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Stem water potential-based regulated deficit irrigation scheduling for olive table trees

Corell, M[1,2], Martín-Palomo, MJ[1,2], Girón, I[2,3], Andreu, L[1,2], Galindo, A. [1,2], Centeno, A[4], Pérez-López, D[4], Moriana, A[1,2]

[1]Universidad de Sevilla, Departamento de Ciencias Agroforestales, ETSIA, Crta de Utrera Km 1. 41013 Seville (Spain) mcorell@us.es

[2] Unidad asociada al CSIC de Uso sostenible del suelo y el agua en la agricultura (US-IRNAS), Crta de Utrera Km 1, 41013, Seville, (Spain)

[3] Consejo Superior de Investigaciones Científicas. IRNAS, Avda Reina Mercedes, 10. 41012 Seville (Spain)

[4] Dpto. Producción Agraria. CEIGRAM-Universidad Politécnica de Madrid. Av. Puerta de Hierro, 2. 28040 Madrid, Spain

ABSTRACT

Regulated deficit irrigation (RDI) involves water stress management in different phenological periods throughout the season. Research in olive trees (oil production) suggested RDI during pit hardening based in pre-dawn and midday stem water potential (SWP) thresholds. However, the previous thresholds may not be extrapolated to table olive because fruit size, a very important feature in the table olive yield quality, is very sensitive to water stress. RDI in table olive deserve further research to determine the optimal water potential thresholds and the duration of the RDI periods for the specificity of the crop (low crop load to promote high fruit size). The aim of this work was to study different RDI schedules during pit hardening, considering different levels and durations of water stress. The experiment was performed in the 2015, 2016 and 2017 seasons, in a commercial mature table olive orchard (cv. Manzanilla) in Dos Hermanas (Seville, Spain). Control treatments were based on midday SWP measurement in order to optimize the water status with values around -1.4 MPa. Two RDI treatments were applied during pit hardening, dated (according to the changes in longitudinal fruit growth) from mid-June to the last week of August) to maintain water potential values around -2 MPa (RDI-1) and -3.5 MPa (RDI-3). Another RDI treatment (RDI-2) received irrigation to maintain values around -3.5 MPa but the recovery was performed at early July in order to obtain different durations of water stress. Irrigation strategies were evaluated with water relations measurements (soil moisture, gas exchange), fruit and shoot growth and quality and quantity yield indicators. Yield was not significantly affected in any of the RDI treatments with an ANOVA analysis. However, fruit drop estimated as the percentage of fruit lost only in the period of water deficit was related with water stress parameters (SWP and stress integral, IS). In addition, the relationship between fruits size and these latter parameters were significant and change according to yield level. Irrigation treatments did not affect next season yield because shoot growth and number of inflorescence at the beginning of each season were not different. RDI effect changed according to yield level, mainly in relation with fruit size. Data suggest that yield levels up to 12 t ha^{-1} were possible to manage RDI without affecting fruit size or reducing commercial quality.

Keywords: Fruit load, fruit size, fruit drop, RDI, water relations, water stress level.

1. Introduction

The water scarcity around the world threat limits irrigation for many crops. In most production areas, water availability in olive orchards is lower than plant requirements and deficit irrigation is common in commercial orchards. In addition, reduction of irrigation could increase orchard profit is quality and quantity yield were not affected. Traditionally, olive irrigation studies based their recommendations in estimations of crop evapotranspiration (ETc) Gucci et al. (2012). Fernández (2014) did a comprehensive review summarising different phenological stages in which drought sensitivity for olive trees is very high and found that these stages were before full bloom, fruit set and before ripening. In the previous work, regulated deficit irrigation (RDI) scheduling was based on those periods and on the percentage of ETc to manage water stress level in the less sensitivity to water stress part of the season (Fernández, 2014). However, in some works, irrigation scheduling with similar ETc reported clear differences in yield in same periods (Lavee et al., 2007; Gómez del Campo, 2013a). Therefore, ETc is not a good approach to manage RDI.

Water status measurements have been suggested for different fruit trees to improve RDI (Steduto et al., 2012). In the last years, several works presented data of stem water potential (SWP), predawn and midday, in almost all phenological stages included in the study by Fernández (2014). Water stress conditions before full bloom are very uncommon because winter rainfall usually allows an almost optimal water status in this period. Moriana et al (2003) reported one season with values of minimum midday SWP around -3 MPa with strong yield reduction and -2 MPa with a moderate reduction. The probability of significant water stress during the period of fruit setting changes according to the orchard location. In southern orchards, this period is dated around Spring (late April and early May in Seville, Spain) and works report that it was very difficult to impose water stress conditions (Moriana et al 2013). But in northern orchards, this period is in early Summer (around July in the northern hemisphere) when periods of water stress are more common. Moderate water stress, around SWP of -2 MPa, reduced endocarp growth, and consequently the fruit size (Toledo, Spain, Gomez del Campo 2013a and Gómez del Campo et al. 2014). Severe water stress affected fruit size and also flower induction in the next season (predawn leaf water potential -3/-4 MPa, Pisa, Italy, Gucci et al 2019). The less sensitivity to water stress phenological stage occurs during massive pit hardening (Goldhamer, 1999) and different water stress levels have been reported in this period. Goldhamer (1999) observed a reduction in yield when predawn leaf water potential reached -1.2 MPa in cv Manzanilla, while no significant differences were found in the same cultivar for a SWP of -2.5 MPa (Moriana et al 2013; Girón et al 2015) or in other oil cultivars (Moriana et al 2003; Iniesta et al. 2009; Gómez del Campo, 2013a; Ahumada-Orellana et al., 2017). In this period, very severe water stress conditions (SWP -7 MPa, Moriana et al 2003; -6 MPa Ahumada-Orelllana et al 2017) reduced yield by 20-30% but did not affect flower induction. The end of this period does not have any morphological indicator and a fixed date at the end of August/early September is used (Fernández, 2014). There are a few works that reported data from this period. Hueso et al (2019) suggested that average SWP around -2 MPa from the end of August until harvest did not reduce yield.

The response to water stress is not always clear and only a few works presented yield or yield components related to water stress level. Gucci et al (2007) and Caruso et al (2013) reported a good agreement between cumulative predawn SWP and oil yield with a linear/parabolic relationship. While Hueso et al (2019) reported a linear decrease of oil yield from -2 MPa of average SWP. All these works presented a great variability between seasons, even when relative values are considered, and part of this variability could be affected by fruit load. Naor et al (2013) reported a very good agreement between yield and fruit load using different equations depending on water stress level. The latter work suggests that yield differences increase with fruit load and when fruit load differences were low, it would be almost null (Naor et al., 2013).

Results relate with the vegetative and fruit growth in RDI strategies explain the yield respond to water stress in the different phenological periods. Olive flowers growth in shoots of previous seasons and alternate bearing of this specie has been related with this process (Rallo, 1997). However, though shoot growth in mature olive is concentrated before pit hardening and is very sensitive to water stress (Gómez del Campo, 2013b), this was enough under a possible moderate water stress such as -1.2 MPa (Moriana et al, 2012). Fruit growth is another important factor in RDI results, mainly in table olive where fruit size is important in the final yield price. Under no water stress conditions, fruit growth was continuous during its development with a linear pattern (Hammami et al., 2011). Moderate water stress conditions after the beginning of pit hardening, around -2 MPa, stopped fruit growth (Girón et al., 2015). But similar fruit sizes to full irrigated trees were obtained with an adequate rehydration (Moriana et al., 2013. Girón et al., 2015) and pulp stone ratio was increased (Girón et al., 2015; Martín-Palomo et al., 2020). Only if this moderate water stress conditions were performed during endocarp growth, before pit hardening, fruit size was not recovered but pulp stone ratio was improving (Gómez del Campo et al., 2014). In addition, significant water stress before pit hardening, reduce fruit size ugh improved pulp stone ratio. Pulp stone ratio has been improved slightly without significant decrease in fruit size with RDI during pit hardening or before harvest (Girón et al., 2015; Martín-Palomo et al 2020). Fruit size is commonly managed in table olive trees with pruning but there is no information about the optimum fruit load because price is very variable between cultivars or even seasons. Effects on other fruit quality parameters in table olive are not commonly reported. Fruit color (evaluated using mature index) was affected but not enough to reduce economical fruit value in green olives even with irrigation restrictions near to harvest (Girón et al, 2015; Martín-Palomo et al., 2020). Moderate water stress conditions decrease bruising (Casanova et al., 2019) and hardness (Martín-Palomo et al., 2020) in table olives which could enhance fruit price. There are no information about long term effect of RDI in physiological olive tree response because irrigation works commonly are performed around 3 seasons. Several authors reported no effect of next flowering season after severe conditions of water stress (Girón et al., 2015; Hueso et al., 2019).

Evaluation of water stress is not easy, though significant relationship between yield and water status were obtained. Water stress labels defined in Naor et al (2013) included water status measurements very variable between seasons and along season. Such disagreement between the water stress target and the actual value measured is usually common (Gucci et al (2007), Moriana et al (2013)). Hsiao (1990) suggested that the real effect of water stress is related to its level and the duration in each phenological stage selected. Then the actual measured level of water stress should be considered in order to evaluate the response to irrigation. Cumulative values of measured SWP could be more useful than average or minimum values (for example, Gucci et al 2007; Caruso et al 2013) although Girón et al. (2015) reported no improvement when using the stress integral instead of minimum SWP.

The aim of this work was to evaluate different RDI strategies during the pit hardening period trying to obtain a wide range of stress integral or minimum which could improve the water stress management in table olive trees. This irrigation management also tries to evaluate the effect of crop load and water stress on fruit size, very important quality parameter in table olive.

2. Material and methods

2.1. Orchard description and irrigation treatments

The experiment was performed during three seasons (2015, 2016 and 2017) in "Doña Ana", a commercial farm located in Dos Hermanas (37º 25′ N, 5º 95′ W, 42 m altitude, Seville, Spain). The orchard presented a loam soil (more than 1 m deep) with a volumetric water content of 0.31 m^3m^{-3} at field capacity and 0.14 m^3m^{-3} at the permanent wilting point. Soil bulk density changed from 1.4 g cm^{-3} in the first 30 cm to 1.35 g cm^{-3} from 30 to 90 cm. The experiment was carried out in a table olive orchard (*Olea europaea* L cv Manzanilla de Sevilla) which in 2015 season was 30 years old and the distance between trees was 7 m between rows and 4 m between trees in each row. Soil management was no tillage with an spontaneous groundcover in the center of the row. The width of vegetation cover was changed along the season (narrower in summer than in winter) and weeds were chemically removed the whole season. Pest control, pruning and fertilization practices were those commonly used by farmers. Fruit thinning is not performed in Spanish commercial table olive orchard. Pruning is commonly used for optimize fruit size and yield. Hard pruning was performed in all trees at the beginning of the experiment (winter 2015) and light ones in the other two seasons. Irrigation system was two side pipes per row of trees with 8 drips (2 L h^{-1}) per plant each (in total 16 emitters per tree). Meteorological data were obtained for the weather station of "IFAPA Los Palacios", around 6 km far from the experimental site, which is part of the Andalusian water stations network (SIAR, 2019). The daily reference evapotranspiration (ETo) was calculated using the Penman-Monteith equation (Allen et al., 1998). The maximum daily vapour pressure deficit (VPD) was calculated from the mean daily maximum temperature and minimum relative humidity.

The experimental design consisted of completely randomized blocks including 4 irrigation treatments and 4 replicates (blocks). Each repetition was in a parcel of 12 trees (3 rows per 4 trees) in which the two central trees in the central row were used as monitored trees. Irrigation management treatments were applied according to the phenological stage of the crop (Table 1). Massive pit hardening was the main phenological stage that defined the season. According to Rapoport et al (2013) pit hardening is a continuous process which change their intensity along the season. The change of rate growth of longitudinal fruit growth is related with the beginning of the massive pit hardening (Rapoport et al 2013).

