Use of Irrigation Technologies for Citrus Trees in Florida

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SUMMARY. **Florida is the most important center of processed citrus (*Citrus* spp.) production in the United States, and all of the crop is irrigated. Irrigation systems include low-volume microirrigation, sprinkler systems, and subsurface irrigation. This review details the relative irrigation efficiencies and factors affecting irrigation uniformity such as design and maintenance. A wide range of soil moisture sensors (e.g., tensiometers, granular matrix, and capacitance) are currently being used for citrus in the state. The use of these sensors and crop evapotranspiration estimation using weather information from the Florida Automated Weather Network in irrigation scheduling are discussed. Current examples of scheduling tools and automated control systems being used on selected fruit crops in Florida are provided. Research data on the effect of irrigation scheduling, soluble fertilizer injection, and soil nutrient movement, particularly nitrate and the use of reclaimed water in Florida, are also reviewed. Concluding this review is a discussion of the potential for adoption of irrigation scheduling and control systems for citrus by Florida growers and future research priorities.**

Florida is located in a subtropical climate zone that normally receives 48 to 60 inches of rainfall annually. This rainfall amount is adequate to meet the requirements of most citrus cultivars. However, annual rainfall distribution does not usually satisfy peak seasonal demands during critical fruit set and early fruit development. During these phenological periods, good irrigation management is critical to reduce stress and the associated young fruit drop resulting in yield reduction. Historically, irrigation types used for tree fruit production have been water wagons, surface flood, subsurface or seepage, perforated pipe, and overhead high-volume sprinkler. Over the past 20 years, nearly all Florida citrus and other tree fruit irrigation have been converted from high-volume sprinkler to low-volume under-tree microsprinkler irrigation (Boman, 2002).

World production of all citrus cultivars totaled 82 million tons in the 2007 crop year (Florida Agricultural Statistics Service, 2007). The main centers of citrus production in the United States are located in Florida (67%), California (28%), Texas (4%), and Arizona (1%) and total 9.4 million tons or 13% of world production. Florida citrus production in 2006–2007 was orange (*Citrus sinensis*) (80%), grapefruit (*C. paradisi*) (17%), and tangerine (*C. reticulata*) (3%). Citrus area in Florida was highest at over 941,000 acres in 1970 and then declined to less than 624,000 acres in 1985 as a result of the effect of three successive freezes (Florida Agricultural Statistics Service, 2007). Since the mid-1980s, the Florida citrus area has rebounded to nearly 857,000 acres in 1998. Citrus area has declined over the past 8 years to 621,373 acres as a result of control of citrus canker (caused by *Xanthamonus axonopodis*), greening (huanglongbing caused by *Laberibacter asiaticus*) diseases, and urbanization.

With a crop value of $1.362 billion in 2006–2007, citrus is one of the most important horticultural crops in Florida. Just over 75% of Florida citrus production is on sandy Spodosols or Alfisols with a spodic or argillic horizon at less than 1 m below the soil surface (Florida Agricultural Statistics Service, 2007). These "flatwood soils" are found in the southwest flatwoods (Hendry, Collier, Desoto, Hardee, Manatee, and Hillsborough counties) and eastern county (St. Lucie, Indian River, Okeechobee, and Martin counties) citrus production areas. Because these soils are sandy, nutrient and water-holding capacities are quite low (Obreza and Collins, 2002; Obreza et al., 1997). Many of these soils have a hardpan composed of aluminum (Al) and iron (Fe) "cemented" together with organic matter or a subsurface layer of loamy material (a mixture of mostly clay and sand with little silt) that have higher water-holding capacity and lower saturated hydraulic conductivity, thus increasing drainage time required. The reduction in drainage caused by these soil horizons can lead to temporary increases in soil water content after rain or excessive irrigations, limiting nutrient leaching. Drainage, the presence or absence of impermeable soil diagnostic horizons, and whether the citrus grove is bedded all have considerable influence on citrus root distribution. Because of the need for adequate drainage, these soils are bedded for commercial citrus production, often with additional ditching to remove excess water. The shallow root system is restricted to the upper 30 to 45 cm of soil with approximately one-third of the root system extending out to the edge of

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
100	bar	kPa	0.01
0.3048	ft	m	3.2808
0.0283	ft^3	m^3	35.3147
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
16.3871	inch^3	cm^3	0.0610
0.0010	µmho/cm	mS·cm^{-1}	1000
1	ppm	mg·L^{-1}	1
0.9072	ton(s)	mg	1.1023
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

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the bed (Bauer et al., 2005). The remainder of the root system is located toward the center of the bed.

