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RESEARCH ARTICLE

YIELD AND FRUIT QUALITY OF ALMOND, PEACH AND PLUM UNDER REGULATED DEFICIT IRRIGATION

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KEYWORDS

fruit quality, fruit yield, *Prunus domestica*, *Prunus dulcis*, *Prunus persica*, regulated deficit irrigation

HIGHLIGHTS

- Regulated deficit irrigation was assessed in almond, peach and plum over 3 years.
- Fruit-growth slowdown stages are appropriate periods to apply deficit irrigation.
- Peach yields were unaffected under a regulated deficit irrigation of 75% ET_C.
- Regulated deficit irrigation of 50% ET_C maintained yields of almond and plum.
- Fruit quality improved under regulated deficit irrigation.

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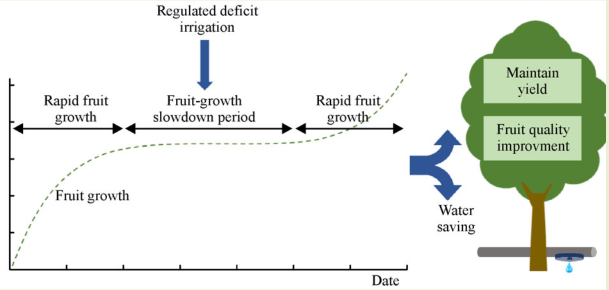
GRAPHICAL ABSTRACT



ABSTRACT

The effects of regulated deficit irrigation (RDI) on the performance of almond cv. Tuono, peach cv. JH-Hall and plum cv. Stanley were assessed on the Saiss Plain (NW, Morocco) over three consecutive growing seasons (2011–2013). Irrigation treatments consisted of a control, irrigation applied to fully satisfy crop water requirements (100% ET_C), and two RDI treatments, irrigation applied to 75% ET_C (RDI-75) and 50% ET_C (RDI-50). These three treatments were applied during fruit-growth slowdown periods corresponding to Stages II and III in almond and Stage II in peach and plum. Yield and fruit quality traits were determined. The effect of RDI differed between species. Yield and fruit size were reduced significantly only in peach under RDI-50. Fruit quality improved in this species in the first year of the experiment, with an increase of sugar/acid ratio and polyphenol content. Plum quality also improved but the effects were significant only in the second and third years. Similar results were recorded in almond kernel, but their epidermal grooves were deeper under RDI-50, and this may have affected their commercial value. It is concluded that water can be saved during the fruit-growth slowdown period by up to 25% in peach and 50% in almond and plum with improvements in fruit quality without affecting total yield.

1 INTRODUCTION

In many areas, particularly in large parts of Morocco, water is a factor limiting agricultural production[1]. Irrigation must be managed economically for the rational use of water resources, especially in the case of crops with higher water requirements such as rosaceous trees[2]. One of the approaches recommended by Food and Agriculture Organization of the United Nations (FAO) in the medium term is regulated deficit irrigation (RDI), an irrigation strategy based on the application of only a fraction of the plant water requirements during certain periods of plant development[3]. The principles behind this approach are that the response of plants to water stress induced by RDI varies with growth stage and that water restrictions applied to plants at non-critical stages may not cause significant negative impacts on plant productivity, even though their normal growth may decline[4]. In the case of rosaceous trees such almond and peach, the fruit-growth slowdown periods are among the least sensitive stages to water stress and are generally characterized by pit hardening and little fruit growth[5,6]. To apply this approach, these periods must be determined in advance by the establishment of fruit growth curves that vary according to species, cultivar and environment[7,8]. RDI is commonly used in fruit trees to save irrigation water with a slight reduction in fruit yield or even without significant losses in yield[9]. Benefits of this technique on total yield have been demonstrated in several fruit species such as almond, apple, apricot, olive, pear and pistachio[10–15].

Yield is generally affected by water deficit and especially severe deficit[16] because it depends on the amount of assimilated carbon but the effects on fruit quality are more complex[17]. Indeed, fruit size and biochemical composition depend in part on carbon and nitrogen assimilation and partly on fruit growth (genetically determined) but are modulated by the environment[18]. A pre-flowering water deficit reduces the number of fruits but fruit size can remain stable or may even increase due to an enhancement of availability of assimilates to each fruit[19]. In this case, water deficit effects on fruit quality are limited. However, the consequences of a post-flowering water deficit are important. In general, the cell division stage that determines potential fruit size is more sensitive than the subsequent cell filling stage[20]. Other physiological and pathological changes are caused by water deficit during the post-flowering stage, including fruit cracking[21]. In addition, calcium deficiency, which is often related to water flow, produces morphological disorders that affect the commercial quality of fruit[22].

The effects of RDI on biochemical traits of fruit quality are inconsistent and differ with crop species or the quality attributes evaluated. Some investigations show that deficit irrigation during fruit growth might have a positive effect on fruit quality by improving fruit taste, associated with an increase in the content of soluble solids (SSC)[23]. RDI applied to peach during the late stages of fruit growth significantly increased the ratio of SSC to titratable acidity with a more reddish coloration of the fruit skin, representing a large improvement in fruit quality[24,25]. Water stress in plum imposed through RDI during the fruit growth period induced an improvement in fruit quality with increasing soluble solid, soluble sugar, phenolic compound and flavonoid contents associated with a decrease in total acidity[26]. Water stress imposed in almond through RDI substantially maintained kernel nutrition quality, especially regarding lipid and tocopherol contents[27]. In general, there is a consensus that RDI maintains or even improves fruit biochemical traits, but the challenge is to reach this goal while maintaining a satisfactory level of fruit physical attributes and yield level that are often affected, particularly under severe water deficit[28]. It is in this context that it is important to test RDI with different intensities during non-critical stages for fruit physical quality and tree yield, such as fruit-growth slowdown periods, while considering differences in terms of sensitivity of the cultivars and climatic conditions imposed by the ecosystem.

