Agricultural Water Management 202 (2018) 263–270

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Influence of rootstock on pistachio (*Pistacia vera* L. cv Kerman) water relations

A. Moriana[a], H. Memmi[b], A. Centeno[c,*], M.J. Martín-Palomo[a], M. Corell[a], A. Torrecillas[d], D. Pérez-López[c]

[a] Dpto de Ciencias Agroforestales, ETSIA, University of Seville, Crta de Utrera s/n, 41013 Seville, Spain
[b] CA "EL Chaparrillo", IRIAF, Crta de Porzuna, Km 4, 13071 Ciudad Real. Spain
[c] Departamento de Producción Agraria, ETSIAAB, Universidad Politécnica de Madrid, Ciudad Universitaria s/n, 28040 Madrid, Spain
[d] Dpto. Riego, Centro de Edafología y Biología Aplicada del Segura (CSIC), P.O. Box 164, E-301000 Espinardo, Murcia, Spain

ARTICLE INFO

Article history:
Received 24 July 2017
Received in revised form
19 December 2017
Accepted 25 December 2017
Available online 10 January 2018

Keywords:
Pistacia atlantica
Pistacia terebinthus
Drought resistance
PV curves
UCB-I

ABSTRACT

Selecting the rootstock in pistachio orchards is one of the most critical decisions, mainly in conditions of water scarcity. However, there are a few works that report the response of pistachio to water stress according to rootstock. Nowadays, UCB-I is one of the most important rootstock around the world. However, its commercial availability and high prices favour the selection of *Pistacia terebinthus* L. or *Pistacia atlantica* Desf. in some regions. The aim of this work is to study the water relations of these three rootstocks using cv Kerman as scion. Thirty pots, in the second year after budding, were subjected to a 28-days water stress period in outdoor conditions. Irrigation was stopped in the water stress treatments during all the 28 days period. The vegetative response was characterised at the end of the experiment. The diameter of the rootstock and scion, number of leaves and the percentage of leaves, trunk and root were measured. Along the experiment water relations parameters such as midday water potential and midday leaf conductance was measured. In order to compare the effect of rootstock and water stress pressure-volume curves were measured before and after the water stress period. Data of vegetative growth suggest that UCB-I was the rootstock less affected for water stress, because these data were not clearly affected. However, water relations parameters suggest that *P. atlantica* was the most resistant to water stress conditions, according to the results derivate from the pressure-volume curves. Possible mechanisms of response to water stress are discussed.

1. Introduction

Pistachio trees (*Pistacia vera* L.) are a very drought and salinity resistant species (Behboudian et al., 1986). Although in the main world pistachio producing countries (USA and Iran), orchards are irrigated, in other countries such as Spain, rainfed conditions are not uncommon. Even in irrigated orchards, some periods of water stress could occur due to water scarcity or deficit irrigation schedules. In addition, the difficulty of pistachio species to root by cutting, make grafting the only reliable method to propagate the trees. Therefore, the combination of rootstock and scion could be used to change the drought resistance capacity in the orchard, affecting the irrigation water management. There are several rootstocks widely used around the world and their selection is, sometimes, more dependant on availability than on the actual information about their agronomical aptitude. *Pistacia terebinthus* L. is the most common in Australia, Italy, Spain and Greece (Couceiro et al., 2013). These regions are characterized for having new orchards, probably with a limitation in plant availability, such as Australia and Spain, and very local and old production, such as Italy and Greece. *P. terebinthus* is considered one of the least vigorous yet most resistant to cold pistachio rootstocks (Ferguson et al., 2005). *Pistacia atlantica* Desf. is native of North Africa and was the main rootstock in the early orchards in California (Ferguson et al., 2005). *P. atlantica* is an intermediate rootstock in terms of vigour and cold resistance, but it is very sensitive to Verticilium wilt, thus it is not used as rootstock in USA nowadays (Ferguson et al., 2005). UCB-I is an interspecific hybrid with closed pollination of *P. atlantica* and *Pistacia integerrima* Steward ex Brandis. Currently, UCB-I is one of the most important rootstocks in the USA. UCB-I is more vigorous than *P. atlantica*, which is the least susceptible to Verticillium wilt, while showing the least tolerance to cold among these three rootstocks (Ferguson et al., 2005).

* Corresponding author.
E-mail address: ana.centeno@upm.es (A. Centeno).

https://doi.org/10.1016/j.agwat.2017.12.026
0378-3774/

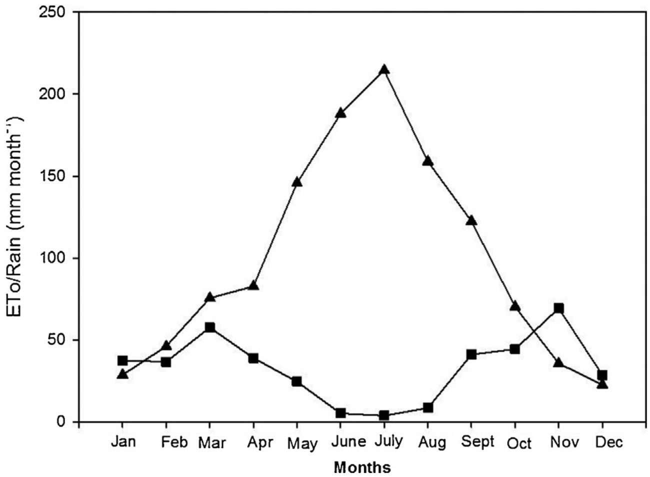

Fig. 1. Annual pattern of rainfall, squares, and reference evapotranspiration, triangles (mm month-1) in Ciudad Real (Spain). Each point is the average of 5 years (from 2012 to 2016).