Approximately 25% of Florida citrus is grown in the central Florida ridge area (Polk, Highlands, and Lake counties) on Entisols, which are characterized by uncoated sand (i.e., sands striped of Al or Fe compounds that increase nutrient-holding capacity) with low organic matter content, therefore have very limited water- and nutrient-holding capacities (Obreza and Collins, 2002; Obreza et al., 1997). These "ridge soils" are deep and well-drained. Root zones on these Entisols are not restricted by soil horizons and are typically 90 cm deep or greater (Morgan et al., 2007).

Tropical tree fruit crop production [e.g., avocado (*Persea americana*) and mango (*Mangifera indica*)] is restricted to ≈3116 ha in Dade and Brevard counties as a result of frost potential elsewhere in the state (Florida Agricultural Statistics Service, 2005). Soils in these lower coastal counties of Florida are dominated by rocky calcareous soils or thin sand soils overlying limestone. These soils are highly porous with low water-holding capacities during periods of low rainfall but can be poorly drained during Florida's summer rainy season because of the proximity to the water table. Temperate fruit crops [e.g., peach (*Prunus persica*) and blueberry (*Vaccinium corymbosum*)] production is located in north–central Florida centered in Marion County. Soils here are sandy Alfisols with higher clay contents and thus water-holding capacities than the soils described thus far; however, irrigation management remains key to optimum productivity.

Nutrient and agricultural chemical movement into surface water and groundwater has become a greater concern in Florida over the past two decades. To preserve water quality within the state, best management practices (BMPs) have been developed for irrigation. Irrigation schedules should focus on optimum crop productivity by encouraging deep rooting and reducing leaching impacts on water quality. The remainder of this review illustrates many irrigation BMPs for citrus production in Florida; however, the application of the BMPs may be applied to perennial fruit crops cultivated in Florida.

Irrigation methods used in citrus and tree fruit crops

Water conservation efforts, BMPs, and frost protection measures have been major impetus to convert irrigation delivery systems from overhead sprinklers to microsprinklers over the last 30 years. Microsprinkler systems have the advantage of lower initial costs compared with solid set sprinkler systems for widely spaced tree crops. Low-volume microsprinkler systems provide a greater degree of freeze protection than both drip and conventional sprinklers. Applications of fertilizers and other chemicals can also be made more timely, uniformly, and cost efficiently using microsprinklers. One drawback is that microsprinkler systems require more maintenance, including filtration and water treatment, than conventional overhead sprinkler systems.

Sprinkler systems in fruit tree groves are designed to use overlapping patterns to provide uniform coverage over an irrigated area. Sprinklers are normally spaced 50% to 60% of their diameter of coverage to provide uniform application in low wind conditions. Application efficiencies of sprinkler systems are relatively low at less than 80%. Because networks of pressurized pipelines are used to distribute water in these systems, the uniformity of water application and the irrigation efficiency are more strongly dependent on the hydraulic properties of the pipe network. Thus, application efficiencies of well-designed and well-managed pressurized sprinkler systems are much less variable than application efficiencies of gravity flow irrigation systems, which depend heavily on soil hydraulic characteristics. Therefore, during water applications, sprinkler irrigation systems lose water as a result of evaporation and wind drift (Haman et al., 2005). More water is lost during windy conditions than calm conditions. More is also lost during high evaporative demand periods (hot, dry days) than during low-demand periods (cool, cloudy, humid days). Thus, sprinkler irrigation systems usually apply water more efficiently at night (and early mornings and late evenings) than during the day (Martínez-Cob et al., 2008).

Application efficiencies of microirrigation systems are typically high because these systems distribute water near or directly into the crop root zone; therefore, water losses resulting from wind drift and evaporation are typically small resulting in a highly efficient (90% to 95%) water delivery system (Boman, 2002). The advantages of microirrigation over sprinkler include: reduced water use, ability to apply fertilizer with the irrigation, precise water distribution, reduced foliar diseases, and the ability to electronically schedule irrigation on large areas with relatively smaller pumps.

