Water stress thresholds for regulated deficit irrigation in pistachio trees: Rootstock influence and effects on yield quality

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ABSTRACT

The response of “Kerman” pistachio trees budded on three different rootstocks (*Pistacia terebinthus*, *Pistacia atlantica* and *Pistacia integerrima*) to regulated deficit irrigation (RDI) in shallow soils was studied for 3 years. The trees were either fully irrigated (C treatment) or subjected to deficit irrigation during Stage II of fruit growth with two water stress thresholds (T1 and T2). The irrigation scheduling for fully-irrigated trees and water-stressed trees was managed by means of midday stem water potential (Ψ_{stem}) measurements. The use of direct measurements of the water status allowed estimating accurately the irrigation requirements for pistachio trees, with water reductions ranging from 46 to 205 mm in fully-irrigated trees. The combination of the Ψ_{stem} use and the RDI regime saved 43–70% in T1 and 48–73% in T2 of water compared to the calculated crop evapotranspiration (ET_c) for fully irrigated treatment (C).

Deficit irrigation during Stage II significantly reduced the vegetative growth of the trees. Yield and fruit quality were not affected by any irrigation regime, except during the first year of the study. Thus, the results indicate that full irrigation scheduling and RDI can be achieved successfully using Ψ_{stem} tool on pistachio trees growing in shallow soils. A Ψ_{stem} threshold of -1.5 MPa during stage II (T1) was suggested for RDI scheduling, as it did not reduce the yield or the production value. However a Ψ_{stem} threshold of -2.0 MPa (T2) resulted in a significant reduction and an extensive delay in the recovery of stomatal conductance (gl), with negative effects on long-term pistachio production.

P. integerrima showed a weaker capacity of adaptation to the study conditions compared to *P. atlantica* and *P. terebinthus*, having a tendency to get more stressed and to produce a lower quality crop.

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1. Introduction

The pistachio tree (*Pistacia vera*) is native from western Asia and Asia minor, where it can still be found growing wild (Crane and Iwakiri, 1981). It has been traditionally cultivated in semi-arid areas of the Middle East and the Mediterranean basin.

The increase in pistachio consumption due to its high nutritious value and favourable taste has led to an intensification and expansion of its cultivation. Thus, planting pistachio trees outside its autochthone area of cultivation has become more common and now it can be found in places such as the USA since 1960 and, more recently, Spain. In 2012, the total pistachio area harvested was 494,000 hectares, including 258,000 hectares in Iran

and 70,000 hectares in the USA (FAOSTAT, 2012). In Spain, the areas used for growing pistachio trees nowadays is estimated at about 5000 hectares, whereas it was negligible in the 90s (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2014). The expansion of pistachio trees cultivation in countries like the USA has been linked to a change in the type of orchard management, with the aim of increasing yield mainly by transforming pistachio from a traditionally rainfed cultivated crop to an irrigated crop. Bilgen (1982) indicated that irrigation should be considered among the most important cultural practices to sustain high yields in pistachio orchards.

Cultivated for a long time in semi-arid areas, the pistachio tree has been considered as a drought-tolerant species (Spiegel-Roy et al., 1977; Behboudian et al., 1986; Rieger, 1995) mainly for its ability to survive under extreme conditions of water stress (Kanber et al., 1990; Goldhamer, 1995). At the same time, the pistachio tree water demand is not known to be particularly low (Goldhamer et al., 1985) and the potential evapotranspiration rate at the max-

imum seasonal evaporative demand is equal or exceeds that of many other deciduous species (Goldhamer et al., 1983). The relation between Crop Evapotranspiration (ET_c) and Reference Evapotranspiration (ET_0) is named Crop coefficient (K_c) and represent the needs of water for each crop. Kanber et al. (1993) estimated a K_c for pistachio between 0.49 and 0.80 from May to August, but suspected that these values underestimated the real water consumption of pistachio trees. Goldhamer (1995) presented a K_c much higher, estimating a maximum of 1.19 from the first fortnight of July to the first fortnight of August. The elevated pistachio water needs became a concern, since the majority of pistachio producing regions were suffering an alarming continuous depletion of their water reserves and could not always sustain the tree water requirements due to the scarcity of rain and the increasing competition for fresh water. This situation led to the need of improving the efficiency of water use. Deficit irrigation is proposed as a tool for this purpose and it consists on imposing a continuous water deficit during the season (sustained deficit irrigation) (Goldhamer et al., 1987) or during specific phenological stages (regulated deficit irrigation). Regulated deficit irrigation (RDI) has been a common research line for most fruit trees (Behboudian and Mills, 1997). The concept of RDI was first suggested by Chalmers et al. (1981) and Mitchell and Chalmers (1982) to control vegetative growth in peach orchards, and they found that savings in irrigation water could be realized without reducing the yield. In order to determine the response of pistachio trees to sub-optimal water application at several periods of growth, Goldhamer (1995) divided the pistachio fruit growth cycle into four phenological stages (stage I, II, III and postharvest). Stage I covers the whole period of shell expansion, stage II the period of shell hardening, and stage III the embryo growth. He observed that stage II and postharvest are the most tolerant stages to water stress. Gijón et al. (2011) ascribed this tolerance during stage II to changes in water relations. In contrast, stage III was reported to be the most sensitive stage to water deficit that can have a dramatically negative impact on all pistachio yield components. Goldhamer and Beede (2004) observed that the water stress during stage I increases shell splitting; however it could affect the final fruit size and increase undesirable premature shell splitting. Gijón et al. (2008) imposed a water stress during stage I and II (50% of ET_c) and observed no differences on yield, but no positive effects were reported either with regards to an increase of nuts splitting. The early nut splitting was more closely associated to a roof temperature than to the water status during stage I.

RDI works in pistachio trees were generally scheduled imposing a water stress that was quantified as a fraction of ET_c during a specific stage. However, the different agronomical conditions (mainly soil characteristics), when different locations are used for experimentation, produce a lack of similarity between results and make them little transferable. To overcome this inconvenience, several authors suggested using plant water status measurements as an efficient tool for irrigation scheduling (Turner, 1990; Fereres and Goldhamer, 1990) rather than indirect estimations. Shackel et al. (1997) carried out probably the first study that suggested using plant water status measurements (leaf water potential) as a tool for irrigation scheduling.

For pistachio trees, Goldhamer et al. (2005) suggested an initial approach based on shaded leaf water potential measurements for a fully irrigated mature orchard, recommending an range from -0.7 MPa to -1.2 MPa in which the shaded leaf water potential decreases gradually from stage I to postharvest, founding also a good correlation between midday shaded leaf water potential and stem water potential ($R^2 = 0.948$). In other deciduous tree crops, such as prunes, almonds or grapevines, the behaviour of the stem water potential was found to be more closely linked to vapour pressure deficit (VPD) variations than to the growth stage (McCutchan and Shackel, 1992; Shackel, 2011; Williams and Baeza, 2007).

A possible cause for the response variations of pistachio to water stress could be the influence of the rootstock used. *Pistacia integerrima* L., *Pistacia atlantica* Desf., *Pistacia terebinthus* L. and UCB-I (a cross between *Pistacia integerrima* L. and *Pistacia atlantica* Desf.) are currently the most widely used rootstocks for pistachio cultivation. *P. integerrima* is recognized as the most vigorous rootstock, *P. atlantica* as having medium vigour, and *P. terebinthus* as the weakest one (Ferguson et al., 2005). There are few studies comparing the water relation responses between pistachio rootstocks. Germana (1997) mentioned that potted *P. atlantica* induced a more intense transpiration and net photosynthetic activity when it was compared to *P. terebinthus*, and this may limit its use in water-deficient areas. Ferguson et al. (2005) considered UCB as the most preferable commercial rootstock under irrigated conditions, and *P. terebinthus* in rainfed conditions.