Source: Servicio de Información Agroclimática para el Regadío. Spanish Agriculture, Food and Environment Ministry (www.siar.es). Own development.

Knowledge about the influence of rootstocks in the water relations of pistachio trees is very scarce. Gijón et al. (2010), in a potted experiment, compared the response of *P. atlantica*, *P. terebinthus* and interspecific hybrid (*P. atlantica* x *P. vera*) to water stress. These authors concluded that *P. atlantica* was the most susceptible to water stress, although they pointed out that these results could not be considered conclusive due to problems in the development of the trees grafted on *P. atlantica.* Ferguson et al. (2002), in a salinity potted experiment, compared the response of *P. atlantica*, UCB-I and *P. integerrima*. They concluded that *P. integerrima* was more sensitive to salinity than *P. atlantica* and UCBI, which showed a very similar response. They also reported that the leaf conductance of *P. atlantica* was not affected by the salinity stress, suggesting a high resistance to these conditions, while it declined around 15% in the other two rootstocks. These results disagree with the ones obtained by Gijón et al. (2010), particularly when considering that both experiments were performed with the same scion (cv. Kerman). Mehdi-Tounsi et al. (2016), using cv Mateur on *P. atlantica* and *P. vera,* also suggested a greater salinity resistance of the former. Rootstock trials in irrigation orchards of California, reported that cv Kerman is more productive on UCB-I than *P. atlantica* (Ferguson et al., 2005). In rainfed experiments in Spain, also with cv Kerman, *P. atlantica* presented a greater cumulative yield after 12 years than *P. terebinthus* (Couceiro et al., 2013).

The selection of the suitable rootstock is very important, particularly in limited water conditions, however only indirect information about the water relations and drought resistance is available. The aim of this work was to study the response of the three rootstocks (UCB-I, *P. atlantica* and *P terebinthus*) commonly used in pistachio orchards in the Mediterranean basin to water stress.

2. Material and methods

2.1. Site description and experimental design

The experiment was conducted during the summer of 2013 at "La Entresierra" Research Station, Ciudad Real, Spain (3° 56′ W, 39° 0′ N; altitude 640 m) in outdoor conditions. Ciudad Real is a city located in the center of Spain. Climate is semiarid, values of reference evapotranspiration (ETo) are higher than rainfall during 9 months in the year (Fig. 1). Rainfalls occur mainly during autumn and winter with dry summer, the average annual rainfall is around 400 mm (Fig. 1). ETo is very high in summer with values around 200 mm month^{-1} in June, July and August. Thirty potted pistachio plants with two-year of age (*Pistacia vera* L. cv Kerman) were budded onto three different rootstocks, *Pistacia atlantica* Desf., *Pistacia terebinthus* L. and UCB-I. Trees grew in 50 L pots filled with a mixture of gravel, sand and peat (5, 80, and 15% respectively). The experiment took place from day of the year (DOY) 178 until DOY 246 and consisted in the implementation of 28 days of water stress to half of the pots (from DOY 200 to DOY 228). Each pot had 4 drippers (4 Lh^{-1}) and was irrigated until slight drainage occurred. During the period of irrigation treatment (from DOY 200–228), stress trees were no irrigated. The experimental design was a split-plot with 5 replicates. The main factor was the rootstock and the secondary factor was irrigation. The different combination of the two factors will be named as follows: *P. atlantica*-control (ATL-C); *P. atlantica*-stress (ATL-S); *P. terebinthus*-control (TER-C); *P. terebinthus*-stress (TER-S); UCB-I-control (UCB-I-C); UCB-I-stress (UCB-I-S).

2.2. Water relations

The water relations were measured using midday stem water potential, leaf conductance and pressure-volume curves. The stem water potential was measured weekly between 12:00 and 02:00 p.m. in leaves covered with aluminium foil for at least 1 h before their removal. Measurements were made for one leaf per tree using a pressure chamber (Soil Moisture Equip., Santa Barbara, CA, U.S.A.). As pistachio leaves exude turpentine, a piece of blotting paper was used to determine the end point; turpentine cannot moisten blotting paper but the xylem contents can. The abaxial leaf conductance (gl) was measured with a steady-state porometer (Model LICOR-1600, U.K.) between 12:00–02:00 p.m. at the central foliole of three sunlit leaves the same dates than water potential measured was performed.

Pressure-volume curves (PV curves) were prepared before and at the end of the stress period. Three leaves per treatment were collected at predawn, placed immediately in plastic bags and taken to the laboratory. There, they were rehydrated for 1 h by covering the leaf and placing the cut end of the petiole under water. A pressure chamber was used to measure the leaf water potential. Before placing them in the pressure chamber, each leaf was wrapped in moist cheesecloth, placed in a black plastic bag and weighed (Hsiao, 1990). The actual fresh weight of each water potential determination was assumed to be the leaf weight measured immediately before the insertion of the leaf in the pressure chamber. Periodic measurements of fresh weight and water potential were taken until the water potential value reached close to −3.5 MPa. Then leaves were dried. Pressure-volume curves were generated by the free transpiration method (Hinckley et al., 1980) and 1/water potential was plotted versus relative water content (RWC). RWC was calculated as the ratio between the differences of actual fresh weight and dry weight vs full rehydrated and dry weight. The zero turgor point was determined using a graphical analysis, considering the lineal portion of the curve. It was calculated with the experimental points that resulted in the maximum determination coefficient (R^2) of the lineal regression. The parameters derived from each curve were: osmotic potential at full turgor (PSI_f), osmotic potential at zero turgor (PSI_0), relative water content at zero turgor (RWC_0) and percentage of the symplastic water content (R) and tissue elasticity (Eo).