Microsprinkler emitter flow rates have different responses to pressure variations depending on design and construction (Boman, 1989; Boman and Parsons, 1993). Most microsprinkler emitters are turbulent flow emitters. Discharge rates for the turbulent flow type of emitter are governed by orifice diameter. Emitters of this type have deflectors that determine the pattern and diameter of water spread. As pressure increases, the water is thrown farther from the emitter, resulting in an increase in the effective coverage area. Typically, diameter of coverage increases more than flow rate with increased pressure, so the precipitation rate as expressed in depth per hour decreases. The second emitter type is vortex flow emitters. Water is forced into a circular pattern before exiting the emitter forming a vortex. These emitters are typically less sensitive to pressure variations compared with turbulent flow emitters. Flow rate of these emitters is controlled by vortex design and orifice diameter. If microsprinkler systems are operated under windy conditions on hot, dry days, wind drift and evaporative losses can be high. Thus, management to avoid these losses is important to achieve high application efficiencies with these systems. The most common application of microirrigation in Florida is that of under-tree microsprinkler systems for citrus. Less efficiency has been found for a microsprinkler system compared with a drip irrigation system. Application efficiencies of drip and line source systems are primarily dependent on hydraulics of design of these systems and on their maintenance and management (Boman, 2002; Boman and Parsons, 1993). Spray uniformity and maintenance are discussed in later sections.

Application uniformity

Improper irrigation system design may result in reduced irrigation efficiency, lower line pressures, and result in poor application uniformity (Boman, 1989, 1990). Wetting patterns of microsprinklers can be an important consideration in sandy soils as a result of low water-holding capacities of these soils. In sandy soils where lateral redistribution of applied water is limited, consideration should be given to selecting emitters with more uniform irrigation patterns. Selection of emitters with uniform water distributions should minimize nutrient-leaching losses (Boman, 1996; Boman and Parsons, 1999). Application patterns are especially important when root zones are limited like in shallow soils of the Florida flatwoods. Vortex flow emitters and turbulent flow emitters with rotating deflectors have been found to provide more continuous wetting throughout the pattern (Boman, 1989). Turbulent flow emitters that produce flat fan patterns or deflectors that break the wetted pattern into several individual streams can produce wetted patterns with 50% to 75% of the area within the pattern receiving little or no water. In a comprehensive study of available emitters, turbulent flow emitters without spinning deflectors applied little to no water in a 2.4- to 3.6-m diameter area centered at the emitter.

Irrigation of young trees with high rate emitters with a reduced diameter (less than 1 m) resulted in leaching of fertilizer nutrients below the root zone with as little as 30 min of irrigation (Boman, 1996). Increased irrigation coverage on sandy soils in a high-density citrus orchard was found to influence tree growth and yield of mature citrus trees. It was reported that irrigation of 50% or greater of the root zone was necessary for optimum production. However, overirrigation can result in excess tree growth and reduced fruit yield and quality.

Irrigation system maintenance

Microirrigation systems are technically more complex than overhead sprinklers or flood irrigation systems (Boman, 2002). Filtration of irrigation water for low-volume systems should be a common practice. Wear on emitter orifices over long periods of operation can significantly increase microsprinkler discharge rates and wetting patterns, especially if irrigation water contains sand (Boman and Parsons, 1993). Emitter application rates increase by 8% to 11% over time with operating times of as little as 2000 h as a result of increased orifice size.

Low-volume irrigation systems require significant maintenance to assure maximum operational efficiency. The performance of a microirrigation system may rapidly deteriorate if it is not maintained properly (Obreza, 2004). Maintenance to improve system uniformity includes checking for leaks, backwashing and cleaning filters, periodic line flushing, chemical injection (e.g., chlorinating and acidifying), and cleaning or replacing plugged emitters. Proper maintenance of a microirrigation system will extend system life, improve performance, minimize downtime, reduce the probability of nonuniform water and fertilizer applications resulting from emitter plugging, reduce operating costs, and save water and fertilizer (Boman, 1990, 1995).

