Simulating Annual Irrigation Requirement for Citrus on Excessively Drained Soils

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Abstract. A water use simulation for citrus (*Citrus sinensis*) was used to estimate the effects of climate, soil-available water, rooting depth, allowable depletion of available water, and partial coverage irrigation on the annual irrigation requirements. The soil in the study was excessively drained Candler sand (hyperthermic, uncoated Typic Quartzipsamments) of the Central Florida Ridge. Variation of annual rainfall from 667 to 1827 mm had a relatively small impact on annual irrigation requirements. Soil-available water, depth of root zone, and allowable depletion of available water all affected irrigation management and the number of irrigations annually. Simulated annual irrigation requirements varied over a wide range depending on the allowable depletion of soil-available water, irrigation depth, and the fraction of the land area that is irrigated. Effective rain estimated by the TR21 method during months of high rainfall was higher than estimates by the water budget. Monthly irrigation requirements varied seasonally and peaked in normally dry spring months of April and May. The irrigation simulation is a useful tool for examining the range of management strategies that can be considered for citrus.

Citrus grown on the excessively drained soils of the Central Florida Ridge (CFR) require irrigation for optimal production (Koo, 1963). The amount of irrigation needed varies with the amount and distribution of rainfall, soil water availability, rooting depth, management of irrigation, and the percent of the land area that is irrigated. Available water is the difference between the soil field capacity (FC) and permanent wilting point, and is dependent on the soil particle characteristics. Understanding the relative importance of these factors on irrigation requirements of citrus could improve irrigation efficiency and provide a basis for allocation of water for citrus production.

The allowable depletion of available water (ADAW) is the percent of available soil water that is depleted before irrigation is scheduled (Smajstrla et al., 1987). The ADAW used for a specific crop depends on the sensitivity of the crop to water stress at various stages of growth. It is important to set the ADAW at a soil water depletion level that will provide the amount of water needed for

optimal production. It is common practice with citrus production to maintain more water in the soil during the spring period of flowering and fruit set and reduce irrigation during the rest of the year. The recommendation for irrigating at 33.3% ADAW in the spring and 66.7% ADAW the rest of the year (33:67 ADAW) was based on overhead sprinkler irrigation systems that covered 100% of the land area (Koo, 1963). The current recommendation for low-volume irrigation systems that provide less than full coverage is to irrigate at 25% depletion in the spring and at 50% the balance of the year (Parsons et al., 2000). When the ADAW is reached, irrigation is applied to bring the root zone back to FC.

Most citrus on the CFR is irrigated with microsprinklers that cover only part of the total land area. The evaporative demand for water is the same for citrus groves receiving partial- or full-coverage irrigation (Smajstrla et al., 1987). During dry weather, the soil water in the irrigated zone is maintained at an optimal level, but the soil water content of the nonirrigated area declines during extended periods without rain. The nonirrigated area supplies significant amounts of water for several days after rain, but this rapidly drops to a trace during dry periods. The rate of water uptake in the wetted area is unaffected

by the water content of the nonwetted area (Morgan et al., 2006). Increasing either the frequency or duration of water applied to the irrigated zone in an attempt to compensate for the lack of full coverage will exceed the water storage capacity of the wetted area (Smajstrla et al., 1987). For example, calculating the irrigation requirements for a full coverage site and applying this amount of water to a site irrigating only 50% of the land area would exceed the water-holding ability of the soil in the irrigated area and result in water loss as a result of deep percolation (DP). There is very little horizontal movement of water in the soils of the CFR (Fares et al., 2001), which further limits the amount of water that can be applied.

