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MUSTAFA ÜNLÜ

RIZA KANBER

DENİZ LEVENT KOÇ

BÜLENT ÖZEKİCİ

UĞUR KEKEÇ

See next page for additional authors

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MUSTAFA ÜNLÜ, RIZA KANBER, DENİZ LEVENT KOÇ, BÜLENT ÖZEKİCİ, UĞUR KEKEÇ, TURGUT YEŞİLOĞLU, İBRAHİM ORTAŞ, FİLİZ ÜNLÜ, BURÇAK KAPUR, SERVET TEKİN, JANA KÄTHNER, ROBIN GEBBERS, MANUELA ZUDE, AVIVA PEETERS, and ALON BEN-GAL

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Irrigation scheduling of grapefruit trees in a Mediterranean environment throughout evaluation of plant water status and evapotranspiration

Mustafa ÜNLÜ[1,*], Rıza KANBER[1], D. Levent KOÇ[1], Bülent ÖZEKİCİ[1], Uğur KEKEÇ[1],
Turgut YEŞİLOĞLU[1], İbrahim ORTAŞ[1], Filiz ÜNLÜ[1], Burçak KAPUR[2], Servet TEKİN[3], Jana KÄTHNER[4],
Robin GEBBERS[4], Manuela ZUDE[4], Aviva PEETERS[5], Alon BEN-GAL[5]
[1]Faculty of Agriculture, Çukurova University, Adana, Turkey
[2]Faculty of Agriculture, Yüzüncü Yıl University, Van, Turkey
[3]Faculty of Agriculture, Kahramanmaraş Sütçü İmam University, Kahramanmaraş, Turkey
[4]Leibniz Institute for Agricultural Engineering, Potsdam, Germany
[5]Agricultural Research Organization, Bet-Dagan, Israel

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Abstract: In this study, 1 full irrigation regime (100% of crop evapotranspiration, I100) and 2 deficit irrigation regimes (70%, I70, and 50%, I50) were evaluated in a Rio Red grapefruit (Citrus paradisi Macfad. 'Rio Red') orchard in Adana, Turkey. Fruit yield, leaf water potential (LWP), and soil water depletion (SWD) were measured among trees from each treatment. Actual evapotranspiration was calculated in 3 ways, using 2 energy balance methods (eddy correlation and Bowen's ratio) and water balance. Evapotranspiration rates of I70 and I50 treatments were 10% and 18% less than I100, respectively. Average irrigation amount for I50 was less than half of the average irrigation amount for I100. Considering that yield for the experimental treatments did not change statistically significantly, the I50 treatment provided about 50% more irrigation water savings than full irrigation conditions. Grapefruit tree LWP was highly correlated to soil water status and significantly associated with irrigation treatment. Average LWP values for treatments were –2.70 MPa for I100, –2.96 MPa for I70, and –3.28 MPa for I50. LWP increased up to a threshold level equivalent to 60%–66% of SWD, above which LWP decreased linearly with a continuous increase of SWD. This indicates that an average LWP of –3.28 MPa can be allowed for grapefruit under these experimental conditions while keeping the crop yield at that of full irrigation levels. The research findings showed that an enhanced understanding of physiological parameters is essential for irrigation scheduling of fruit plants. These will result in obtaining the optimum yield of fruit while conserving water.

Key words: Grapefruit, evapotranspiration, leaf water potential, soil water status, energy balance methods, deficit irrigation

1. Introduction

One of the major challenges to irrigators of tree crops is determining the frequency and amount of water application (Assaf et al., 1982; Kanber et al., 1999). While inadequate water may reduce growth, yield, and fruit quality of a tree, excessive water application may cause several other adverse conditions, such as nutrient leaching, water logging, soil and water salinity, pests, and diseases. It is expected that optimization of water application through proper irrigation scheduling will result in water conservation, reduced production cost, and increased growth, yield, and quality of fruit trees (Fereres, 1997; Pereira and Villa Nova, 2009; Al-Yahyai, 2012).