Thus, the aims of this work were: to test the viability of using stem water potential measurements as a tool for irrigation scheduling, to study the effects of a water stress levels between -1.5 MPa and -2.0 MPa during stage II on the pistachio-water relations, growth, production and yield quality and to compare the behaviour of different rootstocks when subjected to the imposed water stress.

2. Materials and methods

2.1. Experimental site and plant material

The study was conducted for three years, from 2012 to 2014, in an orchard of trees grafted in 2000 and located in "La Entresierra" research station, Ciudad Real (Centre of Spain) ($35^{\circ}56'W$; $39^{\circ}0'N$; altitude 640 m). *P. vera* L. cv. Kerman was budded on three different rootstocks: *P. terebinthus* L., *P. atlantica* Desf. and *P. integerrima* L. Tree spacing was set at 7×6 m (238 trees ha^{-1}). Peter cv. was used as male tree and was distributed evenly throughout the field, in a proportion of 10%.

Irrigation was performed daily using a drip irrigation system with twelve self-compensating emitters (each delivering $4 L h^{-1}$) per tree and irrigation water with an electrical conductivity of 2.6 – $2.9 dS cm^{-1}$. Irrigation lines were separated 1 meter from the tree line and the distance between drippers was also 1 m (Fig. 1).

The soil at the experimental site is an alkaline (pH 8.1) shallow soil with a discontinuous petrocalcic horizon located at 0.50 m (Petrocalcic Palexeralfs), with a clay loam texture, low electrical conductivity ($0.2 dS m^{-1}$), 1.05% of organic matter, 0.12% of nitrogen, $17 \times 10^{-4} mol kg^{-1}$ potassium levels and high cationic exchange capacity ($0.186 mol kg^{-1}$). The volumetric water content of the soil for the first 0.3 m of depth was 22.8% at field capacity (soil matric potential -0.03 MPa) and 12.1% at permanent wilting point (soil matric potential -1.5 MPa); from 0.3 m to 0.5 m it is 43.0% and 21.1%, respectively.

The climate is Mediterranean with an average annual rainfall of 397 mm, mostly distributed outside a four-month summer drought period.

The orchard was managed under no tillage conditions; weeds were controlled with post-emergence herbicides. Pest control and fertilization practices were those usually followed by local growers.

2.2. Rootstocks and irrigation regimes

The experimental design was factorial and completely randomized. Two factors were considered: rootstocks and irrigation; with three levels for each factor.

The three rootstocks used were *P. terebinthus* L., *P. atlantica* Desf. and *P. integerrima* L., while the three irrigation levels were a Control, without water stress, and two RDI treatments.

Fig. 1. Distribution diagram for DIVINER tube access in relation to the tree position. Data in meters.

During the irrigation season, control plants (C treatment) were irrigated at 100% of Crop irrigation requirements (ET_c) of the previous week. ET_c was estimated according to daily reference evapotranspiration (ET_0), calculated using the Penman–Monteith equation (Allen et al., 1998), a crop factor (K_c) based on the time of the year (Goldhamer, 1995) and (K_r) taking into consideration the canopy size (Feres and Goldhamer, 1990). Midday stem water potential (Ψ_{stem}) and soil water balance were considered to modify the ET_c , for example, when Ψ_{stem} values of that week were below -1.0 MPa, a water stress threshold used for several woody crops (Shackel et al., 1997), irrigation amounts were increased a 10%, as Goldhamer and Feres (2001) suggested in order to ensure there was no irrigation-related stress. In addition to C, two RDI treatments (T1 and T2) were applied, intended to avoid water deficit during Stage I and III of fruit growth, this was achieved maintaining the Ψ_{stem} values around the threshold value indicated for C plants. During Stage II, the non-critical period, the water deficit was increased and the threshold values were -1.5 MPa (T1) and -2.0 MPa (T2).

The irrigation protocol for stressed treatments was derived from the methodology proposed by Moriana et al. (2012) for olive trees and was adapted to pistachio trees considering a Ψ_{stem} threshold of -1.00 MPa (Shackel et al., 1997) as an index for no water stress conditions.

Irrigation started when the measured Ψ_{stem} values were lower than the threshold values considered. The first irrigation event was always 1 mm. Then, each increase or decrease of irrigation water supply was scheduled according to the percentage of difference derived from the relationship between measured Ψ_{stem} and the settled threshold for that stage:

- If the deviation rate was lower than 10%, the variation in the irrigation was 0.25 mm day^{-1} .

- If the deviation rate was between 10 and 20%, the variation in the irrigation was 0.5 mm day^{-1} .
- If the deviation rate was between 20 and 30%, the variation in the irrigation was 1 mm day^{-1} .
- If the deviation rate was higher than 30%, the variation in the irrigation was 2 mm day^{-1} .

Irrigation was stopped if this approach indicated a negative application.

The experimental plot was formed by two trees used for measurements, surrounded by trees under the same conditions (rootstock and irrigation). There were eighteen plots in the field following a completely randomized factorial design.

2.3. Soil water content and evapotranspiration measurements

The soil moisture was measured using a portable capacitance probe (Diviner 2000 Sentek Pty. Ltd., Stepney South, Australia) employing the default calibration supplied by the manufacturer. Four access tubes were installed in each experimental plot, measuring 50 cm in length; readings were made each 10 cm. Two access tubes were placed in the middle, between the tree axis and the drip line, at 50 cm from each other. One access tube was installed in front of a dripper. The other was placed in front of the middle of two drippers, at 50 cm from the other access tube. The other two access tubes were placed in the same perpendicular line from the tree axis as the previous access tube, but this time in the middle, between the drip line and the centre of the row. In fact, they were at 1.75 m from the other two access tubes and 2.25 m from the tree axis (Fig. 1). The data thus obtained were used to calculate soil water balance by weighted average based on the area of each moisture zone.

Actual crop evapotranspiration (ET_a) for each treatment and period was derived from the soil water balance of the root zone using the principles of conservation of mass, the expression used was:

$$ET_a = I + P + CR - RO - DP \pm \Delta SW$$

where I is the irrigation, P is the precipitation, CR, is the capillary rise, RO is the surface runoff, DP is the deep percolation and ΔSW is the soil water balance. Irrigation and precipitation were considered as soil water inputs, while actual crop evapotranspiration (ET_a) was established as soil water output. The soil water content balance was taken into account as input or output, depending on its sign. Deep percolation of irrigation water, runoff and capillary rise were assumed to be negligible due to the type of irrigation system and the soil characteristics.

2.4. Vegetative growth

Trunk perimeter was tracked at 20 cm above graft. In order to carry out the measurement at the same place, a strip of the trunk was painted, leaving a narrow line without paint where the measurement was made.

The canopy volume was determined monthly with one vertical and two horizontal diameters of the crown, using a measuring pole with marks every 20 cm.

Each year, at the end of August, the shoot growth, the number of fruit buds and the fruit buds position, as well as the places where, at the moment of measurement, there was or had been a bud, were measured. For this purpose, ten shoots around each control tree were used.

Table 1

Crop reference evapotranspiration (ET_o, mm), Theoretical Crop evapotranspiration (ET_c, mm), Crop Rainfall (mm), Irrigation per treatment (mm), Soil water balance per treatment (mm), Actual crop evapotranspiration per treatment (ET_a, mm), Calculated reduction coefficient of control treatment (K_c) and Calculated crop coefficient of control treatment (K_r) in the three irrigation stages in 2012, 2013 and 2014, * Critical value for comparison in Tukey test.