Data from the PV curves were used to obtain the relationship between the natural logarithms of osmotic potential (independent variable) and the RWC. This relationship provided the osmotic adjustment index (OA index) and the breaking point (BP) (Turner, 2006). The OA index is 1 minus the slope of the lineal relationship. The OA index varies between 0 and 1, and it is an estimation of the

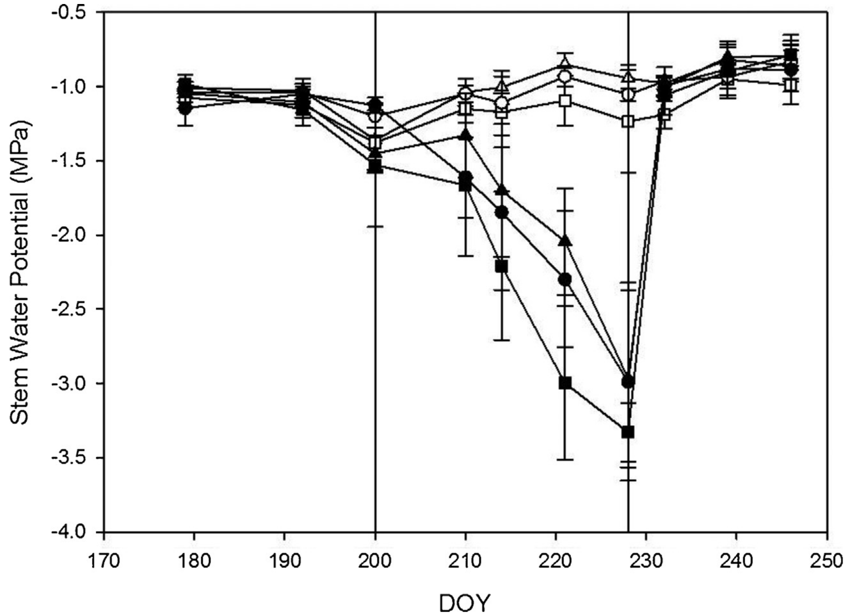

Fig. 2. Pattern of midday stem water potential during the experiment. Each point is the average of 5 data. Vertical bars represent the standard deviation. Vertical lines indicate the period of water stress. Empty symbols are fully irrigated trees. Full symbols are stressed trees. Triangles, squares and circles are P. atlantica, P. terebinthus and UCB-I rootstocks, respectively.

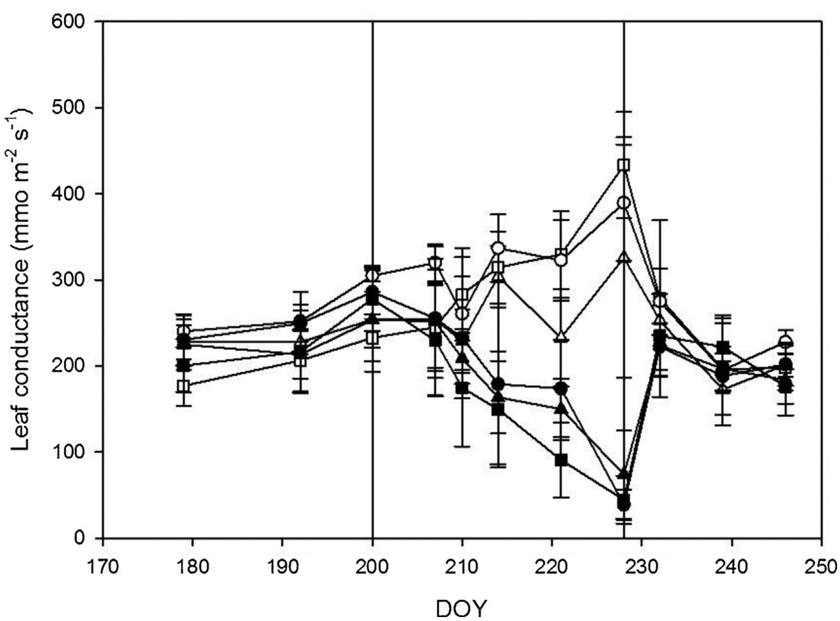

Fig. 3. Pattern of leaf conductance during the experiment. Each point is the average of 10 data. Vertical bars represent the standard deviation. Vertical lines indicate the period of water stress. Empty symbols are fully irrigated trees. Full symbols are stressed trees. Triangles, squares and circles are P. atlantica, P. terebinthus and UCB-I rootstocks, respectively.

degree of osmotic adjustment. The second parameter derived by Turner (2006) is the breaking point (BP). The relationship between the natural logarithms of osmotic potential and the RWC may be constant with no decrease in RWC until a threshold value (BP) is reached, from which that relationship becomes linear. Lower values of BP mean higher capacity of drought resistance.

2.3. Additional measurements

The number of leaves was counted at the beginning and at the end of the experiment. In order to eliminate the variability between trees, the relative increment of the number of the leaves was considered. The initial value was 100%.

The diameter of the rootstock and the scion was measured just before the beginning of the water stress period, at the end of the water stress period and at the end of the experiment.

At the end of the experiment, the trees were removed of the pot and the root system was cleaned. Each tree was separated into roots, trunk and leaves. These three parts were weighed fresh and dried until constant weight at 70 °C. Data were considered as a percentage of the total fresh or dry weight.

