Deficit Irrigation as a Strategy in Irrigating Citrus Tree Plantings Under Water Scarcity Conditions

Mohamed El-Otmani, Fatima Alahian, Charif Azrof, Chouaibi Anouar, and Redouane Choukrallah

Abstract

Citrus is a major fruit crop produced (on 120,000 ha) and exported from Morocco, consuming 10,000 m^3 of irrigation water per ha annually. Currently, irrigation water is becoming very scarce, and drip irrigation is the water supply system used in plantings because of its high water use efficiency and productivity. Recent research indicates that additional water saving and higher efficiency can be obtained via adoption of deficit irrigation strategies such as sustained deficit irrigation (SDI), regulated deficit irrigation (RDI), and partial root zone drying (PRD). These irrigation strategies were applied on citrus clementine (*Citrus reticulata*) plantings for two years at different tree phonological stages. Four cultivars were included: 'Sidi Aissa' and 'Orogrande' in 2017 and 'Bruno', and 'Esbal' in 2018. Results indicate that water saving was in the range of 6 to 31% compared to control fully irrigated plantings depending on the strategy. However, deficit irrigation reduced fruit size, yield, and vegetative growth but enhanced fruit quality with PRD treatments having more significant effect than SDI or RDI. The negative effect of water deficit stress was more pronounced on total yield than on fruit size, particularly in high vapor pressure deficit (VPD) years and for PRD strategy. Under years of mild VPD, this negative effect was significant but equal for fruit size and yield. Water productivity decreased with water amounts applied. However, since clementine fruit is destined to fresh market which demands fruit of large size, it can be safe to recommend use of RDI and avoid PRD under semi-arid conditions.

Keywords

Clementine mandarin • Deficit irrigation • Partial root zone drying • Yield • Fruit quality • Water saving • Water productivity

1 Introduction

In general, Morocco has a semi-arid climate, and agriculture is an important sector of the economy as it contributes 15% of GDP. Because of climate change with increasing global temperatures and decreasing annual precipitations, water is becoming scarce in many areas of the world where the resource used to be plentiful, particularly in arid and semi-arid regions of the globe (Fourouzani & Karami, 2011). With increasing urbanization and demand from industry, agriculture, and tourism, the situation may worsen by 2050 (de Wit & Stankiewicz, 2006; Godfray et al., 2010). Agriculture uses close to 80% of available freshwater resources, and this needs to be re-rationalized to satisfy the development needs of both agriculture itself and the other sectors of the economy for global and inclusive sustainable economic growth. Besides conventional water resources, non-conventional waters (such as treated wastewater, brackish water, and drainage water) can be part of the solution but not yet implemented in most countries (Allam & Allam, 2007) including Morocco. Therefore, smart water saving techniques should be developed to maintain efficient levels of crop production in all sectors. In agriculture and particularly in the fruit crop production sector, drip irrigation has been adopted for several decades as an efficient irrigation technique allowing for water saving per unit area and greater production per unit crop produced (Carr, 2012), but new and more efficient irrigation strategies have been or are being tested in several countries and on various crops from around the world to increase drought resistance and water productivity (Fereres et al., 2003; Khanna-Chopra & Singh, 2011; Chai et al.,

M. El-Otmani (✉) · F. Alahian · C. Azrof · C. Anouar · R. Choukrallah
Department of Horticulture, Institut Agronomique et Vétérinaire Hassan II, Complexe Horticole d'Agadir, 80150 Ait Melloul, Morocco

A. Al-Maktoumi et al. (eds.), *Water Resources in Arid Lands: Management and Sustainability*, Advances in Science, Technology & Innovation, https://doi.org/10.1007/978-3-030-67028-3_20

2016). These strategies include use of genotypes that have high water use efficiency (Condon et al., 2004; Khanna-Chopra & Singh, 2011) and irrigation management using deficit irrigation strategies (Ferreres et al., 2003). These strategies include regulated deficit irrigation (RDI) which consists of imposing water deficit only at certain crop development stages with little or no negative effect on crop yield or quality (Chalmers et al., 1981). Ferreres et al. (2003) indicated that several researchers have tried RDI on several crops, but the results were not always encouraging, and thus, adjustments are needed in relation to crop species, variety, stage of development, soil type, and climate parameters and evaporative demand. Another version of deficit irrigation is sustained deficit irrigation (SDI) which imposes somewhat mild stress on plants throughout the crop cycle by applying 80–85% of crop water needs with no or little effect on production (Goldhamer & Viveros, 2000; Abriquesta & Ayars, 2018). Partial root zone drying (PRD) has also been developed where water deficit is applied by alternating irrigation on each side of the plant (thus, half of the root zone is irrigated alternatively) in scheduled irrigation events although with conflicting results (Sepaskhah & Ahmadi, 2010).

Citrus is major fruit crop produced (with 120,000 ha) and exported from Morocco. It consumes about 10,000 m^3/ha. Under the Souss region of southwestern part of Morocco, a major citrus producing region in the country with 40,000 ha, clementine mandarins (*Citrus reticulata*) flower in the spring (March-mid-April) and fruit set in mid-April to May, whereas fruit enlargement occurs mainly during summer months (June–September) coinciding with period of high temperatures and low air humidity. Fruit maturation is mainly in August-mid-October with some variation according to the cultivar.

