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Citrus Water Requirements: Linking Irrigation Scheduling and Fertilizer Strategies

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Florida citrus trees must be irrigated to reach maximum production due to the low soil water-holding capacity of our sandy soils. Nutrients, especially nitrate-N, move rapidly through these sandy soils with drainage of excess water. In a highly urbanizing state with limited water resources, improved understanding of soil water uptake and movement is needed to optimize irrigation without leaching nutrients and impacting water quality. In a 25-month field study using mature 'Hamlin' orange (*Citrus sinensis* L.) trees, roots were concentrated in the top 30 cm of soil under the tree canopy (0.71 to 1.16 cm roots/cm³ soil), ET_c (crop evapotranspiration) averaged 1137 mm/year, and estimated K_c (crop coefficient) ranged between 0.7 and 1.1. Day of year explained more than 88% of the variation in K_c when soil water content (θ) was near field capacity. The value of K_s (soil water extraction factor) decreased steadily from 1.0 at field capacity (θ = 0.072 cm³·cm⁻³) to approximately 0.5 at 50% available soil water depletion (θ = 0.045 cm³·cm⁻³), where maximum soil water uptake decreased as soil water content decreased. Estimating daily plant water uptake and resulting soil water depletion based on root length density distribution under a citrus tree would provide a reasonable basis for a citrus soil water balance. It has been demonstrated that nutrient uptake is relatively rapid in citrus. However, leaching of nutrients by over-irrigation must be avoided, especially for several days after fertilizer application. Using a water balance approach, irrigation amounts can be estimated to provide adequate water for nutrient uptake and reduce leaching from over-irrigation.

Florida is one of the fastest-growing states in the United States, adding about 700 new residents each day, so the competition for water supply is increasing throughout the state (Smith, 2005). Increasing demands from residential and commercial users are often met at the expense of agricultural and environmental water supplies. As the number of Floridians continues to increase, allocation of water will decrease for agriculture (Marella and Berndt, 2005). Therefore, improving our knowledge of soil and plant factors that affect water uptake by citrus trees is essential to optimize irrigation volume and timing so that water can be more efficiently used. As water for citrus irrigation is reduced, managers must reduce grove water consumption while avoiding tree stress or fruit yield/quality loss due to insufficient irrigation applications. The key to water management efficiency is to satisfy crop demands, addressing the various growth stages of the tree, and including both soil characteristics and weather into decisions regarding irrigation (Allen et al., 1998). Better irrigation scheduling will also reduce negative impacts on groundwater quality due to agrichemical leaching through Florida's highly porous sandy soils (Alva and Paramasivam, 1998).

Management techniques for irrigating commercial citrus groves must take into consideration the differences in soils and related water regimes among different areas of the state. Soils of the same type have similar water- and nutrient-holding capacities. Soil characteristics pose considerable constraints on irrigation practices; the water-holding and drainage characteristics of these soil types greatly influence root distribution. Irrigation practices must address these characteristics to effectively irrigate the trees without leaching nutrients into surface or groundwater. Root development changes with both tree age and soil characteristics. Thus, changes in irrigation management should be based upon knowledge of the root system, and should not be the same for all soil types or similar from new plantings to mature tree production.

Soils of the central Florida ridge are predominantly in the Entisols soil order. Examples of Entisols are Astatula, Archbold, Candler, Satellite, and Tavares (Obreza and Collins, 2002). Soil types in this soil order are relatively newly formed soils without layers. These soils are characterized by rapid infiltration of rain and irrigation water, as well as low water- and nutrient-holding capacities. The water-holding capacity of a soil is defined by the difference between soil field capacity and the plant wilting point. Entisols have water-holding capacities of 4% to 8%, and are often well drained, allowing citrus roots to penetrate deeply into the soil (Castle and Kresdorn, 1975). This root distribution pattern anchors the tree and provides a large volume of soil from which the tree may extract both nutrients and water.

Irrigation duration and flow rate determine the volume of water that is added to the grove. Gravitational and capillary forces move the water downward through the soil until the soil has reached field capacity or the maximum soil water content a soil can hold after drainage stops. Any additional irrigation water either continues through the soil profile below the root zone or reaches the water table. In both cases, water above the amount required to reach field capacity in the root zone is wasted and potentially contributes to nutrient leaching. This simplified model of water movement has been called "piston flow" because water entering the soil from

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irrigation or rainfall forces existing water in the soil deeper into the soil profile (Hillel, 1995). This process also describes the flow of some nutrients in the sandy soils of central and south Florida, making them vulnerable to nutrient leaching.