Physical properties of many fruit trees including almond, peach and plum are the quality attributes that are most attractive to both producers and consumers. These properties include weight, size, shape, color and firmness. Organoleptic quality attributes such as sugar content, acidity, aroma and flavor are also important to consumers. Studies in Morocco on the effects of RDI on fruit quality in almond, peach and plum have been limited. The adoption of the findings obtained in similar experiments conducted in other countries is not appropriate because the results are not conclusive, likely because of differences in experimental conditions and cultivars used. Studies on RDI must therefore consider production potential and physiological behavior of trees under local conditions. In this context, the present study was conducted to determine if deficit irrigation strategies might be used to save water without reducing yield and fruit quality in almond, peach and plum under Moroccan conditions. Two RDI treatments, moderate and severe, were applied during the fruit-growth slowdown periods (considered to be a non-critical stage) with water requirements being fully met during the other growth stages.

2 MATERIALS AND METHODS

2.1 Study site and plant material

The experiment was conducted over three consecutive years

(2011–2013) at the experimental station of the National Agricultural Research Institute (RARI) in Ain Taoujdate, located on the Saiss Plain (500 m asl). The soil texture is sandy-clay according to international standards[29], slightly calcareous, moderately rich in organic matter, phosphorus and potassium, and with a usable water reserve of 1.7 mm·cm^{-1} (Table 1). The climate of the region is semiarid Mediterranean with hot and dry summers. The annual average reference evapotranspiration (ET_0) was 1300 mm for the three years, calculated using the Hargreaves method[30], with 1100 mm during the growing season of almond, peach and plum (March–November) and total annual rainfall over the three years was 475, 394 and 396 mm, respectively. The monthly distribution of rainfall and ET_0 (Fig. 1) show that the rainfall deficit was more marked from May to September with a peak during July and August.

The plant material consisted of 15 trees of almond (*Prunus dulcis* cv. Tuono), peach (*Prunus persica* cv. JH-Hall) and plum (*Prunus domestica* cv. Stanley), planted in parallel rows in 2004 at 5 m × 3 m spacing and pruned to a goblet canopy shape. All trees received the same fertilization, namely 100 kg·ha^{-1} of N, 60 kg·ha^{-1} of P_2O_5 and 120 kg·ha^{-1} of K_2O. Pest control was used according to local commercial practice and weeds were fully controlled.

2.2 Irrigation treatments and experimental design

Crop water requirements (ET_C) were scheduled monthly according to daily ET_0 and the crop coefficients recommended by FAO, adjusted to tree canopy cover (Sc) using the reduction coefficient (Kr) recommended for almond trees expressed as Eq. (1)[31]. On rainy days this was considered the effective rainfall, equivalent to 80% of the recorded rainfall.

$$\mathrm{Kr} = \frac{2 \cdot \mathrm{Sc}}{100} \text{ with } \mathrm{Sc} = \frac{\pi \cdot D^2 \cdot N}{100} \qquad (1)$$

where D is the average of canopy cover diameters and N is the planting density.

The trees were drip-irrigated daily with two emitters per tree. The water applied was changed only during the fruit-growth slowdown periods of each species over three seasons (2011–2013) to give two RDI treatments, 50% ET_C (RDI-50) and 75% ET_C (RDI-75), and a control at 100% ET_C (Table 2). These periods were determined for each species under full irrigation (100% ET_C) by weekly monitoring of fruit diameter, on six fruiting branches, from the fruit set stage through to harvest over four seasons (2007–2010). In almond cv. Tuono the duration of the fruit-growth slowdown period was 4 months and 15 d from April 9 to fruit maturity in early September (0.02 mm·d^{-1} in

Table 1 Physical and chemical proprieties of the soil in the experimental orchard

Soil depth/cm	Clay/%	Silt/%	Sand/%	Organic matter/%	$CaCO_3$/%	P_2O_5/ppm	K_2O/ppm	pH	EC/(mS·cm^{-1})
0–35	43.0	10.2	46.8	2.51	3.0	73.36	458.87	7.30	0.10
35–70	37.6	16.1	46.3	1.58	3.1	15.12	222.48	8.06	0.07

Note: EC, electrical conductivity.

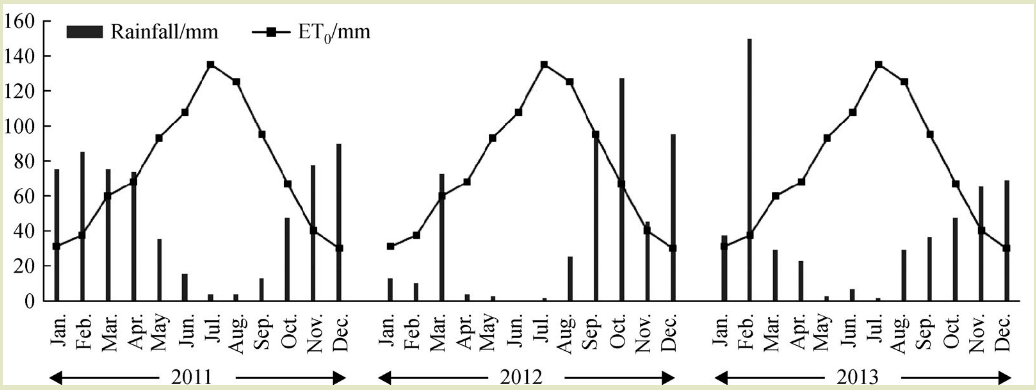


Fig. 1 Monthly rainfall and reference crop evapotranspiration calculated using the Hargreaves model in the experimental orchard over the three years of the study.