Under Spanish conditions, 'Clementina de Nules' mandarin tree response to RDI was reported to vary according to the phenological stage of application with reduced yield and fruit size and increased juice sugar and acid content when the water reduction was applied during the second half of fruit growth and early fruit maturation (Gonzaloz-Altozano & Castel, 1999, 2000). Garcia-Tejero et al. (2010) reported that, under RDI, 'Navelina' orange (Citrus sinensis) had reduced yield when the treatment was applied during flowering and fruit growth but not when it was applied during fruit maturation. Garcia-Tejero et al. (2011a) indicated that cultivars respond differently to deficit irrigation programs and that trees respond differently to the irrigation strategy applied. In particular, they reported that water saving using sustained deficit irrigation (deficit irrigation for a long period of time) caused more stress and reduced yield more than use of RDI (with much shorter period of water deficit) with supply of the same water amount. In addition, RDI allowed water saving but reduced crop yield over low frequency deficit irrigation. This was also confirmed by Nagaz et al. (2017) on 'Meski Maltaise' orange trees subjected to SDI (applying 25 and 50% less water than crop needs) throughout the crop cycle (May–December); reduced yield and fruit size resulted in reduced net income to the grower. However, fruit juice sugar content increased. Gasque et al. (2016) indicated that RDI applied to 'Navelina' orange during initial fruit enlargement phase had no effect on yield or yield provided that stem water potential (a stress indicator) did not surpass a threshold limit of −2.0 MPa.

PRD has been used with success on several fruit crops including grapes, pear, peach, olive, and apple (see Consoli et al., 2017 and the references therein). On citrus, Romero-Conde et al. (2014) indicated that water saving can be achieved with PRD if irrigation supply is properly applied. They also indicated that when PRD is used in the long term may result in severe water stress which can impair growth and physiological parameters. Consoli et al. (2017) reported that PRD supplying 50% of crop water needs to young orange trees with alternating irrigation between the two halves of the root zone at weekly interval increased water use efficiency (calculated as yield/(irrigation water + effective rainfall). This irrigation strategy reduced vegetative growth and individual fruit weight but had no effect on yield or fruit juice content. In an experiment using PRD and SDI (applying 50% of crop needs during fruit growth) on 'Valencia' orange trees, Mossad et al. (2020) reported that yield was not affected by PRD but was reduced by RDI. In addition, fruit juice sugar and acid content as well as juice and sugar productivity per unit of irrigation water were increased as a result of water restriction.

The objective of this paper is to report on the results of experimental research done on four clementine mandarin plantings using SDI, RDI, and PRD applied during the crop cycle of clementine trees grown under the semi-arid climate of the Souss valley of Morocco known for its water scarcity.

2 Materials and Methods

The experiments were done over two years with each year in a different commercial orchard near the city of Taroudant, Morocco. To characterize the climate of the crop season, weather data was obtained from the closest weather station to each of the two experimental fields.

First year experiment was performed during 2017 in a commercial orchard where two mid-early clementine cultivars (*Citrus reticulata* Blanco) were used: 'Sidi Aissa' grafted on 'Carrizo' citrange [*Citrus sinensis* L. (Osb.) × *Poncirus trifoliata* L. (Raf.)], and 'Orogrande' grafted on *Citrus volkameriana*. The trees were planted in 2011 on a sandy loam soil having a field capacity of 28%, a humidity at the permanent wilting point of 14%, a pH of 7.1, and an electric conductivity (EC) of 0.22 mmhos/cm.

Trees were planted at a spacing of 6 m × 2 m (giving a planting density of 833 trees/ha) and ferti-irrigated using two lines of drippers for each tree row. Drippers were 60 cm apart (i.e., 6.6 drippers/tree) with a flow rate of 4 l/h/dripper leading a system rainfall of 2.2 mm/h. Irrigation water had a pH of 6.9 and an EC of 0.22 mmhos/cm.

Irrigation regimes were based on growers' experience coupled with frequent observations of the general status of the tree leaves and of the soil humidity level using capacitive probes. After verifying the root depth of trees and lateral extent of the root system, the net maximum water dose was calculated giving a value of 3.2 mm, i.e., irrigation duration of 1 h 30 min using the irrigation system described above. This amount corresponds to the daily tree needs in the summer period which also correspond to the supply by the grower at that season. Water supply by the grower is based on duration of irrigation. This estimation is shown to be close to crop water needs (also known as crop evapotranspiration ETc) which was estimated using the formula:

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc} \quad (1)$$

where ETo is the reference evapotranspiration and is estimated using FAO Pennman–Monteith equation based on weather data from the closest meteorological station (Allen et al., 1998) and Kc is the crop cultural coefficient. Kc values varied with the season from 0.3 in the winter to 0.6 in the summer based on Doorenbos and Pruitt (1977). Water dosage was applied once a day in mid-morning between 9 and 11 am. In addition, trees received cultural practices that are optimal for the region.

Application of the irrigation strategies had begun on July 06, 2017, and lasted during the whole fruit growth and maturation stages (up to October 5, 2017) according to the specific characteristics described in Table 1.