When water is lost from the soil by evaporation and the citrus tree loses water through the transpiration process, water must be supplied to replace crop evapotranspiration (ET_c) (Allen et al., 1998). A reference evapotranspiration (ET_o) can be used as a basis for estimating the citrus grove evapotranspiration or irrigation demand. Reference ET is calculated on a daily basis using weather data or is available from the nearest Florida Automated Weather Network (FAWN) site (http://fawn.ifas.ufl.edu). The calculation of ET_o using weather data is described in HS179, "Weather Data for Citrus Irrigation Management" (http://edis.ifas.ufl.edu/HS179).

Two factors must be used to convert ET_o to one that addresses citrus growing in specific soils found in the grove of interest. The crop coefficient (K_c) for citrus changes throughout the year and is low during the cooler months when water use is low and higher in the warm summer months when water use by the citrus trees is high (Doorenbos and Pruitt, 1977). The soil water extraction factor (K_s) is an estimate of the trees' reduced ability to remove water with lower soil water content (Allen et al., 1998). As soils dry out, tree roots must expend more and more energy to extract water from the soil. If trees remove less water, the K_s decreases. Reduced water uptake by the tree can result in reduced tree growth and yield (Koo, 1963, 1978). Thus, growers have been advised to keep their grove soil above the recommended maximum allowable water depletions (discussed below) for the given time of the year so that the K_s factor remains as high as possible.

Equation 1 uses these coefficients to estimate the crop ET (ET_c). However, once the ET_c is estimated, another simple set of calculations can be used to predict when irrigation should occur (Allen et al., 1998; Doorenbos and Pruitt, 1977). This method utilizes current soil water information and the ET_c in a simple water budget. That is, what amount of depletion of the soil's available water should be used before irrigating? The UF/IFAS recommendation is to allow 25% to 33% soil water depletion from February through May, and 50% to 66% depletion from June through January. The smaller allowable springtime depletions provide increased soil water for flowering, fruit set, and growth flushes. The larger allowable soil water depletion in the summer and fall allows for the use of rainfall during the rainy season and adequate water for fruit expansion.

$$ET_c = ET_o \times K_c \times K_s \quad \text{[Eq. 1]}$$

where ET_c = soil water evapotranspiration for a given crop and conditions (centimeters or inches); ET_o = soil water evapotranspiration for standard or reference conditions (centimeters or inches); K_c = crop coefficient adjustment to ET_o for time of year; and K_s = soil depletion coefficient adjustment to ET_o for soil water content.

This paper presents information from two previously published studies on fibrous root length density (FRLD) distribution (Morgan et al., 2007) and water uptake for mature citrus trees (Morgan et al., 2006) grown on sandy soils typical of central Florida's citrus producing region. Concepts and calculations found in these two papers are the basis for the more fully developed irrigation concepts discussed in this paper. The objectives of this paper are use root distribution and water uptake information to 1) determine proper placement of fertilizer and water for optimum uptake by mature trees; 2) improve water requirement estimation to reduce wasting water and leaching of fertilizers; and 3) illustrate the need for improved irrigation scheduling methods.

Materials and Methods

Tree and site characteristics. We examined the root systems of two sets of six randomly selected mature 'Hamlin' orange [*Citrus sinensis* (L.) Osbeck] trees each in Feb. 2001 and Jan. 2002 from a commercial citrus grove near Winter Garden in western Orange County, FL (lat. 28°57'N, long. 81°55'W). Each set was comprised of 14-year-old trees planted in 1987 at a spacing of 3 m in-row and 6.1 m between-rows. Three trees of each set were on Swingle citrumelo [*C. paradisi* Macf. x *Poncirus trjfoliata* (L.) Raf.] rootstock, and the remaining three were on Carrizo citrange [*C. sinensis* (L.) Osbeck x *P. trifoliata* (L.) Raf.] rootstock.