Reclaimed water use in Florida

Florida is recognized as a national leader in water reuse totaling over 1.1 billion gallons per day or ≈52% of the state's total domestic wastewater treatment plant capacity in 2001 (Water Reuse Work Group, 2003). Currently there are 440 reclaimed water reuse systems in Florida irrigating 228,000 acres with 634 million gallons per day (Florida Department of Environmental Protection, 2005). The majority of these systems irrigate golf courses, public right-of-ways, and home landscapes. However, 15,175 acres of production agriculture are currently irrigated with reclaimed water with citrus groves orchards accounting for all but 900 acres (Table 1).

Table 1. Reclaimed water use in Florida by type as percentage of total reclaimed water used.[z]

Reuse type	Proportion of total reclaimed water used (%)
Landscape irrigation	44
Agricultural irrigation	19
Ground water recharge	16
Industrial activities	15
Wetland and other activities	16

[z]Water reuse types are irrigation, recharge of groundwater sources, cooling of industrial equipment, and restoration of wetlands (Florida Department of Environmental Protection, 2005).

In 1995, 333,000 $m^3 \cdot d^{-1}$ was used to irrigate ≈13,556 ha of agricultural land. Although most of this reclaimed water was used to irrigate feed and fodder crops, 76,000 $m^3 \cdot d^{-1}$ was used to irrigate over 6150 ha of edible crops. The permitted reuse capacity of all edible crop systems was 155,202 $m^3 \cdot d^{-1}$. Although citrus represents the primary edible crop irrigated with reclaimed water, a wide range of other edible crops [e.g., tomato (*Solanum lycopersicum*), cabbage (*Brassica oleracea* var. *capitata*), bell pepper (*Capsicum annuum*), watermelon (*Citrullus lanatus*), corn (*Zea mays*), eggplant (*Solanum melongena*), strawberry (*Fragaria ananassa*), pea (*Vicia* spp.), squash (*Cucurbita pepo*), cucumber (*Cucumis savivum*), and various herbs] also are irrigated with reclaimed water (Parsons and Wheaton, 1996).

The legislature of Florida established a rule in 1989 regarding the use of reclaimed water to irrigate edible crops. This rule prohibits direct contact application methods (spray irrigation) if reclaimed water is to be used to irrigate crops that will not be peeled, skinned, cooked, or thermally processed before human consumption (the so-called "salad crops"). Indirect contact methods (drip, subsurface, and ridge and furrow irrigation) may be used to irrigate the salad crops. Any type of irrigation system may be used to apply reclaimed water to citrus or any crop that will be peeled, skinned, cooked, or thermally processed before human consumption.

Experiments on 'Marsh' grapefruit trees conducted near Vero Beach found that trees receiving reclaimed wastewater tended to have higher leaf potassium and boron (B) levels than the control trees; however, B levels were not in the toxic range. Leaf phosphorus (P), magnesium, cupper, manganese, and zinc levels were similar for all trees. All reclaimed wastewater treatments caused significantly greater weed growth than the control treatment. Therefore, reclaimed wastewater can be effectively used to irrigate resets with no deleterious effects provided that weed growth is controlled (Maurer et al., 1995).

A project entitled Conserv II provides reclaimed water for agricultural irrigation to portions of Orange and Lake Counties near Orlando. The project currently delivers ≈133,000 $m^3 \cdot d^{-1}$ (275,000 $m^3 \cdot d^{-1}$ maximum flow) ≈32 km west from Orlando and is used to irrigate ≈4061 ha of citrus groves, seven foliage and landscape nurseries, two tree farms, three ferneries, and two golf courses. The capacity of the system is 250,000 $m^3 \cdot d^{-1}$. Approximately 76,000 $m^3 \cdot d^{-1}$ of reclaimed water was used for irrigation and 63,000 $m^3 \cdot d^{-1}$ was used for groundwater recharge in 2000 (Cross et al., 2000). The reclaimed water meets a number of drinking water standards (Table 2), is low in heavy metal concentrations, and has no odor or color.

Studies were conducted to determine if citrus could tolerate high application rates of reclaimed water (Parsons et al., 2001). In research plantings, very high rates of up to 2540 mm per year were applied to two citrus cultivars on four rootstocks. Application of 2540 mm of reclaimed water significantly increased canopy volume and fruit yield compared with 406.4-mm applications of groundwater and reclaimed water.