Second year experiment used a commercial orchard planted in 2013 at tree spacing of 6 m × 3 m (leading a tree density of 555 trees/ha). 'Bruno' and 'Esbal' clementine selections (*Citrus reticulata*), respectively, grafted on *Citrus volkameriana* and *Citrus macrophylla* rootstocks were used. Water and fertilizer application was by drip irrigation using two drip lines per row of trees, one in each side of the row to cover half of the root zone on each side of the tree. Each tree has 15 drippers delivering 1 L/h each. The drippers are 40 cm apart on the line. The soil is sandy with 90% sand and 10% clay. Maximum active root concentration is in the upper 40 cm for the 'Bruno'/*Citrus volkameriana* and 50 cm for 'Esbal'/C. macrophylla (data not shown). Irrigation supply was done according to grower's strategy based on irrigation duration according to leaf water visual evaluation, soil humidity level, and water availability. To avoid water loss by percolation, irrigation dose was divided in two applications per day, one in mid-morning and one in early afternoon. Soil pH in the root zone is 8.0 for 'Bruno' and 8.5 for 'Esbal' planting. Irrigation water has a pH = 8.3 and salinity of 0.5 mmhos/cm. Trees received cultural practices (fertigation, pruning, pest and disease management, etc.) that are optimal for the region. Application of irrigation regimes started on February 01, 2018, and lasted the whole crop cycle. The specifications of each irrigation program are given in Table 2. The experimental design was a complete bloc with four replications (=blocs), and five trees/experimental unit were considered in the test.

For 2017 and 2018 crop cycles, parameters observed included:

- Crop yield: at harvest (on October 2 for 2017 and October 23 for 2018), total number of fruit per tree was obtained for five trees per irrigation strategy.
- Fruit size and juice content: at maturation, composite samples of ten fruit/tree/strategy were obtained for the above five trees. These samples were weighed, and their juice extracted and weighed.
- Fruit juice quality: for the above juice samples, total soluble solids content (TSS) was obtained using a temperature-adjusted laboratory refractometer. In addition, their total acidity (TA) was obtained using a 0.1 N sodium hydroxide solution. Consequently, their maturity index (MI) was calculated as the ratio TSS/TA.

Table 1 Irrigation regimes tested in the year 2017

Irrigation strategy	Specifications
*T*1 (control)	Grower's strategy: supply close to 100% ETc
*T*2 (RDI1)	regulated deficit irrigation with supply of 75% ETc from July 06 to October 05, 2017 (fruit growth to maturation)
*T*3 (PRD4)	Partial root zone drying (PRD) with 3–4 days alternating irrigation (supply of 50% ETc) between the two tree root system halves from July 06 to October 05, 2017
*T*4 (PRD7)	Partial root zone drying (PRD) with 7 days alternating irrigation (supply of 50% ETc) between the two tree root system halves from July 06 to October 05, 2017
*T*5 (RDI2)	Regulated deficit irrigation with supply of 50% crop water needs during fruit maturation (Sept 11–Oct 05, 2017)

Table 2 Irrigation regimes applied during the year 2018

Irrigation strategy	Characteristics of the strategy
*T*1 (control)	Supply of 100% grower's irrigation capacity (full irrigation)
*T*2 (SDI)	Sustained deficit irrigation with application of 73% of the full irrigation regime during the whole crop cycle (February 1–October)
*T*3 (RDI1)	Regulated deficit irrigation with application of 73% of the full irrigation regime during flowering and fruit set (February 1–April 30)
*T*4 (RDI2)	Regulated deficit irrigation with application of 73% of the full irrigation regime during fruit enlargement-to-maturation (August–October)
*T*5 (PRD)	Partial root zone drying applying 73% of full irrigation with one-day alternation between each root zone half during the crop cycle (February 1–October)

For 2018 crop cycle, in addition of the above, irrigation effect was also assessed on the following parameters:

- Flowering and fruit set: flower intensity and fruit set were evaluated using tagged shoots of summer 2017. Four shoots per tree and five trees per treatment were included in the study. Their number of nodes per shoot was counted (Table 3) and used as the base for estimating intensity of flowering and intensity of fruiting. Flowering was assessed by recording number of buds, number of flowers open, number of flowers at petal fall stage, and number of fruitlets set. Observations were recorded at weekly intervals starting on March 23, 2018.
- Fruit set was calculated as the ratio: [maximum number of fruits set/(maximum number of flower buds + open flowers produced)]
- Vegetative growth: Changes in vegetative growth with time were assessed using tagged 2018 spring shoots (born on the tagged 2017 summer shoots) for which shoot length was recorded at weekly intervals starting on May 09, 2018. Four tagged spring shoots per tree with five trees per treatment were used. Because of the heavy load of flowers on trees of 'Bruno,' this selection did not develop spring shoots and was thus excluded from this evaluation.
- Besides that, number of newly born summer shoots was also evaluated using the 2017 summer shoots as the base for calculating shoot development intensity. This parameter was evaluated on the 'Bruno' selection only (Table 4).

3 Results and Discussion

3.1 Characterization of the Climate for the years 2017 and 2018

The year 2017 crop cycle was characterized by temperatures in the range of 7–30 °C in the spring, 15–45 °C in the summer, and 15–35 °C in the fall. Average air relative humidity ranged between 30 and 70%. Thus, leaf vapor pressure deficit (VPD) was in the range of 0.5–3.0 kPa with peak readings of 3.5–5.2 kPa occurring in July and August but with very short durations, coinciding with fruit enlargement. In addition, rainfall was almost nil since there were only about 6 mm total that fell between March and May. However, reference evapotranspiration was in the range of 1.8–5.6 mm/day. These data indicate that the 2017 clementine crop year was very dry and that, except for the few days of heat in the summer, weather conditions were generally acceptable for citrus tree growth and development.