The total amount of water that can be effectively used in partial-coverage irrigation is limited by the fraction of the land that is irrigated and the fraction of tree root length density (RLD) in the wetted zone. The RLD drops rapidly with distance from the trunk (Morgan et al., 2006). Therefore, the rate of water uptake in the irrigated area is proportional to the fraction of the total root length in the wetted area. Thus, irrigation amount is a function of the area and thereby the root mass within the irrigated area. This limitation is of critical importance during Florida's typical dry spring season when water uptake from roots in the nonirrigated area is much reduced. Irrigation expressed on the land area (ILA) basis is used in reporting and permitting water use, but irrigation management is based on the wetted area (IWA). The ILA is lower than IWA for partial-coverage irrigation because the entire land area is not being irrigated.

Water for citrus irrigation in Florida is regulated by several water management districts and the method of allocation is a concern of growers. Most models used by the water management districts (Jacobs and Satti, 2001) calculate irrigation requirement as the difference between estimated monthly crop evapotranspiration (ET_c) and effective rainfall (ER). ER is the portion of rainfall that plants can use to meet their need for water and is an important concept in water allocation policy. The TR21 method developed by the U.S. Department of Agriculture is a general method for estimating monthly ER and predicting irrigation requirements as described by (Obreza and Pitts 2002). Their recent report on ER for citrus on poorly drained shallow soils of southwest Florida compares irrigation requirements based on a daily water budget with the TR21 model. They found the water budget to be effective and obtained good agreement between the water budget and the TR21 method. However, ER calculated by the TR21 method was higher than the water budget calculation during months of high rainfall.

Recent research on water use by citrus growing on the CFR provided a basis for developing a water budget (Morgan et al., 2006). A program was written to simulate irrigation management based on a water budget and to determine the sensitivity of annual

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irrigation requirements to soil, climatic, and management factors. The goal was to determine the relative importance of factors affecting annual irrigation.

Materials and Methods

A 'Hamlin' orange grove in Lake County, Fla., was used as a model for this study. It is located at latitude 28°28'20" N, longitude 81°38'50" W and was planted in 1987 with 'Hamlin' orange trees on Carrizo citrange (*Citrus sinensis* x *Poncirus trifoliata*) rootstock using a 4.56 × 7.60-m spacing. Each tree was irrigated with one microsprinkler, which provided ≈3 mm per h to a wetted area diameter of 4.9 m. The irrigated area covered 52% of the area allocated for each tree. The soil was a Candler fine sand (hyperthermic, Typic Quartzipsamments) with total available water-holding capacity of 0.06 mm.mm⁻¹.

The water budget simulation was run using the soil characteristics of this specific site and historical climate records for this location. Partial-coverage irrigation requires maintaining a water budget for both the irrigated and nonirrigated portion of the space allocated for the tree. The water budget was based on the classic publication by (Smajstrla et al. 1987) and modified with

new information developed by (Morgan et al. 2006). The budget tracked daily gain and loss of water and simulated irrigation whenever the ADAW was reached. It also estimated water loss from DP whenever FC was exceeded. Partial-coverage irrigation increases the complexity of a water budget. The fraction of the land area irrigated and the fraction of the RLD of the fibrous root system in the wetted area affect the irrigation requirements. Water from both the irrigated and nonirrigated zones contributes to the water available to the tree.

The ET_c for both the irrigated and non-irrigated areas was calculated from reference Penman ET (ET_o) adjusted by a seasonal crop coefficient (K_c) and a stress coefficient (K_s). The stress coefficient reduced ET_c as the available water decreased. Values for K_c as a function of day of year (Julian day) and K_s have been determined for CFR environmental conditions and soil characteristics (Morgan et al., 2006). The rate of water uptake from the irrigated area depends on the daily ET_c and on the percent depletion of soil available water (Morgan et al., 2006). It is therefore possible to estimate daily water use and to track the percent depletion of available water for the both the irrigated and non-irrigated zones based on proportions of root mass in each zone. Accuracy is enhanced

because the system is automatically reset to FC whenever irrigation or rain events exceed FC.