Weed growth can be controlled with proper herbicide use and mowing and is not as great a problem in mature groves. Irrigation with reclaimed water increased soil and leaf P, calcium (Ca), and sodium (Na) content. Leaf levels of Na, chloride, and B were elevated but remained below toxic levels (Morgan et al., 2008; Parsons and Wheaton, 1996).

Table 2. Comparison of elemental concentrations and water characteristics for Florida drinking water, typical citrus grove well water, maximum allowable limits for reclaimed water in the Water Conserv II project, and typical Water Conserv II project reclaimed.

	Drinking water MACL[z,y]	Well water typical concn[y]	Conserv II reclaimed water MACL[y]	Typical Conserv II reclaimed water concn[y]
	(mg·L⁻¹)[x]			
Arsenic	0.01	—	0.10	<0.005
Barium	2	—	1	<0.01
Beryllium	0.004	—	0.10	<0.003
Bicarbonate	—	—	200	105
Boron	—	0.02	1.0	<0.25
Cadmium	0.005	—	0.01	<0.002
Calcium	—	39	200	42
Chloride	250	15	100	75–81
Chromium	0.1	—	0.01	<0.005
Copper	1	0.03	0.20	<0.05
Iron	0.3	0.02	5	<0.4
Lead	0.015	—	0.1	<0.003
Magnesium	—	16	25	8.5
Manganese	0.05	0.01	0.20	<0.04
Mercury	0.002	—	0.01	<0.0002
Nickel	0.1	—	0.20	0.01
Nitrate–nitrogen	10	3	10	6.1–7.0
Phosphorus	—	0.01	10	1.1
Potassium	—	6	30	11.5
Selenium	0.05	—	0.02	<0.002
Silver	0.1	—	0.05	<0.003
Sodium	160	18	70	50–70
Sulfate	250	23	100	29–55
Zinc	5	0.02	1	<0.06
EC (µmhos/cm)[w]	781	360	1100	720
pH	6.5–8.5	7.8	6.5–8.4	7.1–7.2

[z] MACL = maximum allowable contaminate limit.

[y] Morgan et al. (2008).

[x] 1 $mg \cdot L^{-1}$ = 1 ppm.

[w] EC = electrical conductivity, 1 µmho/cm = 0.0010 $mS \cdot cm^{-1}$.

Annual energy savings from eliminating irrigation pumping costs can be as much as $316.30/ha (Cross et al., 2000).

In an evaluation of the nutritional value of this reclaimed water, trees that were given no fertilizer and irrigated only with reclaimed water took 2 to 5 years to show nutrient deficiency symptoms and yield declines. In experimental plots, high application rates of reclaimed water maintained yields for 1 year, but yields declined in the second year without additional fertilizer application (Wheaton et al., 1998). Although reclaimed water provides all the P, Ca, and B required by trees in central Florida, this water cannot supply sufficient nitrogen, even if it is applied at high (2540 mm per year) rates (Parsons et al., 1999). A survey of commercial orchards receiving either reclaimed or well water over a 10-year period indicated no detrimental increase in soil or leaf nutrient concentrations over time (Morgan et al., 2008).

Irrigation scheduling

Irrigation scheduling consists simply of applying water to crops at the “right” time and in the “right” amount. Many factors must be considered when determining irrigation schedules (Graser and Allen, 1987). Movement of irrigation water through sandy soils is rapid. The amount of water held in the soil after movement has stopped is field capacity (FC, normally ≈10 kPa of soil water tension). Removal of soil water below field capacity is primarily by plant uptake (transpiration) or surface evaporation commonly referred to as evapotranspiration (ET). The lower limit of soil water availability by trees is called permanent wilting point (PWP). Soil water content approaching PWP (typically 1500 kPa of tension) results in tree wilt, yield reduction, and twig dieback. The amount of water held by the soil between FC and PWP and thus available to the tree is called available water (AW) and varies by soil series. The allowable soil water depletion (ASWD) is the fraction of AW that can be used to meet tree ET demand before irrigation is required without reduction in tree growth and yield. The ASWD depends on several factors, including tree age and phenological stage (Boman, 1997; Koo, 1963, 1978). Current recommendations are for ASWD of 0.25 or less for citrus from February to June and 0.50 the rest of the year (Smajstrla and Koo, 1984). Schedules based on these depletion limits provide adequate water to support critical fruit development stages in the spring and reduced soil water when increased stress does not limit growth or yield.