Year	Period	DOY	ET _o (mm)	ET _c (mm)	Rainfall (mm)	Irrigation (mm)			Soil Water Balance (mm)			ET _a (mm day ⁻¹)			K _r		K _c
						C	T1	T2	C	T1	T2	C	T1	T2	*	C	
2012	Stage I	135–156	131	69	3.2	43	9	8	-0.88	-14.1	-14.4	2.2	1.2	1.2	0.7	0.59	0.60±0.05
	Stage II	157–200	305	246	0.3	187	100	45	14.51	-6.8	-13.7	4	2.5	1.4	1.2	0.78	0.73±0.10
	Stage III	201–270	407	369	22.4	255	275	279	14.81	50.1	54.8	3.8	3.6	3.6	0.8	0.85	0.77±0.15
	Total			684		489	387	337	28.44	33.2	26.7	10.45					
2013	Stage I	148–157	54	39	0.6	11			-0.73	-1.21	-1	1.5	0.2	0.2	0.1	0.71	0.31±0.004
	Stage II	158–211	349	309	4.6	246	30	5	0.08	-4.09	-7	4.8	0.7	0.3	3.5	0.76	1.00±0.21
	Stage III	212–269	308	259	54	144	148	154	-3.17	2.85	3.25	3.6	3.5	3.5	2.1	0.78	0.83±0.24
	Total			607		402	179	162	-3.82	-2.45	-4.75	8.13					
2014	Stage I	126–142	92	63	8.4	32			-11.26	-13.4	-15.4	3.3	1.5	1.4	0.2	0.9	0.63±0.02
	Stage II	143–190	296	294	12.6	260	12	12	15.18	-11.3	-14.6	5.5	0.8	0.8	0.8	0.93	0.94±0.02
	Stage III	191–261	429	439	5.5	458	400	404	5.61	38.2	41.7	6.5	5.3	5.3	2.2	0.9	1.18±0.09
	Total			796		750	411	416	9.53	13.5	11.7	52.86					

2.5. Fruit growth

In the years of high load, 2012 and 2014, fruit samples were taken weekly. Fruit samples in 2013 (low load) were not taken because sampling could disturb the natural pattern of fruit growth.

Fresh weight and transverse diameters were immediately measured on 35 fruits per control tree. In ten of those fruits, kernel, shell and hull were separated to determine fresh and dry kernel weight. Only in 2014, other ten fruits were used to determine the shell hardness using a device specifically developed for this purpose and this was described in detail in Rapoport et al., (2013). The rest of fruits (15) were used to determine the dry weight. To determine dry weights, kernels and fruits were dried in a forced-air oven for 48 hrs at 80 °C.

2.6. Plant water relations

Water relations were characterized along the irrigation season taking weekly measurements of midday stem water potential (Ψ_{stem}) and abaxial leaf conductance (g_l).

Ψ_{stem} was measured at midday using a pressure chamber (Soil Moisture Equip., Santa Barbara, CA, USA) (Hsiao, 1990). One leaf was taken from each control tree in each experimental plot for measurements. The leaf subjected to measurement was selected from the middle and shaded side of the canopy to avoid a sharp change in its state. Then, it was covered with aluminium foil 1 hour before measurement, stopping transpiration and enabling the leaf to reach a balance with the water potential of the stem (Begg and Turner, 1970). Owing to the difficulty in the determination of stem water potential in pistachio tree because of the turpentine exudation, a piece of blotting paper was placed above the petiole cut-off to facilitate the measuring, as that paper does not get wet with turpentine but it does with xylem water.

Measurements of g_l were taken in two sun-exposed and fully expanded leaves per control tree, using a steady state porometer (Model LICOR-1600, U.K.). Both parameters were measured at the same time in order to observe the relationship between them.

2.7. Yield

When fruits reached maturity, a sample of a hundred of them was collected from each control tree. The fresh weight was calculated. Then, fruits were peeled and divided into split; fruits with seed and opened shell non-split; fruits with seed and closed shell and blank fruits; fruits without seed. The fresh weight of each group was determined. The transverse diameter was measured in split nuts. The shell was separated from the kernel and both were weighed for split and non-split fruits. All fractions were dried in a forced-air oven for 48 hrs at 80 °C. Finally they were weighed again to determine the dry weight.

The yield of each control tree was weighed individually.

2.8. Statistical analyses

The results were subjected to ANOVA. Means were compared using the Tukey test. The significance was set at $p < 0.05$. The arc sine transformation was applied to the percentage data.

Data were also subjected to a regression analysis. To check the regression model hypothesis (linearity, homoscedasticity, normality and independency), Kolmogorov–Smirnov was used with the Lilliefors correction, the Shapiro–Wilk tests for normality and Bartlett's test for homoscedasticity. The linearity was observed in the graphics and independency was assumed due to the way that data were obtained. Statical analysis were performed with SPSS 18 statistics program (Analytical Software, Tallahassee, FL, USA).

Fig. 2. Daily mean temperature (T_m , solid line), crop reference evapotranspiration (ET_c , short dashed line), mean daily air vapour pressure deficit (VPD_m , dotted line) and daily rainfall (vertical bars) during years 2012 (A), 2013 (B) and 2014 (C).

3. Results

3.1. Meteorological data and irrigation water applied

During the irrigation season, the average daily maximum and minimum air temperatures were 31.8°C and 13.2°C in 2012, 31.7°C and 12.7°C in 2013 and 30.6°C and 12.6°C in 2014 (Fig. 2). VPD_m ranged from 0.37 to 3.50 kPa in 2012, from 0.51 to 2.85 kPa in 2013 and from 0.34 to 2.76 kPa in 2014 (Fig. 2), and the accumulated ET_c were 843, 711 and 728 mm in 2012, 2013 and 2014, respectively (Fig. 2 and Table 1). Important differences in rainfall were recorded

between seasons. Before the beginning of the irrigation seasons, the rainfall was 110, 347 and 184 mm, respectively (Fig. 2) and during these irrigation seasons, the rainfall was 25.6, 59.2 and 18.9 mm, respectively (Fig. 2 and Table 1).

The calculated crop evapotranspiration (ET_c) was 684, 607 and 796 mm in 2012, 2013 and 2014, respectively, while irrigation water in the C treatment was 489, 402 and 750 mm for the same years. Irrigation was just 71, 66 and 94% of ET_c for this treatment. Irrigation water for T1 was 387, 179 and 411 mm in 2012, 2013 and 2014, respectively, and 337, 162 and 416 mm for T2 in the same years (Table 1).

Table 2
Growth parameters; relative canopy volumen ($\text{m}^3 \text{m}^{-3}$), relative trunk perimeter growth (cm cm^{-1}), shoot growth (cm), no. of buds per shoot and percentage of dropped buds per irrigation treatment and rootstock (PT; *Pistacia terebinthus*, PA; *Pistacia atlantica*, PI; *Pistacia integerrima*). Different letters in the same column mean significant differences between irrigation treatments or rootstocks in each year.

Year	Irrigation treatment/rootstock	Relative canopy volume growth ($\text{m}^3 \text{m}^{-3}$)	Relative trunk perimeter growth (cm cm^{-1})	Shoot growth (cm)	No. buds per shoot	Percentage of dropped buds
2012	C	1.68	0.04a	18.41a	8.89a	62.8
	T1	1.91	0.01b	11.02b	6.79b	67.51
	T2	1.47	0.01b	10.51b	6.73b	70.06
	PT	1.84	0.02	12.98	7.74	70.65
	PA	1.71	0.02	13.31	7.27	64.53
	PI	1.51	0.03	13.65	7.41	65.19
2013	C	0.48	0.1	24.68a	10.67a	30.08b
	T1	0.4	0.08	16.07b	8.01b	45.78a
	T2	0.37	0.08	18.46ab	8.75ab	41.95ab
	PT	0.42	0.09	19.88	9.51a	31.69b
	PA	0.35	0.09	18.25	8.57b	50.20a
	PI	0.48	0.08	21.09	9.36a	35.92b
2014	C	0.24	0.05a	23.07a	9.92a	76.89
	T1	0.26	0.03b	18.30b	8.56b	85.56
	T2	0.15	0.05ab	16.41b	8.72b	85.64
	PT	0.15	0.04	19.78	9.18	86.03
	PA	0.3	0.04	18.32	9.14	80.87
	PI	0.21	0.05	19.67	8.88	81.2
MEAN	C	0.82	0.06a	18.70a	8.10a	56.02
	T1	0.86	0.04b	13.89b	6.27b	66.1
	T2	0.66	0.05b	13.87b	6.47b	65.88
	PT	0.82	0.05	15.59	6.91	62.22
	PA	0.78	0.05	14.8	6.92	65
	PI	0.73	0.05	16.7	7.01	60.77

The soil water balance in the C treatment was mainly positive, showing that the irrigation amount was higher than the water consumption. The period with the lowest value was during stage I in 2014, with a value of -11.3 mm , balanced in the next stage with a positive value of 15.2 mm .