For the 2018 year of study, air temperature was mostly in the range of 4–25 °C in the winter, 10–30 °C in the spring, 18–36 °C in the summer, and these values lasted through the fall (data not shown). Maximum temperature rarely exceeded 38 °C except for 5 days total between mid-July and mid-August when it reached 43 °C. Temperatures in the range of 12–36 °C are reported to be optimal for citrus tree growth and development (INRA, 1968). In addition, minimum air relative humidity was mostly in the range of 30 to

Table 3 Characteristics of the 2017 summer shoots used in evaluating flower intensity and fruiting of trees in 2018

Irrigation strategy	Variety			
	'Bruno'		'Esbal'	
	Average shoot length (cm)	Average number of nodes/shoot	Average shoot length (cm)	Average number of nodes/shoot
*T*1	8.21	7.56	8.64	7.54
*T*2	8.68	7.67	7.55	7.60
*T*3 = *T*4	9.05	8.32	8.79	7.82

Table 4 Effect of irrigation strategy on flowering, fruiting, and vegetative growth of 'Bruno' and 'Esbal' clementine trees (2018 year crop)

Variety	Irrigation strategy	Maximum number of flower buds + open flowers/100 nodes of summer 2017 shoots (March 21, 2018	Maximum number of fruit set/100 nodes of summer-2017 shoots (April 18 and 25, respectively, for 'Bruno' and 'Esbal'	Fruit set (in % relative to total flowers)	Spring 2018 shoot length (cm/shoot)	Number of newly formed summer 2018 shoots/100 summer 2017 shoot nodes
'Bruno'	*T*1 (control)	163.5	80.7	49.4	–[z]	11.0a
	*T*2 (SDI)	164.0	91.8	55.5	–	7.6b
	*T*3 (RDI1)	170.0	107.6	63.0	–	12.2a
	*T*4 (RDI2)	–	–	–	–	–
	*T*5 (PRD)	180.5	86.4	47.9	–	5.5b
	Significance level	NS	NS	NS	–	5%
'Esbal'	*T*1 (control)	174.0	136.4	78.4	12.5	–
	*T*2 (SDI)	190.0	133.4	70.2	12.1	–
	*T*3 (RDI1)	177.0	118.5	66.9	11.9	–
	*T*4 (RDI2)	–	–	–	–	–
	*T*5 (PRD)	174.5	144.3	82.7	11.4	–
	Significance level	NS	NS	NS	NS	–

[z]Not evaluated

60%. Rainfall was 80 mm in February and 55 mm in March coinciding with flowering and 10 mm in September coinciding with end of fruit growth and initial fruit maturation. In addition, reference evapotranspiration rarely exceeded 7 mm/day (data not shown). These data gave leaf VPD values below 2.5 kPa reported to be the maximum limit for best growth and development conditions for citrus trees (Kriedmann, 1968).

Furthermore, in 2018, the main period of tree vegetative growth and that of flowering and fruit development was relatively dry with rainfall of 80, 55, and 10 mm, respectively, for the months of February, March, and September, indicating that the only stage where tree benefited from it was the flowering-early fruit set period (i.e., February–March). The period of fruit enlargement (May–August) was totally dry.

3.2 Flowering and Fruit Set

These parameters were evaluated in 2018 since irrigation strategies commenced in February which included flowering and fruit set, whereas in 2017, irrigation strategies begun only in July coinciding with fruit enlargement. Both 'Bruno' and 'Esbal' clementine cultivars had similar flower intensity with an average number of flower buds in the range of 163 to 180 flowers/100 nodes for 'Bruno' and 174–190 flowers/100 nodes for 'Esbal' (Table 4). Fruit set in numbers and in percent relative to number of flowers produced were generally greater for 'Esbal' compared to 'Bruno.' Furthermore, within cultivars, irrigation strategies, particularly SDI, RDI1, and PRD which were applied before flowering, had no effect on these parameters with greater numbers for 'Esbal.'

3.3 Vegetative Growth

This parameter was evaluated during the 2018 crop year since irrigation strategies that could affect it had begun prior to flowering and spring growth flush. Length of spring shoots was not statistically affected by irrigation strategies applied that could have any influence on this parameter (Table 4). However, influence on number of summer shoots produced was significant with lower numbers for trees receiving 73% of full irrigation whether water was supplied as SDI (*T*2) or as PRD regime (*T*5) with alternating irrigation supply between tree root zone halves at one-day interval (Table 4). Reduced vegetative growth as a result of water deficit application was reported by Consoli et al. (2017) using PRD and by Gonzalo-Altozano and Castel (1999), Perez-Perez et al. (2010) and Ballester et al. (2011) with RDI strategy on citrus trees.

3.4 Water Saving, Fruit Size, Crop Yield, and Water Use Efficiency

Although plantings used in 2017 were older (planted in 2011 vs. 2013) and had higher density (833 vs. 555 trees/ha) compared to those used in 2018, irrigation water needs for control trees were 6675 and 5555 m^3/ha, respectively (Tables 5 and 6). The difference is mainly due to the difference in the different agro-climatic conditions in the experimental years since the climatic conditions of the year 2018 (air temperatures and leaf VPD which were milder) were more adequate for good fruit set and growth than those of the year 2017 (see above). In comparison with fully irrigated trees, restricting water supply allowed water economy between 629 and 2054 m^3/ha in 2017 (Table 5) and between 338 and 1437 m^3/ha in 2018 (Table 6) depending on the strategy, with the lowest amounts for RDI and the greatest for PRD, whereas SDI had intermediate amounts.

