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Mandarin Yield Response to Partial Root Drying and Conventional Deficit Irrigation

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Abstract: Fruit yield response of a mandarin (*Citrus reticulata* cv. Marisol) orchard to deficit irrigation, which was imposed either through conventional deficit irrigation (DI) or a newly evolving irrigation technique, called partial root drying (PRD), was investigated. The PRD practice simply requires wetting of one half of the rooting zone and leaving the other half dry, thereby utilising reduced amount of irrigation water applied. The wetted and dry sides are interchanged in the subsequent irrigations. Six irrigation treatments were tested: (1) TR, traditional farmers' method of irrigation where irrigation management was left to the full control of a grower; (2) FULL irrigation where the full amount of irrigation water (60% Class-A pan evaporation) was applied to the both halves of tree-root zone; (3) 1PRD30 and (4) 1PRD50, 30 and 50% reduced amount of irrigation water, compared respectively to FULL irrigation, was applied alternately on each half side of the tree rows, and the irrigated side was changed every irrigation; (5) 2PRD50, 50% reduced amount of irrigation water was applied on each half side of the tree rows, and the irrigated side was changed every other irrigation; (6) DI50, conventional deficit irrigation where 50% reduced amount of irrigation water, compared to FULL irrigation, was applied to the both halves of the tree-root zone, similar to FULL irrigation. A randomised complete block experiment design with 6 replicates, 4 trees each, was used. The orchard had 6-year-old trees, planted in 5-m rows of a parallelogram arrangement. A drip irrigation system with 2 laterals, laid along the tree rows with trees located 1.2 m midway between the laterals, was used. The drippers with 4 l h^{-1} discharge rate and 75-cm spacing formed 50-cm wide wet bands during irrigation, along the laterals underneath the tree rows. The yield within the range of 36 to 37 tons ha^{-1} was the highest and obtained under the traditional practice (TR) of irrigation where, however, more than double the amount of irrigation water was applied, compared to the control, FULL irrigation. The yield reduction under FULL irrigation was only marginal (10% to 14%), with, however, more than a 2-fold increase of irrigation water use efficiency (IWUE), compared to TR. The treatment 1PRD30 yielded 30.6 and 27.7 tons ha^{-1} in 2001 and 2002, respectively, and followed the yield of control, FULL irrigation treatment. No yield benefit was obtained with the treatment of 2PRD50, which produced the lowest fruit yield, next to the conventional deficit irrigation treatment (DI50). The ranking of fruit-yields, TR>FULL>1PRD30>1PRD50, was maintained over the 2 seasons, 2001 and 2002, although the differences were marginal and not statistically significant ($P \leq 0.01$). However, the IWUE under PRD increased significantly ($P \leq 0.01$) to nearly 3 times that of the TR treatment.

Key Words: Citrus, fruit quality, partial rootzone irrigation, PRD, water use efficiency

Geleneksel Kısıntılı ve Yarı Islatmalı Sulama Uygulmalarına Mandalin Meyve Verim Tepkisi