Table 2 RDI period and total applied water over the three years (2011–2013) in the control and the RDI treatments

Species	RDI application period[a]	Fruit growth[b]/(mm·d^{-1})	Total amount of irrigation per treatment/(m^3·ha^{-1})			
			Treatment	2011	2012	2013
Peach	May 16–June 1	0.45	Control	4064	4192	4622
			RDI-75	4004	4100	4529
			RDI-50	3944	4008	4436
Plum	May 25–July 1 July 16–harvest	0.18	Control	3810	3930	4340
			RDI-75	3190	3335	3687
			RDI-50	2570	2740	3034
Almond	April 19–harvest (September 4)	0.02	Control	3556	3668	4050
			RDI-75	2798	2817	3167
			RDI-50	2040	1966	2284

Note: [a] RDI period corresponds to the fruit-growth slowdown period; [b] daily growth rate of fruit diameter monitored during the fruit-growth slowdown period under full irrigation.

diameter) and in peach cv. JH-Hall it was over 15 d from May 16 to June 1 (0.45 mm·d^{-1}). However, in plum cv. Stanley two slowdown periods were observed; the first period corresponded to the pit hardening stage which took 35 d from May 25 to July 1 (0.18 mm·d^{-1}) and the second took 15 d from the first period until plum fruit maturity (0.005 mm·d^{-1})[32]. The experiment was laid out in completely randomized blocks each with three replicates of five trees. The three central trees from each replicate were used for measurement and the other trees acted as buffer plants.

2.3 Measurements

2.3.1 Yield and fruit physical parameters

Mature fruit samples, about 3 kg each, were collected from 10 randomly selected fruiting branches per replicate to evaluate the following physical parameters: fruit and pit weight, fruit and pit dimensions (length and width), and aspect of the epidermal grooves on almond kernel (number and relief). This method of fruit sampling was adopted because it takes into consideration fruit size variability within individual trees. The epidermal grooves of almond kernels were considered because they are a determinant of the physical quality of this fruit[33]. The relief of these grooves was assessed visually by an internal jury, assigning a qualitative score of 1 for low relief to 5 for the highest. After fruit sampling the remaining fruit was harvested manually and weighed in the field. The variability due to differences in tree vigor was minimized by determining yield values per cm^2 of trunk cross-sectional area (TCSA), estimated by measuring trunk circumference 40 cm above the soil surface.

2.3.2 Fruit chemical and biochemical properties

At harvest, 60 fruits per treatment (20 fruits per replicate) were randomly sampled for chemical quality assessment comprising pH, titratable acidity and sugar content (degrees Brix) in peach and plum pulp. In 2013, water content, soluble sugars, amino acids and polyphenols were determined in the three species, and kernel oil content was also determined in almond. Water content was determined by drying peach and plum pulps and almond kernels for 48 h at 80°C. Soluble sugars and amino acids were extracted by the method of Babu et al.[34] on 5 g of fruit ground in 10 mL of 80% ethanol, and concentrations were determined by spectrophotometry by the method of Dubois et al.[35] (sugars) and Yemm and Cooking[36] (amino acids). Polyphenols were extracted by grinding 5 g of fruit in concentrated methanol and analyzed by the method of Singleton and Rossi[37] using Folin-Ciocalteu reagent. Titratable acidity was determined in a sample of 5 g of pulp by the method of Lichou[38]. The pH of crushed pulp was measured directly with a pH meter. Degrees Brix were measured on drops of juice using a refractometer (Atago PAL-1, Atago Co., Ltd., Tokyo, Japan). Almond oil content was determined by magnetic resonance (NMR Oxford 4000, Oxford Instruments, Tubney Woods, Abingdon, Oxford, UK) on kernels previously ground and dried at 105°C for 48 h.

2.4 Statistical analysis

A weighted analysis of variance (ANOVA; statistical software IBM SPSS Statistics v. 19 for Windows) was used with normality of the data evaluated by Student *t*-test. The significance level was $P \leqslant 0.05$ unless otherwise stated.

3 RESULTS AND DISCUSSION

3.1 Yield and fruit physical quality

Fruit yields under RDI-75 were not statistically different from the control in any of the three species. Similarly, yields of almond and plum under RDI-50 did not differ from the control but peach in this treatment showed a significant decrease in yield (~35%) in each of the three years (Table 3). Total yields are affected by tree vigor and the yields were adjusted for TCSA to avoid this source of variability. After this adjustment the decrease in peach yield under RDI-50 was about 19%.

This reduction in peach yield was anticipated because other studies indicate similar negative RDI effects that are explained by a decrease in nutrient uptake and photosynthetic yield due to stomatal closure and reduction of the number of leaves, resulting from the decrease in shoot growth[16,39]. However, contrasting results have been reported from other studies, indicating that RDI applied to peach during Stage II did not affect fruit yield even under stress levels up to 35% ET_C[40,41]. These results have been explained by the low water requirements of peach trees during Stage II to satisfy normal fruit growth without accentuating their fall, thereby maintaining fruit yield. In some others studies, increased peach yields during RDI Stage II have been observed[42,43]. Mechanisms responsible for increasing fruit yield under RDI are not well understood. However, some workers explain this positive effect of RDI by stimulation of root development, making trees better equipped for the soil water deficit at later growth stages[44] or by a promotion of translocation of photosynthetic assimilates to the fruits to the detriment of shoot and leaf growth[45]. In almond the results were consistent with those from other studies[10,46] in which it was concluded that RDI caused a decrease in water content in almond kernels without significant effects on the mature weight, thereby maintaining yield levels. However, other studies indicate that almond yield decreased when trees received 30% less water than full irrigation[47,48]. Similar observations on plum have been made[49,50]. However, plum yields have also been found to increase with RDI application during Stage II[51]. These contradictory results may be due to differences in the cultivars used and soil properties (texture, depth and water holding capacity).