In addition, under full irrigation regime, cultivar effect on yield is high (compare 19 tons/ha for 'Orogrande' to 15 tons/ha for 'Sidi Aissa' in 2017, and 22 tons/ha for 'Bruno' to 30 tons/ha for 'Esbal' in 2018). Year weather conditions seem to have a greater effect over other agronomic factors such as tree density (yield for 'Sidi Aissa' and 'Orogrande' planted at 833 trees/ha is less than that of 'Bruno' and 'Esbal' planted at 555 trees/ha).

Effect of deficit irrigation on fruit number, fruit size, total yield, and water use efficiency was evaluated on 2017 crop of 'Sidi Aissa' and 'Orogrande' (Table 5) and on 2018 crop of 'Bruno' and 'Esbal' (Table 6) clementine trees. Fruit number per tree was greater for 'Esbal' compared to 'Bruno' (Table 5) which is mainly due to the greater number of flowers and fruit set (Table 4). Fruit number per tree was statistically not affected by irrigation strategy except for 'Sidi Aissa' for which fruit number was lower for trees stressed during fruit enlargement indicating that at this phonological stage, this cultivar is sensitive to water shortage which may have had a thinning effect. Ballester et al. (2011) reported that under water shortage, fruit size is significantly more affected by tree water status than tree fruit number.

Fruit size was reduced for trees subjected to reduction in irrigation water supply during fruit enlargement regardless of the variety or whether or not the irrigation restriction was applied at an earlier stage of fruit development (Tables 5 and 6). RDI during fruit maturation only had no effect on either fruit size or yield.

Furthermore, correlations between water applied and fruit size (by weight) showed positive trend. In addition, 'Bruno' had the lowest correlation coefficient ($R^2 = 0.451$, indicating that 45% only of the variability in individual fruit weight is due to total water quantity applied) followed by 'Esbal' (with $R^2 = 0.758$), whereas 'Orogrande' had the greatest correlation coefficient ($R^2 = 0.971$) followed by 'Sidi Aissa' ($R^2 = 0.845$). This indicated that, overall, fruit size is more dependent on and sensitive to water supply under high VPD year (year 2017 with 'Sidi Aissa' and 'Orogrande'). Garcia-Tejero et al. (2012) reported that tree water status below a certain threshold will have a significant negative effect on fruit daily growth, thus on final fruit size.

Effect of water restriction on yield was more negative with PRD than with SDI or RDI (Tables 5 and 6). In fact,

Table 5 Effect of irrigation strategy on total water applied, fruit size, yield, and water use efficiency (WUE) for 'Sidi Aissa' and 'Orogrande' clementine mandarin (year 2017 crop)

Irrigation strategy	Quantity of water applied (m^3/ha)	'Sidi Aissa'				'Orogrande'			
		Average fruit number/tree	Average fruit weight (g/fruit)	Estimated yield (tons/ha)	WUE (kg/m^3)	Average fruit number/tree	Average fruit weight (g/fruit)	Estimated yield (tons/ha)	WUE (kg/m^3)
*T*1 (control)	6675	334a^Z	55.4a	15.5a	2.31	356a	66.4a	19.7a	2.94
*T*2 (RDI1)	5641 (1034; 15%)^Y	318b	53.6ab (−1.8; −3%)^X	14.2b (−1.3; −8%)^W	2.52	335a	64.3b (−2.1; −3%)^X	17.8a (−1.6; −8%)^W	3.18
*T*3 (PRD4)	4621 (2054; 31%)	295b	51.4b (−4.0; −7%)	12.7c (−2.8; −18%)	2.74	320a	61.4c (5.0; −7%)	16.4b (3.3; −17%)	3.54
*T*4 (PRD7)	4621 (2054; 31%)	279b	52.6b (−2.8; −5%)	12.2c (−3.3; −21%)	2.64	325a	60.7c (5.7; −8%)	16.4b (3.3; −17%)	3.55
*T*5 (RDI2)	6046 (629; 10%)	348a	55.7a (−0.3; 0%)	16.2a (+7.0; + 4%)	2.67	344a	65.5ab (9.0; −1%)	18.7a (1.0; −0.5%)	3.10

[Z]Within columns, values followed by the same letters are not significantly different (Tukey's test at 5% level)
[Y]Numbers within brackets: first number indicates amount of water savings and second number indicates percent saving compared to control

Table 6 Effect of irrigation strategy on total water applied, fruit size, yield, and water use efficiency (WUE) for 'Esbal' and 'Bruno' clementine mandarin (year 2018 crop)

Irrigation strategy	Quantity of water applied (m^3/ha)	'Bruno'				'Esbal'			
		Average fruit number/tree	Average fruit weight (g/fruit)	Estimated yield (tons/ha)	WUE (kg/m^3)	Average fruit number/tree	Average fruit weight (g/fruit)	Estimated yield (tons/ha)	WUE (kg/m^3)
*T*1 (control)	5555	760a[Z]	52.7a	22.2a	4.0	887a	61.3a	30.2a	5.8
*T*2 (SDI)	4118 (1437; 26%)[Y]	785a	45.8b (−6.9; −13%)[X]	19.3bc (−2.9; −13%)[W]	4.7	876a	53.1c (−8.2; −13%)[X]	25.8b (−4.4; −15%)[W]	6.3
*T*3 (RDI 1)	4951 (604; 11%)	756a	52.5a (−0.2; −0.4%)	22.0a (0.2; 1%)	4.5	885a	61.2a (−0.1; −0.1%)	30.0a (−0.2; −0.7%)	6.1
*T*4 (RDI2)	5217 (338; 6%)	793a	45.0b (−7.7; −15%)	19.8b (−2.4; −11%)	3.8	904a	56.9b (−4.4; −7%)	28.6ab (−1.6; −5%)	5.5
*T*5 (PRD1)	4118 (1437; 26%)	756a	43.0b (−9.7; −18%)	18.0c (−4.2; −19%)	4.4	881a	50.8c (−10.5; −17%)	24.8b (−5.4; −18%)	6.0