In the cultivation of tree crops, the grower has to cope with seasonal and spatial site-specific variations in soil and microclimate that affect crop development. Furthermore, in orchards with a lifetime of 8 to 30 years, growers may further face higher uncertainties due to climate change. Successfully optimized irrigation and fertilization regimes will promote predictable and sustainable yields in orchards. In order to optimize irrigation and fertilization, reliable data and information are necessary to drive decision support systems that will look at the irrigation and the crop conceptually. A conceptual decision support system of an irrigation regime must consider yield and quality.

Several techniques are available for revealing the water needs of trees and some of the main advantages and disadvantages of different irrigation scheduling approaches were discussed by Jones (2004). Direct or indirect soil, water, and climatic measurements have been utilized for estimating tree water requirements for a long time. However, those techniques may be more appropriate

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[*] Correspondence: munlu@cu.edu.tr

for herbaceous plants and may not be as appropriate for fruit trees because of their anatomical and morphological structures, as well as their responses to various soil water conditions (Al-Yahyai, 2012).

It is often beneficial to use both soil and plant factors for irrigation scheduling. Physiological processes in fruit trees, such as water potential and gas exchange, are sensitive to changes in soil water content (SWC) (Naor and Cohen, 2003; Al-Yahyai et al., 2005). Several physiological variables are used as indicators of tree water status (Larson et al., 1989; Ortuño et al., 2004; Al-Yahyai et al., 2005). Among the most frequently used is leaf water potential (LWP) (Hsiao, 1990; Al-Yahyai et al., 2005).

LWP is a precise indicator of plant water status that can be used for predicting effects of water deficits on crop yields because small changes in the relative water content of leaf tissues corresponds to large changes in LWP (Hsiao et al., 1976; Hsiao, 1990). Tree water use depends heavily on weather conditions, on leaf area or effective transpiring surface, on phenology, and on soil moisture conditions (Pereira and Villa Nova, 2009).

The main objective of the present study was to determine the LWP of mature grapefruit trees under various soil moisture conditions and establish the relations between LWP and soil water depletion (SWD). Furthermore, the study also aimed to determine if the relationship between LWP and SWD could be used for irrigation scheduling for an orchard with a precision irrigation program.

2. Materials and methods

The experiment was carried out on grapefruit (*Citrus paradisi* Macfad. 'Rio Red') in an orchard located at the Çukurova University Agricultural Farm in 2011 and 2012 in Adana, in the eastern part of the Mediterranean region of Turkey (36°59′N, 35°18′E, 20 m a.s.l). The 3.4-ha orchard was planted in 1993 in an 8 × 8 m pattern (156 trees ha^{-1}). The mean crown size of the grapefruit trees was 57 m^3 (approximately with a conical crown shape) with 5–6 m of height, and they covered about 32% of the ground at the start of the experiment. Tree trunk circumference was measured 10 cm above the grafting points. At the onset of the experiment, trunk circumference in the orchard was fairly uniform. Average circumference was 69.7 cm ($P < 0.01$; $F = 1.79$; degrees of freedom of the error 2, 4).

A typical Mediterranean climate, with cool, rainy winters and hot, dry summers, prevails in the orchard area. The long-term average annual rainfall (1932–2007) is about 650 mm, most of which is received during the winter season, and the corresponding US Weather Bureau Class A pan evaporation is about 1525 mm. The annual rainfalls during the experimental period were 721 and 1073 mm in the years of 2011 and 2012, respectively, with 676.6 and 685 mm of rainfall during irrigation periods in the years of 2011 and 2012, respectively. The mean maximum daily air temperatures varied from 30.1 °C (August) to 31.4 °C (July) in the years of 2011 and 2012. Incoming solar radiation levels ranged from 28.9 MJ m^{-2} per day in June (2011) to 30.7 MJ m^{-2} per day in July (2012). Average daily wind speeds (at 2.0 m) varied from 0.9 to 1.4 m s^{-1} in the years of 2011 and 2012, respectively.

A drip system with in-line emitters of 2.2 L h^{-1} at 1.0 bar located every 0.5 m on a single lateral was used for irrigation of trees. There were a total of 16 drippers per tree.