The water budget was derived from the following equation:

$$SWC_{\text{today}} = SWC_{\text{yesterday}} + \text{rain} + \text{IWA} - \text{DP} - \text{RO} - (\text{ET}_o * K_c * K_s).$$

SWC Soil water content in the irrigated zone (mm)

Rain Daily rainfall (mm)

IWA Daily irrigation based on wetted area (mm)

DP Water loss from deep percolation (mm) when SWC > FC

RO Daily runoff assumed 0 as a result of high soil porosity (mm)

ET_o Reference Penman ET_o (mm)

K_c Crop coefficient seasonal adjustment

K_s Stress index reduces ET_c as soil dries.

Simulations over 5 year included years of low and high rainfall, variation in soil-available water, depth of irrigated zone, percent of land area irrigated, and ADAWs of 25:25, 25:50, 25:75, 50:50, and 50:75. The first number is the percent ADAW for 15 Feb. to 15 June, which is the critical flower and fruit set period. The second value is ADAW for the rest of the year.

Estimated daily ET_o values (Smajstrla, 1993) for this grove site were determined using historic daily weather data obtained

Table 1. The effects of year, rain, ET_o, ET_c, and seasonal ADAW on the irrigation requirements, NI, and DP for citrus growing on the CFR.

Year	DR (mm)	ADAW (%)	IWA (mm)	ILA (mm)	NI	Rain (mm)	DP (mm)	ET _o (mm)	ET _c (mm)	ER (mm)
2000	457	25:25	772	414	93	667	425	1190	1011	242
2000	452	25:50	660	354	58	667	387	1190	937	280
2000	457	25:75	416	223	38	667	240	1190	848	427
2000	457	50:50	621	333	42	667	383	1190	902	284
2000	457	50:75	383	206	23	667	244	1190	812	423
2000	914	25:25	731	392	48	667	335	1190	1054	332
2000	914	25:50	530	284	27	667	216	1190	984	451
2000	914	25:75	367	197	20	667	138	1190	906	529
2000	914	50:50	477	256	17	667	207	1190	941	460
2000	914	50:75	309	166	10	667	125	1190	861	542
2002	457	25:25	592	317	71	1827	1417	1122	1003	410
2002	457	25:50	467	251	44	1827	1340	1122	955	487
2002	457	25:75	295	158	31	1827	1218	1122	904	608
2002	457	50:50	424	227	29	1827	1329	1122	922	497
2002	457	50:75	252	135	16	1827	1208	1122	871	619
2002	914	25:25	526	282	35	1827	1302	1122	1046	524
2002	914	25:50	325	174	19	1827	1140	1122	1007	686
2002	914	25:75	295	158	17	1827	1133	1122	984	694
2002	914	50:50	283	152	10	1827	1132	1122	973	694
2002	914	50:75	241	129	8	1827	1120	1122	943	707
2004	457	25:25	708	380	85	1169	884	1148	995	285
2004	457	25:50	575	308	53	1169	817	1148	929	352
2004	457	25:75	464	249	42	1169	780	1148	855	390
2004	457	50:50	518	278	35	1169	792	1148	896	377
2004	457	50:75	397	213	23	1169	747	1148	821	422
2004	914	25:25	668	358	44	1169	786	1148	1047	383
2004	914	25:50	600	322	29	1169	780	1148	985	389
2004	914	25:75	347	186	19	1169	586	1148	927	583
2004	914	50:50	536	288	19	1169	750	1148	952	420
2004	914	50:75	282	151	9	1169	558	1148	889	611

DR = depth of the root zone; ADAW = allowable depletion of available water; IWA = irrigation based on the wetted area; ILA = irrigation based on the total land area; NI = number of irrigation events; DP = water lost by deep percolation; ET_o = reference evapotranspiration; ET_c = crop evapotranspiration; ER = effective rain calculated from water budget.