Before this period (Phase I), irrigation was optimal in all treatments and water stress started when massive pit hardening was detected (around mid-June, Table 1). The common recovery period started at the end of August but in order to obtain differences in the duration of the water stress an early recovery (Table 1) around one month before was tested. Dates of each phenological stage changes between seasons according to climatic conditions and fruit load. There were 4 irrigation treatments which combined this phenological stages and several water stress levels:

- Control treatment included plants in an optimum water status. Irrigation was scheduled using a pressure bomb technique according to the recommendations of Moriana et al (2012). The threshold values of midday stem water potential (SWP) were −1.2 MPa before the period of pit hardening (Phase I) and −1.4 MPa at beginning of pit hardening until harvest (Phase II and III).
- RDI-1 involved a midday SWP of −1.2 MPa before the period of pit hardening (Phase I), a moderate water stress during pit hardening: -2 MPa (Phase II) and recovery in the last week of August (Phase III).
- RDI-2: involved a midday SWP of −1.2 MPa before the period of pit hardening (Phase I), severe water stress until the middle of pit hardening (-3.5 MPa), early recovery at the end of June/mid July and -1.4 MPa until harvest. This recovery was adjusted in order to reduce the period of water stress in half.
- RDI-3: involved a midday SWP of −1.2 MPa before the period of pit hardening (Phase I), severe water stress at pit hardening: -3.5 MPa (Phase II) and recovery in the last week August (Phase III).

Irrigation was scheduled weekly in each plot using midday SWP measurements. SWP was measured in one leaf in one tree of each plot with a pressure chamber (model 1000, PMS, USA). Water was applied to obtain a water status around the threshold selected and it was measured in each plot with a water meter. The amount of applied water was first estimated as a percentage of the maximum daily crop evapotranspiration (ETc) expected which was calculated as 4 mm day^{-1}, considering crop coefficient (Kc) 0.7 and reduction coefficient (Kr) 0.8 (Steduto et al., 2012). This percentage changed according to the distance of the SWP measurements to the threshold value (Moriana et al 2012). Below 10% of differences in SWP no irrigation was provided. Between 10-20% of differences, 1 mm day^{-1} (25% maximum daily ETc expected) was used. When SWP differences were between 20-30%, irrigation was increased to 2 mm day^{-1} (50% maximum daily ETc expected). If measured SWP was 30% more negative than threshold, irrigation was maximum (4 mm day^{-1}).

2.2. Measurements

Vegetative and flower/fruit development were measured in one tree per plot. Few days after shoot sprouting, each season, ten shoots per tree (with and without fruits) were randomly selected and marked. Along the season, every 2-3 weeks, length and number of inflorescence were counted. When massive pit hardening was dated, number of fruit per inflorescence was also counted in these shoots. In order to estimate the percentage of fruit drop, only shoots with fruits was considered. Percentage of fruit drop was estimated each season as the ratio between the difference between initial fruit number and final fruit number vs initial fruit number. Periodically, a survey of ten fruits per tree were randomly selected. These fruits were not in the marked shoots and were used for fruit volume estimations. Fruit volume was estimated with two measurements of fruit dimensions, longitudinal and equatorial. The former was also used for determination of the beginning of massive pit hardening period (Rapoport et al 2013).

Physiological measurements were used for evaluated irrigation treatments. SWP was determined using leaves near the main trunk which were covered around one hour before. SWP was measured weekly using the pressure chamber technique (Scholander et al., 1965). Water potential baseline equation of Corell et al (2016) was included in the figures of SWP in order to compare the pattern of treatments with theorical optimum SWP. Briefly, this equation is based in average daily maximum temperature and represents the midday water potential when no limitation of water is in the soil and therefore is an indicator of the environmental stress. Because duration of water stress is a factor that affect the physiological responses of the trees, SWP data were used for calculated the water stress integral (Myers, 1988, Eq. (1)) during pit hardening (Phase II). The expression used was:

$$SI = \left|\sum (SWP - (-1.4)) * n\right| \qquad (1)$$

where: SI is the stress integral, SWP is the average midday SWP for any interval, n is the number of days in the interval. The value -1.4 is a SWP reference for this period (Moriana et al., 2012). In the case that SWP were more positive than -1.4, the value will be considered equal to this and SI in this case would be zero.

Leaf gas exchange varied along the day with a maximum in the morning and a decrease until midday, when minimum values are measured (Xiloyannis et al., 1998). Maximum leaf conductance was measured during 2015 (first season) with a permanent state porometer (SC-1, Decagon devices, UK) in two sunny, full expanded leaves per tree around 10:30 am. In the next two seasons (2016 and 2017), minimum leaf conductance was measured in order to minimize the variability between dates. In 2016 and 2017, gas exchange was measured with a portable infrared gas analyser (IRGA) (CI-340, CID Bio-Science, USA). This IRGA is more accurate system than poromoter but requires more time. Then in these two seasons, gas exchange measurements were obtained at midday (minimum daily value).

Soil moisture was measured with a portable FDR system (HH2, Delta-T, UK), using the default calibration suggested for the manufacturer for mineral soils. This system obtained data in 10, 20, 30, 40, and 100 cm depth. One access tube per plot was installed around 30 cm from a drip, which is the zone of greatest root activity (Fernández et al., 1981). These measurements were obtained every week, the same date that the SWP determinations. Only one access tube per plot provide less information and could be more variable between plots. Then data were analyzed relative to the first measurement for identification only of wet and dry cycles.

All treatments and plots were harvested the same day, when the owner started with the rest of the orchard. Each measured tree was harvested, and the yield of each individual tree was weighted in the field. One sample per plot of around 1 kg was moved to the laboratory for the determination of several other properties. Fruit size was estimated with the number of fruit per kilogram (USDA, 2019). Fruit load was estimated as the ratio between yield and fruit size in each plot. Ten fruits per plot was used in the measurements of fruit hardness per plot. Pulp hardness was measured with maximum peak force of the first compression (Szychowski et al 2015) with a force gauge (FM 200, PCE Instruments, Spain). Maturity index (Hermoso et al., 1997) was used in 100 fruits per plot for estimated change in fruit color. Bruising incidence (Jiménez et al., 2011), derived from manual harvest, was also measured in 100 fruits per plot. Pulp vs stone ratio was measured in fresh and dry weight in 3 samples of ten fruits per plot.

Data analyses were carried out with ANOVA and the mean separation was made with a Tukey's test using the Statistix (SX) program (8.0). Significant differences were considered for the p-level <0.05 in both tests. In order to evaluate irrigation treatments according to water stress level, lineal regressions were calculated between percentage of fruit drop vs SI and vs Minimum Midday SWP (Ψ_{min}), number of fruits per kilogram vs yield considering each plot. Multivariable analysis was performed between percentage of fruit drop vs SI and Minimum Midday SWP (Ψ_{min}) to improve these latter relationships. In addition, lineal regressions of number of fruits per kilogram vs SI and vs Minimum Midday SWP (Ψ_{min}) for the three seasons were performed to show the effect of water stress according to yield level. These latter yield levels were defined using the relationship between fruits per kilogram vs yield previously calculated.

3. Results

Water relations

Fig. 1 shows meteorological data for the three seasons of the experiment. The seasonal pattern of the main meteorological data were typical of a Mediterranean area, warm winters and hot and dry summers. Maximum values of daily reference evapotranspiration (ETo) were around 7 mm day^{-1}in July and there was almost no rainfall. Rainfall concentrated from Autumn to early Spring and was very variable from one season to another. In 2015, seasonal precipitation was 289 mm, in 2016, 643 mm and in 201, 345 mm. The average seasonal rainfall in this location is 539 mm (AEMET, 2019). 2015 and 2017 were extremely dry in comparison to the average year. The experimental period (Table 1) from around DOY 120 to 265 in all seasons coincided with the most extreme values of ETo, maximum temperature and vapour pressure deficit (VPD) (Fig. 1). Maximum temperature near 40ºC and VPD around 4 KPa were measured in mid-summer with zero rainfall.

The pattern of applied water is presented in Fig. 2. The maximum seasonal values were applied in 2016 and 2017. In addition, 2017 rainfall was very low and seasonal applied was maximum in all treatments in comparison with the rest of the seasons. In all seasons, Control treatment presented a two phases pattern. First the rate of applied water was slow until water potential reached threshold values and then maximum rates were measured. In the rest of treatments, the increase in the applied water was affected for water potential measurements. In 2015 and 2016, water applied was lower and was delayed in comparison to Control. In 2017, problems with Control irrigation (clogged filters) were detected after pit hardening and the pattern of applied water was slightly different to previous seasons.

The Relative Soil Water Content during the experiment is presented in Fig. 3. The seasonal pattern was very similar for all years. Spring rainfall increased the relative water content in all irrigation treatments in all three seasons. Throughout phase II, soil moisture decreased in the three deficit treatments with minimum values at different moments of the season. Soil moisture in RDI-2 was quickly recovered around mid-summer, while RDI-1 and RDI-3 increased a few weeks before harvest. During 2015 and 2106 seasons, Control soil moisture was lower until mid Summer than others treatment. This pattern could be related with the beginning of the period of greater rate of irrigation. In 2015 and 2016, the irrigation was regular (every week) from around DOY 195 (2015) and DOY 170 (2016) (Figure 2) when soil moisture increased.

The pattern of midday SWP was similar in all three years of study (Fig. 4). Before pit hardening, SWP was similar in the four treatments and above -1.5 MPa. SWP values decreased in all treatments from the beginning of the experiment. After the beginning of pit hardening, when the irrigation restriction started, SWP decreased faster in RDI treatments. During 2015, the lowest fruit load season, such decrease was very slow, Control was almost constant around -1.5 MPa, and the rest of treatments slightly decreased. Significant differences were found only at the end of the deficit period and between RDI-3 and the rest of treatments. During 2016 and 2017, this SWP decrease during pit hardening was greater than in 2015 and, even, Control reached values around -2 MPa some days. Such decrease in Control values was partially predicted by the Corell et al (2016) baseline. Then, Control could be in mild water stress conditions in short periods of 2016 and 2017 seasons. Significant differences were found from the mid of pit hardening period between RDI-3 and Control, and also RDI-1 tended to lower values, mainly during the 2017 season. Minimum SPW values near -4 MPa were reached at the end of this period in these two seasons. The recovery of RDI-2 SWP was not always clear during pit hardening and intermediate values between Control and the rest were measured. After pit hardening, all treatments recovered SWP and were near Control values at the end of the experiment. This rehydration was slower in RDI-1 and RDI-3, while it was almost complete at the end of pit hardening or in the first weeks of the last period in RDI-2.

The stress integral (SI) data presented clear differences between seasons and treatments (Fig. 5). During 2015, no significant differences were found between treatments and the average value was 12 MPa day. This value was greater in the next two seasons, even in Control trees. Maximum SI values were calculated in 2016, the year with the highest fruit load. In this season, significant differences were found between RDI-3 and Control, with more than double SI in the former than in the latter. RDI-1 and RDI-2 were intermediate between these two values, with no significant differences. During the last season, 2017, data were slightly lower than the previous one but followed the same pattern. RDI-3 was around 4 times greater than Control, with significant differences between them. Control values in this season were near the ones obtained in 2015. RDI-1 and RDI-2 were, again, intermediate treatments with no significant differences but clear trends towards greater values than Control, mainly RDI-1, which was almost three times higher than Control.