Soil at the site was classified as Typic Xerofluvent with clay and clay-loam textures (Özbek et al., 1974) and with nearly 287 mm available water capacity calculated for a soil depth of 1.2 m. Some physical and chemical properties of the soil are presented in Table 1. The soil had neither salinity nor drainage problems. No local water table was observed. Fertilizer was applied at a rate of 0.840 kg N and 1.250 kg K_2O to all trees in February and June. Phosphorus was applied as P_2O_5 at a rate of 100 g per tree in June.

Three irrigation treatments were applied: full irrigation and control treatment (I_{100}), slight (DI_{70}), and moderate (DI_{50}). Irrigation water was calculated by Eq. (1) (Kanber et al., 1992; Ertek and Kanber, 2003). The remaining treatments were essentially deficit irrigation treatments,

Table 1. Some chemical and physical properties of the soil in the orchard.

Soil layer cm	ECe* dS m^{-1}	pH	FC* g/g,%	PWP* g/g,%	As g cm^{-3}	$CaCO_3$ %	Organic matter %	Soil texture			Texture class
								Clay %	Silt %	Sand %	
0–30	0.30	7.43	31.8	17.06	1.62	6.8	0.9	34	25.9	40.1	CL
30–60	0.33	7.58	33.8	18.12	1.47	20.4	0.9	51.3	16.1	32.6	C
60–90	0.38	7.53	36.8	19.51	1.56	23.1	0.8	33.6	39	27.4	CL
90–120	0.41	7.41	34.5	20.47	1.55	18.9	0.7	52.3	10.8	36.9	C

* ECe: saturated paste extract electrical conductivity; FC: field capacity; PWP: permanent wilting point (percent water by weight); As: bulk density; CL: clay loam; C: clay.

which received 70% and 50% of the control treatment, respectively.

$$IW = E_{pan} \times K_{cp} \times W_p, \tag{1}$$

where IW is the amount of irrigation water, mm; E_{pan} is the cumulative free surface water evaporation during irrigation interval (mm) measured by a screened Class A pan located nearby the weather station; K_{cp} is the crop pan coefficient, taken as 0.60; and W_p is the wetting percentage, taken as 40% over the irrigation season (Kanber et al., 1992).

In the first application, the same amount of water, equal to the soil water deficit, was given to all the trees. Others irrigations were applied at intervals of 10 or 15 days depending on irrigation system management of the University Farm Authority. SWC in all treatments at a soil depth of 1.2 m with 0.3-m increments was routinely measured at 1- or 2-week intervals, just before each irrigation event, and at harvest using the gravimetric method. SWC was also measured using a neutron water gauge (Hyroprobe 503, CPN Corporation, USA) with access tubes installed midway between trees close to drip line, at the same time of the sampling for gravimetric measurements.

The experiment had a randomized complete block design with 3 replications. Each plot contained 1 row with 23 trees of 1472 m^2 in each replication.

A water balance equation was used for the calculation of evapotranspiration (ET):

$$ET = P + IW + Cr - DP - TW \pm DW, \tag{2}$$

where P and IW are rainfall and total irrigation water depth (mm), respectively; DW is the change of SWC (mm); Cr is the capillary contribution from ground water table to the crop root zone (mm); DP is the deep percolation from the root zone (mm); and TW is the surface runoff water losses (mm). In the experimental area, since there was no water table or runoff losses, Cr and TW were zero. DP was assumed to be negligible because of drip irrigation system characteristics and high soil moisture deficit before irrigation.

ET of grapefruit was also measured using the Bowen ratio-energy balance (BREB) and eddy-covariance (EC) methods. The BREB and EC systems were installed near a chosen tree in the full irrigation treatment on the 255th day of the year (DOY; 13.09.2011) and continued until DOY 300 (28.10.2012). The Bowen ratio is defined as the ratio of sensible to latent heat (Bowen, 1926) and is expressed as:

$$\beta = \frac{H}{LE} , \tag{3}$$

where β is the Bowen ratio, H is the sensible heat flux, and LE is the latent heat flux. The measurements taken by the Bowen system were evaluated in the following order to determine the crop water consumption. The energy balance of a crop stand, neglecting minor terms, is expressed as:

$$Rn = G + LE + H , \tag{4}$$

where Rn is the net radiation, LE is the latent heat flux, H is the sensible heat flux, and G is the heat flux in the soil. All fluxes are expressed in units of J m^{-2} s^{-1}. Taking the energy balance equation into account, LE was rewritten as (Held et al., 1990):

$$LE = \frac{Rn - G}{1 + \beta} . \tag{5}$$

As described before, b is the ratio of H to LE and is calculated by the following equation (Steduto et al., 1997):

$$\beta = \frac{H}{LE} = \frac{\rho_a c_p k_h \frac{\Delta T}{\Delta z}}{\rho_a L k_w \frac{\Delta q}{\Delta z}} = \gamma \frac{\Delta T}{\Delta e} , \tag{6}$$

where ρ_a is the dry air density (mol air^{-1} m^{-3}), c_p is the specific heat capacity of dry air at constant pressure (J mol air^{-1} °C^{-1}), k_h and k_w are the turbulent exchange coefficients for heat transport and water vapor transfer (m^2 s^{-1}), Δq is the difference of the water vapor concentration of 2 heights of the canopy (mol H_2O mol air^{-1}), L is the latent heat of vaporization (J mol H_2O^{-1}), ΔT and Δz are the differences of temperature of 2 heights and measurement heights above the canopy (°C and m), γ is the psychometric constant (kPa °C^{-1}), and Δe is the difference of vapor pressure of 2 heights above the canopy (°C kPa^{-1}).

LE was measured by the EC method, calculated according to Stull (1988):

$$LE = L_v \overline{w' \rho_v'} , \tag{7}$$

where L_v is the latent heat of vaporization, w' is the instantaneous deviation of the mean vertical wind speed (m s^{-1}), and ρ_v' is the instantaneous deviation of the mean water vapor density.

The EC system determined LE with a 3-axis sonic anemometer (Model CSAT3, Campbell Scientific, USA) and LI 7500A LiCOR open path CO_2/H_2O analyzer systems both connected to a datalogger (Model CR3000, Campbell Scientific).

Grapefruit LWP was measured from 1000 to 1400 hours 1 day before and after irrigation with 3 replications in all plots of each treatment. Fully expanded leaves completely exposed to full sunlight from selected trees were cut and LWP was measured using a pressure chamber (3005 Plant Water Status Console, Soil Water Equipment Corp., USA). LWP measurements were also taken every day during the same irrigation interval until the next event. Measurements were conducted from July to October in the first year and from June to October in the second year.

The fruits were harvested according to fruit maturity and potential for export in March (DOY 75–76 and DOY 84) in 2012 and 2013, respectively. All the fruits on the trees in each treatment were counted and weighed during the harvest. Marketable yield was then evaluated.

3. Results

3.1. ET and fruit yield

The amount of irrigation water applied, ET values, and fruit yield are presented in Table 2. Seasonal ET values of treatments were determined using water balance and micrometeorological approaches.

Generally, the first irrigation events were applied by the end of June, and the last ones during October. Treatments were irrigated 11 times during the first year and 8 times in the second year. Irrigation seasons varied between 124 (2011) and 96 (2012) days.

During the experimental years, SWC at the end of year was higher than that at the beginning of the study. This can be explained by the higher than average rainfall received during both previous winters. Average annual ET of treatments ranged from 695 to 852 mm. As expected, the highest ET was observed in the I100 treatment (the treatment receiving the most irrigation water). ET rates of I70 and I50 treatments were 10% and 18% less than I100, respectively. When water stress was developed in the months of July and August, the ET values of experimental treatments decreased depending on the irrigation amount. ET values during this period were 112 and 180 mm in treatment I100, 82 and 141 mm in treatment I70, and 61 and 90 mm in treatment I50 mm for the first and second year, respectively. The precipitation during this time was 8.5 and 9 mm, respectively, for 2011 and 2012. Based on these results, it can be concluded that the I50 treatment had twice as much stress as the I100 treatment.