The recorded declines in peach yield under RDI-50 are largely linked to differences in fruit weight (Table 4) because the RDI treatment was applied after fruit set and there were no differences in physiologic fruit drop. Indeed, the significance of RDI effects on fruit weight was the same as that observed on fruit yield, with a significant reduction recorded only in peach (about 22%) under RDI-50 in each of the three years. The RDI effect on fruit yield was related to fruit growth rate during RDI application which was higher in peach (0.45 mm·d^{-1}), than in plum (0.18 mm·d^{-1}) or almond (0.02 mm·d^{-1}). According to this hypothesis the RDI effect on total yield can be extrapolated within a species and only in cultivars with a similar rate of fruit growth. In fact, the effect of water stress on peach during Stage II was more pronounced in cultivars in which this stage occurs over a longer time period with a substantial rate of fruit

Table 3 Yield and fruit weight of peach, almond and plum over the three years (2011–2013) in the control and the RDI treatments

Species	Treatment	Yield per tree/kg			Yield efficiency of TCSA/(kg·cm^{-2})			Fruit weight/g		
		2011	2012	2013	2011	2012	2013	2011	2012	2013
Peach	Control	28.3 a	19.8 a	24.0 a	0.14 a	0.09 a	0.12 a	118 a	123 a	121 a
	RDI-75	26.7 a	18.6 a	22.5 a	0.13 a	0.09 a	0.11 a	106 a	118 a	118 a
	RDI-50	16.7 b	13.6 b	16.1 b	0.10 b	0.08 b	0.10 b	90 b	96 b	97 b
	ANOVA	*	*	*	*	*	*	**	**	**
Plum	Control	33.9	21.9	32.0	0.22	0.14	0.21	38	40	37
	RDI-75	31.7	20.6	30.0	0.23	0.15	0.22	35	39	36
	RDI-50	30.1	19.5	28.5	0.22	0.14	0.20	35	36	36
	ANOVA	ns	ns	ns	ns	ns	ns	ns	ns	ns
Almond	Control	10.6	8.0	8.1	0.06	0.04	0.06	2.7	2.8	2.7
	RDI-75	10.0	7.6	7.7	0.05	0.04	0.05	2.6	2.7	2.6
	RDI-50	9.8	7.4	7.5	0.05	0.03	0.04	2.6	2.5	2.5
	ANOVA	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: Within each species, mean values within column/year followed by the same letter are not significantly different at $P = 0.05$ using the Student-Newman and Keuls test. ns, not significant; *, $P < 0.05$; and **, $P < 0.01$ by analysis of variance with complete randomized blocks.

growth[52]. Also, the observed reduction in peach weight exceeded its recorded growth rate during RDI application, thereby indicating that the water deficit effect persisted during the final stage of fruit growth (Stage III), despite the trees being fully irrigated during this stage. This may be due to a reduction in vegetative growth in response to RDI during Stage II that continued to affect photosynthate accumulation in the fruit during Stage III[40]. In addition, fruit weight reduction in peach resulted from simultaneous declines in fruit dimensions and pulp and pit weights, likely because there was no significant difference in the pit/fruit ratio. The weight reductions were not caused by a decrease in fruit water content which was unaffected by the treatments. In fact, previous work shows that water stress induced a decrease in fruit water content but this effect was quickly reversed after returning to full irrigation during the final phase of fruit growth[51].

Weight is an important criterion in fruit commercial quality assessment without necessarily describing high quality fruit as having a particular weight[53]. Generally, peach, fruit weight is described as desirable when it equates to a certain number of fruits per kg. According to a survey in Morocco (unpublished data) the optimum number varies from 7 to 11 fruits per kg in cultivars with potential fruit weights similar to those used in the present study. The recorded reduction in peach weight under RDI-50 does not therefore represent a production defect because it was no more than 11 fruits per kg, within the range of the most requested peach weights in the market.

It is also well known that epidermal grooves on almond kernels become more pronounced under water stress[54]. In the present study this effect was observed under RDI-50, producing a slight increase in relief of these epidermal grooves without a significant change in their number per kernel (Table 5). This change in the physical quality of almond kernels can affect their commercial value, but this may vary across markets and needs to be evaluated by consumer surveys.

3.2 Chemical and biochemical quality indices

Significant changes were recorded in chemical properties and biochemical composition of fruits in response to RDI. Under the RDI treatments 50% and 75% ET_C there was a significant increase in SSC associated with a decrease in amino acid content (AAC) (Table 6). In peach, SSC increased significantly under RDI-50 by about 14% compared to the control. AAC decreased in peach under both RDI treatments, about 15% (RDI-75) and 28% (RDI-50) in 2013. RDI-75 increased SSC in plum and

Table 4 Average values for three years (2011–2013) of weight and dimensions of peach and plum fruits in the control and the RDI treatments

Species	Treatment	Fruit weight/g	Fruit length/mm	Fruit width/mm	Pit weight/g	Weight ratio pit per fruit
Peach	Control	120.67 a	5.80 a	6.31 a	6.54 a	0.06
	RDI-75	114.00 a	5.68 a	5.87 a	6.07 a	0.06
	RDI-50	94.33 b	5.32 b	5.52 b	4.60 b	0.06
	ANOVA	**	**	**	**	ns
Plum	Control	38.33	5.20	3.58	2.09	0.06
	RDI-75	36.67	5.10	3.44	2.00	0.06
	RDI-50	35.67	5.06	3.46	1.78	0.06
	ANOVA	ns	ns	ns	ns	ns

Note: Within each species, mean values within each column followed by the same letter are not significantly different at $P = 0.05$ using the Student-Newman and Keuls test. ns, not significant; and **, $P < 0.01$ by analysis of variance with complete randomized blocks.