2.4. Statistical analysis

Statistical analyses of variance and Tukey test (SX 8.0, Analytical software) were performed for treatment comparison. Percentage

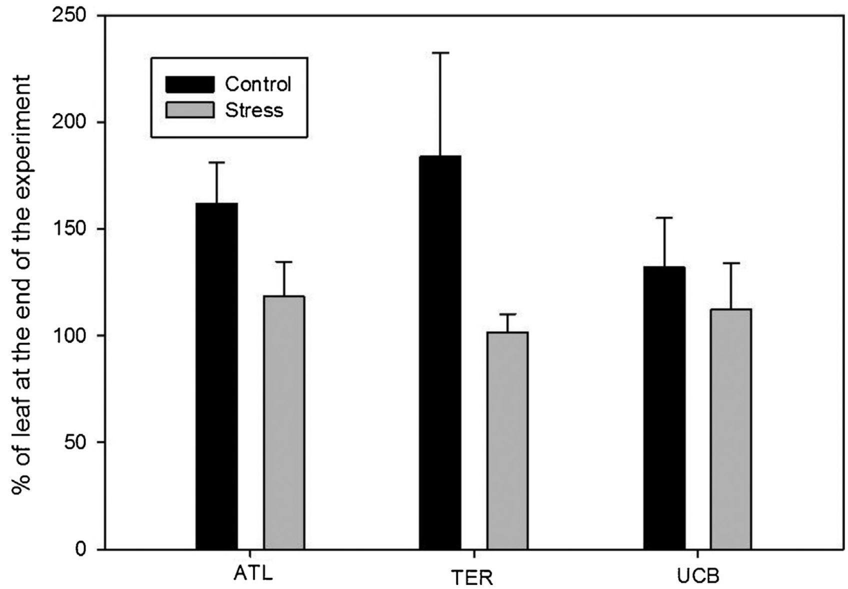

Fig. 4. Percentage of the number leaves at the end of the experiment. 100% represents the number at the beginning of the experiment. Each bar is the average of 5 measurements. Vertical lines represent the standard deviation. ATL, P. atlantica; TER, P. terebinthus; UCB, UCB-I. Significant differences are explained in the text.

data were transformed using the arcsin function. Treatment differences were considered statistically significant at $P < 0.05$.

3. Results

Irrigation and rootstock treatments affected the water potential. Fig. 2 shows the midday stem water potential throughout the experiment. The rootstock factor was significant in different dates of the experiment: on day of the year (DOY) 200, 221, 232 and 239. In these four dates, *Pistacia terebinthus* (TER) were significantly the lowest, while UCB-I and *Pistacia atlantica* (ATL) were usually no different (only on DOY 200, UCB-I was significantly higher than ATL). The irrigation factor was also significant only during the period of water stress conditions on DOY 210, 214, 221, 228. Significant differences between control and trees subjected to stress were found after 10 days of the beginning of the irrigation restriction, but these differences disappeared four days after rehydration, on the first date of measurement. During the period of water stress, the midday stem water potential varied from −1.0 MPa to values slightly lower than −3.0 MPa. The interaction irrigation*rootstock was not significant on any of the dates.

The leaf conductance was also affected by the irrigation and the rootstock (Fig. 3). The effect of the rootstock was more limited than in water potential data and it only was significant on DOY 200 and 246, for the entire water stress period. On both dates, the UCB-I was significantly higher than the ATL, but only higher than the TER on the last date. The irrigation treatments were significantly different for the same period as water potential, on DOY 210, 214, 221 and 228. The leaf conductance presented a higher variability than the water potential. Maximum values were measured at the end of the water stress period (around 400 mmol m^{-2} s^{-1}) while the minimum ones were around 40 mmol m^{-2} s^{-1}. The interaction irrigation*rootstock was significant only on DOY 221. But the TER tended to present a more severe stomatal closure in comparison to the other two rootstocks throughout the water stress period.

The final number of leaves is presented as percentage of the total number at the beginning of the experiment (Fig. 4). These data were not affected significantly by the rootstock factor. The variability was very high and there were no clear trends. However, the effect of irrigation was significant. In stressed trees, all the rootstocks presented values around 100%, therefore the increase in the number of leaves was almost low, while in control trees, the number of leaves increased from 30 to 80%. The interaction irrigation*rootstock was not significant, likely due to the great variability. However, there was a clear trend towards a greater increase in control UCB-1 than in control TER.

Fig. 5 shows the diameter growth rate for the rootstock and the scion in the three periods of the experiment (two of irrigation and one of water stress). The rootstock growth (Fig. 5a) was not significantly affected by the type of rootstock in any of the periods considered and this was likely due to the great variability between trees. In the periods with no water stress, ATL tended to show rates higher than UCB-I. The irrigation had a significant effect during the period of water stress. In this period, the growth rate decreased sharply in stress trees for all the rootstocks. Although the interaction irrigation*rootstock was not significant, there was a clear trend towards a greater reduction of the growth rate in TER and, especially, UCB-I rootstocks in comparison with ATL during the period of water stress. Similar results were obtained when the scion growth rate was considered (Fig. 5b). The scion growth was higher than the rootstock growth (Figs. 5b vs 4a). The rootstock had no significant effects on this parameter in any of the periods. However, the irrigation had a considerable impact, albeit only during the period of water stress. The scion growth decreased in all the rootstocks. The interaction irrigation*rootstock was not significant and, in this case, there were no clear trends.