The change of daily ET over the growing seasons as calculated by the energy balance approaches is shown in Figure 1. Both the BREB and EC approaches showed the same variation of daily ET. However, absolute measured values were different. ET values measured by both methods decreased rapidly as the winter approached and reached minimum levels of 0.33 mm day^{-1} for BREB, and 0.52 mm day^{-1} for EC (DOY: 10 and 11). The maximum daily ET was recorded in mid-June for BREB with 4.66 mm day^{-1} and at the end of May for EC with 3.71 mm day^{-1}. During the stress period (July and August), daily ET measured by both methods sharply decreased to 1.17 mm day^{-1} for BREB and 1.65 mm day^{-1} for EC. After the stress period, daily ET values again increased. Yearly ET of grapefruit was measured as 716.9 mm with BREB and 640.4 mm with EC. In 2011, only autumn and winter seasons were measured. ET during this time was 198.5 mm for BREB and 160.9 mm for EC.

Table 2. Irrigation, evapotranspiration, and yield results for treatments.

Components	Treatments					
	I_{100}		I_{70}		I_{50}	
	2011*	2012**	2011	2012	2011	2012
Irrigation water (I)[1], mm	264.7	214.7	191.4	150.3	143.42	85.1
Rainfall (P)[2], mm	676.6	685	676.6	685	676.6	685
Change of SWC (ΔS)[3], mm	−130.8	−6.8	−143.3	−27.7	−125.6	−74.0
Evapotranspiration, mm	810.5	892.9	724.7	807.6	694.4	696.1
Yield, kg per tree	320 n.s.	50.4 n.s	306 n.s.	51.7 n.s.	330 n.s.	99.2 n.s.
Average standard error	26.96	17.44				
F value	0.083	2.54				

*Evapotranspiration values are for 29 June 2011 to 31 March 2012 (first year) and **30 May 2012 to 31 March 2013 (second year). [1]Calculated by dividing the volume of water applied to the plots by total plot area (1472 m^2). [2]As periodically, total rainfall received from 29 June 2011 to 31 March 2012 for the first year and 1 April 2012 to 31 March 2013 for second year; all the rainfall has been accepted to be effective. [3]Calculated for 29 June 2011 to 6 January 2012 in the first year, and 30 May 2012 to 26 March 2013 in the second year.

3.2. SWC

Gravimetric measurements of SWC during the 2 growing seasons were low in all treatments, not reaching field capacity, even immediately following irrigation events (Figure 2).

The treatment with the greatest water stress (I50) showed significantly lower SWC throughout the growing season compared to full irrigation treatment of I100. In I50, SWC fluctuated around the permanent wilting point, indicating considerable water stress. Significant differences in SWC were observed between irrigation treatments at the last 40–50 days of the season when precipitation was high in 2011. In 2012, during the rainfall period, SWC was very high, near field capacity in all treatments, but there were no differences among them.

Grapefruit yield was strongly correlated with average SWD measured just before irrigation events (Figure 3). This suggests that water stress during the irrigation period particularly contributes to yield reduction even if rainfall received after irrigation season could not remove this yield reduction effect.

3.3. LWP

Average midday LWP measured before irrigation events was −2.70 MPa for I100, −2.96 MPa for I70, and −3.28 MPa for I50 in 2011 (Figure 4). In the second year, LWP values were −2.45, −2.62, and −2.77 MPa for treatments, respectively. During the irrigation seasons, LWP of trees in the treatments changed similarly with time. However, LWP in mild and severe stress treatments was significantly lower than that of the fully irrigated trees. In the water stress period, these values gradually fell, reaching minimum values on DOY 268 in 2011 and DOY 245 in 2012. Minimum values of LWP changed from −3.10