Scheduling often consists of grower judgment or a calendar-based schedule of irrigation events based on previous seasons. Several factors such as plant evaporative demand, soil characteristics, and root distribution are taken into account as well to establish proper irrigation scheduling (Locascio, 2005). A wide range of irrigation scheduling methods is used in Florida with corresponding levels of water managements. There are two basic approaches to irrigation scheduling: monitoring of soil moisture status or maintaining a water budget. Often a combination of both approaches is used. Several devices are available to determine in situ soil moisture status.

Soil moisture measurement

Electromagnetic techniques (resistive, capacitance, and time-domain reflectometry sensor) include methods that depend on the effect of water on the electrical properties of a soil.

GRAVIMETRIC. The gravimetric or oven-drying technique is probably the most widely used method for measuring soil water and is the standard method for calibration of most other soil water determination techniques (Erbach, 1983). However, the gravimetric method itself is subject to errors because of the sampling, transporting, and repeated weighing. This method is destructive in nature and cannot be repeated for the same location over time as can the methods that follow. Samples are collected from a site, weighed, oven-dried at 105 °C, and then reweighed. Reweighing of the dried sample should be repeated until a consistent weight is obtained because drying time required is dependent on soil characteristics and varies from 1 d to several days. The volume of the sample obtained or the sample bulk density must be determined to obtain soil water content by volume. Measurement of sample bulk density in the field is difficult and subject to errors.

TENSIOMETERS. Tensiometers are devices that measure the soil water potential of the soil and are not a direct measure of soil water content. They do not measure the amount of water in the soil but a measure of the energy a plant must exert to extract water from the soil (Smajstrla and Koo, 1986). A tensiometer consists of a porous ceramic tip sealed to the base of a water-filled tube, which is sealed at the top with a removable cap. A vacuum is applied to the tensiometer to remove any trapped air. A vacuum gauge at the top of the tensiometers measures the vacuum caused by water removed by the soil through the porous tip. Tensiometers are used to schedule irrigation at specific soil water potential values; however, a soil water release curve must be developed specific for the soil measured to determine the amount of water to apply. Periodic maintenance (refilling and air removal) is critical to the proper use of tensiometers (Smajstrla and Pitts, 1997).

RESISTIVE SENSORS. Soil resistivity depends on water content. Soil resistivity is measured between electrodes in a material in equilibrium with the soil (Bouyoucos and Mick, 1948). Resistivity is dependent not only on water content, but ion concentrations as well; thus, these sensors are typically sensitive to fertilizer salts. The advantages of resistive sensors are the relatively low cost and the possibility of measuring the same location in the profile throughout the season.

CAPACITANCE SENSORS. Capacitance sensors measure the dielectric constant of the soil using an electric circuit arrangement in which the soil is the dielectric media (Dean et al., 1987). Capacitance-based sensors rely on the fact that water has a much higher dielectric constant than air or dry soil; hence, relatively small changes in soil water content are reflected in large capacitance changes. Sensor configuration can vary in number and depths measured. Capacitive sensors provide absolute soil water content with a relatively high level of precision when soil-specific calibrations are used (Morgan et al., 1999). The primary disadvantage of capacitive systems is the relatively high costs.

TIME-DOMAIN REFLECTOMETER. Time-domain reflectometry (TDR) determinations involve measuring the movement (propagation) of electromagnetic (EM) waves through soil (Baker and Allmaras, 1990). Propagation constants for EM waves in soil (i.e., velocity and attenuation) depend on soil properties, especially water content and electrical conductivity. The waves are propagated along a transmission line or rod and are reflected back to the TDR device. The velocity and amplitude of the reflected wave are measured and related to water content of the soil. Although TDR systems are generally costly, they provide soil moisture measurements that are independent of soil texture, temperature, and salt content.