T1 and T2 had negative values during stage I and II due to the effect of the irrigation strategy followed, while in stage III, they had positive values for the same reason.

The actual crop evapotranspiration (ET_a) in the C treatment ranged from 1.5 to 5.5 mm day^{-1} , with different means in each stage; 2.3 , 4.8 and 4.6 mm day^{-1} for stage I, II and III, respectively. This results, ET_0 and K_f were used to calculate the K_c of the control treatment (without water stress), which ranged from 0.31 to 1.18 . The means of the control K_c calculated were 0.51 , 0.89 and 0.93 for stage I, II and III, respectively (Table 1).

The ET_a in T1 and T2 treatments were always lower than C, especially in stage II.

3.2. Growth

Canopy volume and trunk perimeter growth have been related to the initial measurement of each year to offset the initial size difference among trees, so in its denominations were used relative.

The relative canopy volume growth (RCVG) ranged from 0.15 to $1.9 \text{ m}^3 \text{m}^{-3}$, with no differences between irrigation treatments or rootstocks (Table 2). The RCVG was decreasing from one year to the next while the canopy volume was increasing from one year to the next (Table 1; K_f), therefore the yearly rate of canopy increase was inversely proportional to the canopy volume. When the soil cover was at its maximum ($K_f = 0.9$, Table 1), RCVG was at its minimum, with values around 0.24 in the C trees. Although there were no significant differences in the RCVG values, T2 tended to show lower values than C trees in all seasons. The effect of rootstock was not significant.

The relative trunk perimeter growth ranged from 0.008 to 0.095 cm cm^{-1} (Table 2). The years with high crop load, "ON years" (2012 and 2014) had lower values (0.04 and 0.05 cm cm^{-1} in the C treatment) than the year with low crop load "OFF year" (0.10 cm cm^{-1} in the C treatment). There were statistical differences between irrigation treatments in the years of high fruit load, being the C growth higher than the T1 in both years and higher than T2 in 2012. There were statistical differences between C and the other two treatments in mean data. The effect of rootstock was not significant.

Shoot growth ranged from 11 to 25 cm (Table 2), being higher in the C treatment than T1 in all years and higher than T2 in 2012 and 2014 (years "ON"). The number of buds per shoot ranged from 7 to 11 with the same statistical differences as the shoot growth. In fact, the number of buds per shoots was related to the shoot growth ($N = 4.11 + 0.25 \text{ Shoot-growth}$; $R^2 = 0.8049$; $p < 0.0001$; $\text{MSE} = 1.7494$; $N = 1082$; data not shown). In 2013, there were fewer buds per shoot when the rootstock was *P. atlantica* than when the other two were used.

The percentage of dropped buds ranged from 30 to 86% (Table 2). In years ON, the percentage of dropped buds was significantly higher (63 and 77% in the C treatment) than in year OFF (30% in the C treatment). The effect of the irrigation treatment was significant only in 2013, when the T1 treatment dropped more buds than C. During the 2012 and 2014 seasons, though no significant differences were found, T1 and T2 tended to produce lower values than the C treatment. The effect of rootstock was not clear. Only in 2013, *P. atlantica* significantly dropped more buds than the other two rootstocks. However, the trends for the rest of the seasons were not always consistent with this.

3.2.1. Fruit growth

The transverse diameter had a rapid growth in the last weeks of May and the first of June, reaching a maximum of around 14 mm , on Day of Year (DOY) 156 and 142 mm in 2012 and 2014, respec-

Fig. 3. Transverse fruit diameter (closed symbols in A, mm), shell hardening (grey symbols in A, MPa), kernel fresh weight (open symbols in A, g), fresh fruit weight (closed symbols in B, g) and dry fruit weight (open symbols in B, g) values (mean $\pm$ SE, not shown when smaller than symbols, $n = 12$) in pistachio fruits during year 2014 by irrigation treatment (C, circle; T1, square; T2, triangle up). Vertical dashed lines indicate the stages I, II, III and post-harvesting. Asterisks indicate significant differences between treatments.

tively. There were no differences between irrigation treatments or rootstocks.

The kernel fresh weight showed a sigmoid pattern (Fig. 3A), without differences between irrigation treatments or rootstocks.

The shell hardness showed a sigmoid pattern, starting to increase when fruit reached its maximum volume and ending about 20 days after the beginning of the kernel growth (Fig. 3A). There were no differences between irrigation treatments or rootstocks.

The fresh fruit weight showed a double sigmoidal pattern (Fig. 3B). In 2012, there were statistical differences between treatments in the last week of May and in three weeks of June, with the C treatment being heavier than T1, and in two cases, heavier than T2 (data not shown). In 2014, there were statistical differences three times (Fig. 3B), with differences between irrigation treatments without a regular pattern.

The dry fruit weight showed a linear pattern in 2012 (data not shown) and 2014 (Fig. 3B). In 2012, there were no statistical differences. In 2014, T2 had a heavier dry weight than T1 until DOY 175 and C until DOY 204.

In 2012 there were no statistical differences between rootstocks. In 2014, fruits from trees on *P. atlantica* were heavier than on *P.*

integerrima on several dates (Fig. 4B) and also heavier than on *P. terebinthus*. These differences were both in fresh weight and dry weight, but the differences in dry weight were noticeable in every sample, from the beginning of fruit growth to DOY 183, while in fresh weight, they were observed in the samples during the whole season without any difference.

3.3. Plant water relations

The midday stem water potential (Ψ_{stem}) ranged in C from -0.65 MPa in 2013 to -1.39 MPa in 2014, with similar minimum values in 2012 (-1.36 MPa) and 2013 (-1.37 MPa). During stage I and due to the development of the leaf, only one measurement was done, showing a Ψ_{stem} value of around -1.0 MPa for T1 and T2 in 2013 and 2014. In 2012, Ψ_{stem} was -1.24 and -1.16 MPa for T1 and T2, respectively. During stage II, when a water stress was imposed, T1 ranged from -1.04 to -1.79 MPa in 2012, from -0.69 to -1.52 MPa in 2013 and from -0.99 to -1.43 MPa in 2014. During this stage, T2 ranged from -1.14 to -2.27 MPa in 2012, from -0.67 to -1.69 MPa in 2013 and from -0.94 to -1.72 MPa in 2014. Stage III started with the recovery and then maintained a good water

Fig. 4. Transverse fruit diameter (closed symbols in A, mm), shell hardening (grey symbols in A, MPa), kernel fresh weight (open symbols in A, g), fresh fruit weight (closed symbols in B, g) and dry fruit weight (open symbols in B, g) values (mean $\pm$ SE, not shown when smaller than symbols, $n=12$) in pistachio fruits during year 2014 by rootstocks (*Pistacia terebinthus*, PT, triangles down; *Pistacia atlantica*, PA, diamonds; *Pistacia integerrima*, PI, hexagons). Vertical dashed lines indicate the stages I, II, III and post-harvesting. Asterisks indicate significant differences between treatments.

situation. During this stage, T1 ranged from -0.72 MPa in 2013 to -1.60 MPa in 2012 and T2 ranged from -0.70 MPa in 2013 to -1.58 MPa in 2012 (Fig. 5).