Three mature (14-year-old) 'Hamlin' orange grafted on Carrizo citrange from the same commercial block were used to determine water uptake. The trees had been pruned along the top and sides of their canopies in each of the previous 3 years, forming a hedgerow approximately 3.8 m wide and 5.9 m tall. Herbicides were applied as needed to maintain a nearly weed-free strip 3.5 to 4.0 m wide beneath the tree canopies. Trees were irrigated by a row of microsprinklers positioned along the tree row underneath the canopy. There was one emitter per tree, each with a 3.7-m diameter, 360° circular spray pattern, and a flow rate of 61 $L \cdot h^{-1}$. The irrigated area covered about 57% of the soil surface area allocated to each tree. The equivalent precipitation rate of the sprinkler in the irrigated zone was 0.58 $cm \cdot h^{-1}$.

Soil water content in the irrigated zones of each tree was maintained within a relatively narrow range of field capacity to 25% depletion of available soil water during the late winter to early summer months of February through June to support flowering and fruit set. Soil water content in the irrigated zone ranged between field capacity and 50% available soil water depletion the remainder of the year. Irrigation scheduling was provided by an automated irrigation control system with switching tensiometers at 15- and 30-cm depths in the irrigated zone. Duration of irrigation events was adjusted seasonally to provide water at the given set point to refill the soil to a depth of 0.8–1.0 m. All irrigation events occurred between 200 and 600 h to minimize surface evaporation from both wind and radiation. The use of switching tensiometers eliminated irrigation after rainfall events until soil water content returned to the appropriate set point. The tensiometers were inspected at approximately weekly intervals to ensure proper scheduling. With the exception of rainfall events greater than approximately 12 mm, little water drained through the profile to the 1.5-m depth. All trees had been fertilized with N at a rate of 240 $kg \cdot ha^{-1}$ per year for the previous 5 years through the microirrigation system.

The soil series was Candler fine sand (hyperthermic, uncoated, Typic Quartzipsamment). This soil is typical of the central Florida ridge and has field capacity water content of 0.06 to 0.08 $m^3 \cdot m^{-3}$ in the upper 1 m. The Candler series consists of excessively drained, highly permeable soils formed from marine sediments located in upland areas with slope from 0% to 12%. The A and E horizons consist of single-grained fine sand (>96%), have a loose texture, and are strongly acidic. A Bt horizon is located 2 m deep or more and includes loamy lamellae 0.1 to 3.5 cm thick and 5 to 15 cm long.

Root length density samples. Three soil cores were removed from under each of 12 trees at 0.5-m increments in the row to the

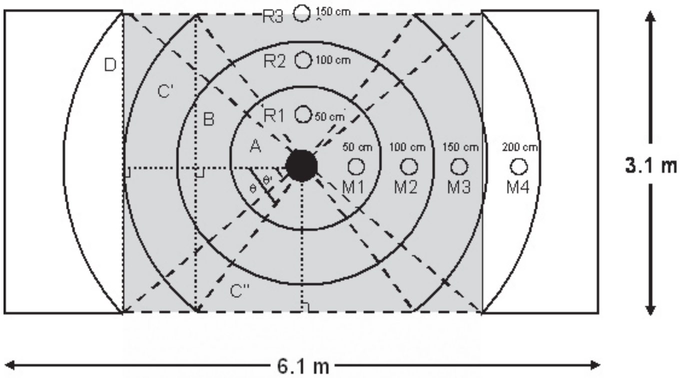

Fig. 1. Diagram of citrus tree root length sample sites in row (R1, R2, and R3) and perpendicular to the tree row (M1, M2, M3, and M4).

midpoint between trees (R1, R2, and R3; Fig. 1) and four cores at 0.5-m increments between tree rows to a distance of 2 m from the tree trunk (M1, M2, M3, and M4; Fig. 1). Cores were taken with a 7.6-cm-diameter bucket auger at 0.15-m increments from 0 to 0.9 m. Roots were subsequently separated into size categories by diameter (0–4 mm, and >4 mm). Root length of fibrous roots <4 mm in diameter was determined using the line intersect method (Newman, 1966). Fibrous root length density (FRLD, $cm \cdot cm^{-3}$) was determined by dividing the sample fibrous root length by the sample soil volume. We estimated root length for the soil volumes represented by each sample distance and depth increment for each of the 12 orange trees. Soil volumes were determined using concentric rings with radii equal to the midpoints between soil sample locations (Fig. 1).