The distribution of assimilates at the end of the experiment in leaves, trunk and roots was affected by the rootstock and the irrigation treatment (Fig. 6). In all the treatments, both in fresh and dry weight, the trunk represents more than 50% of the total weight (Fig. 6). The rootstock effect on the fresh weight (Fig. 6a) was significant and ATL presented the greatest percentage in leaves (31%) and trunk (58%), while the lowest was shown in roots (11%). UCB-I and TER rootstocks were not substantially different, with around 20% in leaves, 50% in trunk and 30% in roots. The irrigation treatment was also important in leaves and roots, but not in the trunk. Water stress conditions reduced the weight of leaves but increased that of roots in all the rootstocks. Although the trunk percentage was not statistically affected, there was a slightly trend towards a reduction in all rootstocks in conditions of water stress. The interaction irrigation*rootstock was not significant. However, there were clear trends of a greater decrease of leaves and increase of roots in ATL

Table 1
Parameters of the PV curves during the period with no stress conditions for the six different treatments. Relative water content at turgor loss point (RWC_0, %), Osmotic water potential at turgor loss point (PSI_0, MPa), Osmotic potential at full turgor point (PSI_f, MPa), Elastic modulus (MPa), Symplastic water content (%), Osmotic adjustment index (OA), Breaking point (BP, MPa). Each figure is the average ± standard deviation of three measurements. Sig. effect shows the significant effect in each variable: R, rootstock, "ns" no significant. Between brackets the average separation.

	RWC_0	PSI_0	PSI_f	E_0	R	OA	BP
ATL-C	85.2 ± 1.1	−2.8 ± 0.2	−2.4 ± 0.3	12.2± 6.4	35.2 ± 17.3	0.4 ± 0.2	−2.0 ± 0.2
ATL-S	84.7 ± 1.1	−2.9 ± 0.4	−2.4 ± 0.4	12.1 ± 13.3	34.1 ± 19.3	0.4 ± 0.2	−2.2 ± 0.3
TER-C	87.8 ± 0.1	−2.4 ± 0.6	−1.9 ± 0.6	14.1 ± 14.7	48.1 ± 15.2	0.6 ± 0.2	−1.8 ± 0.7
TER-S	87.6 ± 1.3	−2.7 ± 0.1	−1.8 ± 0.1	6.8± 5.9	63.0± 6.9	0.7 ± 0.1	−1.8 ± 0.1
UCB-I-C	87.3 ± 1.3	−2.7 ± 0.1	−2.2 ± 0.2	14.3 ± 3.7	30.9 ± 16.9	0.2 ± 0.3	−2.3 ± 0.3
UCB-I-S	92.4 ± 4.0	−2.3 ± 0.4	−2.0 ± 0.2	13.7 ± 3.2	45.3 ± 14.0	0.4 ± 0.1	−2.2 ± 0.3
Sig effect	R (aabb)	ns	ns	ns	ns	ns	ns

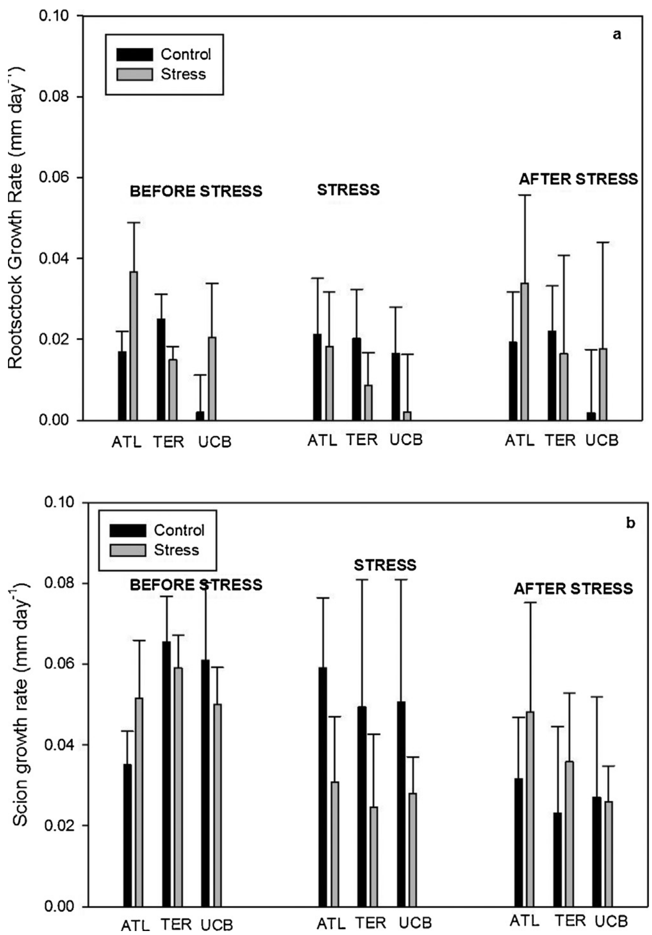

Fig. 5. Diameter growth rate of the rootstock (a) and the scion (b) during the three periods in which the experiment was divided. Each bar is the average of 5 data. Vertical lines represent the standard deviation. ATL, P. atlantica; TER, P. terebinthus; UCB, UCB-I. Significant differences are explained in the text.

and TER than in UCB-I, which remained almost constant. The results in dry weight were similar (Fig. 6b). The effect of rootstocks was important only in the percentage of leaves and roots. ATL presented a percentage of dry weight greater in leaves and lower in roots than TER and UCB-I, which were similar. UCB-I tended towards a slightly lower percentage in leaves and higher in roots than TER. The rootstock did not have a major impact on the percentage of trunk dry weight, although ATL tended towards higher values than the rest. Additionally, the irrigation was important only in the percentage of leaves and roots dry weight. Water stress reduced the percentage of leaves dry weight and increased that of roots, with no impact on the percentage of trunk dry weight. The interaction irrigation*rootstock was not significant. However, there were clear trends of greater decrease of leaves and increase in roots in ATL and TER than in UCB-I, which was almost constant.

Ratio between shoots and roots dry weight at the end of the experiment are presented at Fig. 7. Shoots is the sum of leaves and trunk weight. The effect of rootstock, irrigation treatment and the interaction between them was significant. Rootstock ATL presented a significant greater ratio than the other two. Water stress conditions reduced the ratio in all rootstocks significantly. Such reduction was greater in ATL than in the other two rootstocks. ATL reduced around 50% this ratio, while UCB and TER presented a similar reduction with only 24% and 30% respectively.