The Ψ_{stem} in C was significantly higher than T1 and T2 from DOY 146 to 227 in 2012, from DOY 163 to 211 in 2013 and from DOY 161 to 217 in 2014, with some isolated days with no significant differences within periods (Fig. 5). In addition, T1 had significantly higher Ψ_{stem} than T2 from DOY 172 to 199 in 2012, on DOY 204 in 2013 and on DOY 182 and 188 in 2014.

The abaxial leaf conductance (g_l) in the C treatment ranged from 213 to 363 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2012, from 262 to 403 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2013 and from 239 to 403 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2014. The maximum values of g_l were slightly higher in stage II than in stage III in 2012 and 2013, 363 and 335 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2012 and 403 and 347 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2013, respectively. In 2014, the maximum values were similar in stage II and stage III, 392 to 403 $\text{mmol m}^{-2} \text{s}^{-1}$ (Fig. 6).

In T1, g_l ranged from 173 to 258 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2012, from 226 to 383 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2013 and from 222 to 403 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2014. For T2, g_l ranged from 159 to 261 $\text{mmol m}^{-2} \text{s}^{-1}$ in

2012, from 186 to 356 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2013 and from 234 to 426 $\text{mmol m}^{-2} \text{s}^{-1}$ in 2014.

In the C treatment, g_l was higher than T2 from DOY 156 to 254 in 2012, on DOY 211 and 218 in 2013 and on DOY 188 in 2014 (Fig. 6). G_l in T1 was lower than C on DOY 156, 166, 192 and 213 in 2012, on DOY 163 and 190 in 2013, and none in 2014.

The Ψ_{stem} was higher in trees on *P. terebinthus* rootstocks than those on *P. integerrima* rootstocks on DOY 248, 254 and 269 in 2012, on DOY 204 and from 235 to 252 in 2013 and on DOY 203 and 230 in 2014. The Ψ_{stem} was also higher in trees on *P. terebinthus* rootstocks than in trees on *P. atlantica* rootstocks on DOY 242 in 2013. The Ψ_{stem} was higher in trees on *P. atlantica* rootstocks than in trees on *P. integerrima* rootstocks on DOY 217 in 2013 (Fig. 7).

The Ψ_{stem} was higher in trees on *P. integerrima* rootstocks than in trees on *P. terebinthus* rootstocks on DOY 163 and 183 in 2013, on DOY 139 and 146 in 2014. The Ψ_{stem} was also higher in trees on *P. integerrima* rootstocks than in trees on *P. atlantica* rootstocks on DOY 169 in 2013 and on DOY 146 in 2014.

There were no statistical differences in g_l among trees using the three rootstocks, except on DOY 166 in 2012 and on DOY 153

Fig. 5. Stem water potential (Ψ_s) values (mean $\pm$ SE, not shown when smaller than symbols, $n = 12$) for pistachio trees. Vertical dashed lines indicate the stages I, II, III and post-harvesting. Asterisks indicate significant differences between treatments.

in 2014. In both cases *P. integerrima* showed higher values than *P. atlantica* (Fig. 8).

3.4. Yield

The yield in the C treatment was 49, 11 and 57 kg tree⁻¹ in 2012, 2013 and 2014, respectively. In T1, it was 36, 12 and 48 kg tree⁻¹ and in T2, 36, 13 and 49 kg tree⁻¹ in 2012, 2013 and 2014, respectively (Table 3).

Therefore, the yield in the C treatment was higher than that for the other treatments in the ON years, although this difference was significant only in 2012; while in 2013, the yield in C was lower without statistical significance. These facts made alternate bearing higher in the C treatment than in the other treatments.

Fig. 6. Abaxial leaf conductance (g_l) values (mean $\pm$ SE, not shown when smaller than symbols, $n = 12$) for pistachio trees. Vertical dashed lines indicate the stages I, II, III and post-harvesting. Asterisks indicate significant differences between treatments.

The mean yield for the three years was 39, 33 and 33 kg tree⁻¹ in the C, T1 and T2 treatments respectively, without statistical differences (Table 3).

When the yield was adjusted based on the canopy to offset the tree size effect, there were differences between irrigation treatments only in 2014, then the T1 treatment had higher value (2.15 kg m⁻³ canopy tree⁻¹) than the C treatment (1.66 kg m⁻³ canopy tree⁻¹) while the T2 treatment was 1.91 kg m⁻³ canopy tree⁻¹, with no statistical difference with the other treatments (Table 3).

The nut weight varied in relation to yield, with lower values (less than 3 g nut⁻¹) the year with highest yield (2014) and higher values (more than 3.3 g nut⁻¹) the year with the lowest yield (2013).

Table 3
Yield (Kg tree⁻¹), yield per canopy volume (kg m⁻³), nut weight (g nut⁻¹) and crop load (n° nuts tree⁻¹) per irrigation treatment and rootstock (PT; *Pistacia terebinthus*, PA; *Pistacia atlantica*, PI; *Pistacia integerrima*) in 2012, 2013 and 2013 and mean data. Different letters in the same column mean significant differences between irrigation treatments or rootstocks in each year.

Year	Irrigation treatment/rootstock	Total yield (Kg tree ⁻¹)	Total yield (Kg m ⁻³ canopy)	Nut weight (g nut ⁻¹)	Crop load (No. nuts tree ⁻¹)
2012	C	48.90a	4.28	3.2	15.569a
	T1	35.79b	4.91	3.11	11.897b
	T2	35.56b	3.69	3.01	11.386b
	Pt	38.14	4.95	3.21	12.143
	Pa	42	4.26	3.07	13.584
	Pi	40.11	3.67	3.05	13.125
2013	C	10.52	0.49	3.45	2.838
	T1	12.17	0.77	3.33	3.615
	T2	13.34	0.79	3.38	3.922
	Pt	8.83b	0.51	3.44	2.278b
	Pa	16.98a	0.96	3.36	5.077a
	Pi	10.23ab	0.51	3.36	3.020b
2014	C	57.23	1.66b	2.98	19.161
	T1	48.42	2.15a	2.95	16.4
	T2	48.86	1.91ab	2.93	16.685
	Pt	49.93	1.98a	3.00a	16.599
	Pa	57.57	2.12a	3.01a	19.156
	Pi	47.02	1.61b	2.85b	16.491
MEAN	C	38.94	2.19	3.22	12.33
	T1	32.67	2.61	3.13	10.467
	T2	32.05	2.13	3.11	10.835
	Pt	32.36	2.52	3.22	10.148
	Pa	38.85	2.45	3.15	12.605
	Pi	32.45	1.95	3.08	10.879

However the variation in nut weight was lower than the variation in yield. There were no statistical differences in nut weigh between the irrigation treatments (Table 3).

The crop load (no. of nuts per tree) varied according to the yield, with the same statistical differences (Table 3).

There were statistical differences in yield between trees on different rootstocks in 2013, and trees on *P. atlantica* had a higher yield than trees on *P. terebinthus*. This effect was also observed in the crop load for the same year.

In 2014, there were statistical differences in yield adjusted according to the canopy size, with trees on *P. integerrima* showing the lowest values. The same differences between rootstocks were recorded in the nut weight.

3.4.1. Yield quality

The kernels of split fruits were heavier than the kernels of non-split fruits in several cases in 2012 and 2013 (Table 4). In those years, the dry weight of the kernels of split fruits was always heavier than that of non-split fruits. The fresh weight of the kernels of split fruits was also heavier in all cases than that of non-split fruits, but a statistical significance was only found in the T1 treatment in 2012 and the C and T2 treatments in 2013. There were no statistical differences in 2014.