Soil water content measurements. A set of EnviroSCAN (Sentek Pty. Ltd., South Australia, Australia) capacitance probes with sensors 10, 20, 40, and 80 cm beneath the soil surface were used to measure soil water content at soil depths of 0 to 15, 15 to 30, 30 to 60, and 60 to 100 cm. Sensors at 150 cm depth under one tree were used to monitor leaching below the root zone. The 5-cm diameter acrylonitrile butadiene styrene access tubes that housed the probes were placed adjacent to three trees. To aid in calculating water uptake, the root zone of each of three measurement trees were partitioned into five sections based on the positioning of the probes (Fig. 2). In-row and between-row sensors were placed 0.75 m and 0.90 m from the tree trunk, respectively.

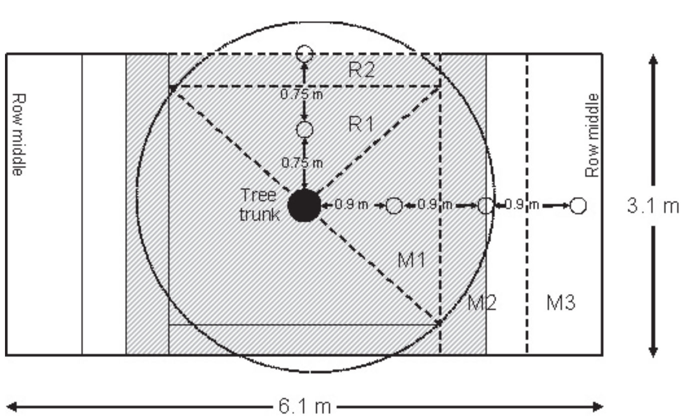

Fig. 2. Diagram of soil water content sensor locations in the tree row (R1 and R2) and perpendicular to the tree row (M1, M2, and M3).

Each sensor was individually normalized according to manufacturer instructions. A calibration curve relating sensor output to θ was developed for the Candler soil using a gravimetric method (Morgan et al., 1999). Water content was recorded every 30 min during two consecutive annual cycles (plus 1 extra month) beginning in Apr. 2000 and concluding in Apr. 2002. Daily Penman ET_o (Jones et al., 1984; Zazueta et al., 1991) was obtained from a FAWN (FAWN, 2004) station located about 0.4 km from the field site.

Daily mean tree water use (ET_c) was estimated for the three study trees during a 24-month period and compared with calculated daily ET_o. The ratios of estimated daily ET_c to calculated daily ET_o for each of the three trees were averaged to estimate the ET_o correction factor discussed in the introduction, which was assumed to be equivilent to the product $(K_c)(K_s)$. To eliminate the effects of decreased θ on water uptake, only ET_c/ET_o ratios on days where mean θ was not less than 95% of field capacity in both the irrigated and non-irrigated zones (i.e. K_s assumed to be 1) were used to estimate daily K_c. The relationship between daily K_c and day of year (DOY) was determined by non-linear regression analysis using a quadratic model. Daily ET_c/ET_o ratios [equivalent to $(K_c)(K_s)$] were calculated throughout the year and compared with mean daily water content in the top 1 m of soil within the allocated tree space. The ratio of ET_c to $(ET_o)(K_c)$ using the K_c for the DOY was used to estimate the value of K_s using linear regression.

Results and Discussions

Mature 'Hamlin' orange tree root distribution. Fibrous root length density was not significantly different ($P > 0.05$) among years indicating little year to year change in mature 'Hamlin' orange tree root length density once containment size was obtained (Morgan et al., 2007). Therefore, the FRLD were pooled (n=12) and analyzed for interactions among rootstock, soil depth, and distance from the tree trunk. Although average FRLD to a 0.9 m depth for the tree allocated space was not statistically different ($P < 0.05$) between rootstocks (Table 1) a significant interaction ($P < 0.01$) of rootstock and depth suggests distinctly different root distribution patterns between the two rootstocks. Trees on Swingle citrumelo had significantly greater ($P < 0.05$) FRLD at the 0–30 cm depth than trees on Carrizo citrange (Table 1). However, FRLD in the top 0.15 m at a distance of 1.5 m or less for trees on Swingle citrumelo, was significantly greater than for trees on Carrizo citrange at the same depth and distance.