The maximum leaf conductance data during 2015 (Fig. 6a) was very variable throughout the season, with some dates showing values around half those on other dates. Such differences were likely related to the time when the measurement was obtained, because maximum daily values are very difficult to standardize. Before pit hardening, treatments were almost equal and maximum seasonal values were measured. Significant differences were observed only at the beginning of the pit hardening period between RDI-3 and Control. After DOY 220, these values decreased in all treatments and no significant differences were found. During 2016 (Fig. 6b), only one significant difference was observed before pit hardening and most values were very similar. After the beginning of pit hardening, significant differences were found at around DOY 180 between Control and all deficit treatments, and they were permanent until the end of this deficit period. RDI-3RDI-2 data slightly recovered a few weeks before the end of pit hardening, but this rehydration was completed only one week before harvest, when no significant differences between any treatments were found. During 2017 (Fig 6c), differences in minimum leaf conductance between treatments were small. Only during pit hardening, RDI-2 was significantly lower than Control before recovery and higher than RDI-3 after this moment. During irrigation recovery, all treatments were very similar in their observed values.

Vegetative growth and fruit development

Shoot elongation (Fig 7), taking as a reference the length of the first spring measurement, showed a similar seasonal pattern in all treatments. Most of the shoot growth occurred before pit hardening and growth sharply decreased or even stopped in all treatments after the beginning of pit hardening. Differences between treatments were established before this period. The average growth was very similar between seasons but the differences between treatments changed. During the 2015 season (Fig. 7a), significant differences were observed between RDI-3 and the rest of the irrigation treatments before pit hardening. After the beginning of pit hardening, growth was almost zero in all treatments. During the 2016 season (Fig. 7b), growth stopped in all treatments several weeks after the beginning of pit hardening. Significant differences between RDI-1 and the rest of treatments were found from two weeks before the beginning of pit hardening. The rest of treatments presented similar values around the average of 2015. In the 2017 season (Fig, 7c), shoot elongation was very similar between treatments. Before pit hardening, RDI-3 tended to greater values than the rest, even with two dates when significant differences were found. However, from the beginning of pit hardening, no significant differences were found, and Control and RDI-1 tended to lower values. In this last season, shoot elongation was slightly higher than in the two previous seasons.

The number of inflorescences per shoot were measured throughout the season (Fig. 8). All treatments presented a similar seasonal pattern, with a maximum peak at the beginning, followed by a sharp decrease until pit hardening. Although there were some significant differences at the beginning of the season in 2015 and 2016, the number of inflorescences were almost equal from pit hardening. No clear influences of irrigation strategies in the following season were found. After the first season and with different irrigation strategies, Control and RDI-2 presented a significantly higher number of inflorescences at the beginning of 2016, but no differences were found at the beginning of 2017. In all seasons, no drop was measured during the pit hardening period in any of the treatments. The number of fruits per shoot was also measured but only from pit hardening (Fig. 9). In all treatments, the number of fruits was constant from this date until harvest. Only in 2016, Control trees presented a significant lower number of fruits number during the complete period; in the rest of the seasons no significant differences were found between treatments. The percentage of fruit drop data were compared to the stress integral obtained during Phase II (Fig. 10a) and minimum SWP (Fig.9b). For both figures, the increase of water stress also increased fruit drop. Both relationships were significant, although the stress integral (Fig. 10a) was the most robust. Data of fruit drop in RDI-3 during the 2017 season were lower than expected for all indicators and it is not included in the adjustment (data circled in Fig. 10). There was a linear increase until values around 50 MPa day (SI, Fig. 10a) and -2.5 MPa (SWP, Fig. 10b), reaching a 30% of fruit drop in each shoot. The multivariable regression with SI and SWP was not significantly better than the SI adjustment.

The pattern of fruit volume showed differences between seasons and treatments (Fig. 11). Fruit volume at harvest was affected by the fruit load. The greatest sizes were found in the 2015 season, while the smallest occurred in 2016. During the 2015 season, the one with lowest fruit load, there were no differences between the irrigation treatments for most dates, only in the last measurement before harvesting, a smaller size was observed in RDI-3 (Fig. 11a). The seasonal pattern of growth was almost linear during this season for all treatments. In 2016 and 2017, significant differences were observed in the volume of fruit between irrigation treatments in phase II and they did not disappear until the end of the experiment. These differences were mainly between Control and RDI-3 and they were around 15%. Control and RDI-1 presented a very similar linear pattern of development, while RDI-2 and RDI-3 showed a reduction of fruit growth on some dates during pit hardening. RDI-2 was completely recovered even before the end of pit hardening. However, RDI-3 remained at the same level as Control by the end of 2016 but not in 2017, when differences were permanent.

Yield quality and quantity

Fruit yield, applied water and fruit quality are showed in Table 2. There were no significant differences between treatments in fruit yield for any season. However, Control and RDI-2 tended to higher values in the 2016 and 2017 seasons and the cumulative yield was almost equal for these two treatments (33.6 for Control vs. 33.0 t ha^{-1} for RDI-2). On the other hand, RDI-1 and RDI-3 tended to lower values and had both a very similar yield. The percentage of yield reduction in these two RDIs, in comparison to Control, was found to be around 20% in 2016 and 2017. Cumulative yield at the end of the experiment was also lower for both treatments (RDI-1 25.9 and RDI-3 28.7 vs. Control 33.6 t ha^{-1}). Considering the water applied, Control and RDI-2 presented, again, very close values in all seasons. But, although the water applied during RDI-1 and RDI-3 was lower than in Control, clear differences were found between these two treatments. Water saving in RDI-1 was variable according to the season considered, around 50% less than Control in 2015, but only 28% in 2016 and equal in 2017. On the contrary, RDI-3 received clearly less water than the rest of treatments, with around 75% less than Control in 2015, 59% in 2016 and 62% in 2017. The greater values of water applied in RD-1 and RDI-3 occurred during the rehydration period, because some plots needed more water to reach the correct rehydration. There were no significant differences between treatments in pulp vs. stone ratio in fresh or dry weight. In fresh weight, the pulp vs. stone ratio was similar in 2015 and 2017, and slightly lower in 2016, the season with the highest yield. During 2015, the lowest fruit load season, RDI-2 was the treatments with the lowest yield and it tended to greater values of this measurement. In 2016 and 2017, RDI-3 tended to lower values of pulp vs. stone ratio, with a reduction of 19% in comparison to Control. The rest of treatments were almost equal with differences lower than 10%. The variations of this parameter in dry weight for different treatments were similar, and the lowest values were obtained in all treatments during 2016.

The maturity index, which evaluates colour, bruising incidence and hardness, was not significantly affected by irrigation treatment and in all seasons it was within commercially expected values.

Final fruit sizes were strongly related with the season, but not significantly affected by the irrigation treatments (Table 2). In order to evaluate irrigation treatments considering the fruit yield, fruit size vs. yield for all treatments is presented in Fig. 12. Fruit size decreased linearly with the increase in yield, but slope changed according to the irrigation treatments considered. Significant differences were found between these relationships, Control and RDI-2 showed near fits than RDI-1 and RDI-3. For the same value of yield, fruit size was reduced more in the latter group than in the former, and this reduction was greater when yield increased. An almost equal number of fruit per kg was found when yield was below 5 t ha^{-1}. From this yield, RDI-1 and RDI-3 increased the slope of size reduction in comparison with Control and RDI-2. Only when the yield was greater than 15 t ha^{-1} RDI-2, fit presented greater slope of reduction than Control. At the highest level of yield (20 t ha^{-1}), the reduction of fruit size was around 30% greater in RDI 1 and 3 than in Control, while the difference estimated with RDI-2 was only 9%. These data of fruit per kg were compared with minimum SWP and SI but grouped according to yield intervals (below 6 t ha^{-1}, between 6 to 14 tha^{-1} and greater than 14 t ha^{-1}) in Fig. 13. No significant relationship was found in the lowest level of yield in any of the water stress indicators. The increase in the water stress level increased the number of fruit per kg with better agreement in the SI than in the minimum SWP In the other two yield level, significant differences in the y-intercept were observed only in SI. No significant differences were fund in the slope of both figures.

4. Discussion

The yield data presented clear trends of yield reduction in RDI-1 and RDI-3 in comparison with Control and RDI-2 (Table 2) and such decrease was explained by an increase of fruit size with optimum water status and a reduction in fruit size in the more severe RDI treatments (Figs. 10 and 13) and when yield level was considered (Fig. 12). Yield reduction was likely related only to fruit size and fruit drop, because flower induction in the following season was not affected (Fig. 8) and neither was shoot growth (Fig. 7). Significant reduction of shoot expansion before pit gardening (Fig. 7) showed that SWP is not the earliest indicator of water stress which is commonly reported in the literature (Hsiao, 1990; Pérez-López et al, 2007). Although this could be a limitation of the methodology in young orchards, it would be not in mature where low shoot expansion (Fig. 7) was not associated with lower yield in next season (Table 2) which is one of the reasons suggested for alternated bearing in olive trees (Rallo, 1997).

Fruit drop was a current season effect of water stress. The estimation of fruit drop in the present work probably over-estimated yield reductions because the percentage of fruit drop was greater than the average yield reduction (Fig. 10 vs. Table 2). The relationship of Fig. 10 was very close to the one reported by Girón et al (2015) for the same cv., but in a wide range of water stress levels (these latter data are incorporated to this Fig).

This latter work also over-estimated yield reduction (Girón et al., 2015). The over-estimation would be likely related to the sampled zone, which varied throughout the season. At the beginning, shoots were at the sampler height but when fruits increased their weight this height of decreased. These changes in fruit height could reduce the level of radiation and increase potential damage due to handling. The influence of light on fruit development has been reported in different cultivars and densities (Cherbity-Hoffman et al., 2012; Caruso et al., 2017) and could affect the fruit drop.

Fruit size is very important in table olive trees because, in addition to yield reduction, there is a quality penalty. However, when data of reduction in yield and size in Table 2 are considered, most of the yield decrease was likely related to fruit drop (maximum reduction in yield around 21% vs. a decrease in fruit size of 8%, Table 2). Similar results have been reported in cv Manzanilla, in which yield decreases from 8 to 24% were associated with size impact from zero to 6% (Goldhamer, 1999; Girón et al., 2015). On the contrary, Ahumada-Orellana et al (2017) in cv Arbequina reported a reduction of fruit size at all levels of water stress from 9% to 29% with yield reductions of 9% to 39%. Therefore, fruit drop would be likely related only to the highest level of water stress, with a reduction in yield of 8-10% for this cv (Ahumada-Orellana et al., 2017), while cv Manzanilla would be more sensitive, as suggested by Fig. 10, and the effects would be more noticeable than for cv Arbequina, with around a 13-18%.

The reduction in fruit size was likely related to the impact on the mesocarp because the water stress was applied after the end of endocarp growth (Rapoport et al 2013) and could have affected the pulp vs. stone ratio, which is another important fruit feature for table olives. The reduction of this parameter in RDI-1 was almost zero in fresh and dry weight (Table 2) which suggests only a small dehydration in this treatment. On the contrary, RDI-3 showed a higher impact, with a clear trend in the 2016 and 2017 seasons (Table 2) and a significant reduction in the fruit volume pattern during the 2017 season

(Fig. 11). Gucci et al (2009) worked with cv Leccino, reported a maximum mesocarp area obtained from -1 to -2 daily integrated SWP with a linear decrease from this level of water stress. In the present work, the decrease in fruit size for both RDI treatments of the present work was likely related to cell size and it could be recovered. Hammani et al (2011) reported that the number and the size of fruit cell increased throughout the season in olive trees of the cv Manzanilla, although the cell number decelerated from maximum endocarp size. Gomez del Campo et al (2014) concluded that, in olive trees (cv Arbequina), the cell area was more sensitive to drought conditions than the cell number, which was hardly affected during the irrigation restriction. Therefore, the reduction of pulp vs. stone ratio in RDI-3 in comparison to RDI-1 suggests that the recovery of the former was not enough, although SWP values were similar to Control at harvest (Fig. 4).