Fig. 1. The water requirements of citrus (ET_c) remained nearly constant over years of low and high rainfall. Irrigation requirements (IWA) and the percent of rain that was effective (ER) decreased as rain increased. However, the amount of effective rain (ER) used by citrus increased. The sum of IWA and ER was equal to ET_c. High rainfall increased deep percolation (DP). These results were based on measured ET_c and rainfall, a rooting depth of 914 mm, an ADAW of 25:50, and simulated IWA, ER, and DP.

from a Florida Automated Weather Network (FAWN) station less than 1 km away. ER was calculated from the water budget as $ER = (rain - RO - DP)$. Because of the high percolation of the soils, RO can be disregarded for CFR citrus. DP is generated by the

daily water budget when excess rain or IWA exceeded FC. ER was also calculated using the USDA TR21 method (see Obreja and Pitts, 2002). Monthly irrigation requirements for this site were estimated using both the water budget and the TR21 methods.

Fig. 2. Increasing the allowable depletion of available water (ADAW) reduced the irrigation requirement (IWA), slightly reduced crop water use (ET_c), and increased the effective rainfall. Average over 5 year and two rooting depths.

An experiment was established at this site in 2003 using the same combinations of ADAWs (25:25 to 50:75) used in the simulations reported here. The seasonal changes and wide range of ADAW simulated will provide new information on citrus yield and quality responses to irrigation.

Results

A daily water balance simulating the irrigation of a citrus grove provided insight on the importance of factors affecting the annual irrigation requirement. Irrigation requirements and loss of water by DP varied with the amount and distribution of rain, rooting depth, ADAW, and percent of the land area covered by irrigation. The simulation was run for 5 year. Detailed results (Table 1) are provided for years 2000, 2002, and 2004 representing a dry year, a wet year, and a year with near average rainfall, respectively. Simulations were run for two rooting depths and five ADAWs.

Annual variation in rainfall had a relatively small effect on irrigation requirement but was a significant factor in DP. The 5-year average IWA and ILA were 468 and 251 mm, respectively. The IWA and percent of the total rainfall that was effective decreased as rainfall increased, but the effect on required irrigation was relatively small considering the nearly threefold (667–1827 mm) variation in rainfall. The average ET_c of 996 mm remained nearly constant over the 5 years (Fig. 1), and the sum of ER and IWA was equal to ET_c. The relatively small response of IWA to rainfall may be the result of the concentration of rainfall in the months of June through September with less rain during the rest of the year. Water movement below the root zone increased with increasing rainfall and varied more than fivefold ranging from 216 mm during a dry year to 1140 mm in the wettest year. Annual ET_c (Table 1) and ET_c (Fig. 1) were nearly constant over the 5 year with only a small increase associated with dryer years. The nearly constant annual irrigation requirement is consistent with the nearly constant ET_c. The insensitivity of irrigation requirements to rainfall suggests that annual rainfall may not be a suitable basis for allocating irrigation water in Florida.

The ADAW or set point for starting irrigation was also a factor in determining annual irrigation requirement. As expected, higher ADAWs created dryer conditions, reduced the annual irrigation requirement, and increased ER (Fig. 2). The 5-year average IWA for an ADAW of 25:25 was 643 mm. In contrast, only 291 mm of irrigation was required for a 50:75 ADAW. The higher ADAW delayed irrigation, allowed the soil to become dryer, and allowed more rainfall to be stored. The simulated ADAWs include values below and above the range of values used in traditional irrigation and will provide the basis to evaluate tree responses over a wide range of conditions.

The number of irrigations (NI) required per year was affected by factors that influence

Fig. 3. The number of irrigations (NI) decreased when the ADAW increased and when the depth of rooting (DR) increased from 457 to 914 mm. Values are 5-year means.

soil water storage ability (Fig. 3). The NI ranged from 6 to 93 and varied with year, ADAW, and rooting depth. NI increased as the ADAW decreased. At a low ADAW such as 25:25, removal of very little water initiated irrigation. Changing from a 25:25 to a 50:75 ADAW at a 457-mm rooting depth reduced average NI from 81 to 20. Increasing the rooting depth from 457 to 914 mm at an ADAW of 25:50 reduced NI from 50 to 24 but only changed IWA from 547 to 468 mm (data not shown). NI is quite sensitive to

ADAW. The number of irrigation events may not be important if irrigation is controlled automatically, but may be a significant factor with manual operation.