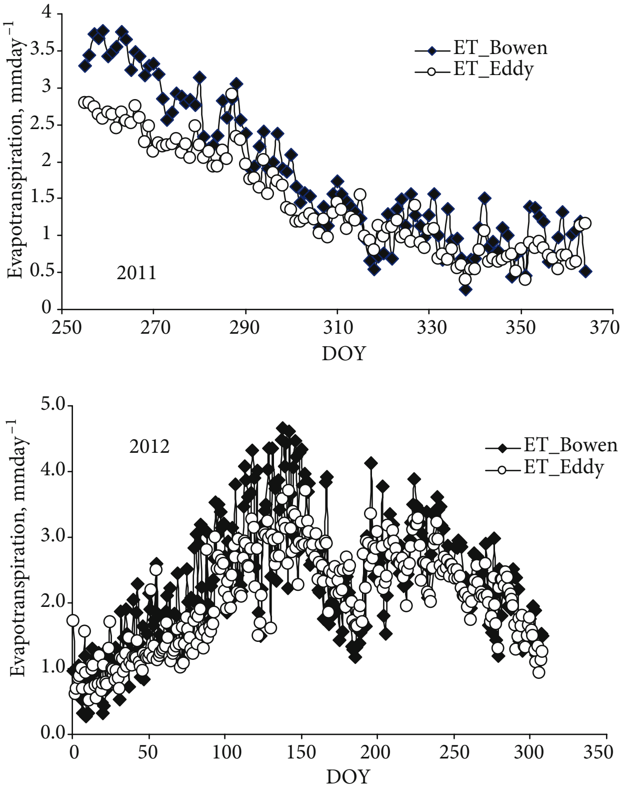

Figure 1. Change of daily evapotranspiration for I100 treatment taken from BREB and EC approaches.

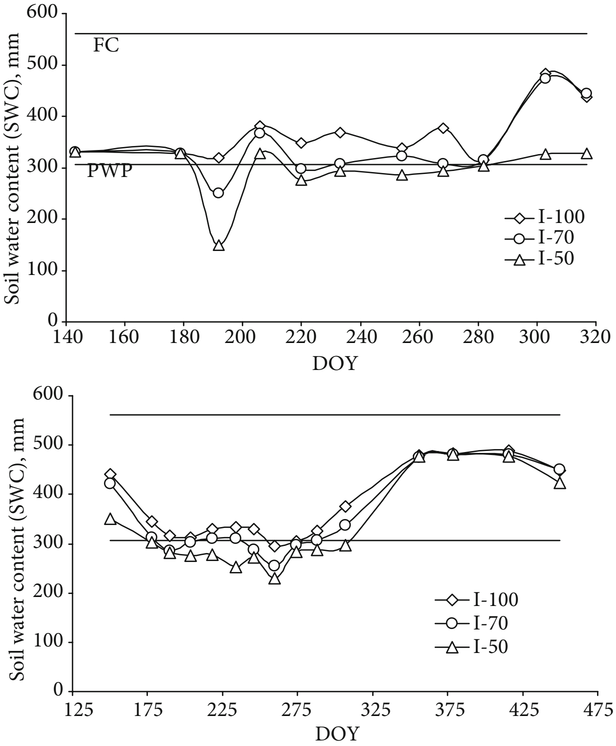

Figure 2. SWC over time for the first (upper) and second (lower) years.

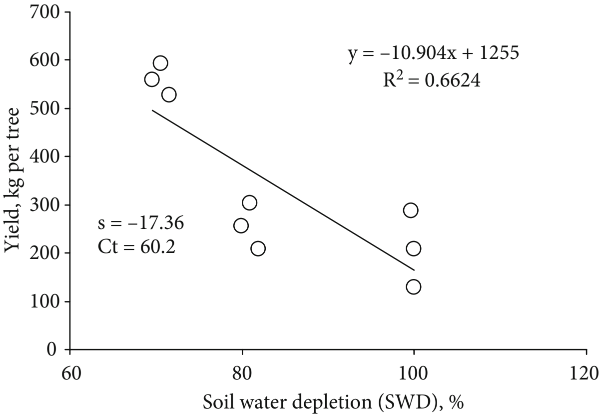

Figure 3. Relationship between SWD and fruit yield for grapefruit. Ct is threshold SWD value and S is slope of line above the threshold.