The FRLD distribution among the 12 mature 'Hamlin' trees was similar to the intensive distribution described by Castle and Krezdorn (1975) with 50% to 66% of the total fibrous roots to a 0.9 m deep were within the upper 0.30 m and few fibrous roots below 0.75 m (10%). Lateral fibrous roots were less developed in mature trees on both rootstocks with approximately 11% of fibrous roots beyond 1.75 m from the tree trunk. Hassan (1984) reported similar root density distribution for Swingle citrumelo and an unnamed citrange. Finding a similarly high proportion of fibrous roots and nutrient uptake in the upper 0.5 m of soil, Thakur et al. (1981) concluded that "citrus is basically a surface feeder." We found the upper 0.45 m of soil contained ~76% of Swingle citrumelo fibrous root length. This finding compares well with a study by Mikhail and El-Zefhoui (1979) who found that 79% of total fibrous root weight of 'Valencia' oranges occurred in the first 0.60 m of soil on sandy soils whereas clay soils contained 94% in the same depth. However, trees grown on Carrizo citrange

Table 1. Mature 'Hamlin' orange tree mean fibrous root length density, estimated root length, and percentage of root system in the upper 0.9 m of soil by rootstock and soil depth.

	Carrizo citrange			Swingle citrumelo		
Soil depth (cm)	FRLD[z] (cm·cm^{-3})	Root length[y] (m)	Root length 0–90 cm[z] (%)	FRLD[z] (cm·cm^{-3})	Root length[y] (m)	Root length 0–90 cm (%)[z]
0–15[x]	0.84 A	432	38 A	1.39 A	620	53 A
15–30	0.27 B	143	13 B	0.35 B	150	13 B
30–45	0.16 B	82	7 C	0.16 B	85	7 C
45–60	0.28 B	155	14 B	0.19 B	88	8 C
60–75	0.32 B	176	16 B	0.21 B	118	10 B
75–90	0.28 B	149	12 B	0.25 B	107	9 BC

[z]Fibrous root length density (FRLD) for 'Hamlin' orange trees at the 0–15 cm depth was significantly different ($P < 0.05$) for Swingle citrumelo rootstock compared with Carrizo citrange. FRDL was not significantly different by rootstock for remaining depth increments.
[y]Calculated root length from mean FRLD, tree space area (3.0 × 6.1 m = 18.3 m^2), and soil layer depth.
[x]Fibrous root length density (FRLD) for mature 'Hamlin' orange trees extracted from soil samples at 15-cm increments. Mean (n=6) separation by Duncan's multiple range test. Values followed by different letter within a column are significantly different ($P < 0.05$) from other values in the same column.

Table 2. Mature 'Hamlin' orange tree mean fibrous root length density, estimated root length, and percentage of root system in the upper 0.9 m of soil by rootstock and distance from the tree trunk.

Distance	Carrizo citrange			Swingle citrumelo		
from trunk (cm)	FRLD[z] (cm·cm^{-3})	Root length[y] (m)	Root length 0–225 cm[z] (%)	FRLD[z] (cm·cm^{-3})	Root length[y] (m)	Root length 0–225 cm (%)[z]
0–75[x]	0.39 A	100	15 A	0.64 A	163	25 A
75–125	0.42 A	198	29 A	0.36 AB	171	26 A
125–175	0.34 AB	310	45 A	0.29 AB	248	38 A
175–225	0.17 B	78	11 B	0.15 B	70	11 B

[z]Fibrous root length density (FRLD) for 'Hamlin' orange trees extracted from soil samples at selected distances from the tree trunk. Mean (n=6) separation by Duncan's multiple range test. Values followed by different letter within a column are significantly different ($P < 0.05$) from other values in the same column.
[y]Calculated root length from mean FRLD, tree space area (3.0 × 6.1 m = 18.3 m^2), and soil layer depth.
[x]FRLD for 'Hamlin' orange trees at the 0–75 cm distance was significantly different ($P < 0.05$) for Swingle citrumelo rootstock compared with Carrizo citrange. FRDL was not significantly different by rootstock for remaining distances.

had more FRLD deeper than 0.45 m compared with trees grown on Swingle citrumelo, resulting in only 58% of Carrizo tree root length above the 0.45-m depth (Table 1).Unlike soil depth, we found that distance from the tree trunk had less effect on distribution of fibrous roots among rootstocks (Table 2). Nearly 90% of the estimated total root length of both rootstocks was within 1.75 m of the trunk. This distance corresponds roughly to the extent of both the tree canopy and the irrigated zone (Fig. 1*)*.