The percent of the land area irrigated by microsprinklers used in Florida citrus production typically ranges from $\approx 20\%$ to 80% and depends on the spacing and wetted diameter of the microsprinkler being used (Fig. 4). Microsprinklers in common use provide a circular wetted area with diameters of 3.4 to 6.4 m. There is usually one microsprinkler for

Fig. 4. Microsprinkler spacing and the diameter of the wetted (WD) area were important factors in determining the percent of the land area that was irrigated.

each tree so the wetted area depends on both the sprinkler characteristics and the tree spacing. The land area wetted by a micro-sprinkler depends on spacing and sprinkler specifications. One commonly used micro-sprinkler provides a wetted diameter of ≈ 3.4 m, which would wet 20% to 50% of the land area for commonly used spacings.

The annual irrigation requirements decrease as soil water-holding capacity increases either as a result of a soil with more water-holding capacity or a deeper root zone. Citrus roots may extend downward for several meters, but the majority of the roots and water uptake occurs in the upper 914 mm.

The amount of water per hectare that can be effectively applied to citrus plantings decreases as the percent wetted area decreases. Less than 50% irrigation coverage substantially reduces the amount of water that can be applied and may promote water stress, reduce tree growth, and cause poor production. The percent of the land area that is irrigated may be the limiting factor in citrus irrigation.

The amount of irrigation that can be applied to partial-coverage sites is somewhat larger than would be expected based only on the fraction of the land that is irrigated. The RLD is not uniform but is highest near the trunk of the tree and declines rapidly with distance from the tree trunk. The placement of the microsprinkler near to the trunk of the tree where the RLD is highest increases the rate of water uptake. For example, a system that wetted only 40% of the land might contain 50% to 60% of the total root mass as a result of the location of the wetted area in areas of high RLD. This advantage cannot completely compensate for small coverage, however. Annual irrigation requirements increased from 400 to 500 mm as the wetted area was increased from 3.4 to 6.4 m. These irrigation rates are within the normal range for irrigation of CFR citrus. The increased coverage requires significantly more water and should reduce water stress.

Monthly ER was calculated for 5 year using the water budget and TR21 methods. The estimated mean annual ER was 525 mm for the water budget using a 25:50 ADAW and rooting depth of 914 mm and 594 mm for the TR21 method. The average annual irrigation requirement was 468 and 557 mm by these two methods. Monthly irrigation requirements calculated by both methods were highest in April and May. The water budget and TR21 methods of calculating monthly required irrigation over the 5 year were linearly related as $IWA (\text{water budget}) = 0.7391 + 0.9759 * IWA (\text{TR21})$ ($R^2 = 0.86$). Similar results were obtained for citrus growing on shallow, poorly drained soils (Obreza and Pitts, 2002). The water budget and TR21 provided similar estimates of annual irrigation requirements for both citrus-growing areas.

Discussion

Approximately 70% of the land area in a mature grove is covered with tree canopy and is the area of greatest root density

Fig. 5. The depletion of soil available water (AWD) was slow in January (upper graph) as a result of the low winter ET_c . Light rain on day 10 temporarily increased available water, but depletion continued until the set point (50% depletion) was reached. Irrigation and subsequent rain maintained the site below the set point for the rest of the month. The higher daily ET_c in July (lower graph) increased depletion from field capacity to the set point in ≈ 1 week, but subsequent frequent rainfall eliminated the need for irrigation.