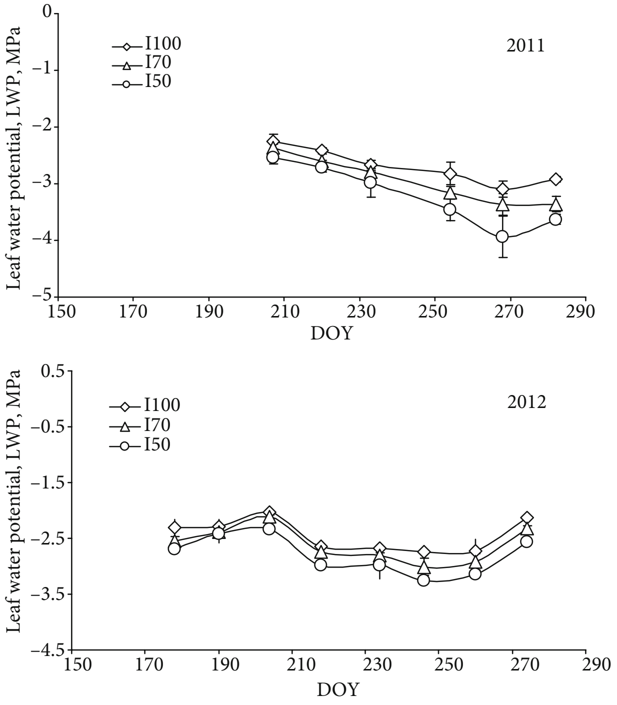

Figure 4. Midday LWP of grapefruit trees in the treatments during the irrigation seasons. Vertical bars are twice the overall mean standard error. Each point is the mean of 9 values.

(I100) to −3.93 (I50) MPa in 2011; corresponding values in 2012 were −2.74 MPa for I100, −3.01 MPa for I70, and −3.26 MPa for I50. LWP values in 2012 fluctuated in all treatments, such fluctuations being more pronounced in I70 and I50 trees. During this period, treatment I100 was fairly constant. However, no significant differences were found among trees irrigated at different levels over the full irrigation treatment.

A piecewise linear response function between SWD and LWP was observed (Figure 5). The function (Genuchten and Hoffman, 1984) is defined by a threshold SWD value of 66.1%, below which LWP is not affected, and a slope of 0.022 describing decreasing LWP with every unit increase of SWD.

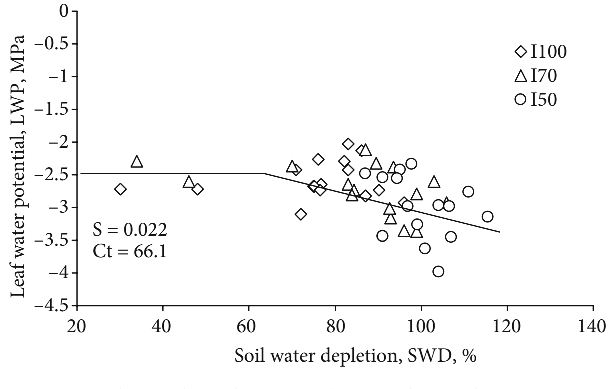

Figure 5. Relationship of SWD and LWP of grapefruit trees. Ct is threshold SWD value and S is slope of line above the threshold.

Tree yield correlated significantly with average LWP (R = 0.822) (Figure 6). Yield decreased linearly with increasing LWP with a slope of 731.48, beginning with the lowest measure LWP (−2.52 MPa). It has been suggested that LWP of −2.52 MPa is the threshold value for both tree yield and SWD of grapefruit orchards.

4. Discussion

The average annual ET of treatment I100 by water balance was 16% and 25% higher than those of BREB and EC (Table 2; Figure 1). The difference may be due to deep percolation losses, particularly of rainfall, which could not be measured, as explained by Kanber et al. (1992, 1999).

There was no significant difference between yields due to irrigation treatments (Table 2). It can be reasoned that a 2-year study is insufficient to evaluate the effects of irrigation on a mature perennial grapefruit crop. In the second year, yields were smaller than those of the first year. This could be caused by periodicity or by some other condition or limiting factors outside of the scope of this study. As seen in Figure 2, SWC changed based on the irrigation schedule, climatic conditions, plant canopy structure, rootstock, and physical characteristics of the soil. One or all of these factors and their interactions may have resulted in the lack of significant difference in SWC (Naor and Cohen, 2003; Al-Yahyai, 2012).

Average SWD was a good indicator for estimating the tree yield in this study (Figure 3). Similar results from Al-Yahyai (2012) indicate that tree yield is highly correlated to soil water status.

