Microsprinkler, and Conventional in spring and summer 2011 at the Spodosol site.

the Spodosol and the Entisol sites though slightly greater water use was observed with ACPS. The high uptake in the ACPS irrigation methods was ascribed to frequent and/or pulsed irrigation that kept soil moisture very close to field capacity. Polynomial models of the third order described the hourly sap flow vs. time of day very well and could be used for optimizing citrus irrigation events to coincide with peak water use. The relationships between daily water use and TASW were not consistent by irrigation method or season though Drip in spring 2011 (R^2 = 0.93), and Conventional in summer 2011 (R^2 = 0.60) at SS and Conventional in summer 2010 (R^2 = 0.50) and Restricted Microsprinkler in summer 2011 (R^2 = 0.59) ES showed a good response of daily water use to TASW. In addition, there was no difference in water use between HLB infected and noninfected trees suggesting similar irrigation water requirements. All the irrigation methods were similar and maintained soil moisture close to or above field capacity largely in the range of 7 and 15%, suggesting that soil moisture was nonlimiting.

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