The differences we found in FRLD between rootstocks indicate that irrigation depth and the depth for fertilizer placement based on root distribution should be rootstock specific. Thus, mature citrus trees on Swingle citrumelo rootstock should be irrigated to a shallower depth compared with trees on Carrizo citrange. Deep irrigation beyond 0.45 m for Swingle citrumelo or 0.6 m for Carrizo citrange in these soils will waste water and greatly increase the risk of leaching soil N below the effective root zone, potentially decreasing nutrient uptake efficiency.

Soil water uptake. Daily ET_c was lower than or equal to daily ET_o and followed a seasonal fluctuation. ET_c approached ET_o from June through August, but only when the soil was at or near field capacity. The citrus ET_c values determined here compared closely with those measured in humid climates by other researchers (Boman, 1994; Castel et al., 1987; Doorenbos and Pruitt, 1977; Rogers et al., 1983). In contrast to the current study, Martin et al. (1997) reported ET_c for citrus in Arizona under arid conditions, indicating similar minimum but nearly doubled maximum daily ET_c compared with humid conditions in Florida.

Reported K_c values for central Florida citrus ranged from about 0.6 in winter to 1.1 in summer (Boman, 1994; Fares and Alva, 1999; Rogers et. al., 1983). K_c at field capacity in the top 1 m of soil ranged from 0.7 in January to 1.1 in June (Fig. 3). Thus, K_c estimated here agrees well with previous studies. Day of year (DOY) explained more than 88% of the variation in the ET_c:ET_o ratios when θ was at field capacity, so Equation 1 provides a good approximation of K_c for a given DOY.

A region of readily available water (RAW) exists between field capacity and approximately 30 to 50% of the allowable soil water deficit (ASWD) for loam and loamy clay soils where essentially no crop water stress occurs (Allen et al., 1998). However, the region of RAW is considerably reduced for sandy soils. Linear regression analysis determined the range of RAW to be less than 1% of ASWD in the upper 1 m of the total soil voume within the tree allocated space (Fig. 4). Estimates for K_s decreased from 1 at 1% ASWD to approximately 0.5 at 50% ASWD for all soil volumes indicating a reduction of 50% in ET_c between field capacity and 50% ASWD.

Stress associated with ASWD greater than 33% during periods of flowering, fruit set, and rapid vegetative growth in the spring was found to reduce yield of overhead irrigated citrus grown on sandy soils under Florida climatic conditions (Koo,1963, 1978). Koo also determined that ASWD of 66% could be tolerated during summer, fall, and winter months. Thus, the potential onset

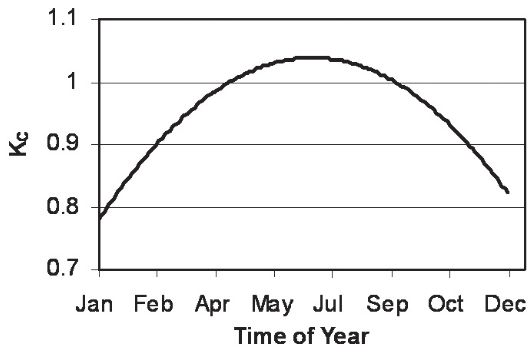

Fig. 3. Estimated citrus crop coefficients (K_c) by time of year.

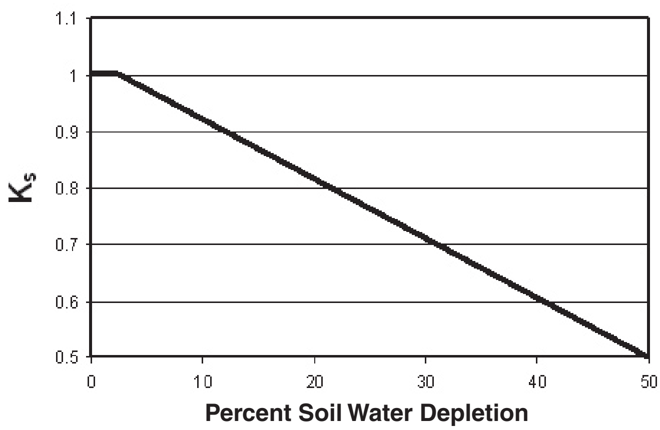

Fig. 4. Reduction of estimated soil water content coefficient with decrease in soil water content calculated as percentage of allowable soil water depletion.