[Z]Within columns, values followed by the same letters are not significantly different (Tukey's test at 5% level)
[Y]Numbers within brackets: first number indicates amount of water savings and second number indicates percent saving compared to control

alternating irrigation between tree root zone sides had similar negative effect, with a yield reduction of 17–21% compared to full irrigation, regardless whether the alternation interval was seven days or even one day. RDI had less effect on yield (reduction between 0 and 11% with 'the greatest reduction for 'Bruno'), whereas SDI had an intermediate effect (13–15% reduction). Restricting water supply during fruit maturation only (RDI-2 treatment) had no effect on yield across the varieties, but water saving was very small (6–10% compared to control full irrigation).

Although the cultivars used during the two years of investigation are not the same from year-to-year, it is noteworthy that: (1) during a dry and hot year (2017), fruit yield seems to be more sensitive to water restrictions applied during fruit growth (with yield reductions between 8 and 21% for 'Sidi Aissa' and 8 and 17% for 'Orogrande) than fruit size itself (with reductions between 3 and 8% only) (Table 5); and (2) during a relatively mild year (2018), both fruit size and yield seem to be affected by irrigation water restrictions with the same degree (Table 6). This indicates that fruit yield suffers significantly more under water restrictions applied during fruit enlargement stage and high VPD. Effect of water restriction on yield and fruit size was reported to be dependent upon the phonological stage of application (Gonzalo-Altozano & Castel, 1999), rootstock genotype (Romero et al., 2006; Treeby et al., 2007), timing and severity of the degree of water deficit stress applied (Ferreres & Soriano, 2007; Ballester et al., 2011; Nagaz et al., 2017), and the variety genotype (Garcia-Tejero et al., 2011a; b).

Water productivity values for the 2018 crop were almost double those for the 2017 crop with the lowest values recorded for 'Sidi Aissa' regardless of the irrigation strategy. This is certainly the result of the greater stress conditions in 2017 as well as differences in terms of variety tolerance to stress with 'Sidi Aissa' being the most sensitive. Furthermore, correlation coefficients between the quantity of water applied and yield were positive for all varieties tested with correlation coefficients (R^2) values in the range 0.63 and 0.99. Increased water productivity as a result of deficit irrigation was reported by others (Nagaz et al., 2017) and Garcia-Tejero et al. (2011a, b) indicated that effect of water deficit on yield was closely related to irrigation strategy rather than to amount of irrigation water alone.

Furthermore, although no straight forward conclusion can be made for water productivity as related to irrigation strategy, it appears that it negatively correlates with water quantities applied with some differences among varieties (Table 7) which is in agreement with results of Consoli et al. (2017). In addition, at least 48% of the variability observed in water use efficiency (WUE) (R^2 = 0.482) is explained by water amounts applied.

3.5 Fruit Juice Content and Quality

Effect of irrigation treatments on fruit juice content and quality was evaluated on 'Sidi Aissa' and 'Orogrande' for the 2017 crop (Table 8) and on 'Bruno' and 'Esbal' clementine for the 2018 crop (Table 9).

Table 7 Linear and quadratic relationships between water amounts used and water use efficiency (with y in kg/m^3 and x in m^3)

Variety	Quadratic equation		Linear equation	
	Equation	R^2	Equation	R^2
'Bruno'	$y = -2 \times 10^{-7}x^2 + 0.0013x + 2.3292$	0.612	$y = -0.0004x + 6.3887$	0.600
'Esbal'	$y = 3 \times 10^{-8}x^2 - 0.0006x + 8.1063$	0.482	$y = -0.0003x + 7.4975$	0.482
'Orogrande'	$y = 5 \times 10^{-8}x^2 - 0.0009x + 6.4232$	0.998	$y = -0.0003x + 4.924$	0.989
'Sidi Aissa'	$y = -10^{-7}x^2 + 0.0010x + 0.1425$	0.703	$y = -0.0001x + 3.3756$	0.598

Table 8 Effect of irrigation strategy on fruit juice content, total soluble solids (TSS), and maturity index for 'Sidi Aissa' and 'Orogrande' clementine mandarin (year 2017 crop; date of observation: Oct 2, 2018)

Irrigation strategy	'Sidi Aissa'			'Orogrande'		
	Juice content (%)	TSS (%)	Maturity index	Juice content (%)	TSS (%)	Maturity index
T1 (control)	51.7a[z]	10.5c	7.7c	49.7a	11.2b	9.8c
T2 (RDI1)	48.8ab	10.8ab	8.5ab	49.4a	11.6ab	10.3ab
T3 (PRD4)	46.7b	10.9ab	8.8a	45.9b	11.7a	10.4a
T4 (PRD7)	46.3b	11.0a	8.8a	46.8b	11.7a	10.5a
T5 (RDI2)	49.3ab	10.7bc	8.3b	48.8a	11.5b	10.0bc

[Z]Within columns, values followed by the same letters are not significantly different (Tukey's test at 5% level)

Table 9 Effect of irrigation strategy on fruit juice content, total soluble solids (TSS), and maturity index for 'Bruno' and 'Esbal' clementine (year 2018 crop; Sept 28, 2018)