Özet: Bu çalışmada mandalinin (*Citrus reticulata* cv. Marisol) geleneksel kısıntılı (DI) ve yeni ortaya atılan yarı ıslatmalı (PRD) sulama uygulamaları altında verimi incelenmiştir. Yarı ıslatmalı sulama uygulaması altında, bitki köklerinin yarısı ıslatılırken diğer yarısı görece kuru bırakılmakta ve dolayısiyle uygulanan sulama suyundan tasarruf saglanmaktadır. Su verilerek ıslatılan ve görece kuru bırakılan kök bölgeleri takip eden sulamalarda ardışık olarak değiştirilmektedir. Çalışmada altı sulama konusu test edilmiştir: (1) TR, sulamanın yetiştiriciye bırakıldığı çiftçi sulaması; (2) FULL, sulama suyunun eksiksiz, tam olarak (A-Sınıfı buhar kabı buharlaşmasının %60'ı) bitki köklerinin iki yanına birden verildiği; (3) 1PRD30 ve (4) 1PRD50, FULL konusuna verilenden sıra ile %30 ve %50 eksik suyun bitki sıralarının birer yanına her sulamada ardışık olarak değiştirilerek verildiği; (5) 2PRD50, %50 eksik suyun bitki sıralarının bir yanına, iki sulamada bir ardışık olarak değiştirilerek verildiği yarı ıslatmalı sulama uygulamaları ve (6) DI50, %50 eksik suyun bitki sıralarının iki tarafına FULL konusundaki gibi verildiği geleneksel kısıntılı sulama konusu. Deneme, her yinelemede 4 ağaç olmak üzere 6 yinelemeli tesadüf blokları deneme desenine göre düzenlenmiştir. Deneme bahçesi, bitki sıra aralığı 5 m olan eşkenar dörtgen düzeninde tesis edilmiş, 6 yaşındaki mandalin ağaçlarından oluşmaktadır. Sulamada, ağaç sıralarının iki yanına 1.2 m uzaklıkta yerleştirilmiş iki lateralli damla sulama metodu kullanılmıştır. Sulama sırasında lateral üzerinde 75 cm aralıkla yerleştirilmiş 4 l h^{-1} verdili damlatıcılar, ağaç sıraları altındaki lateraller boyunca 50 cm genişliğinde ıslak bant oluşturmuştur. Sulamanın tamamen yetiştiricinin insiyatifine bırakıldığı TR sulama konusu altında, meyve verimi 36 ile 37 ton ha^{-1} aralığında tüm konular içinde en yüksek bulunmuş ise de, kullanılan su FULL konusunda uygulanan su miktarının iki katı daha yüksetir. Buna karşın meyve verimi FULL konusu altında önemsiz bir azalma (%10-14) gösterirken, sulama suyu kullanım etkinliği (IWUE), TR konusuna kıyasla iki kat artmıştır. Yarı

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ıslatmalı sulama 1PRD30 konusu altında meyve verimi, 2001 ve 2002 yıllarında sıra ile 30.6 ile 27.7 ton ha^{-1} aralığında değişerek, FULL sulama konusunu takip etmiştir. Islak ve kuru bırakılmanın 2 sulamada bir değiştirildiği 2PRD50 konusu altındaki meyve verimi, geleneksel kısıntılı sulama (DI50) konusu ile birlikte en alt sırada kalmıştır. Verimler arasındaki farklılık önemli olmasa da ($P > 0.05$), meyve verim sıralaması, TR>FULL>1PRD30>1PRD50, 2001 ve 2002 yıllarındaki 2 yıllık deneme süresince değişmemiştir. Ancak sulama suyu kullanım randımanı (IWUE), yarı ıslatmalı sulama (PRD) uygulamaları altında, TR konusuna kıyasla 3 kat artarak önemli ($P < 0.05$) farklılık göstermiştir.

Anahtar Sözcükler: Narenciye, meyva kalitesi, kısmi kök bölgesi sulaması, YIS, su kullanım etkinliği

Introduction

Increase of urban population adds additional demand for increased share of fresh water allocation, which in turn decreases availability of fresh water resources for use in irrigated agriculture. It is essential therefore to take steps and measures to conserve and effectively use of water in irrigation schemes. To this effect, new irrigation management practices and irrigation scheduling, not necessarily based on full crop water requirement, but aiming at increasing efficient use of allocated irrigation water – higher crop yields with unit use of water – must be developed.

Irrigation methods with high crop water use efficiency are of utmost importance in water-scarce regions. One approach is conventional deficit irrigation (DI), which is either implemented throughout the whole growing season or is confined over certain growth stages (Kirda et al., 1999; Kang et al., 2000a). Use of DI practice can reduce water use without significant yield reduction. However, since DI requires prior knowledge of specific crop-growth stages tolerant to water stress, growers may have difficulty using it effectively.

An alternative irrigation practice to conventional DI has evolved from split-root studies, which have shown that plants with 2 halves of its roots exposed alternately to drying and wetting cycles develop normally with reduced stomatal opening with no visible leaf water deficit (e.g., Zhang et al., 1987; Davies and Zhang, 1991; Davies et al., 1994). Plants with 2 halves of its roots under alternate drying and wetting go through partial root drying (PRD), which produce root signals to shoots to trigger physiological mechanisms to save and use water efficiently through stomatal regulation (Davies and Zhang, 1991). Extensive research work over the last dozen years has revealed that stomatal regulation is controlled through chemical signals from plant roots to the leaves, resulting from exposure of plant roots to drying cycles. Increased concentration of abscisic acid (ABA) in the xylem flow from roots to the leaves triggers closure of stomata (Zhang and Davies, 1989, 1990, 1991; Gowing et al., 1993) and activates genes for drought tolerance (Bray et al., 1999). Other mechanisms controlling stomatal aperture include hydraulic signals (Tardieu and Davies, 1993; Auge and Moore, 2002) and changes of pH of xylem sap (Wilkinson and Davies, 1997; Bacon et al., 1998). It was shown that stomatal closure effectively reduced transpiration without limiting photosynthesis (Jones, 1992). Practical implications of stomatal regulation based on root-to-shoot signalling, brought about by partial root drying (PRD), has led to the development of a new irrigation practice where the 2 halves of plant-root zone are exposed alternately to dry and wet cycles (Kang et al., 1997). It is expected that such a practice may increase irrigation-water-use efficiency (IWUE), yield per unit application of irrigation water, and thereby reduce irrigation water requirement, which is of utmost importance in water-scarce regions.