Evapotranspiration measurement

The ET term is used to describe the sum of evaporation and plant transpiration from a given land surface to atmosphere, which practically can be translated to crop water requirements. The crop water requirements are closely related to crop type, stage of growth, and climatic conditions. Many field-calibrated ET models meet the objective of forecasting irrigation dates with continuous weather updating. However, a major problem still exists in determining the proper amount of water to apply to irrigated fields (Thomson and Ross, 1996). Over the years, some sensor-based scheduling methods have been used to indicate how much water to apply. These methods observed sensor responses to wetting to adjust subsequent water amounts (Fischbach and Schleusener, 1961; Stolzy et al., 1959). Use of crop ET (ET_c) is currently being used in citrus irrigation.

Allen et al. (1998) proposed that ET_c can be derived from a reference ET (ET_o) as follows:

$$ET_c = (ET_o)(K_c)(K_s)$$

where: ET_c = crop evapotranspiration ($mm \cdot d^{-1}$);

ET_o = potential evapotranspiration ($mm \cdot d^{-1}$);

K_c = crop coefficient;

K_s = soil water depletion coefficient.

The crop coefficient (K_c) is defined as the ratio of ET_c to ET_o when soil water availability is nonlimiting. In this case, the soil water depletion coefficient (K_s) is assumed to be equal to unity. K_c is indicative of climatic and/or developmental effects on ET_c compared with ET_o. Estimates of K_c for a wide range of citrus tree sizes span from 0.6 in the fall and winter to 1.2 during the summer months (Boman, 1994; Fares and Alva, 1999; Jia et al., 2007; Martin et al., 1997; Morgan et al., 2006a; Rogers et al., 1983; Rogers and Bartholic, 1976). Crop coefficients determined under Florida climatic conditions are similar to those found in other citrus production regions of the world (Castel et al., 1987; Castel and Buj, 1992; Doorenbos and Pruitt, 1997; Hoffman et al., 1982; Martin et al., 1997). As soil water content (WC) decreases, soil water potential (WP) also decreases, resulting in lower plant soil water uptake and thus lower ET_c/ET_o ratios.

Allen et al. (1998) suggested that for most soils, a value of WP less than FC exists where water uptake is not limited by WP. They referred to the range of WC above a critical threshold value as readily-available water (RAW) and used it to estimate K_s as the ratio of remaining available soil water to soil water that is not readily available.

$$K_s = \frac{[TAW - (\theta_{FC} - \theta)]}{TAW - RAW} = \frac{\theta - \theta_{WP}}{\theta_t - \theta_{WP}}$$

where: K_s = soil water depletion coefficient ($K_s \leq 1$);

$TAW = \theta_{FC} - \theta_{WP}$ = total available water ($cm^3 \cdot cm^{-3}$);

θ_{WP} = permanent wilting point soil water content ($cm^3 \cdot cm^{-3}$);

θ = soil water content ($cm^3 \cdot cm^{-3}$);

θ_{FC} = field capacity soil water content ($cm^3 \cdot cm^{-3}$);

θ_t = minimum soil water content with no reduction in plant water uptake ($cm^3 \cdot cm^{-3}$);

$RAW = \theta_{FC} - \theta_t$ = readily available water ($cm^3 \cdot cm^{-3}$).

The greater the RAW for a given soil, the longer water can be withdrawn from it before ET_c is limited. Thus, K_s is a measure of the reduction in ET_c caused by reduced soil water uptake resulting from decreased WC and WP. However, our experience in Florida has suggested that RAW in sandy citrus soils is much smaller than the relative amount suggested by Allen et al. (1998). If one assumes that K_c is constant over relatively short time periods, then the reduced ET_c/ET_o ratios must be a result of lower K_s values. Therefore, the correction coefficient used to estimate ET_c from ET_o is a product of K_c and K_s $[(K_c)(K_s)]$. Morgan et al. (2006a) found the region of RAW was 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 volume within the tree-allocated space. Estimates for K_s decreased from unity at 1% ASWD to ≈0.5 at 50% ASWD for all soil volumes. A K_s value of 0.5 translates to a reduction of 50% in ET_c between field capacity and 50% depletion of AW (DAW).