Irrigation strategy	'Bruno'			'Esbal'		
	Juice content (%)	TSS (%)	Maturity index	Juice content (%)	TSS (%)	Maturity index
T1 (control)	53.3a[z]	10.2b	11.9b	53.0a	9.6b	10.7b
T2 (SDI)	51.1a	11.2a	12.1a	51.3ab	11.2a	12.2a
T3 (RDI 1)	52.5a	10.5b	11.5b	53.5a	9.8b	10.7b
T4 (RDI2)	53.3a	11.1a	11.8b	49.7b	11.0a	11.8ab
T5 (PRD1)	51.9a	11.4a	12.1a	50.4b	11.4a	12.2a

[Z]Within columns, values followed by the same letters are not significantly different (Tukey's test at 5% level)

Restricting water supply to clementine trees tended to reduce fruit juice content, but the degree of this reduction was cultivar and irrigation strategy dependent (Tables 8 and 9). In fact, PRD strategy had the greatest reduction effect compared to control full irrigation, and 'Bruno' and 'Orogrande' were less sensitive than the other two selections. Mossad et al. (2020) reported reduced fruit size and juice content for 'Valencia' orange fruit from trees under SDI (supplying 50% ETc) but not under PRD (supplying 50% ETc).

However, deficit irrigation treatments all had a significant increase effect on juice total soluble solids content which is an indicator of sugar concentration in fruit juice (Tables 8 and 9). This increase was more evident in fruit of PRD trees regardless of the irrigation alternation interval between tree root zone halves. In addition, this increase had a significant positive effect on fruit maturity index indicating an enhancement of fruit maturation as a result of water stress application. SDI and RDI treatments had an intermediate effect between control trees receiving full irrigation and PRD treatment. Increased fruit juice sugars as a result of deficit irrigation were reported by Treeby et al. (2007) and Nagaz et al. (2017). In addition, juice and sugar productivity per unit of irrigation water was increased as a result of water restriction (Nagaz et al., 2017). Mossad et al. (2020) reported an increase in juice sugar content as well as fruit, juice, and sugar productivity per unit irrigation water for PRD and SDI.

4 Conclusions

Taken together, the results indicate that: (1) there is a significant cultivar and/or year effect of the response of trees to deficit stress; (2) reduced water application reduced water supply but reduced fruit size and yield with the latter being more sensitive than the former particularly during the year of high VPD year; (3) RDI had less of an effect (particularly if applied during the fruit maturation stage only), SDI had a more pronounced effect, and PRD had a severe effect; (4) deficit irrigation increased fruit sugar content, thus improving fruit quality; (5) retaining water effect on fruit juiciness is cultivar- and irrigation strategy-dependent with the general trend that PRD reduces fruit juice content; (6) water restriction reduced vegetative growth which can be an advantage in that it should reduce pruning costs.

Enhanced quality can also be considered an advantage in that it can lead to earlier harvest time than usual which can be a comparative advantage in the market place particularly since clementine cultivars are the first citrus fruit in the market in the beginning of the citrus fruit season, and thus, earliness can bring better prices to the grower. Whether the amount of water saved, the degree of earliness in fruit maturation and potential reduction in pruning costs will offset the cost of reduced fruit size and yield, particularly for irrigation strategies with high amounts of water savings, which remains to be elucidated.

It is noteworthy that fruit of the clementine mandarin grown in the Mediterranean is mainly geared toward fresh fruit export and that fruit size matters as large fruit procures higher prices in the market place. In addition, for arid and semi-arid regions, under water scarcity conditions and very dry years, reducing water supply may be the only alternative to the citrus growers particularly under climate change and adverse climate events to ensure sustainability of the production system. It can thus be recommended to avoid using PRD strategy as it negatively affects both fruit size and yield and that RDI can be a safer strategy to adopt when water is scarce.

References

Abriquesta, I., & Ayars, J. E. (2018). Effect of alternative irrigation strategies on yield and quality of Fiesta raisingrapes grown in California. *Water, 10*, 583. https://doi.org/10.3390/w10050583

Allam, M. N., & Allam, G. I. (2007). Water resources in Egypt: Future challenges and opportunities. *International Water Resources Association—International Water, 32,* 205–218.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*. Rome: FAO

Ballester, C., Castel, J., Introgliolo, D. S., & Castel, J. R. (2011). Response of Clementina de Nules citrus trees to summer deficit irrigation. Yield components and fruit composition. *Agricultural Water Management, 98,* 1027–1032.

Carr, M. K. V. (2012). The water relations and irrigation requirements of citrus (Citrus spp.): A review. *Experimental Agriculture, 48,* 347–377.

Chai, Q., Gan, Y., Zhao, C., Hui-Lian, Xu., Waskom, R. M., Niu, Y., & Siddique, K. H. M. (2016). Regulated deficit irrigation for crop production under drought stress: A review. *Agronomy for Sustainable Development, 36,* 3. https://doi.org/10.1007/s13593-015-0338-6.

Chalmers, D. J., Mitchell, P. D., van Heek, L. (1981). Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. *Journal of the American Society for Horticultural Science, 106*, 307–312

Condon, A. G., Richards, R. A., Rebetzke, G. J., & Farquhar, G. D. (2004). Breeding for high water-use efficiency. *Journal of Experimental Botany, 55,* 2447–2460.