Data of the pressure-volume curves (PV curves) obtained during the period of no stress are presented at Table 1. Differences were only considerable in the relative water content at the turgor loss point (RWC_0) and only due to the rootstock effect. The ATL rootstock presented a substantially lower RWC_0 than UCB-I, while TER was similar for both rootstocks. ATL presented a RWC_0 of 85%, while UCB-I was 90%. There were no major differences in the rest of parameters, although some trends could be considered. The water potential at turgor loss point (PSI_0) tended towards lower values in ATL, −2.85 MPa, than the other two rootstocks, around −2.50 MPa. Also, the osmotic water potential at full turgor (PSI_f) was clearly lower in ATL than in the rest (-2.4 MPa vs values slightly higher than −2.0 MPa). No clear trends could be identified in elastic modulus (E_0) and symplastic water (R). The osmotic adjustment index (OA) and the breaking point (BP) were both slightly higher in TER than in ATL and UCB-I, suggesting a faster and more intensive osmotic adjustment.

Data of PV curves during water stress period are presented in Table 2. The effect of rootstock was not substantial in this period, but that of the irrigation treatment was. The relative water content at turgor loss point (RWC_0), the osmotic potential at full turgor (PSI_f) and at turgor loss point (PSI_0) and the breaking point (BP) were lower in stress trees than in control trees for all rootstocks. The interaction rootstock*irrigation was not major, but there were clear trends suggesting a different response to stress according to the rootstocks. The PSI_0 decreased more clearly in TER than in ATL or UCB-I, while the reduction in PSI_f, OA index and BP was slightly higher in ATL than in the other two. On the other hand, UCB-I tended towards higher values of RWC_0, PSI_0, PSI_f and BP than TER and ATL. No clear results were obtained for the E_o and R data.

4. Discussion

The response of pistachio trees to water stress during the experiment consisted of a great reduction in the water potential and leaf conductance, with a severe level of dehydration (Figs. 2 and 3). Such level of dehydration reduced the vegetative growth, with a very low increase in the number leaves (Fig. 4) and the diameter growth (Fig. 5) during the water stress. But this affection of the vegetative growth promoted the increase of the root weight (Fig. 6). Pistachio is considered very resistant to water stress and

Table 2
Parameters of the PV curves during the period with water stress conditions for the six different treatments. Relative water content at turgor loss point (RWC_0, %), Osmotic water potential at turgor loss point (PSI_0, MPa), Osmotic potential at full turgor point (PSI_f, MPa), Elastic modulus (MPa), Symplastic water content (%), Osmotic adjustment index (OA), Breaking point (BP, MPa). Each figure is the average ± standard deviation of three measurements. Sig. effect show the significant effect of each factor: S, stress treatment, "ns" no significant differences.

	RWC_0	PSI_0	PSI_f	E_0	R	OA	BP
ATL-C	84.5 ± 1.9	−2.7 ± 0.1	−2.0 ± 0.2	7.9 ± 7.1	35.0 ± 2.7	0.4 ± 0.0	−2.0 ± 0.2
ATL-S	78.8 ± 5.0	−3.3 ± 0.4	−2.4 ± 0.1	4.8 ± 5.1	20.7 ± 4.9	0.3 ± 0.0	−2.4 ± 0.1
TER-C	88.8 ± 0.0	−2.3 ± 0.2	−2.0 ± 0.2	27.0 ± 12.2	17.2 ± 8.1	0.2 ± 0.1	−2.0 ± 0.2
TER-S	78.8 ± 8.8	−3.3 ± 1.0	−2.2 ± 0.2	17.5 ± 15.6	24.0 ± 18.1	0.2 ± 0.4	−2.3 ± 0.4
UCB-I-C	89.6 ± 0.8	−2.2 ± 0.1	−1.7 ± 0.1	9.7 ± 4.2	48.8 ± 21.3	0.6 ± 0.2	−1.7 ± 0.1
UCB-I-S	82.9 ± 2.0	−2.7 ± 0.2	−2.0 ± 0.1	5.3 ± 3.8	36.7 ± 14.2	0.5 ± 0.2	−1.9 ± 0.2
Sig effect	S	S	S	ns	ns	ns	S