The SWD of grapefruit trees remained below 30% in I100, 20% in I70, and 10% in I50 treatments throughout

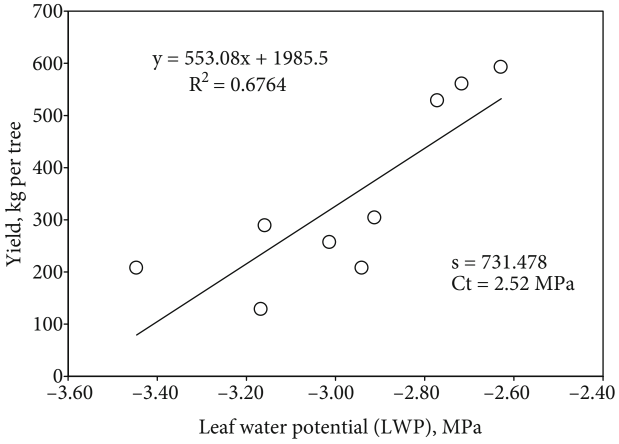

Figure 6. Relationship between fruit yield and average LWP for grapefruit trees. Ct is threshold LWP value and S is slope of line above the threshold.

the year 2012. Within the range of SWD from 0% to 60%, LWP remained above –2.50 MPa and did not significantly correlate with SWD (Figure 5), presumably due to sufficient SWC, especially in the I100 treatment. Similar results were reported by Al-Yahyai (2012) and Al-Yahyai et al. (2005) for apple and carambola trees, Larson et al. (1989) for mango trees, and Ortuño et al. (2004) for lemon trees. The LWP of these trees ranged from –1.0 to –2.5 MPa when SWD increased from 0% to 50%–60%, above which stem water potential was reduced linearly with a decline in SWD. However, LWP was not influenced by SWD of up to 30% under field conditions. Contrarily, results from Ortuño et al. (2006) and Garcia-Tejero et al. (2011) showed that maximum daily trunk shrinkage is a very suitable plant-based indicator for precise irrigation scheduling in adult lemon trees and orange trees, respectively. Similar results were taken from almond trees by Goldhammer and Fereres (2004). Results from another study showed that midday and predawn LWP threshold values were –2.5 and –1.0 MPa, respectively, for young citrus plants (Ortuño et al., 2004). Information on a crop's water status, which is required when planning irrigation programs, is best provided by physiological indicators (Remorini and Massai, 2003). In this sense, Shackel et al. (1997) and Naor (2000) demonstrated the merits of estimating stem water potential for irrigation management. Ebel et al. (1995) reported that stem water potential of fruit trees changes little over a range of SWD values as high as 80%. Thus, a corresponding reduction in growth and yield response can only be detected when trees are severely stressed at SWD levels below 25%. According to Ruiz-Sanchez et al. (1996), lemon tree water relations under flooding conditions are characterized by substantial decreases in leaf conductance and LWP. In another study by Silva et al. (2005) on the irrigation of Tahiti lime trees, the threshold available soil water content (AWC) level for the onset of ET decline was 43%, and 60% for stomatal conductance, assimilation, transpiration, and predawn LWP. Additionally, predawn LWP was more sensitive to AWC than midday LWP and is therefore a better tool for irrigation. When AWC was around 60%, values of predawn and soil water potentials were –0.62 MPa and –48.8 kPa, respectively. In this study, similar results were observed, and the relationship between yield and LWP appeared to confirm this (Figure 6).

In this study, data showed that ET rates of I70 and I50 treatments were 10% and 18% less than I100, respectively. Average irrigation amount for I50 was less than half of the average irrigation amount for the I100. Considering that the yield for the experimental treatments did not change statistically significantly, the I50 treatment provided irrigation water savings of about 50% compared to full irrigation conditions. This is significant for semiarid climate conditions where water is scarce. Furthermore, based on the results of LWP, it is concluded that an average LWP of –3.28 MPa can be allowed for grapefruit under these experimental conditions while keeping the crop yield at that of full irrigation levels. Monitoring LWP might result in noninvasive soil and crop management while keeping the crop yield at desirable levels.

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