Table 5 Average values for the three years (2011–2013) of weight and dimensions of almond fruits in the control and the RDI treatments

Treatment	Nut weight/g	Nut length/mm	Nut width/mm	Kernel weight/g	Weight ratio Kernel/Nut	Epidermal grooves in kernels	
						Number per kernel	Relief[a]
Control	2.73	2.86	1.54	1.12	0.42	10.5	2.2 b
RDI-75	2.63	2.82	1.52	1.04	0.39	11.0	2.2 b
RDI-50	2.53	2.93	1.56	1.01	0.39	11.1	3.0 a
ANOVA	ns	ns	ns	ns	ns	ns	**

Note: Means within columns followed by the same letter are not significantly different at $P = 0.05$ using the Student-Newman and Keuls test. ns, not significant; and **, $P < 0.01$ by analysis of variance with complete randomized blocks. [a]Assessed visually by an internal jury, assigning a qualitative score from 1 to 5.

almond by about 6% and 10%, respectively, and by 10% and 15% under RDI-50. The RDI treatments resulted in similar decreases in AAC in plum and almond (13% and 6%, respectively). A decrease in AAC is to be expected with increasing SSC because amino acids are precursors in sugar biosynthesis[55]. The RDI treatments therefore increased the SSC/AAC ratio in fruits, giving them a sweeter taste. This effect was maximum in almond at twice the control value, and in peach the increases were about 30% under RDI-75 and 59% under RDI-50. Plum showed the smallest increases at about 20% under RDI-75 and 29% under RDI-50.

RDI treatments increased the sugar contents in peach and plum and this was associated with a decrease in titratable acidity and a slight rise in pH, with the effect of RDI-50 most pronounced (Table 7). Differences in these parameters in peach were significant from the first year of the experiment. The recorded increases in sugar content in peach under RDI-75 were similar in the three years with an average value of 1.3°Bx. Under RDI-50 the increase in sugar content in peach was the same as under RDI-75 in 2011 and 2012, but the increase was about 3.2°Bx in 2013. In contrast, the RDI effects in plum were significant only in the second (degrees Brix) and third (titratable acidity) years and

Table 6 Moisture, soluble sugar (SSC), amino acid (AAC) and polyphenol content in peach and plum pulp and almond kernels in the control and the RDI treatments in 2013

Species	Treatment	Moisture/%	SSC/(mg·g^{-1} dw)	AAC/(mg·g^{-1} dw)	Polyphenol/(mg per 100 g dw)	Ratio (SSC/AAC)
Peach	Control	82.5	390.7 c	29.2 a	513.4 c	13.38 c
	RDI-75	81.2	428.5 c	24.7 b	614.0 b	17.35 b
	RDI-50	80.1	444.4 a	20.9 c	905.4 a	21.26 a
	ANOVA	ns	**	*	*	*
Plum	Control	74.9	418.9 c	35.2 a	1477.1 c	11.90 c
	RDI-75	74.9	445.8 b	31.2 b	1869.5 b	14.29 b
	RDI-50	74.9	459.9 a	30.0 b	3099.0 a	15.33 a
	ANOVA	ns	*	*	**	*
Almond	Control	3.9	2.0 b	143.2 a	6.9 c	0.01 b
	RDI-75	3.9	2.2 ab	134.2 b	22.4 b	0.02 a
	RDI-50	3.9	2.3 a	134.8 b	54.4 a	0.02 a
	ANOVA	ns	*	*	**	*

Note: Within each species, mean values within a column followed by the same letter are not significantly different at $P = 0.05$ using the Student-Newman and Keuls test. ns, not significant; *, $P < 0.05$; and **, $P < 0.01$ by analysis of variance with complete randomized blocks.

Table 7 Sugar content (degrees Brix), titratable acidity and pH of peach and plum pulp in the control and the RDI treatments

Species	Treatment	Degrees Brix/°Bx			Titratable acidity (meq per 100 g fw)			pH		
		2011	2012	2013	2011	2012	2013	2011	2012	2013
Peach	Control	12.2 b	13.6 b	14.4 c	22.0 a	21.9 a	22.0 a	6.9 b	6.9 b	7.0 b
	RDI-75	13.5 a	15.1 a	15.6 b	20.0 b	19.9 b	19.5 b	7.1 a	7.1 a	7.2 a
	RDI-50	13.6 a	15.2 a	17.6 a	16.4 c	16.3 c	14.7 c	7.2 a	7.2 a	7.3 a
	ANOVA	**	**	**	**	**	**	*	*	*
Plum	Control	25.3	19.9 c	22.2 c	5.3	5.2	4.9 a	7.1	7.0	7.1
	RDI-75	24.6	21.5 b	24.0 b	4.8	4.7	4.5 a	6.6	6.8	6.7
	RDI-50	22.7	24.2 a	26.9 a	4.6	4.5	4.0 b	6.6	6.8	6.6
	ANOVA	ns	**	**	ns	ns	*	ns	ns	ns

Note: Within each species, mean values within a column/year followed by the same letter are not significantly different at $P = 0.05$ using the Student-Newman and Keuls test. ns, not significant; *, $P < 0.05$; and **, $P < 0.01$ by analysis of variance with complete randomized blocks.

there was no effect on pH. In 2012 and 2013, the increase in sugar content under RDI was higher in plum than in peach, with average values of 1.7°Bx under RDI-75 and 4.5°Bx under RDI-50.

RDI increased fruit polyphenol contents which are known for their nutritional and dietary value because of their antioxidant properties, and also in conferring an astringent taste to fruit[56]. RDI strongly increased polyphenols in almond kernels, especially under RDI-50 with eight times the control polyphenol content and three times under RDI-75. RDI increased the polyphenol contents in peach and plum by 20% and 27%, respectively, under RDI-75 and by 76% and 110% under RDI-50. The greater RDI effect on polyphenol content in almond kernels is likely to be linked to the longer period of RDI application than in peach and plum. In addition, RDI of peach and plum was achieved by full irrigation and this may have contributed to lower accumulation of phenolic compounds through aqueous dissolution[57].