Early field tests of this evolving irrigation practice on grapevines in Australia showed that IWUE was doubled while producing better quality grapes with no significant yield reduction (Gowing et al., 1993; Dry et al., 1996; Fuller, 1997; Dry and Loveys, 1998). Recent results on maize (Kang et al., 2000b; Kirda et al., 2005), greenhouse grown tomato (Kirda et al., 2004), pot-grown pepper (Kang et al., 2001) and orchard pear (Kang et al., 2002) had again confirmed earlier findings: increased IWUE with only marginal yield reduction. Field tests of the new irrigation practice, PRD, carried out for only a few crops should be extended to other irrigated crops. Citrus, with a mean annual production of over 100 million tonnes (http://www.unctad.org/infocomm/anglais/orange/market.htm), is one of the most important horticultural crops. Fifty percent of the world's citrus production comes from irrigated orchards, which are all in arid and semi-arid regions of high water scarcity. The objective of this work was therefore to assess comparative yield response of a citrus orchard, planted to mandarin (*Citrus reticulata* cv. Marisol), to deficit irrigation, which was imposed either through conventional deficit irrigation (DI) or PRD practice, and to FULL irrigation where irrigation water requirement was fully met.

Materials and Methods

The experiment was conducted in 2001 and 2002 at Subtropical Fruits Research Institute, Çukurova University (36º59′ N latitude, 35º18′ E longitude; 161 m altitude), Adana, Turkey. The area has a typical Mediterranean climate, with cool and rainy winter and hot and dry summer months, with long-years annual-average rainfall of 653.2 mm (Table 1). The rainfall and temperature data during the experiment, shown in Table 1, were from a nearby a meteorological station. The evaporation data, however, were measured directly in the experimental site, using a Class-A pan. The heavy gravelly clay textured soil with a bulk density of 1.44 g cm^{-3} is classified as a Lithic Rpodoxeralf and has an average field capacity (–0.033 MPa) of 0.33 cm^3 cm^{-3} and permanent wilting point (–1.5 MPa) of 0.06 cm^3 cm^{-3} within the 45-cm topsoil. Soil extract salinity EC and pH and organic matter content were 0.30 dS m^{-1}, 7.6 and 0.75%, respectively.

The orchard had 6-year-old mandarin trees (*Citrus Reticulata* cv. Marisol) of about 50% canopy coverage, grafted over *Citrus auratium* L. The trees were planted 5 m apart within and between the rows in a parallelogram pattern. A randomised complete block experiment design, with 6 irrigation treatments and 6 replicates, each having 4 trees, was used in the experiment.

Tree rows were centred between 2 lateral drip irrigation lines spaced 120 cm apart. Drippers having a discharge rate of 4 l h^{-1} and spaced every 75 cm along the laterals, formed a 50-cm wide wet band along the tree rows. Irrigation water requirement of the orchard was assumed to be 60% of class-A pan evaporation, based on the results of an earlier work, conducted in the same climate by Tuzcu et al. (1988). Treatments were (1) traditional irrigation (TR) with only single drip lateral laid along the trees; (2) full irrigation (FULL) where irrigation water equivalent to 60% of Class-A pan evaporation, reduced by 50% for the canopy coverage adjustment, was applied twice weekly, wetting the 2 halves of tree-root zone, using the 2 drip laterals; (3) 1PRD30 and (4) 1PRD50, 30 and 50% reduced amount of irrigation water, compared respectively to FULL irrigation, was applied alternately on each half side of the tree rows, and the irrigated side was changed every irrigation; (5) 2PRD50, 50% reduced amount of irrigation water was applied on each half side of the tree rows, and the irrigated side was changed every other irrigation; (6) DI50, conventional deficit irrigation where 50% reduced amount of irrigation water, compared to FULL irrigation, was applied to the both halves of the tree-root zone, similar to FULL irrigation. Irrigation water was measured

Table 1. Climatic data near the experimental site.