Management and evaluation of irrigation strategies become difficult because the SWP recovery did not involve the optimum management of water stress. The relationship of the fruit size (Fig. 13) and the fruit drop (Fig. 10) with the stress integral was better than with the minimum water potential. These results suggest that the duration and intensity of water stress are better indicators than only its intensity. This would also explain also the better response of early recoveries (as in RD-1 and RDI-2) although all treatments reached a similar SWP at the end. Therefore, similar amounts of water applied could produce different yield results according to water status. In olive irrigation literature, the water applied is the most common recommendation (i.e. Goldhamer, 1999; Fernandez et al., 2013) but there are examples in which similar amounts of water changed yield results (i.e. Lavee et al., 2007; Gómez del Campo, 2013a). But recommendations based on water status measurements are also difficult because if the duration was important, the frequency of water status measurements could be limited. Crop load is another factor that could change the irrigation strategy. The present work suggests that yield results were the sum of both effects, fruit drop and fruit size, but with different intensity according to the fruit load. In conditions of low yield (lower than 4 tha^{-1}) water stress did not affect fruit size (Fig. 12 and 12) and neither did fruit drop (Fig. 10). Naor et al (2013) reported that fruit load is a key point to evaluate irrigation strategies and in this latter work, only significant differences were found in oil yield between irrigation treatments for medium and high fruit load seasons (Naor et al., 2013). Water relations in olive trees are strongly affected by very low fruit load, which limited the decrease of the SWP (Martín-Vertedor et al. 2011, Naor et al.,2013). From 4 t ha^{-1}, the decrease in fruit size was linear with the water stress level (Fig. 13). Differences in Figs. 12 and 13 between yield levels were due to fully irrigation Control starting from smaller size in the highest yield (Fig. 12 and 13). Therefore, in very high yield conditions (from 12 t ha^{-1}), optimum conditions will produce very small fruits, more than 250 fruits kg^{-1} (USDA, 2019), and RDI would be very limited because the greatest differences in size could be expected (Fig. 12 and 13). In yields between 4 to 12 t ha^{-1}, RDI will be possible in moderate water stress conditions, which minimize fruit drop, around 40 MPa day or -2 MPa minimum SWP, during massive pit hardening. In such conditions, complete rehydration will be also important. Similar threshold values of SWP for olive trees have been suggested by other authors (table, Girón et al 2015; oil, Hueso et al 2019) but the importance of considering the water stress duration (for instance with the stress integral) has not been studied.

5. Conclusions

RDI during pit hardening should be adapted to the yield level expected, in table olive. Low yield level (lower than 4 tha^{-1}) was not affected by any irrigation restrictions at this phenological stage. In years with low yields, could be recommended deficit irrigation strategies because the grower will not observe any benefit associated to an increase of irrigation. But in order to minimize fruit dehydration, levels lower than -2 MPa before harvest should be avoided. For medium yield (from 4 to 12 t ha^{-1}) a RDI management with low effect on yield was possible. An SWP lower than -2 MPa or a stress integral lower than 40 MP per day during pit hardening likely prevent fruit drop. The stress integral could be a good indicator to manage and interpret water stress. In addition, an efficient recovery before harvest reduced the effect on fruit size and pulp vs. stone ratio. Such recovery would be based on the level of SWP and on the time that trees were at an optimum level. Very high yield level (from 12 t ha^{-1}) will limit the RDI management because, even in full irrigated conditions, fruit size could reduce their commercial value. In addition, the greater transpiration would increase the water stress level easily and maximize fruit drop. These results would be useful for farmers in two ways. Monitoring water status in large orchard with pressure bomb technique could be not easy but they could be use as identification of irrigation problems or more accurate water management in difficult part of the orchard, such as shallow soils. On the other hand, these data could support the definition of threshold values to other techniques such as canopy temperature.

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Table 1.
Day of the year (DOY) and date (month/day) of each phenological stage of the three seasons experiments. The beginning of pit hardening was dated according to Rapoport et al (2013). Early recovery was adjusted in order to reduce the water stress period in half.

	2015	**2016**	**2017**
Start irrigation	120 (30/4)	154 (3/6)	140 (20/5)
Beginning of massive pit hardening (Phase II)	161 (10/6)	159 (8/6)	163 (12/6)
Early recovery	202 (21/7)	197 (16/7)	203 (22/7)
Regular recovery (Phase III)	237 (25/8)	223 (11/8)	241 (29/8)
Harvest	252 (9/9)	264 (21/9)	262 (19/9)

Table 2. Summary of yield quality and quantity during the 3 years of the experiment. (average± standard error)

	Yield	Load	AW	PS F	PS D	Size	MI	B_I	H
2015									
Control	3.1 ± 1.0a	1723 ± 217a	154 ± 28a	5.1 ± 0.4a	2.3 ± 0.0a	192 ± 8a	1.16 ± 0.03a	0.14 ± 0.01a	39.1 ± 0.7a
RDI-1	1.9 ± 0.5a	1036 ± 98a	89 ± 13a	5.3 ± 0.6a	2.3 ± 0.2a	198 ± 15a	0.97 ± 0.02a	0.44± 0.03a	41.9 ± 0.4a
RDI-2	1.9 ± 0.6a	989 ± 91a	108 ± 28a	5.9 ± 0.2a	2.5 ± 0.1a	185 ± 6a	1.22 ± 0.04a	0.30 ± 0.01a	37.9 ± 0.9a
RDI-3	3.4 ± 0.9a	2180± 272a	54 ± 16a	5.2 ± 0.2a	2.3 ± 0.1a	210 ± 20a	0.97 ± 0.01a	0.38 ± 0.00a	43.2 ± 0.2a
2016									
Control	18.3 ± 2.1a	16565 ± 737a	264 ± 39a	4.2 ± 0.2a	1.6 ± 0.0a	324 ± 13a	1.39 ± 0.17a	0.22 ± 0.02a	60.4 ± 0.3a
RDI-1	14.5 ± 1.1a	14260 ± 492a	190 ± 26a	4.1 ± 0.1a	1.7 ± 0.0a	349 ± 17a	1.00 ± 0.00a	0.44 ± 0.03a	55.4 ± 0.2a
RDI-2	17.3 ± 1.5a	16999 ± 354a	266 ± 90a	4.4 ± 0.3a	1.8 ± 0.1a	353 ± 11a	0.92 ± 0.01a	0.30 ± 0.01a	58.2 ± 1.1a
RDI-3	14.8 ± 1.5a	15421 ± 515a	108 ± 22a	3.4 ± 0.4a	1.5 ± 0.1a	372 ± 13a	0.94 ± 0.01a	0.38 ± 0.00a	55.7 ± 0.8a
2017									
Control	12.2 ± 2.0a	8368 ± 328a	274 ± 35a	5.8 ± 0.1a	2.3 ± 0.0a	244 ± 3a	1.04 ± 0.02a	0.62 ± 0.00a	38.0 ± 0.7a
RDI-1	9.5 ± 1.1a	7016 ± 330a	295 ± 39a	5.5 ± 0.2a	2.4 ± 0.1a	262 ± 16a	1.00 ± 0.00a	0.58 ± 0.02a	38.9 ± 0.2a
RDI-2	13.8 ± 0.5a	9727 ± 175a	360 ± 52a	5.7 ± 0.2a	2.4 ± 0.1a	252 ± 11a	1.08 ± 0.02a	0.63 ± 0.02a	37.7 ± 0.3a
RDI-3	10.5 ± 1.4a	8402 ± 303a	105 ± 14b	4.7 ± 0.1a	2.2 ± 0.1a	286 ± 8a	0.97 ± 0.00a	0.60 ± 0.02a	41.1 ± 0.5a

Different letters indicate significant differences in the same year ($p<0.05$, Tukey Test). Yield (n=4 per treatment, t·ha^{-1}); Load (n=4, fruit.tree^{-1}) Applied water (AW n=4, mm); pulp stone weight ratio fresh (n=12, PS F) and dry (n=12, PS D); Size (n=4, Fruits·kg^{-1}); Maturity Index (n=4, MI); Bruising Incidence (n=4, B_I); Hardness (n=40, H, N)

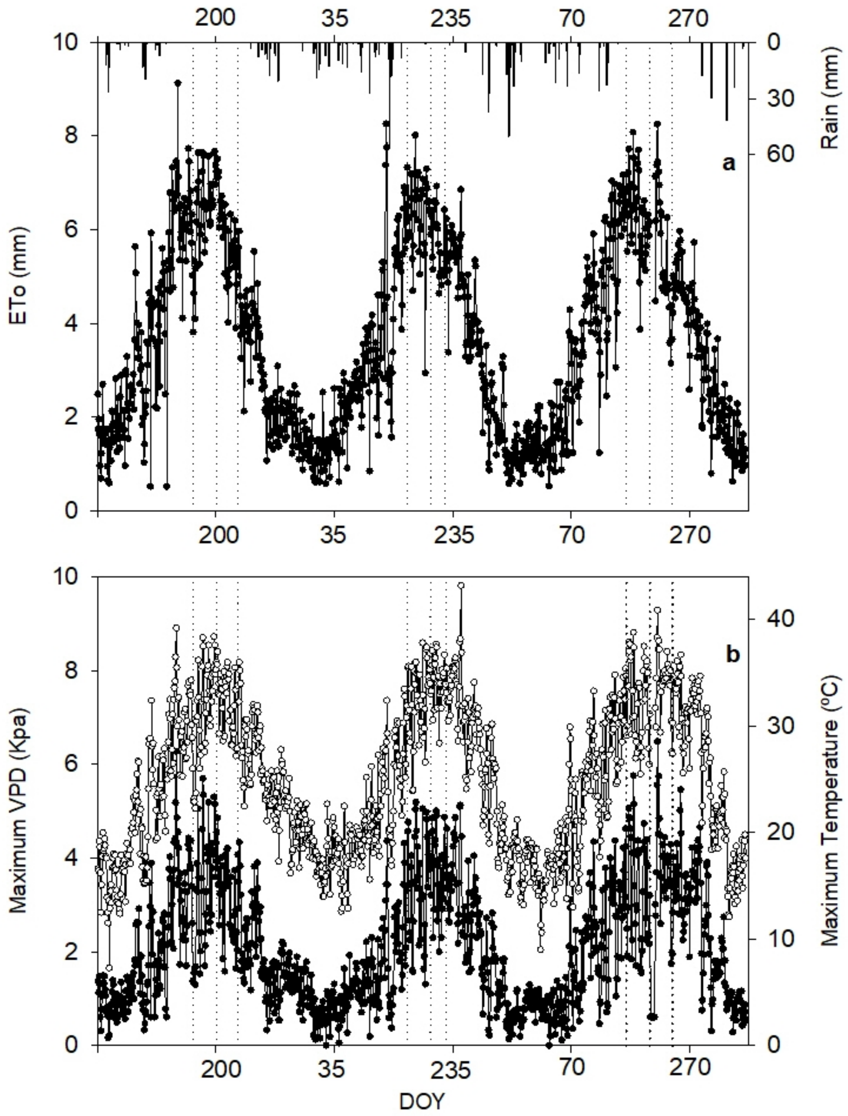


Figure. 1 Climatic conditions during the three experimental seasons. (a) Seasonal daily reference Evapotraspiration (circles) and Rain (bars). (b) Seasonal daily maximum air temperature (white circles) and maximum vapor pressure deficit (VPD)(black circles). Vertical dots lines indicated, from right to left each season, the beginning of pit hardening, early recovery and regular recovery.