These changes in chemical properties and biochemical composition of fruit induced by RDI have been reported previously in similar studies[51,57] but with quantitative differences due to different experimental conditions, RDI intensities and cultivars. Increased SSC in plum was found to be largely due to an enhancement of sucrose accumulation in the fruit and not because glucose and fructose concentrations decreased under RDI[26]. The higher accumulation of sucrose in fruit under RDI is likely related to an increase in starch hydrolysis and carbohydrate translocation from vegetative organs to the fruit under water stress conditions[58]. This is explained by the observation that under water stress the trees promote fruit growth by reducing the storage of carbon compounds in leaves[59]. However, some studies indicate that increased SSC and polyphenol content under water stress may be linked a decrease in fruit water content[54]. This explanation is not supported by the present study because the water contents of the fruit tested did not change with RDI. It has been shown in peach that fruit water content decreases during RDI application but this effect is gradually reversed after return to full irrigation[60]. This finding may explain the effect of RDI on SSC and polyphenol content in peach and plum, since they were fully irrigated during the final stages of fruit growth, which was not the case for almond. This indicates that RDI induced changes in metabolite biosynthesis and the translocation of metabolites that led to an increase in SSC and polyphenol content in fruit independently of fruit water content. It has also been shown that in various plants under water deficit the intercellular CO_2 concentration in leaves decreases in response to a decrease in stomatal conductance, while the photosynthetic capacity is maintained[61,62]. This decline in CO_2 may induce changes in gene expression, leading to the inhibition of some enzymes and activation of others, thereby affecting fruit quality without significantly changing fruit weight or water content[63,64]. Other studies have linked changes in fruit quality under RDI to early maturity of fruit because water stress produces a decrease in vegetative growth and therefore an increase in solar interception, making the fruits ripen faster[60]. This hypothesis may explain the results reported here as changes in fruit quality followed the normal evolution of fruit composition during the ripening stage. Although the effects of RDI on fruit quality have been increasingly documented in a range of plant species, the molecular and biochemical mechanisms involved remain to be determined.

RDI-50 significantly increased almond oil content by an average of 2.4% dw (Table 8). This considerable increase indicates that RDI may induce a significant increase in oil yield because total fruit yield was maintained. The effect of drought stress on the oil percentage in almond kernels is not reported. However, studies in other species show that water stress can increase oil content by improving the light environment for oil accumulation and hastening fruit maturity[65]. Trees growing under RDI had shorter branches than control trees (data not shown) and, although the light environment was not measured, these trees likely had a greater proportion of their fruits exposed to high irradiance, and this is likely to have contributed to the increased oil content. Other reports link maximizing fruit oil content to high irradiance[66].

Table 8 Oil contents in almond kernels, in the control and the RDI treatments in 2013

Treatment	Oil content (% dw)
Control	56.7 b
RDI-75	56.9 b
RDI-50	59.0 a
ANOVA	*

Note: Mean values followed by the same letter are not significantly different at $P = 0.05$ using the Student-Newman and Keuls test. *, $P < 0.05$ by analysis of variance with complete randomized blocks.

4 CONCLUSIONS

Over the three years of the study, peach yields were unaffected under an RDI of 75% ET_C applied during the fruit-growth slowdown period. In contrast, there was no significant effect on yields of plum or almond under an RDI of 50% ET_C. The physical attributes of fruit quality remained unaffected under the two RDI treatments, thereby making the tested RDI strategy a promising way to save water in these species. Also, some biochemical attributes of fruit quality such as the level of soluble sugars, sweetness/acidity ratio and polyphenol content were enhanced by RDI in these species, and in almond with an RDI of 50% ET_C the oil concentration increased substantially. However, a negative effect of RDI on fruit quality was recorded in almond kernels with a significant increase in the relief of their epidermal grooves under an RDI of 50% ET_C. This physical change in almond kernels may affect their commercial value but this may vary with end use and requires verification through consumer surveys.

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Compliance with ethics guidelines

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REFERENCES

1. Kurtze J, Morais M, Platko E, Thompson H. Advancing Water Management Strategies in Morocco. Rabat: *Ribat Al Fath Association for Sustainable Development*, 2015
2. Vaysse P, Soing P, Peyremorte P. Irrigation of fruit trees. Paris: *Interprofessional Technical Center for Fruits and Vegetables*, 1990
3. Goodwin I, Boland A M. Water Reports 22. Scheduling deficit irrigation of fruit tree for optimizing water use efficiency. Rome: *FAO*, 2002, 67–78
4. Capra A, Consoli S, Scicolone B. Deficit irrigation: theory and practice. In: Alonso D, Iglesias H J, eds. Agricultural Irrigation Research Progress. Hauppauge: *Nova Science Publishers*, 2008, 53–83
5. Kathleen M, Thomas W. Tree fruit Irrigation: a comprehensive manual of deciduous tree fruit irrigation needs. Wenatchee: *Good Fruit Growers*, 1994
6. Duncan R. The scoop on fruits and nuts in Stanislaus County: drought irrigation strategies for peaches and almonds. *Cooperative Extension of University of California*, 2014, **19**(1): 1– 3
7. Bretaudeau J, Faure Y. Atlas of fruit tree growing. Paris: *Techniques and Documentation*, 1991
8. Pinto C, Reginato G, Mesa K, Shinya P, Díaz M, Infante R. Monitoring the flesh softening and the ripening of peach during the last phase of growth on-tree. *HortScience*, 2016, **51**(8): 995–1000
9. Kriedemann P E, Goodwin I. Regulated deficit irrigation and partial rootzone drying. Canberra: *Land and Water Australia*, 2003
10. Goldhamer D A, Fereres E, Salinas M. Can almond trees directly dictate their irrigation needs. *California Agriculture*, 2003, **57**(4): 138–144
11. Ruiz-Sánchez M CTorrecillas A, Perez-Pastor A, Domingo R. Regulated deficit irrigation in apricot trees. *Acta Horticulturae*, 2000, **537**(537): 759–766
12. Ebel R C, Proebsting E L, Evans R G. Deficit irrigation to control vegetative growth in apple and monitoring fruit growth to schedule irrigation. *HortScience*, 1995, **30**(6): 1229–1232
13. Mitchell P D, Van Den Ende B, Jerie P H, Chalmers D J. Response of Bartlett pear to withholding irrigation, regulated deficit irrigation, and tree spacing. *Journal of the American Society for Horticultural Science*, 1989, **114**(1): 15–19
14. Goldhamer D A, Beede R H. Regulated deficit irrigation effects on yield, nut quality and water use efficiency of mature pistachio trees. *Journal of Horticultural Science & Biotechnology*, 2004, **79** (4): 538–545
15. Moriana A, Orgaz F, Pastor M, Fereres E. Yield responses of mature olive orchard to water deficits. *Journal of the American Society for Horticultural Science*, 2003, **123**(3): 425–431
16. Girona J, Mata M, Arbones A, Alegre S, Rufat J, Marsal J. Peach tree response to single and combined regulated deficit irrigation under shallow soils. *Journal of the American Society for Horticultural Science* , 2003, **128**(3): 432–440
17. Gelly M, Recasens I, Mata M, Arbones A, Rufat J, Girona J, Marsal J. Effects of water deficit during stage II of peach fruit development and postharvest on fruit quality and ethylene production. *Journal of Horticultural Science & Biotechnology*, 2003, **78**(3): 324–330
18. Lawlor D W. Carbon and nitrogen assimilation in relation to yield: mechanisms are the key to understanding production systems. *Journal of Experimental Botany*, 2002, **53**(370): 773–787
19. Fanwoua J, Bairam E, Delaire M, Buck-Sorlin G. The role of