	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.-Oct.	Total
					Rainfall (mm)				
1930-2001	73.9	124.4	109.4	88.9	65.8	52.5	47.0	91.3	653.2
2001	88.1	320.9	8.6	74.9	46.6	8.8	130.4	78.5	756.8
2002	25.7	77.9	109.2	68.1	40.3	88.8	22.0	46.2	478.2
					Temperature (ºC)				
1930-2001	15.5	11.1	9.4	10.4	13.1	17.2	21.4	21.1	---
2001	13.9	10.7	10.7	10.9	16.5	18.7	21.8	26.6	---
2002	16.4	8.8	7.9	12.3	14.7	16.5	21.4	26.5	---
					Evaporation (mm)				
1974-2001	67.0	46.7	48.3	56.2	83.1	114.1	160.0	963.6	1539.0
2001	73.4	36.1	45.6	43.9	69.2	112.3	176.0	1039.7	1596.2
2002	74.3	77.9	58.9	71.4	88.9	72.5	155.2	945.1	1544.2

and applied through a control unit having flow meters for each irrigation treatment.

Fertilising and insect control were the same for all trees. During the first season in 2001, the trees had received 135.2 g, 47.9 g and 90.2 g of N, P and K per tree, respectively. The fertiliser rate in the second year was increased by 14%, following the general recommendation for fertilising of young orchards. Fertilisers were applied in liquid form and injected directly in irrigation water twice monthly, from May until late September. Following general practice in the region, petroleum oil (150 kg ha^{-1}) against *Phyllocoptruta oleivora* in February, agrimec (Abamectin 18) (250 ml ha^{-1}) against *Phyllocnistis citralle* and *Pononychus citri* in May, suprasit (Methidathion) (1 l ha^{-1}) against *Aodiella aurantii* and consult (Hexaflumoron 10) (0.5 l ha^{-1}) against *Phyllocnistis citralle* in June were sprayed in both seasons. The orchard was cleared of weeds twice annually in May and August.

Irrigation season was started on 7 and 30 May in 2001 and 2002, respectively, and continued for 5 months until harvest in late October (25 and 28 October, respectively in 2001 and 2002). Number of irrigations in 2001 and 2002 were 36 and 41, respectively. Traditional irrigation TR was scheduled twice weekly and carried out by a field worker whose criterion for adequacy of irrigation was his visual satisfaction. However, we measured the irrigation water applied to each TR plot. Root zone soil water content was continuously measured with nylon resistance blocks calibrated against soil capillary pressure, before and after irrigation throughout the season, to control if the irrigation treatments were properly implemented. Because the soil where the orchard was set up had very shallow soil of about 50 cm depth, the nylon blocks were installed in 30 cm soil depth at 100 cm spacing toward tree trunk in three replicates. Evapotranspiration (ET, mm) was estimated using the water balance equation

$$ET = P + I - D \pm \Delta S \quad (1)$$

where P is rainfall (mm), I is irrigation (mm), ΔS is the change in soil water storage (mm), assessed with gravimetric sampling, over the tree-root zone during irrigation season and D is the deep percolation (mm). The deep percolation D was assumed zero in all irrigation treatments except TR, where it was estimated using graphs of fruit yield versus ET, following the procedure described by Saeed and El-Nadi (1997), who showed the existence of a linear relation between ET and the yield. The deep percolation loss under the TR treatment was simply the difference between irrigation water applied and the ET, estimated using the relation ET versus the fruit yields.

Rainfall and daily pan evaporation were measured in the experimental site during both seasons in 2001 and 2002. Fruit-yield assessment was based on fruits harvested from the 4 trees in each replicate. Annual growth rate of tree-trunk perimeter, measured using a simple measuring tape 1 cm above the grafting point, was also assessed in the final year 2002. Four randomly collected fruits from each tree, totalling 16 fruits from each replicate, were used to assess average fruit weight and diameter. Also during the final year in October 2002, diurnal leaf water potential, before and after irrigation, was measured using Scholander pressure chamber on newly formed summer-flushing leaves so that the tested treatments could fully reflect their effects on the leaves.