Irrigation scheduling strategies

Irrigation scheduling strategies use one or a combination of two basic methods. These methods are use of soil moisture sensors and/or crop ET. Regardless of the methods used, the goals of providing optimum soil moisture for plant growth and productivity and reduction of fertilizer nutrient leaching are the same. Several field studies have determined the importance of proper irrigation scheduling on citrus growth and production on the low water-holding nutrient-retention soils of central Florida (Boman, 1994; Morgan et al., 2006a; Parsons et al., 2001; Scholberg et al., 2002). A field-scale fertilizer and irrigation rate study was conducted on trees over a 10-year period (Morgan et al., 2009). Leaf nitrogen (N) and fruit soluble solid concentrations of trees less than 6 years old decreased with increased irrigation rate. Irrigation and N rate were both important factors for trees 8 to 10 years old. Canopy size and yield were highest at the moderate irrigation level compared with the low irrigation rate. :ole with the young tree study, fruit soluble solids significantly decreased with increased irrigation, but total soluble solids per hectare were greater with increased irrigation rate. These results would indicate that high, but not excessive, irrigation is required in addition to proper N rate for optimum tree growth.

Stress associated with DAW greater than 33% during periods of bloom, 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 DAW of 66% could be tolerated during summer, fall, and winter months. Thus, the potential onset 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 water use.

Water balance-based irrigation scheduling

Generic tables and water budget models are examples of systems that will improve the likelihood of obtaining the irrigation goals of reduced leaching and improved nutrient uptake. Generic irrigation schedules have been reduced to a tabular format and are available in publications (Parsons and Morgan, 2002) and on the Florida Automated Weather Network (FAWN) program web site. These tables are used to schedule microsprinkler irrigation for young trees and mature ridge or flatwoods trees. In cases of high ET, additional water may be necessary to reduce stress on the trees and frequent irrigation would be more beneficial rather than lengthening the duration of irrigation.

The second method is the use of water budget models. Two models have been developed for Florida citrus production (Morgan et al., 2006b). An ET_o can be used as a basis for estimating the citrus grove ET_c or irrigation demand. Reference ET is calculated on a daily basis using weather data or is available from the nearest FAWN site. However, once the crop ET is estimated, irrigation interval and duration can be calculated based on irrigation application rates and allowable soil water depletion. The University of Florida, Institute of Food and Agricultural Sciences recommendation is to allow 25% to 33% soil-water depletion during February through May and 50% to 66% depletion during June through January. These allowable depletions provide increased soil water in the spring of the year for blooming, fruit set, and growth flushes. The increased allowable soil water depletion in the summer and fall allows for the use of rainfall during our rainy season and adequate water for fruit expansion. Rooting depth adds another layer of precision to this irrigation budget model.

Two models have been developed and validated using weather station data and water uptake at six mature citrus orchards in central Florida (K. T. Morgan, unpublished data). One model is available on the web site and provides seasonally adjusted irrigation intervals and durations based on user site inputs and FAWN ET_o. The second model determines day of the week irrigation schedules on a site-specific basis for multiple irrigation blocks.

Conclusion

The goal of irrigation scheduling is to reduce tree stress to promote vegetative and/or reproductive growth while at the same time reducing leaching of fertilizers and other agrichemicals below the root zone. Supplemental irrigation of tree fruit crops in Florida came into use in the 1940s. Various irrigation methods were used, including water wagons, surface flood, subirrigation, and overhead sprinklers. Water use efficiency of irrigation must also be considered in evaluating irrigation systems. Currently, low-volume drip and microsprinkler irrigation systems have become the standard for Florida tree fruit crops. Compared with overhead sprinklers, low-volume systems can save water if they are properly managed. Because these systems usually operate at lower pressures than conventional overhead systems, there can also be appreciable savings from reduced energy costs. Scheduling of these systems varies among users in Florida. Factors influencing grower decisions on irrigation scheduling are costs of equipment, equipment maintenance requirements, and the technical level of operators. With the current increased emphasis on reducing fertilizer nutrients below the crop root zone, use of the irrigation scheduling strategies outlined in this article will increase. Use of reclaimed water as an irrigation source has been well received by growers in general, citrus growers particularly. The processing, pipeline, and distribution systems associated with distribution of reclaimed water to agricultural users are very expensive and the limiting factor in use of reclaimed water for agricultural irrigation. Scheduling techniques discussed here have been shown to increase citrus yield and quality.

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