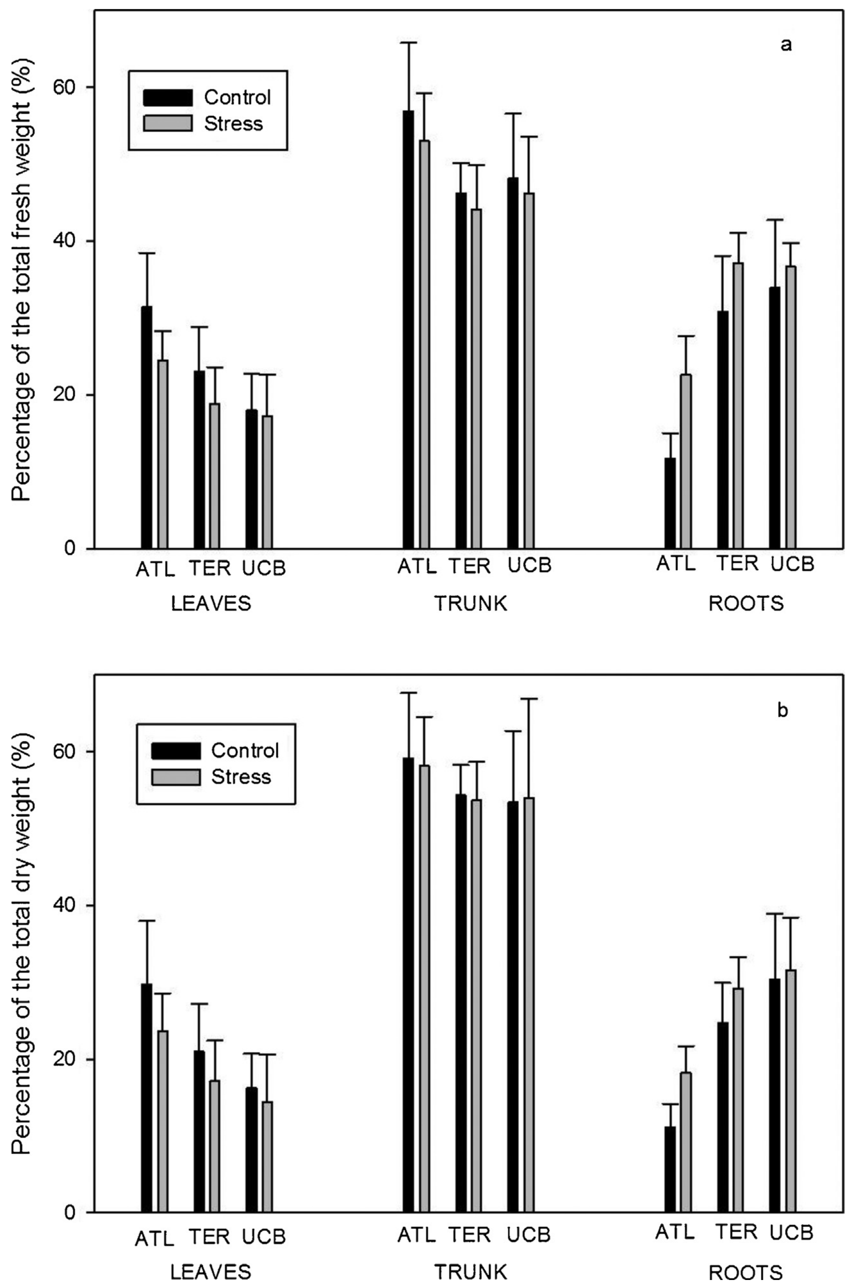

Fig. 6. Percentage of the total weight of leaves, trunk and roots in fresh (a) and dry (b) weight. Each bar is the average of 5 trees. Vertical lines represent the standard deviation. ATL, P. atlantica; TER, P. terebinthus; UCB, UCB-I. Significant differences are explained in the text.

salinity conditions, and very high levels of dehydration have been reported (Behboudian et al., 1986). The growth is known to be a process very sensitive to wager stress conditions (Hsiao, 1990). The rehydration capacity is also very important in this species and the water potential and leaf conductance were quickly recovered (Figs. 2 and 3).

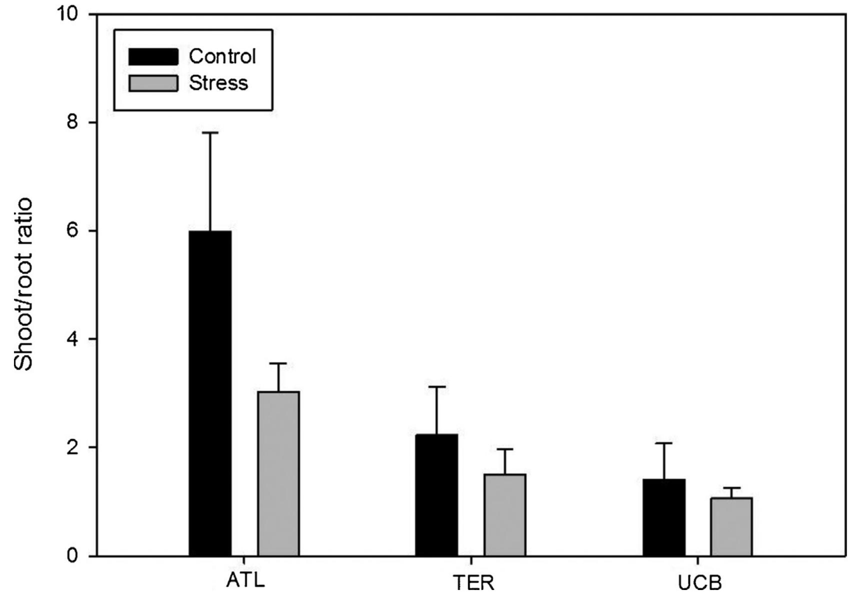

Fig. 7. Shoot to root ratio in dry weight. Shoot is the sum of leaves and trunk. Each bar is the average of 5 trees. Vertical lines represent the standard deviation. ATL, P. atlantica; TER, P. terebinthus; UCB, UCB-I. Significant differences are explained in the text.

The data for vegetative growth and water relations suggest that there are different mechanisms of response to water stress based on the rootstock. During the water stress period, TER tended towards higher levels of dehydration and reduction of leaf conductance than ATL and UCB-I (Figs. 2 and 3). The differences in the number of leaves was also greater in TER (Fig. 4) but the maximum reduction in the rootstock diameter occurred in UCB-I (Fig. 5a), with no differential effects measured in the scion diameter (Fig. 5b). According to these results, UCB-I would be the most tolerance to water stress, because the vegetative growth of the scion (number of leaves and diameter) was almost constant for this rootstock, even when the water stress level was the same than other rootstocks. TER would be the most sensitive due to the greatest reduction in leaf conductance and number of leaves. Memmi et al. (2016a,b) suggested that TER is more sensitive than ATL, but Gijón et al. (2010) reported the opposite. The work produced by Gijón et al. (2010) was carried out with pots and they reported that the ATL size was smaller than TER, which could affect the conclusions. Potted experiments could limit in their conclusions because of limited space for root growth, which could affect to water relations. In addition, the speed and level of water stress would be also higher than in field conditions which could change the trees physiological response and, therefore, the rootstock effect. Couceiro et al. (2013) in rainfed field conditions reported a higher average and cumulative yield in ATL than TER for mature trees. Ferguson et al. (2005) reported that UCB-I was less tolerant to salinity but more productive than ATL in irrigated conditions. Although salinity and water stress are similar, the response of the trees could be different to each stress and not directly comparable.