Neither fresh nor dry weight of kernel of split or non-split fruits showed statistical differences for different irrigation treatments, except for the kernel of split fruits in 2014, whose kernel dry weight of the T1 treatment was heavier than that of the C treatment.

The percentage of split fruits in the fresh weight ranged from 46 to 80%, and it was related to the yield (Table 4). The percentage of non-split fruits in the fresh weight ranged from 16 to 41% and it was also related to the yield. For both cases, there were no statistical differences between irrigation treatments.

The relationship between percentages in fresh and dry weight did not follow any pattern. The percentage in dry weight in 2012 kept a more or less equal trend to the fresh weight and only the percentage of blank fruits was lower than in fresh weight. In 2013, the percentage of split fruits in dry weight decreased, and that for non-split fruits increased when compared to the fresh weight. The

percentage of blank fruits kept a more or less equal trend. This trend was the opposite in 2014, when the percentage of split fruits increased in dry weight when compared to fresh weight and the percentage of non-split fruits decreased similarly to the percentage of blank fruits.

The diameter of split nuts was related to the yield and it ranged from 12.78 mm to 14.44 mm. There was a statistical significance in 2014, when the diameter of the T1 treatment was larger than that of the C treatment (Table 4).

The production from trees on *P. integerrima* had a lower percentage of split fruits than that from trees on *P. terebinthus* in fresh weight in 2012, 2013 and 2014, also lower than trees on *P. atlantica* in 2012 and 2013. These differences were observed in the dry weight as well, except in 2013, when the pattern was the same but differences were not significant enough (Table 4).

Split fruits from trees on *P. atlantica* had a larger diameter than from those from trees on *P. integerrima*.

4. Discussion

4.1. Plant water relations

4.1.1. Irrigation scheduling in fully irrigated conditions

The fact that Ψ_{stem} and g_l values in C plants were high and almost constant during the three years (Figs. 5 and 6) suggested that the irrigation applied to this treatment was sufficient to prevent any water deficit during the measurement period. The variations of Ψ_{stem} were lineal in relation to changes in VPD (Fig. 9) and estimated a baseline that could support irrigation scheduling decisions. This baseline was not affected by the phenological stage of the trees and this could explain the clear reduction of Ψ_{stem} in mid-summer. A similar decrease in Ψ_{stem} has been reported in pistachio trees (Goldhamer et al., 2005; Gijón et al., 2008) and in olive trees (Moriana et al., 2003; 2012). Similar baselines have been found in other crops, such as prunes (McCutchan and Shackel, 1992) or grapevines (Williams and Baeza, 2007) and they can be a useful tool for irrigation scheduling based on the plant water status. The water potential has been used as a scheduling irrigation tool for decidu-

Table 4

Quality parameters of production; weight of split kernel (g kernel^{-1}), weight of non-split kernel (g kernel^{-1}), percentage of split, non-split and blank fruits in fresh and dry matter per irrigation treatment and rootstock (PT; *Pistacia terebinthus*, PA; *Pistacia atlantica*, PI; *Pistacia integerrima*) in 2012, 2013 and 2014 and mean data. Different capital letters in the same row mean significant differences between split and non-split weight kernels. Different lowercase letters in the same column mean significant differences between irrigation treatments or rootstocks in each year.

Year	Irrigation treatment/ rootstock	Fresh weight					Dry weight					Diameter of split nuts (mm)
		Split kernel (g kernel ⁻¹)	Non split kernel (g kernel ⁻¹)	Percentage			Split kernel (g kernel ⁻¹)	Non split kernel (g kernel ⁻¹)	Percentage			
				Splits	Non-splits	Blanks			Splits	Non-splits	Blanks	
2012	C	1.22	1.15	53.5	28.8	19.6	0.68A	0.58B	54.38	28.9	16.72	13.1
	T1	1.19A	1.13B	58.3	23.1	22	0.66A	0.61B	57.32	24.61	18.07	12.93
	T2	1.15	1.12	48.2	29.9	23.6	0.63A	0.58B	48.87	31.03	20.1	12.78
	Pt	1.22A	1.15B	60.3a	23.2b	18.9	0.66A	0.59B	59.31a	24.54b	16.15	12.98
	Pa	1.17	1.09	57.0a	24.3ab	20.7	0.64A	0.57B	57.06a	25.51ab	17.44	12.76
	Pi	1.17A	1.15B	42.7b	34.3a	25.6	0.67A	0.61B	44.20b	34.50a	21.3	13.07
2013	C	1.32A	1.17B	74.5	20.2	9	0.71A	0.59B	57.32	34.65	9.24	14.44
	T1	1.29	1.2	80	16.1	7.7	0.72A	0.58B	65.56	27.74	7.7	14.37
	T2	1.31A	1.20B	74.7	16.8	9.2	0.72A	0.61B	61.3	30	8.71	14.37
	Pt	1.35A	1.17B	81.0a	10.8b	9.6	0.72A	0.56B	64.57	27	9.63	14.54
	Pa	1.28	1.16	83.5a	12.7b	8.1	0.72A	0.58B	65.41	27.92	6.67	14.3
	Pi	1.30A	1.23B	64.7b	29.5a	8.5	0.70A	0.63B	53.19	37.47	9.35	14.34
2014	C	1.16	1.18	46.2	40.5	15.2	0.62b	0.63	56.88	32.8	10.32	13.10b
	T1	1.17	1.19	57.9	32	12.4	0.65a	0.64	64.49	26.81	8.7	13.32a
	T2	1.17	1.18	51	34	17.1	0.63ab	0.63	58.92	28.78	12.3	13.26ab
	Pt	1.20a	1.18	68.6a	21.4b	12.2	0.64a	0.62	72.61a	18.69b	8.69	13.26ab
	Pa	1.20a	1.18	50.9ab	36.5ab	14.5	0.65a	0.63	59.83ab	30.02ab	10.16	13.32a
	Pi	1.10bB	1.18A	35.6b	48.6a	18	0.62bB	0.65A	47.85b	39.69a	12.47	13.09b
MEAN	C	1.24A	1.13B	58.4	29.4	14.7	0.67A	0.58B	56.42	31.47	12.1	13.56
	T1	1.22	1.17	65.4	23.7	14	0.67A	0.61B	62.12	26.38	11.49	13.54
	T2	1.21	1.17	58	26.9	16.6	0.66A	0.61B	56.36	29.94	13.7	13.47
	Pt	1.26aA	1.13B	70.3a	18.0b	13.6	0.67A	0.58aB	65.73a	22.76b	11.51	13.61
	Pa	1.22abA	1.15B	63.8a	24.5b	14.4	0.67A	0.59abB	60.77a	27.81b	11.42	13.46
	Pi	1.19b	1.19	47.7b	37.5a	17.3	0.66A	0.63aB	48.41b	37.22a	14.37	13.5

ous fruit trees (Shackel et al., 1997), grapevines (Girona et al., 2006; Williams et al., 2012) and olive trees (Mariana et al., 2012).