Irrigation-water-use efficiency (IWUE), which was used to assess comparative benefits of the irrigation treatments, was calculated using the equation

$$IWUE = Y/I \quad (2)$$

where Y is fruit yield (kg ha^{-1}) and I is seasonal irrigation water applied (mm) to different irrigation treatments.

Results

Among the irrigation treatments tested, the tree-root zone was the wettest under TR with excess irrigation being evident with capillary pressure at levels generally higher than –0.033 MPa (i.e. field capacity) and rarely reaching –0.4 MPa before irrigation (Figure 1). Because the FULL irrigation received 50% to 60% less irrigation water than the TR (Table 2), capillary pressures in the root zone were comparably low and maintained within the interval of –0.006 to –0.1 MPa (Figure 1). Capillary pressures under DI50 rarely reached field capacity (FC). On the other hand, under 1PRD30 following irrigation, values of about –0.04 MPa manifested within the irrigated half of the root zone. Irrigation water, equivalent to 60% class-A pan evaporation (in reality 30% with canopy adjustment), applied under FULL irrigation was considered sufficient and within the recommended range in the Mediterranean region during summer months (e.g., Stanhill, 1972; Swietlik, 1992;

Table 2. Mandarin fruit yield and irrigation water use efficiency[a].
ET: Evapotranspiration; IWUE: irrigation-water-use efficiency; I: irrigation. Data represent means (n = 6) ± SE.

Treatments*	2001				2002			
	Yield (tons ha^{-1})	I (mm)	ET (mm)	IWUE (kg ha^{-1} mm^{-1})	Yield (tons ha^{-1})	I (mm)	ET (mm)	IWUE (kg ha^{-1} mm^{-1})
TR	36.4 ± 5.1 a	836.6	396.5	41.1 ± 5.8 b	37.0 ± 2.1 a	636.8	356.7	56.1 ± 3.1 c
FULL	32.7 ± 6.9 ab	309.7	374.9	90.9 ± 19.1 a	31.6 ± 6.1 ab	298.5	344.7	117.2 ± 22.7 b
1PRD30	30.6 ± 2.7 abc	229.9	298.0	109.2 ± 9.1 a	27.7 ± 2.6 ab	207.9	275.0	145.8 ± 13.6 ab
1PRD50	23.9 ± 2.8 bc	168.5	223.6	99.9 ± 12.9 a	22.7 ± 1.8 b	150.1	201.3	163.2 ± 13.1 a
DI50	20.8 ± 1.6 bc	168.5	255.0	90.8 ± 6.7 a	21.7 ± 1.7 b	150.1	244.3	159.3 ± 11.9 ab
2PRD50	19.9 ± 2.6 c	168.5	216.8	95.2 ± 12.0 a	21.5 ± 2.3 b	150.1	207.3	154.3 ± 16.7 ab
Tukey's HSD	12.2	---	---	34.1	10.4	---	---	45.7

[a] Rows of data within a column followed with different letters are significantly different (P = 0.05) based on Tukey's mean range test.

*TR: traditional farmers' method of irrigation
FULL: full amount of irrigation water applied
1PRD30 and 1PRD50: 30% and 50% reduced amount of irrigation water were applied, respectively;
DI50: conventional deficit irrigation where 50% reduced amount of irrigation water, compared to FULL irrigation, was applied
2PRD50: 50% reduced amount of irrigation water was applied

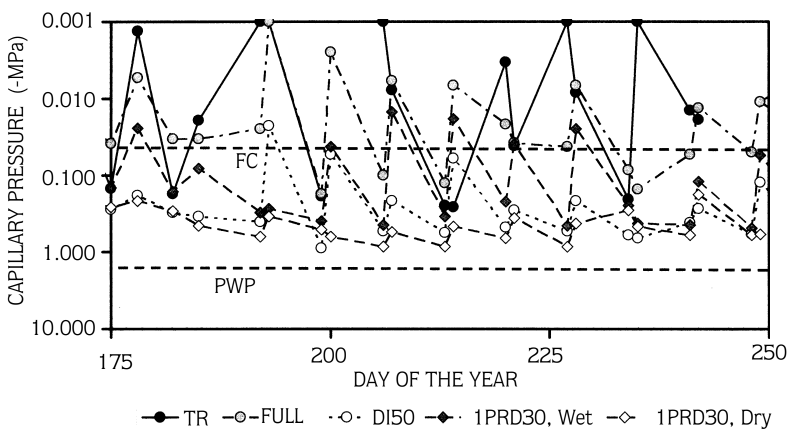

Figure 1. Changes of capillary pressure in tree-root zone under different irrigation treatments in 2002. For abbreviations see the legend of Table 2.