These variations in water stress response are likely related with different adaptations. According to the PV curves (Tables 1 and 2), ATL were the most resistant rootstocks (significantly lower RWC_0, trends to lower PSI_0 and PSI_f in no water stress conditions). The PV curves also suggest that TER presented a more efficient osmotic adjustment than the rest of the rootstocks because, in conditions of no stress, the OA index and the BP tended towards slightly higher values than UCB-I or ATL (Table 1), such result is confirmed by the lower PSI_0 in water stress conditions (Table 2). The osmotic adjustment is a process that delays the effect of water stress in the plant physiology, but it is not imply higher levels of resistance. Therefore, these data suggest two different ways for water stress tolerance mechanisms. ATL was more resistant than TER as their PV curves showed though the percentage of root weight was clearly lower. Probably, the absorption capacity of the roots in ATL was higher than in TER. In addition, in water stress conditions, ATL increased the root weight greatly and, even though the root weight was still slightly lower than in TER (Fig. 6), the reduction in water potential, leaf conductance and number of leaves in TER was higher (Figs. 2–4). The greater capacity of osmotic adjustment of TER over ATL could only offset the low level of water stress. None of the PV curves indicators analysed suggested that UCB-I was the most resistant, although according to the vegetative response, it could be. Only the percentage of root weight was clearly higher in UCB-I than in the rest. UCB-I is an interspecific closed hybrid of *Pistacia atlantica* and *Pistacia integerrima* Steward ex Brandis. Because *Pistacia atlantica* is one of the parents of UCB-I, this hybrid could have also a greater root absorption capacity than TER.

5. Conclusions

Pistachio is a very drought resistant tree that tolerates high levels of tissue dehydration with a quick capacity of rehydration. The data suggest two main mechanisms for this drought resistance. The osmotic adjustment was identified in all the rootstocks, but in TER it happened earlier and with more intensity than in ATL and UCB-I. ATL was apparently the most drought resistant according to parameter of the PV curves and this could be linked to a greater activity of the roots. However, the response of the vegetative growth (number of leaves, diameter of the scion) suggest that UCB-I was even more resistant than ATL. As UCB-I is an interspecific closed hybrid of ATL, and the percentage of root weight was the greatest, a high capacity of water uptake was associated with this conclusion.

Acknowledgement

Spanish Secretary of State of Research, Development and Innovation (SEIDI), (AGL2013-45922-C2-1-R).

References

Behboudian, M.H., Walker, R.R., Törökfalvy, E., 1986. Effects of water stress and salinity on photosynthesis on pistachio. Sci. Hortic. 29, 251–261.

Couceiro, J.F., Guerrero, J., Gijón, M.C., Moriana, A., Pérez-López, D., Rodriguez, M., 2013. El Cultivo Del Pistacho. MundiPrensa, Madrid.
Ferguson, L., Poss, J.A., Grattan, S.R., Brieve, C.M., Wang, D., Wilson, C., Donovan, T.J., Chao, C.T., 2002. Pistachio rootstocks influence scion growth and ion relations under salinity and boron stress. J. Amer. Soc. Hort. Sci. 127, 194–199.
Ferguson, L., Reyes, H., Sanden, B., Grattan, S., Epstein, L., Krueger, B., 2005. Pistachio rootstocks. In: Ferguson, L. (Ed.), Pistachio Production Manual. Center of fruit and nut research and information, Davis, pp. 67–73.
Gijón, M.C., Giménez, C., Pérez-López, D., Guerrero, J., Couceiro, J.F., Moriana, A., 2010. Rootstock influences the responses of pistachio (*Pistacia vera* L. cv. Kerman) to water stress and rehydration. Sci. Hortic. 125, 666–671.
Hinckley, T.M., Duhme, F., Hinckley, A.R., Richter, H., 1980. Water relations of drought hardy shrubs: osmotic potential and stomatal reactivity. Plant Cell Environ. 3, 131–140.
Hsiao, T.C., 1990. Measurements of plant water status. Chap. 9. In: Steward, B.A., Nielsen, D.R. (Eds.), Irrigation of Agricultural Crops, 30. American Society of Agronomy, Madison, pp. 243–279, Agronomy Monograph.
Mehdi-Tounsi, H., Chelli-Chaabouni, A., Boujnah, D., Boukriss, M., 2016. Rootstock influences the response of pistachio (*Pistacia vera* L. cv Mateur) under saline stress conditions. J. New Sci. 3, 1209–12016.
Memmi, H., Gijón, M.C., Couceiro, J.F., Pérez-López, D., 2016a. Water stress thresholds for regulated deficit irrigation in pistachio trees: rootstock influence and effects on yield quality. Agric. Water Manag. 164, 58–72.
Memmi, H., Couceiro, J.F., Gijón, M.C., Pérez-López, D., 2016b. b. Impact of water stress, environment and rootstock on the diurnal behavior of stem water potential and leaf conductance in pistachio (*Pistacia vera* L.). Span. J. Agric. Res., http://dx.doi.org/10.5424/sjar/2016142-8207.
Turner, D.W., 2006. An index of osmotic adjustment that allows comparison of its magnitude across species and experiments. Physiol. Plant 127, 478–482.