Consoli, S., Stagno, F., Vanella, D., Boaga, J., Cassiani, G., & Raccuzzo, G. (2017). Partial root-zone drying irrigation in orange orchards: Effects on water use and crop production characteristics. *European Journal of Agronomy, 82,* 190–202.

de Wit, M., & J. and Stankiewicz. 2006. Changes in water supply across Africa with predicted climate change. *Science, 31*(311), 1917–1921. https://doi.org/10.1126/science.1119929

Doorenbos, J., Pruitt, W. O. (1977). *Crop water requirements. Irrigation and Drainage*. Paper no: 24. Rome, Italy: FAO.

Ferreres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany, 58,* 147–159.

Ferreres, E., Goldhamer, D. A., & Parsons, L. R. (2003). Irrigation water management of horticultural crops. *HortScience, 38,* 1036–1042.

Fourouzani, M., & Karami, E. (2011). Agricultural water poverty index and sustainability. *Agronomy for Sustainable Development, 31,* 415–432. https://doi.org/10.1051/agro/2010026.

Garcia-Tejero, I., Jimenez-Bocanegra, J. A., Duran-Zuazo, V. H., Romero, V. R., & Muriel-Fernandez, J. L. (2010). Positive impact of deficit irrigation on physiological response and fruit yield in citrus orchards: Implication for sustainable water savings. *Journal of Agricultural Science and Technology, 4,* 38–44.

Garcia-Tejero, I., Duran-Zuazo, V. H., Jimenez-Bocanegra, J. A., & Muriel-Fernandez, J. L. (2011a). Improved water use efficiency by deficit irrigation programmes : Implications for saving water in citrus orchards. *Scientia Horticulturae, 128,* 274–282.

Garcia-Tejero, I., Duran-Zuazo, V. H., Jimenez-Bocanegra, J. A., & Muriel-Fernandez, J. L. (2011b). Improved water-use efficiency by deficit irrigation programmes: Implications for saving water in citrus orchards. *Scientia Horticulturae, 128,* 274–282.

Garcia-Tejero, I. F., Duran-Zuazo, V. H., Arriaga, J., & Muriel-Fernandez, J. L. (2012). Relationshipsbetweentrunk- and fruit-diametergrowthsunderdeficit irrigation programmes in orange trees. *Scientia Horticulturae, 133,* 64–71.

Gasque, M. P., Marti, B. G., & Gonzalez-Altozano, P. (2016). Effects of long-term summer deficit irrigation on 'Navelina ' citrus trees. *Agricultural Water Management, 169,* 140–147.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., et al. (2010). Food security: The challenge of feeding 9 billion people. *Science, 327,* 812–818. https://doi.org/10.1111/j.1439-037X.2009.00411.x.

Goldhamer, D. A., & Viveros, M. (2000). Effects of preharvest irrigation cutoff durationsand postharvest water deprivation on almonds tree performance. *Irrigation Science, 19,* 125–131.

González-Altozano, P., & Castel, J. R. (1999). Regulated deficit irrigation in 'Clementina de Nules' citrus trees. I. Yield and fruit quality effects. *The Journal of Horticultural Science and Biotechnology, 74*, 706–713

González-Altozano, P., & Castel, J. R. (2000). Effects of regulated deficit irrigation on 'Clementina de Nules' citrus trees growth, yield and fruit quality. *Acta Horticulturae, 537,* 749–758.

INRA. (1968). *Les Agrumes au Maroc. Collection Technique et Production Agricoles*. Institut National de la Recherche Agronomique, Rabat, Morocco.

Khanna-Chopra, R., & Singh, S. (2011). Approaches to increase water use efficiency in horticultural and grain crops—An overview. *Plant Stress, 5,* 52–63.

Kriedmann, P. E. (1968). Some photosynthetic characteristics of citrus leaves. *The Australian Journal of Biological Sciences, 21,* 895–905.

Mossad, A., Farina, V., Lo Bianco, R. (2020). Fruit yield and quality of 'Valencia' orange trees under long-term partial rootzone drying. *Agronomy, 10*, 164. https://doi.org/10.3390/agronomy10020164

Nagaz, K., El Mokh, F., Ben Hassen, N., Masmoudi, M. M., Ben Mechlia, N., Baba Sy, M. O., Belkheiri, O., & Ghiglieri, G. (2017). Irrigation and Drainage. https://doi.org/10.1002/ird.2201

Perez-Perez, J. G. J., Garcia, J. M., & Robles and P. Botia. . (2010). Economic analysis of navel orange cv. Lane Late grown on two different drought-tolerant rootstocks under deficit irrigation in Southeastern Spain. *Agricultural Water Management, 97,* 157–164.

Romero-Conde, A., Kusakabe, A., & Melgar, J. C. (2014). Physiological responses of citrus to partial rootzone drying irrigation. *Scientia Horticulturae, 169,* 234–238.

Romero, P., Navarro, J. F., Perez-Perez, J. G., Garcia-Sanchez, F., Gomez-Gomez, A., Porras, I., et al. (2006). Deficit irrigation and rootstock: Their effects on water relations, vegetative development, yield fruit quality and mineral nutrition of Clemenules mandarin. *Tree Physiology, 26,* 1537–1548.

Sepaskhah, A. R., & Ahmadi, S. H. (2010). A review on partial root-zone drying irrigation. *International Journal of Plant Prodution, 4,* 241–258.

Treeby, M. T., Henroid, R. E., Bevington, K. B., Milne, D. J., & Storey, R. (2007). Irrigation management and rootstock effects on navel orange [*Citrus sinensis* L. Osbeck] fruit quality. *Agricultural Water Management, 91,* 24–32.