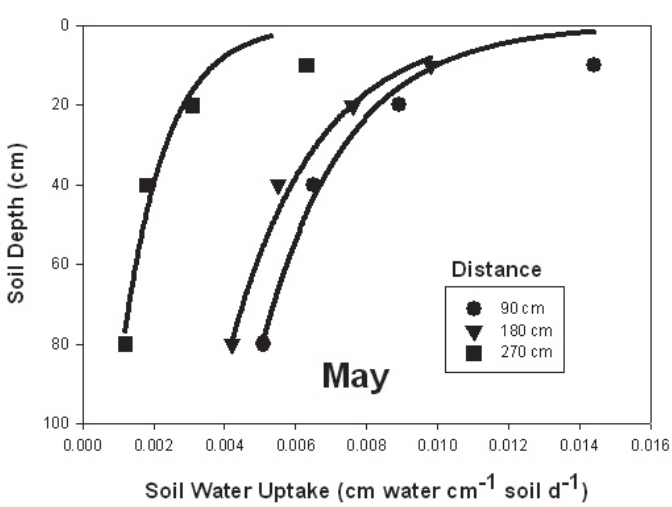

Fig. 5. Relationship of soil water uptake to root length density as a function of soil depth and distance from the tree trunk.

of crop water stress associated with K_s of 0.7 from February through June and 0.4 from June through January should be used to schedule irrigation to maximize yields while minimizing the water requirement..

The daily rate of soil water uptake decreased with increased soil depth (Fig. 5). Citrus tree roots were concentrated in the top 30 cm of soil under the canopy and decreased with soil depth (Table 1). Daily depth-adjusted uptake rates at all depths and distances followed the root length density distribution in Table 1, indicating that soil water uptake was proportional to root length density. Thus, soil regions containing higher root length density will dry out at a proportionally higher rate. Hence, a model of soil water uptake and depletion based on root length density would be appropriate for citrus.

Improved nutrient use. Nutrients move through the soil at various rates if they are not taken up by plants. Nitrate nitrogen moves rapidly and is found just above the depth that the water wets the soil while P moves much more slowly (Alva and Parmasvam, 1998). Nitrogen uptake by citrus has been shown to be proportional to the soil concentration and length of time the nutrient is the vicinity of the tree roots (Scholberg et al., 2002). Therefore, irrigation scheduling is the most important factor in placing nutrients (particularly N) in a location that exposes the nutrient to the tree roots for uptake. Fertilizers should be applied in locations of maximum interception by roots and irrigation must be managed to prevent nutrient leaching below the root zone. In both cases root density patterns and water uptake dynamics must be considered for the particular tree size, rootstock, water use (ET), and time of year.

Irrigation scheduling for optimum water and nutrient use. To use irrigation water correctly, avoiding too wet or too dry conditions, three aspects of irrigation must be determined: the area to be wetted, the depth of wetting, and the total amount of water to be applied. Proper irrigation scheduling to replace water used by the tree requires that the majority of the root system be irrigated. As we discussed previously, the distribution of tree roots are soil type and rootstock dependent. Applying irrigation or fertilizers evenly over the area under the tree canopy will provide water to 75% to 90% of the root system of these microsprinkler irrigated trees. The depth to which soil should be brought to field capacity for proper irrigation is not as easily determined. As we discussed previously, trees on Swingle citrumelo rootstock were relatively shallow rooted and had 75% or more of their roots in the top 0.45 cm. Trees grown on Carrizzo citrange rootstock had less than 60% in the 0- and 0.45-cm depth, requiring irrigation to depths of 0.60 cm or more.

A simple irrigation water applications estimate can be easily calculated using available information discussed in this paper. Candler soils, for example, have a field capacity of approximately 0.08 $cm \cdot cm^{-1}$ or 8%. For Swingle citrumelo rootstock, 0.8 cm of water would fill the soil to field capacity to a depth of approximately 45 cm, at 25% depletion (spring irrigation) of available soil water using equation 2. However, it would take 1.6 cm to fill the same depth of soil to field capacity at 50% depletion (fall irrigation). Using the same available soil water for a 60-cm depth (Carrizzo citrange rooting depth), the required water would be 1.1 and 2.1 cm at 25% and 50% depletion, respectively. Calculated irrigation pumping time required using Equation 3 would be 2.3 and 4.7 h to fill the soil to field capacity to a depth of 45 cm for the two depletions (assuming 0.38 $cm \cdot h^{-1}$, 90% efficiency). The amount of pumping time required to irrigate the same soil to a 60-cm depth would be 3.2 and 6.2 h at the same depletion levels.