(Wheaton et al., 1978). Water applied in the row middles is rapidly lost by evaporation from direct sunlight and transpiration from vegetative cover growing in the middles (Morgan et al., 2006). Thus, an irrigation system that wets only 70% of the land area that is under the canopy should be more efficient and require less water than full-coverage irrigation. Increased water uptake efficiency may partially explain the success of lower irrigation rates with partial-cover irrigation. The apparent success of irrigation systems that cover less than half of the root zone and provide less than half the calculated annual irrigation requirement may result from the frequent rainfall, which usually does not allow the nonirrigated zone to become severely depleted.

The RLD is an important factor in water uptake and declines with distance from the tree trunk (Morgan et al., 2006). Partial-coverage irrigation benefits from this by

locating microsprinklers in areas of higher RLD. Irrigation in the area of highest root density increases the efficiency and rate of water uptake and thus more water can be supplied to the tree without movement of water below the root zone.

Optimal citrus irrigation requires information on the soil water content throughout the year that will result in the best economic returns. Good soil moisture is maintained during flowering and fruit set to ensure a good crop. Less is known about the importance of tree water stress in other seasons of the year. Moderate water stress in the fall and winter may improve cold hardiness and induce better flowering in the spring (Valiente and Albrigo, 2003). The same amount of stress in the spring may reduce fruit set and tree growth. For example, a 50% ADAW may be beneficial for a mature crop of oranges awaiting harvest in December but could reduce fruit set during a hot and dry period

in May. Although the importance of irrigation during flowering and fruit set is undisputed, little is known about the importance of irrigation during the rest of the year. Substantial water savings would be possible if a 25:75 ADAW were shown to be adequate for citrus. The water budget is a useful aid in answering that question and for estimating how much irrigation requirements would be reduced. The simulation benefits in accuracy by resetting the SWC to total available water every time the water-holding capacity of the soil is exceeded. This automatic calibration ensures the SWC remains reasonably accurate over extended times.

The use of a water budget to manage irrigation is illustrated in Figure 5. The percent depletion of available water is tracked daily and increases until the ADAW is reached. Irrigation or rainfall reduces the depletion level, and thus the soil water content is maintained in the desired range. Water depletion in January was relatively slow as a result of the low ET_c during the winter. When 50% ADAW was reached, irrigation was applied to return the soil to FC. In the absence of rain, irrigation in January would be required every 2 to 3 weeks. The highest ET_c occurred in July, but this is a month of higher rainfall and usually requires very little irrigation. The simulated water budget for July 2003 required only one irrigation and maintained an average depletion of less than 20%.

These figures illustrate the complexity of irrigation scheduling. Simple guidelines such as irrigate for 2 to 3 h two to three times each week are beneficial, but will not provide optimal soil water content or minimize the movement of water and nutrients below the root zone. Although the TR21 method provides a good estimate of average monthly effective rain, it cannot provide guidance for daily irrigation. Partial-coverage irrigation inherently reduces the amount of water that can be taken up by the tree, but little is known about the impact of partial coverage on production. Under conditions of low ET_c , partial coverage may be able to supply adequate water. However, it is difficult to understand how coverage of less than 50% planted area can meet the evaporative demand during extended droughts with high daily ET_c .

The water budget is an effective method of evaluating irrigation management options for citrus. The simulation demonstrated the relative effects of several factors on the amount and frequency of irrigation. Modification of the program to control instead of simulate irrigation would provide an excellent method of irrigation management. The system could be fully automated or run manually. Irrigation scheduling based on soil moisture sensors is limited by the spatial variability of soil water content and the small volume of soil being monitored. This is not a limitation for a water budget that requires only local daily rain and ET_c data.

Simulating irrigation will not answer questions about the effect of water stress on tree growth and fruit yield. However, experiments

designed to study these responses will be improved by having a defined basis for scheduling irrigation. Irrigation based on a water budget will enhance understanding of the role of water stress on citrus production. Simulation provides useful information on the relative importance of factors determining the water status of citrus and the annual water requirements.

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