branch architecture in assimilate production and partitioning: the example of apple (*Malus domestica*). *Frontiers of Plant Science*, 2014, **5**(338): 338

20. Ben Mechlia N, Ghrab M, Zitouna R, Ben Mimoun B, Masmoudi M. Cumulative effect over five years of deficit irrigation on peach yield and quality. *Acta Horticulturae*, 2002, **592**(42): 301–307
21. Jaroszewska A. Quality of fruit cherry, peach and plum cultivated under different water and fertilization regimes. *Journal of Elementology*, 2011, **16**(1): 51–58
22. Shah S T, Sajid M. Influence of calcium sources and concentrations on the quality and storage performance of peach. *Sarhad Journal of Agriculture*, 2017, **33**(4): 532–539
23. Gelly M, Recasens I, Girona J, Mata M, Arbones A, Rufat J, Marsal J. Effects of stage II and postharvest deficit irrigation on peach quality during maturation and after cold storage. *Journal of the Science of Food and Agriculture*, 2004, **84**(6): 561–568
24. Naor A. Irrigation scheduling of peach deficit irrigation at different phenological stages and water stress assessment. *Acta Horticulturae*, 2006, **713**(713): 339–349
25. Rahmati M, Vercambre G, Davarynejad G, Bannayan M, Azizi M, Génard M. Water scarcity conditions affect peach fruit size and polyphenol contents more severely than other fruit quality traits. *Journal of the Science of Food and Agriculture*, 2015, **95**(5): 1055–1065
26. Maatallah S, Guizani M, Hjlaoui H, Boughattas N, Lopez-Lauri F, Ennajeh M. Improvement of fruit quality by moderate water deficit in three plum cultivars (*Prunus salicina* L.) cultivated in a semi-arid region. *Fruits*, 2015, **70**(6): 325–332
27. Zhu Y, Taylor C, Sommer K, Wilkinson K, Wirthensohn M. Effect of deficit irrigation on almond kernel constituents. In: Proceedings of the International Symposium on Almonds and Pistachios 2014, VIth. Leuven. *Acta Horticulturae*, 2014, (1028): 221–223
28. Ripoll J, Urban L, Staudt M, Lopez-Lauri F, Bidel L P R, Bertin N. Water shortage and quality of fleshy fruits—making the most of the unavoidable. *Journal of Experimental Botany*, 2014, **65**(15): 4097–4117
29. Food and Agriculture Organization of the United Nations (FAO). Guidelines for soil description. 4th ed. Rome: *FAO*, 2006
30. Hargreaves G H. Defining and using reference evapotranspiration. *Journal of Irrigation and Drainage Engineering*, 1994, **120**(6): 1132–1139
31. Fereres E, Pruitt W O, Beutel J A, Henderson D W, Holzapfel E, Shulbach H, Uriu K. ET and drip irrigation scheduling. In: Fereres E, ed. Drip irrigation management. *University of California*, 21259, 1981, 8–13
32. Razouk R, Ibijbijen J, Kajji A, Karrou M. Response of peach, plum and almond to water restrictions applied during slowdown periods of fruit growth. *American Journal of Plant Sciences*, 2013, **4**(3): 561–570
33. Kodad O, Lebrigui L, El-Amrani L, Socias I, Company R. Physical fruit traits in Moroccan almond seedlings: quality aspects and post-harvest uses. *International Journal of Fruit Science*, 2015, **15**(1): 36–53
34. Babu S V, Shareef M M, Shetty A P, Shetty K T. HPLC method for amino acids profile in biological fluids and inborn metabolic disorders of aminoacidopathies. *Indian Journal of Clinical Biochemistry*, 2002, **17**(2): 7–26
35. Dubois F, Gilles X A, Hamilton J K, Rebecs P A, Smith F. Colorimetric method for determination of sugars and related substances. *Analytical Chemistry*, 1956, **28**(3): 350–356
36. Yemm E, Cooking W. Determination of amino acids with ninhydrin. *Analysis*, 1955, **80**(948): 209–213
37. Singleton V L, Rossi J A. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture*, 1965, **16**(3): 144–153
38. Lichou J. Apricot: varieties, instructions for use. Paris: *Interprofessional Technical Center for Fruits and Vegetables*, 1998
39. Goldhamer D, Salinas M, Crisosto C, Day K, Soler M, Moriana A. Effects of regulated deficit irrigation and partial root zone drying on late harvest peach tree performance. *Acta Horticulturae*, 2002, **592**(592): 343–350
40. Sotiropoulos T, Kalfountzos D, Aleksiou I, Kotsopoulos S, Koutinas N. Response of a clingstone peach cultivar to regulated deficit irrigation. *Scientia Agrícola*, 2010, **67**(2): 164–169
41. Boland A M, Jerie P H, Mitchell P D, Goodwin I, Connor D J. Long-term effects of restricted root volume and regulated deficit irrigation on peach: productivity and water use. *Journal of the American Society for Horticultural Science*, 2000, **125**(1): 143–148
42. Chalmers D J, Mitchell P D, Van Heek L. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. *Journal of the American Society for Horticultural Science*, 1981, **106**(3): 307–312
43. Mitchell P D, Chalmers D J. The effect of reduced water supply on peach tree growth and yields. *Journal of the American Society for Horticultural Science*, 1982, **107**: 853–856
44. Cui N B, Du T S, Li F S, Tong L, Kang S Z, Wang M X, Liu X Z, Li Z J. Response of vegetative growth and fruit development to regulated deficit irrigation at different growth stages of pear-jujube tree. *Agricultural Water Management*, 2009, **96**(8): 1237–1246
45. Du T S, Kang S Z, Zhang J H, Li F S. Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of north-west China. *Irrigation Science*, 2008, **26**(2): 147–159
46. Valverde M, Madrid R, Garcia A L. Effect of the irrigation regime, type of fertilization, and culture year on the physical proprieties of almond (cv. Guara). *Journal of Food Engineering*, 2006, **76**(4): 584–593
47. Girona J, Mata M, Marsal J. Regulated deficit irrigation during the kernel-filling period and optimal irrigation rates in almond. *Agricultural Water Management*, 2005, **75**(2): 152–167
48. Garcia-Tegero I F, Duran-Zuazo V H, Velez L M, Hernandez A, Salguero A, Muruel-Fernandez J L. Improving almond productivity under deficit irrigation in semiarid zones. *Open Agricul-*