Sepaskhah and Kashefipour, 1994). With the treatment TR, receiving twice the amount of irrigation water applied to the FULL treatment, the capillary pressures, following immediately irrigation, were of near saturation (≥0.001 MPa) (Figure 1). Occasionally, there was incidence of run off observed under blocks of TR treatment. Therefore, irrigation water applied to TR was considered in excess of actual requirement. We thus used FULL irrigation treatment, not the TR treatment, as the basis for comparison of irrigation water quantity to elucidate if the PRD practice can be more advantageous in saving irrigation water than conventional DI practice.

Table 2 shows mandarin fruit yield and IWUE in 2001 and 2002. The highest yield was obtained under traditional irrigation practice. It should be noted that there was only marginal reduction (6.4% - 12.3%) of yield under 1PRD30, compared to FULL irrigation. The conventional deficit irrigation treatment (DI50) fell in the last group of the lowest fruit-yield treatments (Table 2). No yield advantage was obtained by interchanging irrigated side of the roots every other irrigation instead of every irrigation (i.e. 1PRD versus 2PRD) (Table 2).

The lowest IWUE (kg $ha^{-1}mm^{-1}$) was achieved under the traditional (TR) irrigation treatment where the grower used no quantitative assessment to determine the amount of irrigation water to be applied (Table 2). All of the other treatments fell in the same statistical group with differences observed in IWUE not being statistically significant ($P \leq 0.05$). The PRD treatments with 30% and 50% less irrigation water applications (i.e. 1PRD30, 1PRD50) gave proportionally higher IWUE compared to other treatments (Table 2). Our results therefore suggest that savings of irrigation water as high as 70%, compared to traditional practice, is achievable in the Mediterranean countries if growers adopt the PRD practice.

There was a profound effect of irrigation water quantity on mandarin fruit size (Figure 2). The highest fruit size, with respect to weight and diameter of the fruit, was obtained under TR and FULL irrigations, which were followed by the treatments of 1PRD30 and 1PRD50 (Table 3). Effect of irrigation treatments on annual enlargement of the tree-trunk perimeter was nearly the same as the effects on fruit size, and the largest enlargement was noted under TR, which was followed by FULL, 1PRD30 and 1PRD50 treatments. The conventional DI and 2PRD50 had the smallest enlargement (Table 3).

Leaf-water-potential measurements under DI50 followed closely the measurements under FULL treatment until noon, irrespective of whether it was before or after irrigation (Figure 3). The measurements under the PRD effect were continually lower than both the conventional DI and the FULL treatments (Figure 3).

Discussion

The fruit-yield reduction under FULL treatment was not significant ($P > 0.05$) compared to traditional practice of irrigation (TR), which received as high as 2.7 times more water (Table 2). The results simply show that the citrus growers apply excess irrigation water, most probably because of rather low or nearly free cost of irrigation water in the area. However the question of our interest was why the PRD irrigation with 30% reduced irrigation water application (1PRD30) compared to FULL irrigation would give only marginal and non-significant ($P > 0.05$) fruit-yield reduction. Davies et al. (2000) attributed this effect to redirecting of assimilates, which would have partitioned for vegetative growth, to fruits under PRD practice, compared to treatments of high water application. The earlier works by Zhang and Davies (1990, 1991), Bacon et al. (1998) and many others demonstrated that the responsible mechanism was root-to-shoot signalling, which prevented luxury transpiration and optimised water use when half of the roots are

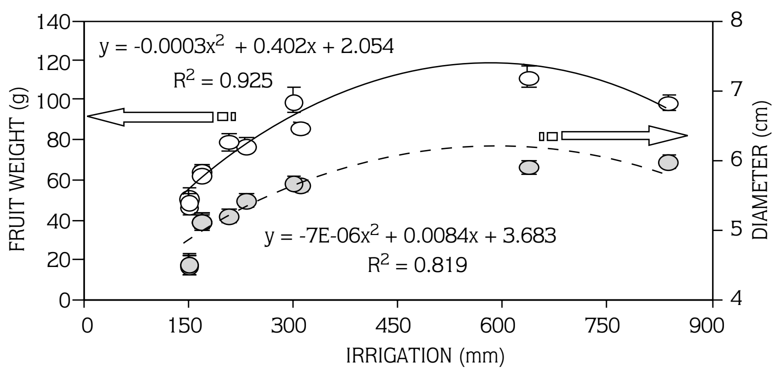

Figure 2. Mandarin fruit size dependence on irrigation water quantity. The trend lines are fitted to the pooled two-year data of 2001 and 2002. Data points are means (n = 16) ± SE.