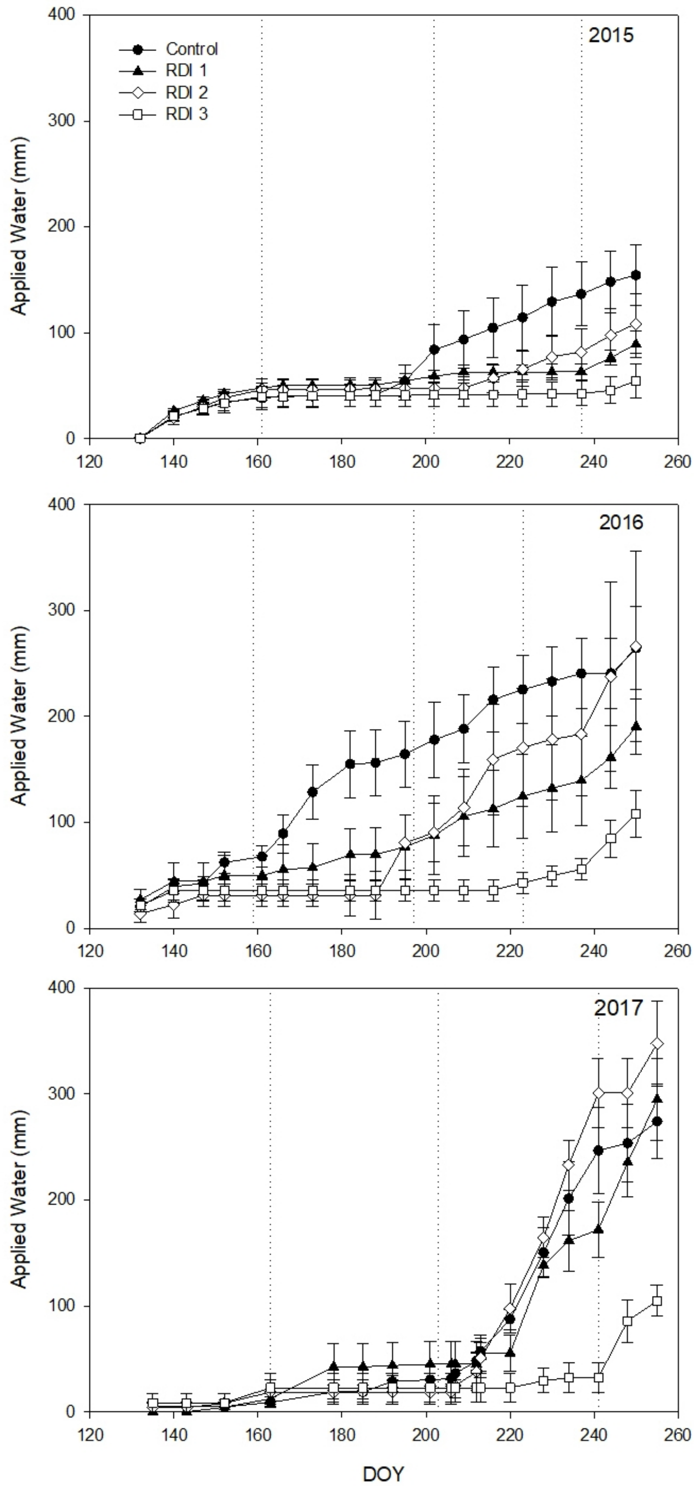


Fig. 2. Pattern of Applied Water along the experiment during 2015, 2016 and 2017 seasons. Each point is the average of 4 data. Vertical bars represented standard error. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery.

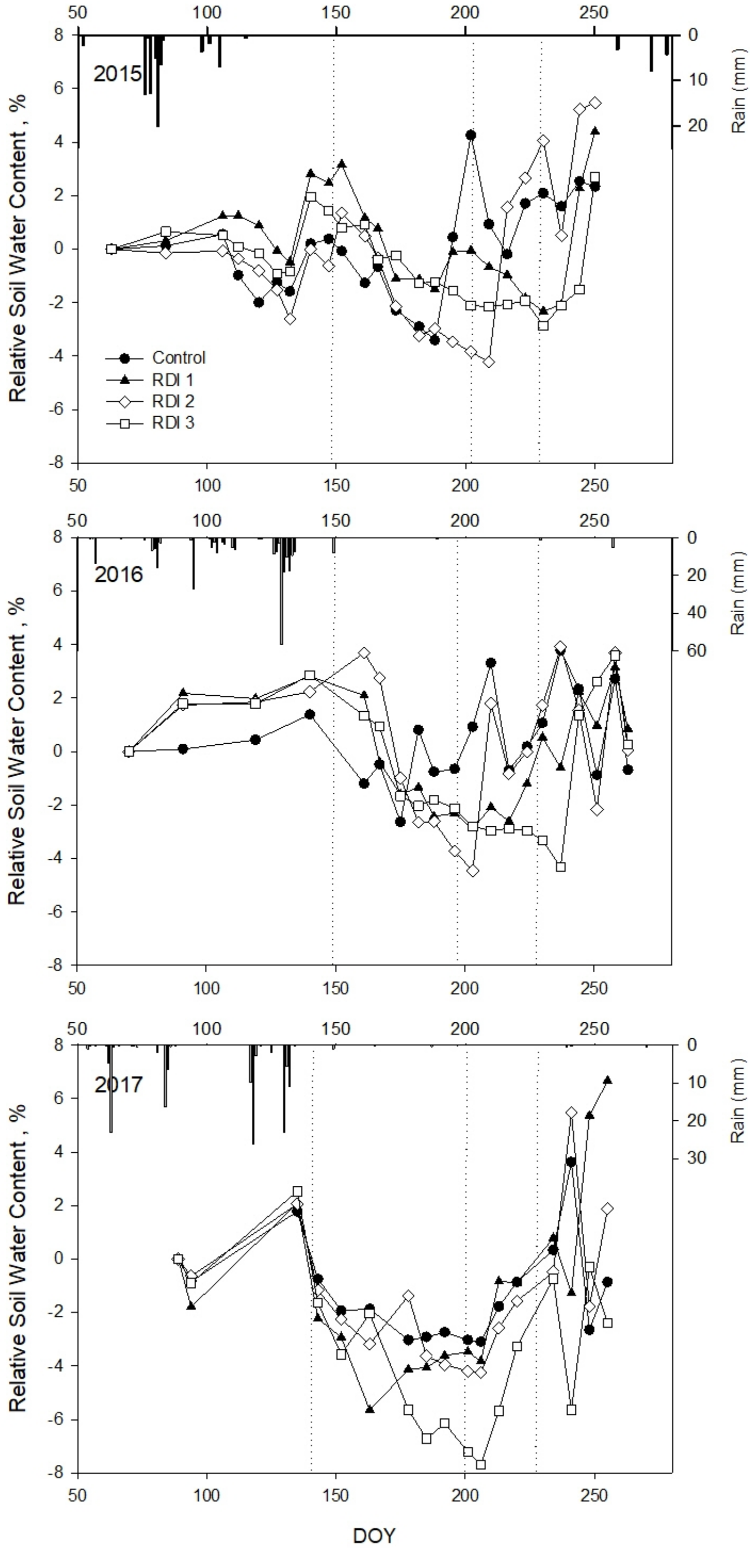


Fig. 3. Pattern of Relative Soil Water Content (lines, left) and rain (bars, right) along the experiment during 2015, 2016 and 2017 seasons. Each point is the average of 4 data. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery.

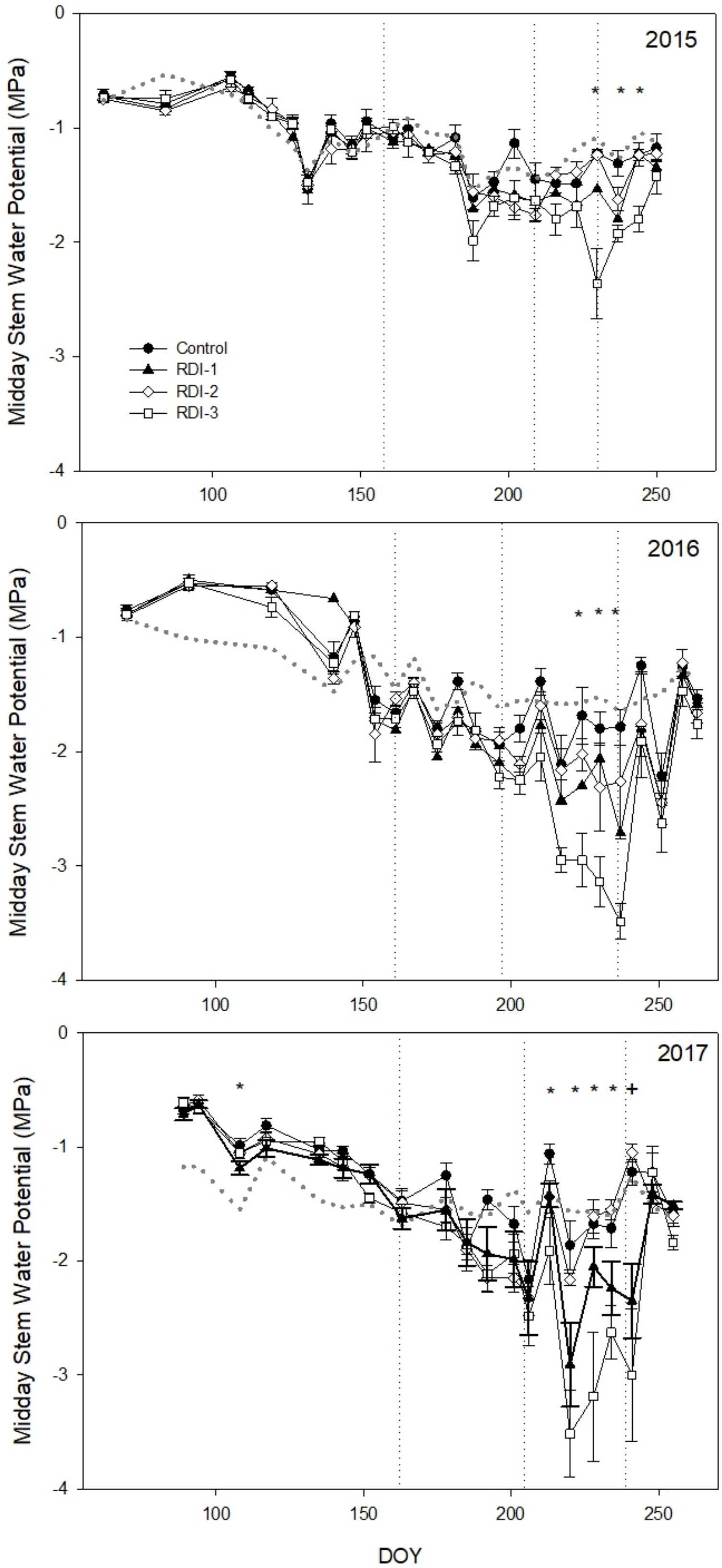


Fig. 4. Pattern of Midday Stem Water Potential (SWP) along the experiment during 2015, 2016 and 2017 seasons. Each point is the average of 4 data. Vertical bars represented standard error. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery. Stars indicates dates where statistical differences were significant (*p<0,05, + p<0,01, Tukey Test). The gray dotted line is the estimated midday stem water potential for full irrigated conditions based on maximum daily temperature (Corell et al. 2016).