$$I = [(FC - PWP) \times A] \times D \text{ or } I = (AW \times A) \times D \qquad \text{[Eq. 2]}$$

where I = irrigation water depth (cm or inches); FC = soil water content at field capacity (centimeters or inches); PWP = soil water content at permanent wilting point (centimeters or inches); A = available water content in irrigation zone (percentage); D = depth of soil to bottom of irrigated zone (centimeters or inches); and AW = available soil water or amount of water available to the plant (centimeters or inches).

$$H = \frac{I}{PR \times E} \qquad \text{[Eq. 3]}$$

where H = irrigation time required (hours); I = irrigation water depth (centimeters or inches, Equation 1); PR = precipitation rate of the irrigation emitter (centimeters or inches per hour); and E = irrigation system efficiency (percentage).

These calculations assume that the soil has the same depletion from the surface to the bottom of the irrigation depth. As we have demonstrated, the soil does not dry out at the same rate, due to root density differences. This predictable but irregular soil drying pattern is true for various soil depths and distances from the tree trunk. Proper irrigation durations and depths require additional information and/or complex calculations. Irrigation amount can be calculated using the equations described above. However, the amount of time required between irrigations, or irrigation frequency, requires soil moisture measurement or information on ET_c, K_c and K_s (Equation 1) discussed above. Soil moisture sensors and computer models can assist growers in determining proper irrigation schedule frequencies quickly and easily.

Use of soil moisture sensors for irrigation scheduling. The direct measurement of soil water has also been used to schedule irrigation scheduling for decades. Recent advances in soil water sensor technology and the proliferation of computers in production agriculture has made using these devices easier and more commonplace. The simplest device is a tensiometer, which measures the force or tension that water is held to the soil. As soils dry, the water remaining in the soil is held more tightly by the soil and is thus less available to the tree. The soil can not be allowed to dry too much or plant stress will increase, thus reducing growth and yield. Discussion of the installation, maintenance, and use of these devices is described in AE146, "Tensiometers for Soil Moisture Measurement and Irrigation Scheduling" (http://edis.ifas.ufl.edu/AE146).

A wide range of electronic sensors are also available to citrus growers for measurement of soil water content or tension. These sensors are typically more expensive than the simple tensiometer but have the advantages of high accuracy, low maintenance, and most will connect directly to computers or irrigation controllers for data collection. These sensors are described in AE266, "Field Devices for Monitoring Soil Water Content" (http://edis.ifas.ufl.edu/AE266). Regardless of the measurement device, knowledge of the soil characteristics is needed to determine the soil tension or content for the particular soil location and depth to start irrigation. The amount of water required to fill the soil profile to field capacity must also be calculated using both equations described above (Equations 2 and 3).

Use of soil water balance models for irrigation scheduling. Soil water balance models are now being developed using the soil water uptake information discussed earlier. One soil water balance model used for irrigation scheduling (www.fawn.ifas.ufl.edu/citrus irrigation scheduler) is available through the FAWN weather system, a web-based weather reporting system for agricultural users. The model can determine the length of time required to return the soil to field capacity to a specific depth and the frequency (days between) that irrigation needs to occur. Soil water contents are estimated for several distances and soil depths using calculated ET_c deductions based on K_c, K_s, and root density at each location described earlier in the paper. Crop ET is determined using weather data from the FAWN Station nearest the grove on a daily basis. Both K_c and K_s are automatically calculated daily depending on day of year and estimated soil water content.

Conclusions

With future population increases, Florida citrus growers will be expected to further improve there irrigation and fertilizer practices to maintain, or improve, current water quantity and quality levels across the state. The application of water and fertilizer to high root density areas will be key to these improvements. Placement of water and fertilizers under the tree canopy where 65% to 90% of the fibrous roots grow will improve both water and nutrient uptake efficiency of the trees and reduce the risk of nutrient leaching outside the tree canopy where few roots exist. Likewise, determining the proper irrigation amounts to replace the amount of water used by the tree for optimum water use will extend the allowable consumptive water use for the grove and potentially reduce nutrient leaching under the tree. Soil moisture sensors and water balance models are available to provide the information needed for irrigation scheduling.

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