Table 3. Fruit yield attributes[a]. Data represent means (n = 16) ± SE.

Treatments*	2001		2002		
	Fruit weight (g fruit^{-1})	Fruit diameter (cm)	Fruit weight (g fruit^{-1})	Fruit diameter (cm)	Annual trunk perimeter growth cm
TR	98.8 ± 3.9 a	5.97 ± 0.10 a	111.7 ± 5.7 a	5.90 ± 0.11 a	3.33 ± 0.14 a
FULL	86.2 ± 2.6 ab	5.63 ± 0.09 ab	99.7 ± 6.3 a	5.67 ± 0.08 ab	2.92 ± 0.12 a
1PRD30	77.1 ± 3.9 bc	5.43 ± 0.10 bc	78.9 ± 4.8 b	5.20 ± 0.10 b	1.87 ± 0.20 b
1PRD50	63.8 ± 3.9 c	5.12 ± 0.11 c	50.5 ± 4.9 c	4.48 ± 0.15 c	1.78 ± 0.39 b
DI50	63.6 ± 2.9 c	5.10 ± 0.10 c	46.4 ± 4.0 c	4.51 ± 0.11 c	1.53 ± 0.07 b
2PRD50	62.5 ± 4.3 c	5.12 ± 0.11 c	48.7 ± 4.5 c	4.50 ± 0.15 c	1.53 ± 0.33 b
Tukey's HSD	15.0	0.48	19.7	0.41	1.05

[a] Rows of data within a column followed with different letters are significantly different (P = 0.05) based on Tukey's mean range test.

*TR: traditional farmers' method of irrigation
FULL: full amount of irrigation water applied
1PRD30 and 1PRD50: 30 and 50% reduced amount of irrigation water were applied, respectively;
DI50: conventional deficit irrigation where 50% reduced amount of irrigation water, compared to FULL irrigation, was applied
2PRD50: 50% reduced amount of irrigation water was applied

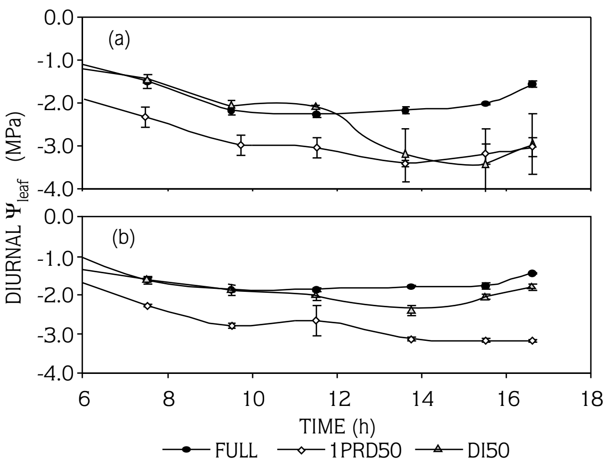

Figure 3. Diurnal leaf water potential of mandarin trees toward the end of irrigation season (a) before and (b) after irrigation on 4 and 6 October 2002. Data points are means (n = 8) ± SE. For abbreviations see the legend of Table 2.

exposed to partial drying. A laboratory work by Zekri and Parsons (1990) further showed that citrus trees can survive water stress if the stress influences roots non-uniformly as was the case under PRD treatments, compared to conventional DI. Supporting their work, the fruit yield under DI50, receiving the same amount of irrigation water as 1PRD50, was reduced the most (Table 2), although not significantly. Response of citrus trees to PRD was therefore very much like field crops (e.g., Kirda et al., 2005) which gave only marginal yield benefit if the deficit irrigation was imposed through the PRD practice, compared against conventional DI. Although the conventional deficit irrigation (DI50), where the roots were exposed uniformly to the same level of water deficit, fell in the low fruit-yield-group treatments (Table 2), both deficit practices (PRD & DI) were equally effective in saving irrigation water.