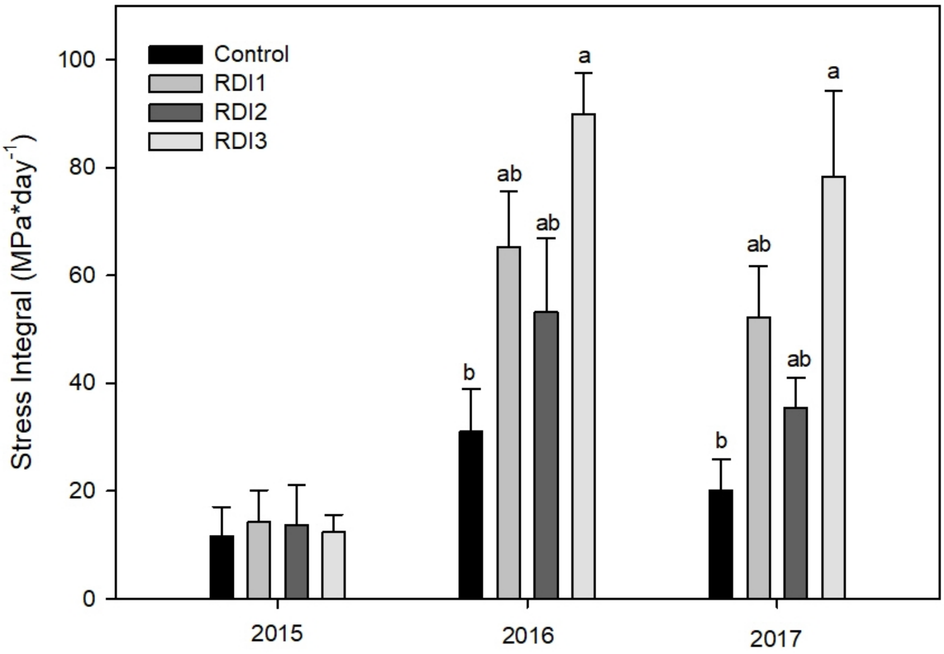


Fig. 5. Stress integral (SI) during Phase II in the 3 years of the experiment. Each bar is the average of 4 data. Vertical lines represented standard error. Different letters at the same season indicate significant differences ($p < 0.05$, Tukey test).

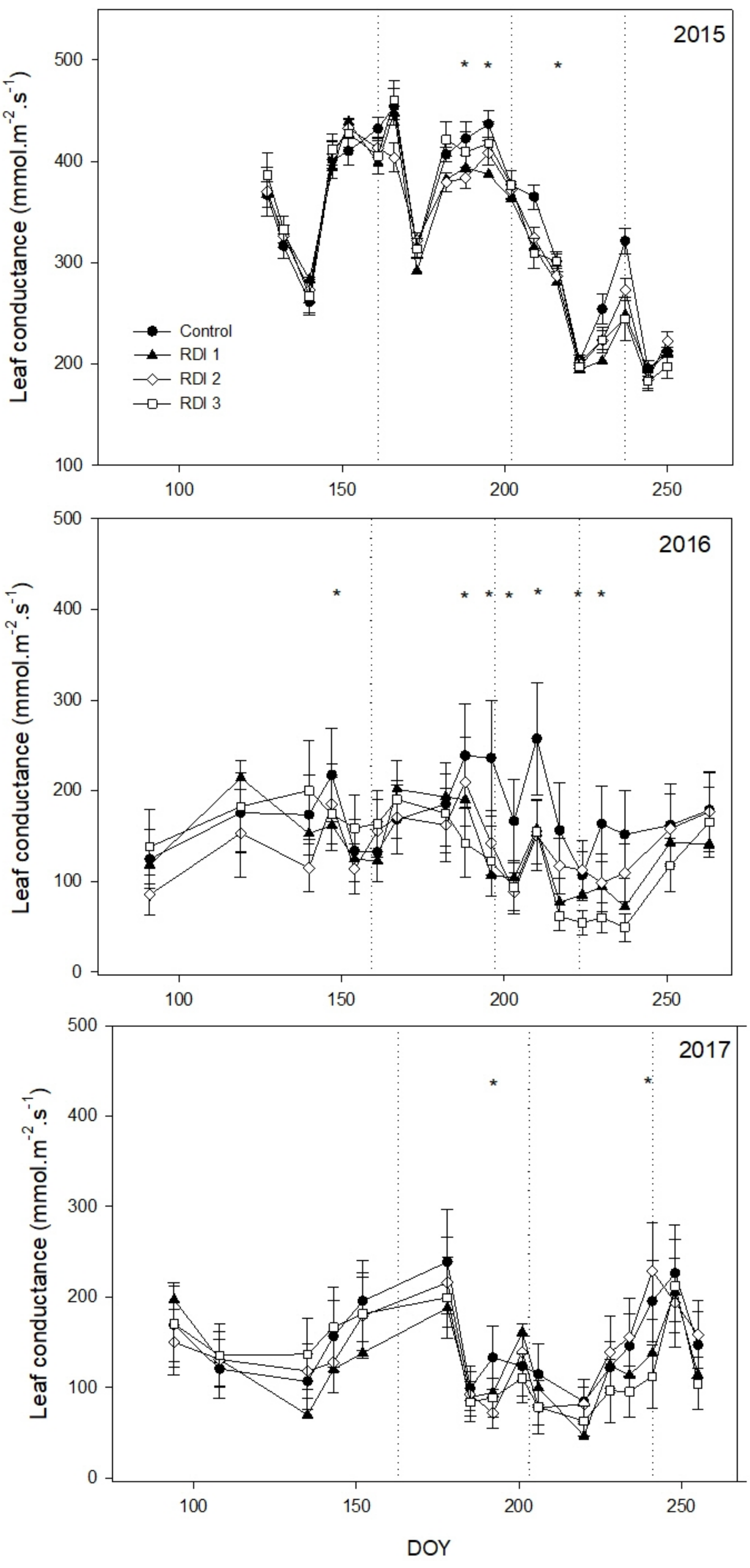


Fig. 6. Pattern of Maximum Leaf conductance along the experiment during 2015 and Minimum Leaf conductance during 2016 and 2017 seasons. Each point is the average of 4 data. Vertical bars represented standard error. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery. Stars indicates dates where statistical differences were significant (*p<0,05, Tukey Test).

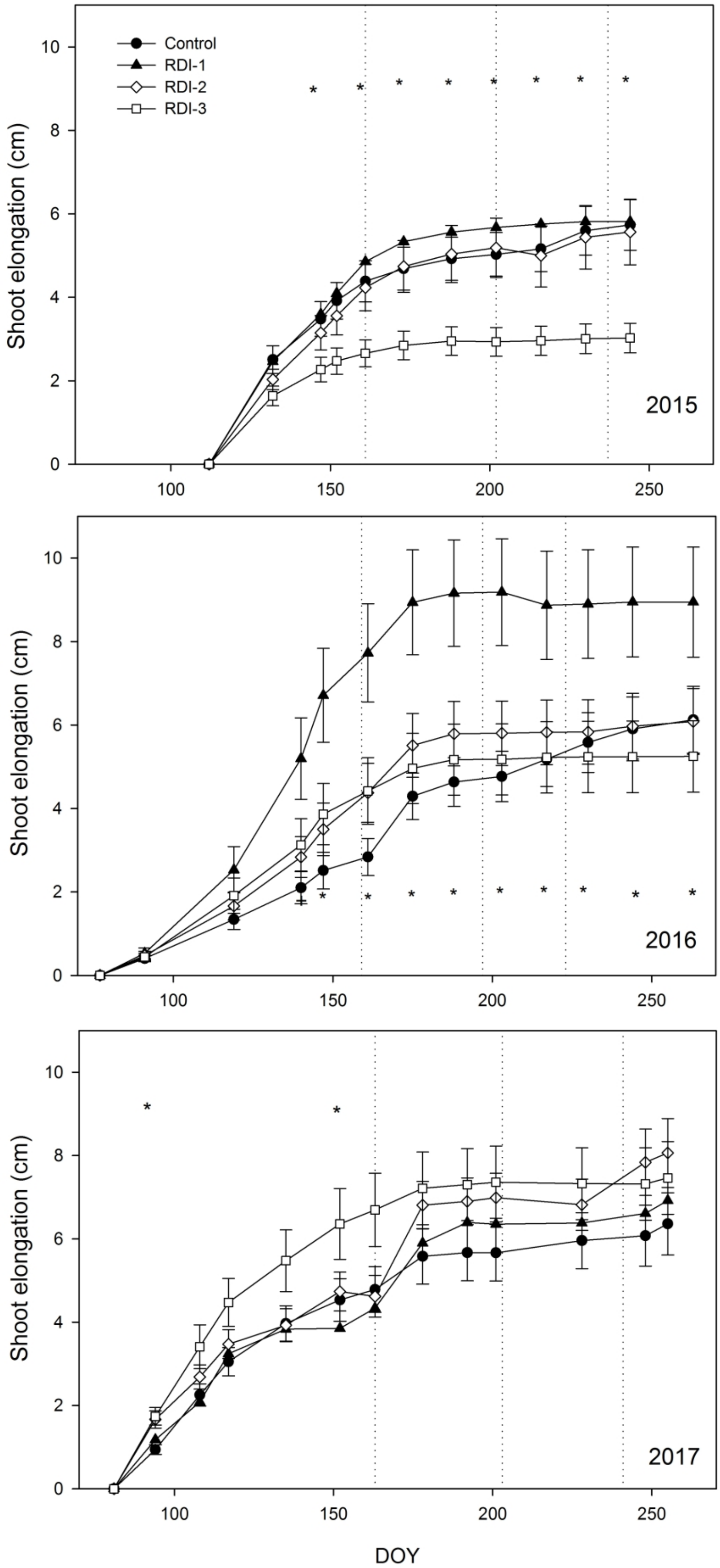


Fig. 7. Pattern of Shoot Elongation along the experiment during 2015, 2016 and 2017 Each point is the average of 40 shoots. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery. Stars indicates dates where statistical differences were significant (*p<0,05, Tukey Test).

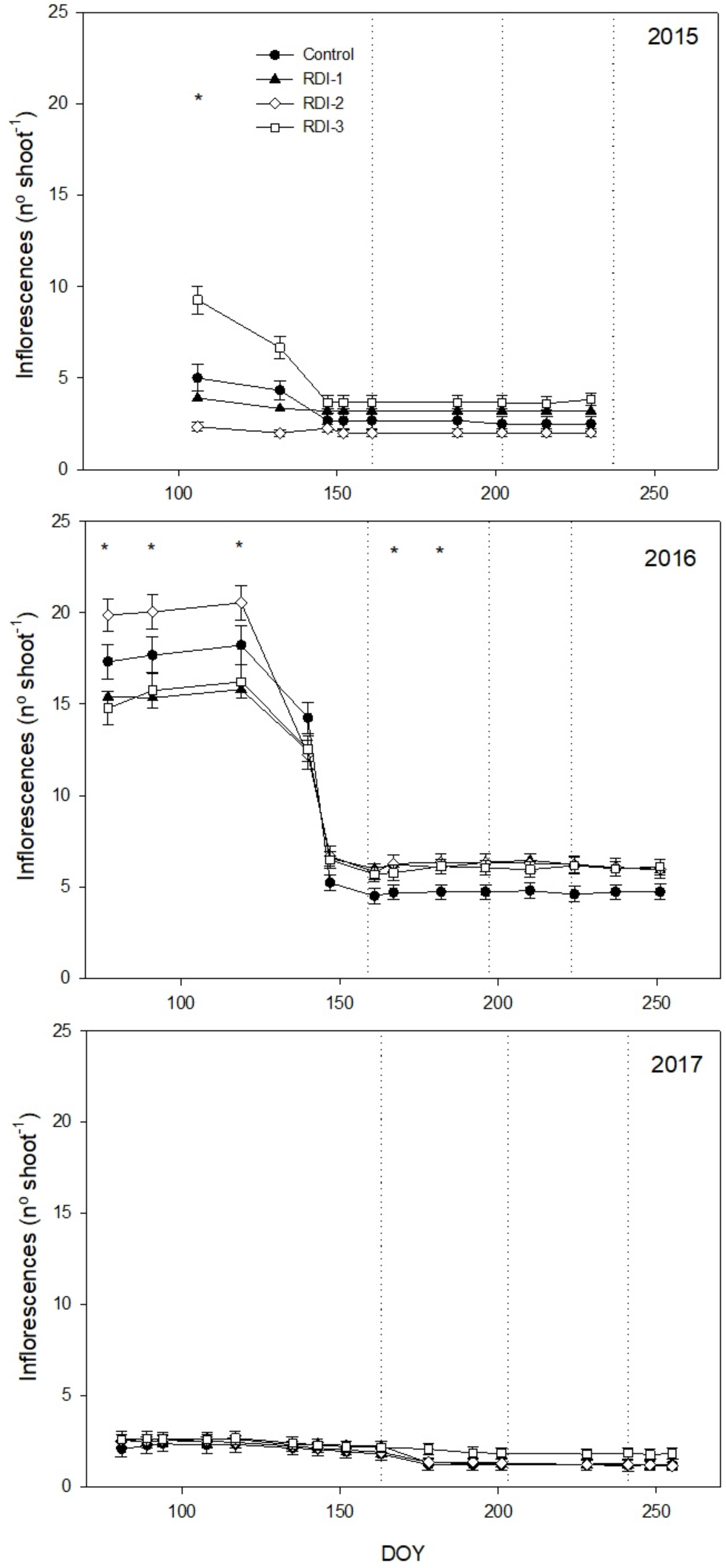


Fig. 8. Seasonal pattern of number of Inflorescences along the experiment during 2015, 2016 and 2017 seasons. Each point is the average of 40 shoots. Vertical bars represented standard error. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery. Stars indicates dates where statistical differences were significant (*p<0,05, Tukey Test).