The water deficit in the C treatment was prevented with irrigation water amounts lower than those calculated using just the Penman–Monteith equation. Water was not extracted from soil in two of the three years of the assay, seasonal soil water balance in the C treatment was positive (Table 1), therefore water was accumulated in the soil those years. The water saving achieved each season ranged from 46 to 205 mm. The average crop coefficients (K_c) calculated from the water balance (0.51, 0.89 and 0.93 for stage I, II and III, respectively) were around 18% lower in stage II and III than literature values (Goldhamer, 1995). These K_{cs} were in the same range than the data obtained by Kanber et al., (1993) but lower than those obtained by Iniesta et al. (2008), who reported even greater values than Goldhamer (1995). Maximum differences between K_{cs} calculated in the present work and K_{cs} estimated by Iniesta et al. (2008) were 26% in stage II and 40% in stage III. The irrigation technique can explain partially these differences, while Goldhamer (1995) and Iniesta et al., (2008) used micro-sprinkler with high frequency irrigations, Kanber et al., (1993) applied the irrigation with a hose every 20 days. Iniesta et al., (2008) assumed evaporation losses of 7.5% of water applied, but Koumanov et al., (1997), in an almond orchard irrigated by micro-sprinkler, reported water losses ranging from 21 to 27% of the applied water. Therefore, the irrigation scheduling based on the Ψ_{stem} adjusted the water needs to calculate accurate K_c values. Although K_c data of the present work were calculated during three years only, they must be considered in drip irrigation scheduling to obtain important water savings.

4.1.2. Effect of water stress

Water stress in T1 and T2 was increased at the same rate in 2012 and 2013, both treatments had different water stress only when irrigation was used in T1 to maintain the water stress around the threshold of the treatment. However, in 2014, the decrease in Ψ_{stem} in T2 was faster than in T1. Such response could be related to an increase of embolism and it could produce a negative response to RDI scheduling in the long term (such as in almond, Fereres and Goldhamer, 1990). There are no data in the literature for pistachio trees about the threshold of the xylem pressure where the loss of conductivity begins. In olive trees, a similar species in terms of drought resistance, the loss of conductivity increased rapidly from -1.3 MPa (Torres-Ruiz et al., 2013). This pressure is quite near the water stress threshold of T1, so embolism could be even much more frequent in T2 than in T1. In addition, some species presented a cavitation fatigue, which produces an increase of the embolism for each new cycle of water stress (Hacke et al., 2001).

The effect of the fruit load could reduce the accuracy of Ψ_{stem} in the detection of water stress. In theory, Ψ_{stem} integrates the effects of irrigation and crop load (Naor, 2001). In the present work, no clear trends of lower values of Ψ_{stem} were observed in the ON year compared to the OFF year in C trees (Fig. 5), as it was found in olive trees (Martín-Vertedor et al., 2011) or peach trees (Alcobendas et al., 2012). Therefore the same baseline could be used. Although no influence of fruit load was detected in full irrigated conditions, Ψ_{stem} values in T1 and T2 were nearer to C during OFF than during ON seasons.

The pattern of leaf conductance (g_l) could suggest a threshold of the water stress level. Significant reductions in g_l were measured when the Ψ_{stem} was lower than -1.5 MPa. Such threshold could

Fig. 7. Stem water potential (Ψ_s) values (mean $\pm$ SE, not shown when smaller than symbols, $n = 12$) for pistachio trees. Vertical dashed lines indicate the stages I, II, III and post-harvesting. Asterisks indicate significant differences between treatments.

indicate the beginning of severe water stress conditions. Significant decreases in g_l values were also related to the recovery period, which was the greater the g_l reduction was. The slow recovery of pistachio trees shortened the period of permissible water stress that should be taken into consideration to ensure the tree full water requirements were met in the sensitive stage. Pérez-López et al., (2008) suggested that a greater increase in the soil water content accelerated the rehydration in olive trees.

4.2. Growth

4.2.1. Vegetative growth

The water stress during stage II at the threshold of -1.5 MPa of Ψ_{stem} reduced the neo-formed shoots growth. This response

Fig. 8. Abaxial leaf conductance (g_l) values (mean $\pm$ SE, not shown when smaller than symbols, $n = 12$) for pistachio trees. Vertical dashed lines indicate the stages I, II, III and post-harvesting. Asterisks indicate significant differences between treatments.

has been reported generally when water stress is applied during both stage I and II in pistachio tree but not during stage II only (Goldhamer, 2012). The neo-formed shoot growth was always higher in the C treatment than in stress treatments (Mean 3 years: 5 cm of difference between C and stress treatments). Additionally, the stress reduced the number of buds per shoot in T1 and T2 (Mean of 2 buds per shoot less than in C) with a similar bud retention percentage to the control treatment (Table 2). However, these differences were not translated into a greater crop load or yield in C, except the first year of the experiment and this could be probably related to the previous year's conditions.

These results indicate that the difference between the control and the stress treatments in the neo-formed shoot growth is mostly unproductive, confirming the previous works of Spann et al. (unpublished) mentioned by Goldhamer (2012) stating that

Fig. 9. Relationship between stem water potential (Ψ_s , $n=12$) and vapour pressure deficit in C treatment. Adjusted line in continuous thick line, confidence intervals at $p < 0.05$ in short dash line, prediction intervals at $p < 0.05$ in medium dashed line. Asterisks indicate $p < 0.0001$.

fruit positions are found mostly on the short shoots (pre-formed shoots) and that these later reach a full elongation before the onset of stage II. The stress applied in the above mentioned work was around -1.6 MPa midday shaded leaf water potential (Goldhamer, 2012), which could be the most similar to that of the T1 treatment of the present work and showed no reduction in pre-formed shoot growth. It seems that a more severe stress (-2.0 MPa in T2) did not affect neither the initiation of short shoots in the short term, since yield was little affected by this level of stress in this study.

The pistachio shoot growth was not particularly dependent on the crop load (ON or OFF year) and the growth reached during the stress treatment was sufficient to reach the productivity that makes the application of RDI viable during ON and OFF years. The growth lost by water stress could imply a saving during the pruning practice, since the main part of production is initiated in stage I. Tree water needs during this stage are generally satisfied from the soil water reserve. Spiegel-Roy et al. (1977) found that 54 to 163 mm of annual precipitation were sufficient for dryland trees to differentiate enough flower buds and obtain appreciable yields.

4.2.2. Determination of the water stress tolerant period

The pistachio fresh fruit weight follows a double sigmoidal pattern (Fig. 3B). This pattern is widely assumed to be similar to the fleshy drupes pattern when represented as fresh weight. However, the tissues of the pistachio fruit develop in time and space like those of drupe, in general, while others develop quite differently (Crane, 1986). The growth in diameter of pericarp fleshy drupaceous fruits, such as apricot, cherry and peach, occurs in three distinct periods with two rapid growth cycles separated by one of slow growth. In pistachios, the pericarp growth is fully completed in one period, since transverse diameter has a rapid growth in the last weeks of May and the first of June, reaching a maximum of around 14 mm (Fig. 3). This period is defined as stage I of fruit growth for pistachio trees. Contrary to stone fruits, the growth of the pericarp and the growth of the seed in pistachio trees are separated in time. The seed growth in pistachio trees follows a simple sigmoidal pattern, starts after a fresh weight lag behaviour and defines the stage III.

The pit hardening has been used for irrigation scheduling in peach trees (Chalmers et al., 1981; Domingo et al., 2011), cherry trees (Papenfuss and Black, 2010), nectarine trees (Thakur and Singh, 2012) and olive trees (Pérez-López et al., 2008; Gucci et al., 2009; Hidalgo et al., 2011) to mark the period of tolerance to water stress.

There are not previous data about shell hardening in pistachio fruits, so by analogy with nut trees, the stage II and shell hardening are named interchangeably (Doster et al., 2001; Sajjadinia et al., 2010). Shell hardening is characterized by a simple sigmoid curve in which, the first point of inflection collapses with the maximum diameter of fruit growth. Approximately in the middle of shell hardening period, the kernel starts its accelerated growth. When the shell hardening reaches its maximum (around 40 MPa), the pistachio fruit accumulates approximately 80% of its final dry weight (Fig. 3A). Therefore, the period of shell hardening, associated traditionally to stage II in pistachios (Goldhamer, 1995) is, in fact, made up of two phases, one with only shell hardening and the other with both processes; shell hardening and kernel growth. Even the role that the shell hardening can play in pistachio water stress tolerance is still unknown. The fact that it could be related to water stress tolerance opens the way to the possibility of a longer water stress period during the growth cycle.