Works by Mills et al. (1999) and Ortuno et al. (2004) showed that a strong association exists between leaf water potential (LWP) and stomatal conductance in citrus trees such that the higher is the LWP, the higher is the stomatal conductance. Although we had no data on stomatal conductance, the similarity of diurnal-LWP measurements of DI50 in the morning to FULL irrigation (Figure 3) suggests that stomatal conductance of the trees under conventional DI was same as under FULL irrigation. One can assume therefore that the trees under conventional DI continued transpiring until noon at the same rate as FULL irrigation, irrespective of whether it was before or after irrigation. High evaporative demand in the afternoon caused lowering of LWP (Figure 3) under DI50 following most likely closure of stomata. The trees under PRD effect (both 1PRD50 and 2PRD50) had continually lower LWP compared to FULL irrigation (Figure 3) and therefore one should expect reduced transpiration rate under PRD effect as observed in Table 2. Because of short irrigation interval of 3 to 4 days, small differences in water usage, described with LWP measurements alone as noted under PRD and conventional DI, were not reflected in fruit yields. There are numerous work documenting the existence of root-to-shoot signalling, regulating crop water use of annual crops, through stomatal control (e.g., Zhang and Davies, 1991; Gowing et al., 1993; Bacon et al., 1998; Auge and Moore, 2002). The data availed with this work, however, could not lead to solid conclusions, regarding if root-to-shoot signalling exists and how it works with the tree crops. Future studies should address what likely mechanisms, if they exist, are in operation for controlling root-to-shoot signalling in tree crops under water stress.

Although it was not significant, a 6% to 16% yield reduction was evident if the irrigated side of the roots was interchanged every other irrigation instead of every irrigation (i.e. 1PRD versus 2PRD) (Table 2). The reason might be that if the root-to-shoot signalling was indeed operative, 1-week drying period of one half side of the roots, as was the case under 2PRD50, was too long and might have caused suberisation of root epidermis and loss of secondary roots (North and Nobel, 1991), which prevented regeneration of active roots when re-wetted (Asseng et al., 1998).

The lowest IWUE (kg $ha^{-1}mm^{-1}$) was achieved under the traditional (TR) irrigation (Table 2). All other tested treatments fell in the same statistical group, and the differences observed in IWUE were not statistically significant ($P > 0.05$). The PRD treatments with 30% and 50% less irrigation water applications (i.e. 1PRD30, 1PRD50) gave comparatively higher IWUE than the traditional irrigation treatment (Table 2). Our results therefore suggest that irrigation water requirements of citrus plantations can easily be reduced by 30% to 50% of traditional farmers' method of irrigation, without significant yield reduction in the Mediterranean countries if the PRD practices are adopted.

Although yield decrease was marginal under PRD practice compared to treatments of high water application (i.e. TR and FULL), it was accompanied by a decreasing trend in fruit weight and size (Table 3), which increased with irrigation water application. Fruit-size increase was achieved up to 400 to 450 mm of irrigation water application (Figure 2) during 5 months of irrigation season, from early June to late October. Irrigation water application more than 450 mm had no effect on both fruit yield (Table 2) and fruit size (Figure 2). The results were consistent with the work by Sepaskhah and Kashefipour (1994), who found that fruit weight increased with higher water application.

Conclusions

This study showed that amount of irrigation water commonly applied under farmers' practice of irrigation in citrus orchards where irrigation scheduling and water requirement were based on empirical and visual assessment of the orchards was higher than actually needed. While recommended irrigation water requirement is 60% to 75% of class-A pan evaporation, farmers apply nearly double that amount. If there is scarcity of water resources in a given region and means are sought to overcome the problem, stopping farmers' habit of excess water application is a primary necessity. Additional savings of irrigation water can be achieved if the deficit-irrigation practices are adopted. No yield advantages of the PRD practice over conventional DI could be demonstrated with the present two-year work. When PRD irrigation was applied using 30% less water than the actual water requirement (60% of class-A pan evaporation, with 50% canopy adjustment), mandarin yield was not significantly reduced ($P > 0.05$). A further reduction of irrigation water caused inferior fruit quality with a reduction in size and weight. While the lowest IWUE was recorded under traditional farmers' practice of irrigation, the IWUE under deficit treatments, PRD or conventional DI, was comparatively higher than FULL irrigation. Fruit weight and size was strongly correlated with quantity of irrigation water applied. Thus, the deficit irrigation, either through PRD or conventional DI, must consider and balance savings of water and depreciation of marketable fruit quality.

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