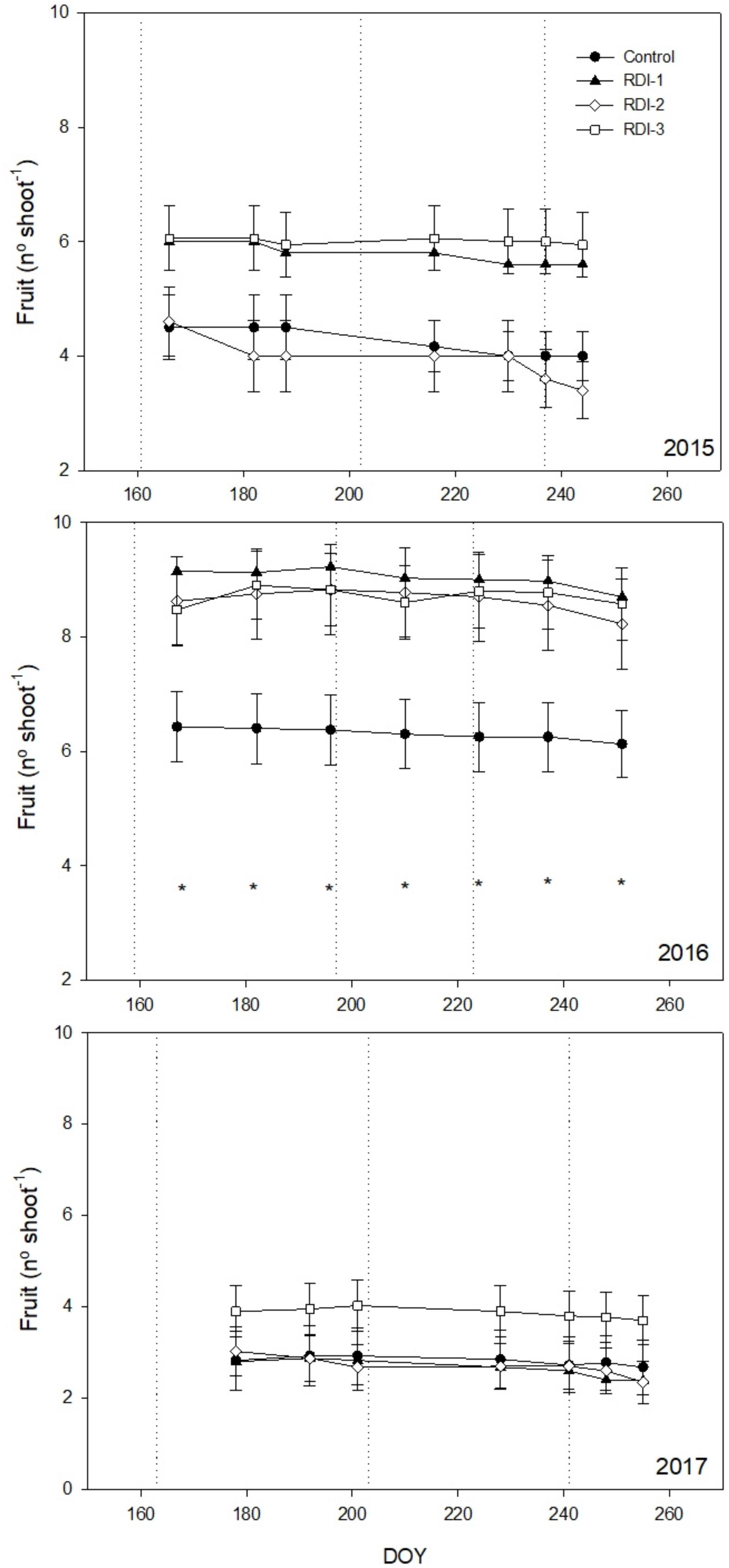


Fig. 9. Pattern of Fruit per shoot along the experiment during 2015, 2016 and 2017 seasons. Each point is the average of 40 data. Vertical bars represented standard error. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery. Stars indicates dates where statistical differences were significant (*p<0,05, + p<0,01, Tukey Test).

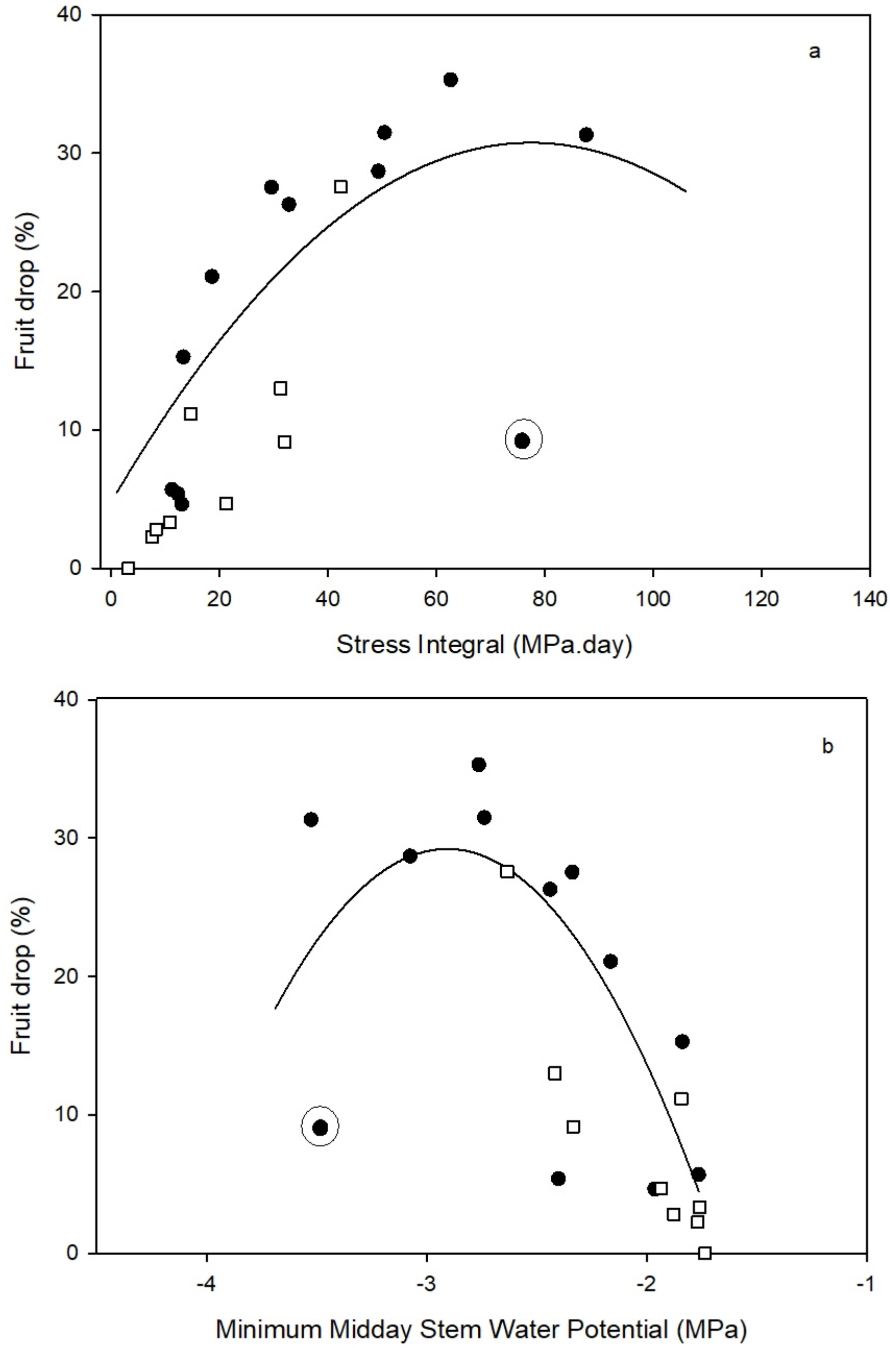


Fig. 910. a. Relationship between fruit drop per shoot (%) and Stress Intregral (SI, MPa.day^{-1}) along the experiment (2015-2017 seasons, circles). Each point is the average of 4 data of the treatment and were estimated considered only shoots with fruits (see Material and MethoddsMethods section). Point with a circle is not included in both relationship. Regression equation (circles): Drop fruit = -0.0089SI^2 – 1.165SI-3.0868, R^2 = 0,867**, n=11, standard error = 4.502%). b. Relationship between Drop fruit (%) and Minimum Midday Stem Water Potential (ΣΩΠΨ_{min}, MPa) along the experiment (2015-2017 seasons, circles). Regression equation (circles): Drop fruit = -9.781 MMΨ_{min}SWP^2 -66.074MMSWO074 Ψ_{min} - 79,425 R^2 = 0,5067*, n=11, standard error = 8.66%). Only shoots with fruits at the beginning of the pit hardening were considered. Square are the data published at Girón et al (2015) for the same relationships and are not included in the regression equation presented.