Chalmers et al. (1981) showed that the water stress during stage II in peaches has no effect on the final yield, as there is a stagnation in the dry matter accumulation. Goldhamer and Beede (2004) found that Stage II was also a stress tolerant period in pistachio trees, as it had been found for other double sigmoid development fruit crops, such as peach, plum, and nectarine. Contrary to Crane and Al-shalan (1974), they found that dry matter accumulation decrease during stage II as in stone fruits. In Fig. 3B, the dry matter accumulation seems to follow a linear trajectory, no lag phase was observed in dry weight accumulation and no difference between the growth slopes was found between stages (data not shown). The continuous dry matter increase pattern suggests that, although there was a good tolerance reported to stage II, an uncontrolled tree water deficit between stage I and III could affect yield and should be avoided.

4.3. Production

The mean yield for three years was not reduced in T1 and T2 compared to the C treatment. This was achieved with water savings of 40 % in T1 and 45 % in T2, and the water saving of the C treatment must be added. Only in 2012, the yield in the C treatment was higher than in the RDI treatments, caused by a greater number of fruits rather than greater fruits (Table 3). The number of fruits was related to the canopy size, since there was no difference in canopy productivity in this year. In fact, the canopy productivity was higher in the T1 treatment in 2014, according to Monastra et al., 1995 that observed the number of fruit per inflorescence being negatively influenced by high volume irrigation. Therefore, for the same canopy size, the T1 treatment could even reach a higher yield than the control one. This treatment had also higher intensities of characteristic sensory attributes and a greater level of satisfaction among international consumers (Carbonell-Barrachina et al., 2014).

Management practices, especially the irrigation management, are reported to enhance shell splitting (Goldhamer et al., 1987; Kanber et al., 1993). Closed shell nuts can be as low as 5% of the harvested nut load and as high as 60% (Goldhamer, 2012). In this study, the percentage of split fruits in fresh weight ranged from 46 to 80% and non-split fruits went from 16 to 41 %. Both percentages were related to yield and were not statistically different between irrigation treatments (Table 4).

The amount of water applied during stage II for T1 and T2 (Ψ_{stem} threshold of -1.5 and -2.0 MPa) was equivalent to 40, 10 and 4% of ET_c in 2012, 2013 and 2014 for T1 and 18, 1.6 and 4% of ET_c for T2. Goldhamer and Beede (2004), imposed a stress of 0, 25 and 50% of ET_c during the stage II of fruit growth and no effect of any water regime on kernel weight and split nut percentage was observed either. However, a trend toward lighter nuts when stage II irrigation was totally eliminated was mentioned. In the T2 treatment, the water inputs were practically eliminated during stage II; however

no reduction of kernel weight was observed. The little amount of water supplied during stage II could have been sufficient to prevent this effect. Ψ_{stem} thresholds reached by T1 and T2 during stage II seem to be tolerated by pistachio trees during this stage, since it does not affect this yield component.

The kernel weight of split fruits was heavier than the kernel weight of non-split fruits in many occasions (Table 4). These results support the hypothesis presented by Nevo et al. (1974) stating that there were no structural differences between the two types of nuts, suggesting the possibility that physical forces, exerted as the drying shell shrinks and encounters resistance from the kernel, may be responsible for inducing endocarp dehiscence. However, if physical forces were the only cause of nut dehiscence, this trend should be generalized in the study amongst all treatments and all years, since the splitting percentage was not enhanced by any water regime. Crane and Iwakiri (1982) and Crane (1986) presented a different approach considering the shell dehiscence as a result of biochemical factors produced by the growing embryo that activated a dehiscence response in the endocarp. On the other hand, Polito and Pinney (1999) based the dehiscence process on two distinct events; the first is driven by kernel growth and enlargement and is responsible for the longitudinal dehiscence; the second is responsible for apical dehiscence and may result from the developmentally mediated cell-separation processes. Although the dehiscence process mechanisms are still little known, the physical forces seem to play a role in the dehiscence process, since heavier kernels generate a major percentage of split fruits (Table 4).

4.4. Rootstocks

The effect of rootstock was not significant in any of the years. But water relations in *P. intergerima* showed clear changes in g_i and Ψ_{stem} during stage II. Trees with this rootstock tended to show greater g_i and lower Ψ_{stem} during stage II (Figs. 7 and 8). Such results could be related to root distribution, in length and density, which could increase water and nutrient uptake (Ferguson et al., 2005); and with root to shoot signal, which could change the g_i and Ψ_{stem} response. It is widely known that stomatal closure is strongly regulated by abscisic acid and cytokinins and auxins relation (Tanaka et al., 2006). Cytokinins are produced in roots; therefore a rootstock with a high production of cytokinins would produce a lower stomatal closure. Then, a high concentration in cytokinins made the trees growth faster and with a higher yield, at least during the first years of production. Ferguson et al., (2005) reported that in trees on *P. integerrima* the yield was a 20% higher than on *P. atlantica* in fully irrigated conditions. The lower weight and diameter of split kernel on *P. integerrima* can be caused by the lower Ψ_{stem} , since growth is the most sensitive parameter to water stress (Hsiao, 1973). The minor percentage of split fruits could be due to the lower weight of split kernel, since a physical effect may be partially responsible for inducing endocarp dehiscence.

P. atlantica fruits had a higher growth than others rootstocks, then when fruits reached its genetically regulated size, the size amongst rootstocks becomes more even. Although in the mean yield there were no significant differences, *P. atlantica* showed the highest yield with significant differences in 2013 and 2014 per volume unit. Due to the relationship between yield and percentage of dropped buds, the high yield in 2013 produced a high percentage of dropped buds.

The differences with Ferguson et al., (2005) that recorded a higher yield in *P. integerrima* than *P. atlantica*, can be caused by the worst physiological status of *P. integerrima* during most of the season.

5. Conclusions

Efficient irrigation management requires an accurate quantification of the tree water needs. Under fully irrigated conditions, the pistachio stem water potential seems to be mainly governed by VPD, the found relationship between Ψ_{stem} and VPD could be a useful for pistachio irrigation. When Ψ_{stem} measurements were used for irrigation scheduling under drip irrigation, the K_c decreased and it was quantified to about 18% of water saving compared to the typically used K_c for pistachio trees.

The RDI was successfully assessed in shallow soils with drip irrigation systems by means of Ψ_{stem} measurements satisfying the fundamental requirements of the technique by reducing the vegetative growth without affecting yield or yield quality. A Ψ_{stem} threshold of around -1.5 MPa could be recommended as stress level during stage II for pistachio trees that does not reduce yield or causes any undesirable effects. A stem water threshold of -2.0 MPa seems to be tolerated by pistachio trees during stage II, as the yield was not affected. The influence of this stress level on g_i indicates that a long term stress could be detrimental for pistachio production.

Even though there is a generalized association between stage II in pistachio and shell hardening, the shell hardening process actually takes place until the middle of stage III. The sum of the different histological process involved in the fruit growth causes the pistachio dry matter accumulation to show a linear behaviour.

Pistachio tree seems to be more sensitive to water stress during high bearing years, having a more pronounced tendency to lower Ψ_{stem} and to delay the recovery. Also the kernel weight and percentage of split fruits were inferior in ON than OFF years. These two parameters seem to be strongly correlated, which led to suggest that fruit dehiscence is partially caused by mechanical effects.

P. integerrima does not have a good acclimation to the edaphoclimatic conditions of the zone, with the worst physiological status. Although there were not significant differences in the response between *P. terebinthus* and *P. atlantica*, the latter seems to have better potential to reach a higher productivity.

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