ture Journal, 2011, **5**(1): 56–62

49. Battilani A. Regulated deficit of irrigation effects on growth and yield of plum tree. *Acta Horticulturae*, 2004, **664**(4): 55–62
50. Intrigliolo D S, Castel J R. Performance of various water stress indicators for prediction of fruit size response to deficit irrigation in plum. *Agricultural Water Management*, 2006, **83** (1–2): 173–180
51. Bruce D L, Kenneth A S, Stephen M S, Bill O, James T Y. Sensitivity of yield and fruit quality of french prune to water deprivation at different fruit growth stage. *Journal of the American Society for Horticultural Science*, 1995, **120**(2): 139–140
52. Hilaire C, Giauque P, Mathieu V, Soing P, Osaer A, Scandella D, Lichou J, Maillard F, Hutin C. The peach. Paris: *Interprofessional Technical Center for Fruits and Vegetables*, 2003
53. Plenet D, Simon S, Vercambre G, Lescourret F. Cropping systems in fruit tree growing and fruit quality. *Innovations Agronomiques*, 2010, **9**: 85–105
54. Grasselly C, Gall H. Pomological study of forty varieties of almond tree. *Technical Information Bulletin*, 1969, **241**: 507–521
55. Lombardo V A, Osorio S, Borsani J, Lauxmann M A, Bustamante C A, Budde C O, Andreo C S, Lara M V, Fernie A R, Drincovich M F. Metabolic profiling during peach fruit development and ripening reveals the metabolic networks that underpin each developmental stage. *Plant Physiology*, 2011, **157** (4): 1696–1710
56. Carbonaro M, Mattera M. Polyphenoloxidase activity and polyphenol levels in organically and conventionally grown peach (*Prunus persica* L., cv. Regina bianca) and pear (*Pyrus communis* L., cv. Williams). *Food Chemistry*, 2001, **72**(4): 419–424
57. Wu B H, Genard M, Lescourret F, Gomez L, Li S H. Influence of assimilate and water supply on seasonal variation of acids in peach (cv. Suncrest). *Journal of the Science of Food and Agriculture*, 2002, **82**(15): 1829– 1836
58. Génard M, Lescourret F, Gomez L, Habib R. Changes in fruit sugar concentrations in response to assimilate supply, metabolism and dilution: a modeling approach applied to peach fruit (*Prunus persica*). *Tree Physiology*, 2003, **23**(6): 373–385
59. Becel C. Root growth in peach orchard: influence of water distribution in soil and availability of carbon assimilates. Avignon: *University of Avignon and the Vaucluse*, 2010
60. López GArbones A, Del Campo J, Mata M, Vallverdu X, Girona J, Marsal J. Response of peach trees to regulated deficit irrigation during stage II of fruit development and summer pruning. *Spanish Journal of Agricultural Research*, 2008, **6**(3): 479–491
61. Chaves M M, Maroco J P, Pereira J S. Understanding plant response to drought: from genes to the whole plant. *Functional Plant Biology*, 2003, **30**(3): 239–264
62. Loreto F, Di Marco G, Tricoli D, Sharkey T D. Measurements of mesophyll conductance, photosynthetic electron transport and alternative electron sinks of field grown wheat leaves. *Photosynthesis Research*, 1994, **41**(3): 397–403
63. Chaves M M, Oliveira M M. Mechanisms underlying plant resilience to water deficits: prospects for water-saving agriculture. *Journal of Experimental Botany*, 2004, **55**(407): 2365–2384
64. Cornic G, Le Gouallec J L, Briantais J M, Hodges M. Effect of dehydration and high light on photosynthesis of two C3 plants (*Phaseolus vulgaris* L. and *Elatostema repens* (Lour.) Hall f.). *Hall Plantation*, 1989, **177**(1): 84–90
65. Rosecrance R C, Krueger W H, Milliron L, Bloese J, Garcia C, Mori B. Moderate regulated deficit irrigation can increase olive oil yields and decrease tree growth in super high density ‘Arbequina’ olive orchards. *Scientia Horticulturae*, 2015, **190**: 75–82
66. Cherbiy-Hoffmann S U, Hall A J, Rousseaux M C. Fruit, yield, and vegetative growth responses to photosynthetically active radiation during oil synthesis in olive trees. *Scientia Horticulturae*, 2013, **150**: 110–116