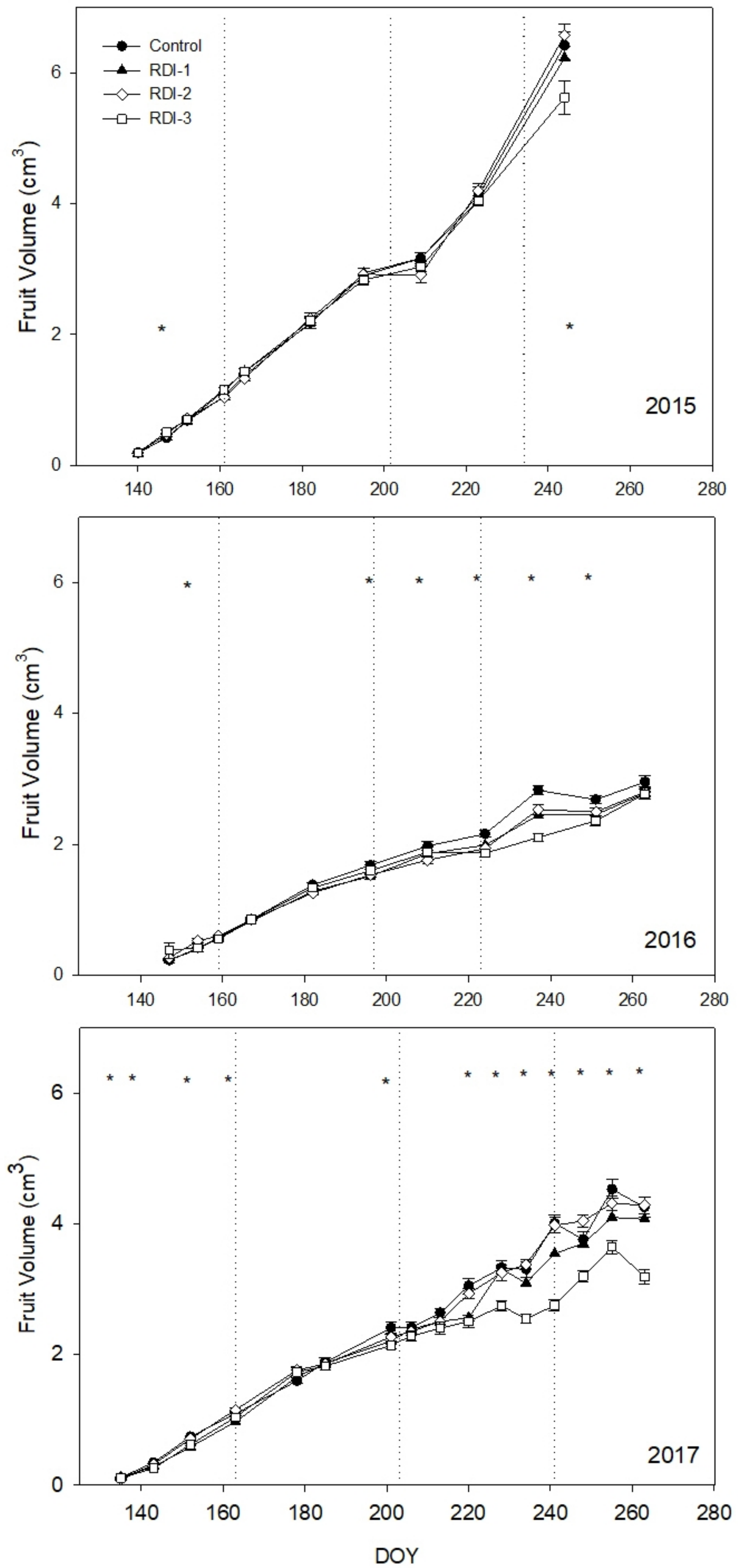


Fig. 11. Pattern of Fruit Volume along the experiment during 2015, 2016 and 2017 seasons. Each point is the average of 40 data. Vertical bars represented standard error. First vertical line shows the beginning of pit hardening period, second show early recovery and third regular recovery. Stars indicates dates where statistical differences were significant (*p<0,05, Tukey Test).

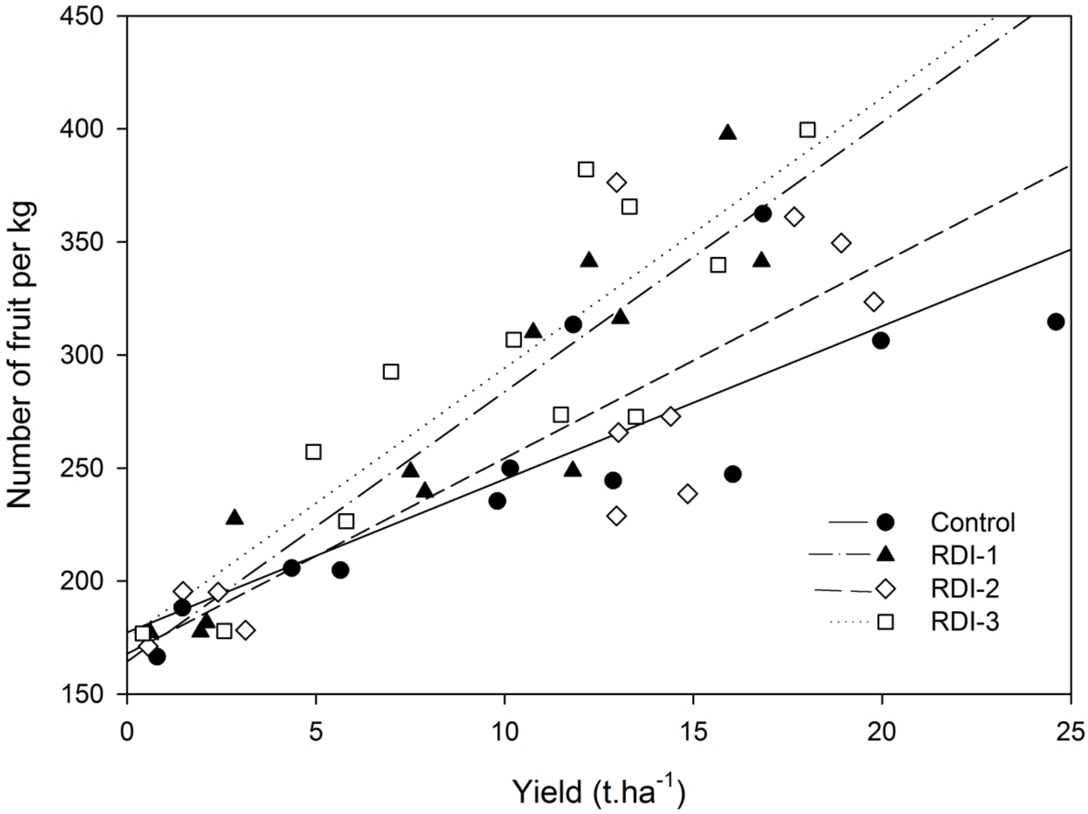
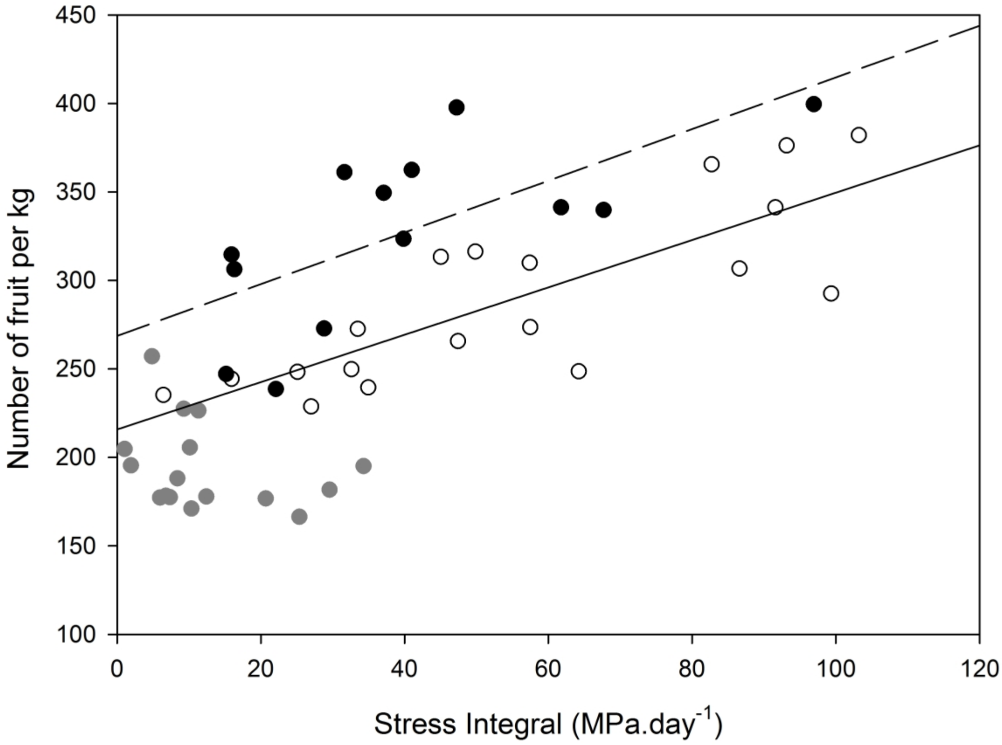


Fig. 12. Relationship between number of fruit per kg (Fruit·kg^{-1}) and yield (t ha^{-1}) along the experiment (2015-2017 seasons) for each treatment. Each point is the individual data of each plot and season. Regression equations obtained for each irrigation treatment: Control (–, Fruit·kg^{-1}= 6.77 Yield+177.34, R^2 = 0,68***, n=12, standard error = 33.9), RDI-1(- · -, Fruit·kg^{-1}= 11.93 Yield+164.43, R^2 = 0,84***, n = 12, standard error = 28.9), RDI-2 (---, Fruit·kg^{-1}= 8.65 Yield+167.78, R^2 = 0,66***, n=12, standard error = 43.07), and RDI-3 (······, Fruit·kg^{-1}=11.95 Yield +174.66, R^2 = 0,75***, n=12, standard error =37.17) (***p<0,001, multivariant analysis).



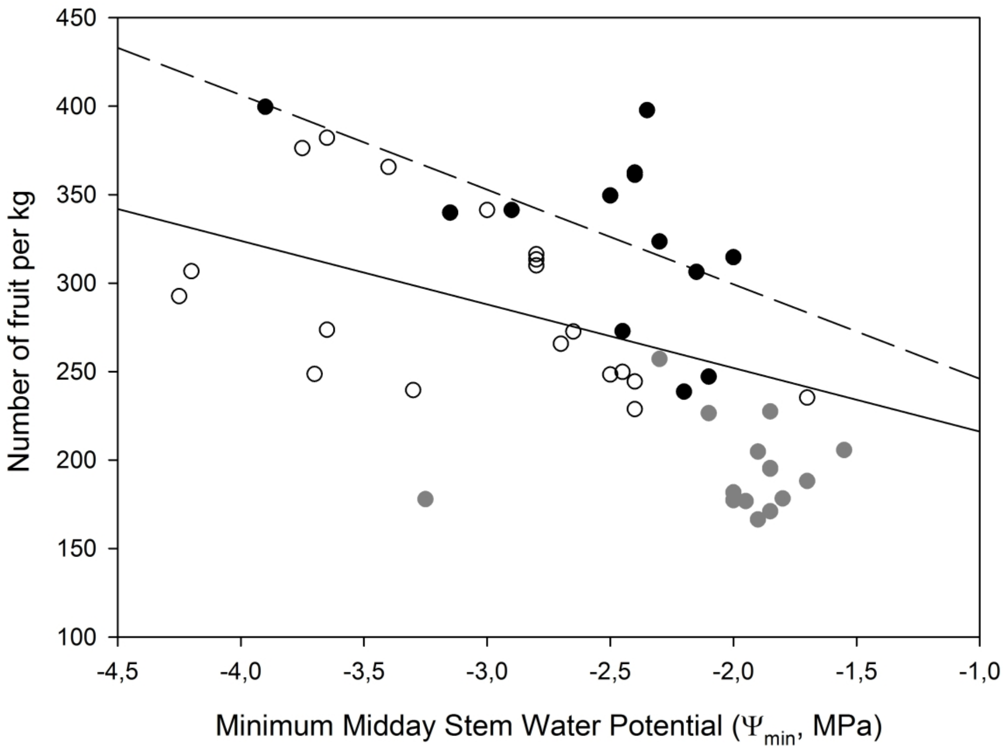


Fig. 13. a. Relationship between fruit size number of fruit per kg (Fruit·kg^{-1}) vs Stress Integral (a, SI, MPa·day^{-1}) and Minimum Midday Stem Water Potential (b, Ψ_{min}, MPa) according to yield level along the experiment (2015-2017 seasons). Each point is the data of individual plot for each season. Grey circle, yield level until 4 t ha^{-1}, white circle from 4 to 12 t ha^{-1}, black circle, greater than 12 t ha^{-1}. (a) Regression equation obtained for until 4 t ha^{-1} kg: no significant, n=16; 4 to 12 t ha^{-1}: Fruit·kg^{-1}= 1.3376 SI + 215.87, R^2 = 0,66**, n=19, standard error = 29.77); greater than 12 t h^{-1}: Fruit·kg^{-1}= 1.4604 SI + 268.68, R^2 = 0,47**, n=13, standard error = 39.00). (b) 4 t ha^{-1} kg: no significant relationship, n=16; 4 to 12 t ha^{-1}: Fruit·kg^{-1}= -35.91 Ψ_{min} + 180.24, R^2 = 0,25*, n=19, standard error = 44.05); greater than 12 t h^{-1}: Fruit·kg^{-1} = -54.72 Ψ_{min} + 128.25, R^2 = 0,31**, n=13, standard error = 10.64).