Manuscript Details

Manuscript number	AGWAT_2018_1369
Title	~~Limitations of using trunk diameter fluctuations for deficit irrigation scheduling in almond orchards~~.
Article type	Research Paper

Abstract

Irrigation needs in mature almond orchards are very high. Although almond trees grow in rainfed conditions, the yield response is very sensitive to irrigation. Continuous monitoring of the water status could be an adequate tool to optimize deficit irrigation. In this sense, trunk diameter fluctuations appeared as a very promising indicator at the beginning of the century, but few data have been published. The aim of this work is to present data about almond irrigation scheduling using trunk diameter fluctuations and the effect of water stress in the current yield. The experiment was performed in a commercial farm in Dos Hermanas (Seville, Spain) during the 2017 season on a 7-years-old orchard (cv Vayro). The irrigation treatments were Control (100% ETc), sustained deficit irrigation (SDI) with a maximum seasonal irrigation of 100mm and two regulated deficit treatments (RDI). Both RDI treatments (RDI-1 and RDI-2) were scheduled using the signal of maximum daily shrinkage (signal) and the midday stem water potential (SWP). In RDI-1, full irrigation conditions were provided before kernel filling and during postharvest, using the threshold values suggested in the bibliography. During kernel filling, the water stress level was approximately -1.5MPa (SWP) and 1.75 (signal). RDI-2 trees were irrigated using the same scheduling as RDI-1, but reaching a higher level of water stress in kernel filling (-2MPa and 2.75) and with a maximum seasonal amount of water of 100mm. SWP in Control trees was near the McCutchan and Shackel baseline for most of the season. None of the deficit treatments reached the signal values suggested. Moreover, the signal values were almost equal between treatments, with no water stress effect. The trunk growth rate (TGR) presented clear differences depending on the water status. There was a yield reduction, approximately 20%, and it was probably due to the effect of nut load in the current season.

Keywords	Kernel filling; kernel weight; maximum daily shrinkage; MDS; trunk growth rate; TGR.
Taxonomy	Crop Production, Agricultural Sensor, Crop Management

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Suggested reviewers	Peter Searles, Ricardo Gucci, Ken Shackel

Título modificado por la revista:

Pattern of trunk diameter fluctuations of almond trees in deficit irrigation scheduling during the first seasons

~~Limitations of using trunk diameter fluctuations for deficit irrigation scheduling in almond orchards.~~

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ABSTRACT

Irrigation needs in mature almond orchards are very high. Although almond trees grow in rainfed conditions, the yield response is very sensitive to irrigation. Continuous monitoring of the water status could be an adequate tool to optimize deficit irrigation. In this sense, trunk diameter fluctuations appeared as a very promising indicator at the beginning of the century, but few data have been published. The aim of this work is to present data about almond irrigation scheduling using trunk diameter fluctuations and the effect of water stress in the current yield. The experiment was performed in a commercial farm in Dos Hermanas (Seville, Spain) during the 2017 season on a 7-years-old orchard (cv Vayro). The irrigation treatments were Control (100% ETc), sustained deficit irrigation (SDI) with a maximum seasonal irrigation of 100mm and two regulated deficit treatments (RDI). Both RDI treatments (RDI-1 and RDI-2) were scheduled using the signal of maximum daily shrinkage (signal) and the midday stem water potential (SWP).

In RDI-1, full irrigation conditions were provided before kernel filling and during postharvest, using the threshold values suggested in the bibliography. During kernel filling, the water stress level was approximately -1.5MPa (SWP) and 1.75 (signal). RDI-2 trees were irrigated using the same scheduling as RDI-1, but reaching a higher level of water stress in kernel filling (-2MPa and 2.75) and with a maximum seasonal amount of water of 100mm. SWP in Control trees was near the McCutchan and Shackel baseline for most of the season. None of the deficit treatments reached the signal values suggested. Moreover, the signal values were almost equal between treatments, with no water stress effect. The trunk growth rate (TGR) presented clear differences depending on the water status. There was a yield reduction, approximately 20%, and it was probably due to the effect theof nut load in the current season.

Keywords: Kernel filling, kernel weight, maximum daily shrinkage, MDS, trunk growth rate, TGR.

INTRODUCTION

Almond trees (*Prunus dulcis* (Mill) DA Webb) are one of the main deciduous fruit crops in Mediterranean climate zones. This fruit species is considered drought resistant (Castel and Fereres, 1982) and, although cultivated in irrigated lands, there is also a large rainfed surface used around the world. Yield differences of about 10-fold have been reported between irrigated and rainfed orchards (Girona, 1992). The drought responses of this fruit species involve different processes of resistance and water stress avoidance. Water deficit conditions could produce minimum pre-dawn water values down to -4.0MPa in almond orchards, although they would cause a severe reduction in yield in the current and following seasons (Goldhamer and Viveros, 2000).

Goldhamer and Fereres (2017) suggested that, under the conditions of the San Joaquin valley (USA), the irrigation needs in mature almonds orchard is approximately 1250mm, with a maximum marginal water productivity close to 1080mm. Goldhamer and Girona (2012), in a review of several studies, suggested that a reduction of 10-15% in crop evapotranspiration (ETc) had an almost negligible effect on yield. Therefore, the potential capacity of the almond production is very sensitive to water stress, even though it is possible to reduce the water needs. Regulated deficit irrigation (RDI) scheduling in almond crops is not easy because of this great drought sensitivity. The final nut yield is commonly related to two main periods, namely kernel filling and postharvest. There is a general consensus about postharvest water stress reducing the yield in the next season, with a reduction of the nut load (Goldhamer and Viveros, 2000; Esparza et al. 2001; Girona et al., 2005; Goldhamer et al., 2006). Goldhamer and Girona (2012) reported that, even in severe conditions of water stress before harvest, when trees were rehydrated during postharvest, the next season's yield was not affected. But the duration of this recovery period and the water status that trees should reach is not clear. Conversely, there is no clear results about the impact of water stress during kernel filling periods, such lacks in the results have been associated with the level of water stress (García-Tejero et al., 2018).

An accurate water management is very important to optimize irrigation in zones with scarce water resources. Continuous monitoring of the water status could improve yield results with deficit irrigations. However, there is little information about indicators and the relationship between yield responses and water stress levels. Goldhamer and Fereres (2004) reported very good results of controlled deficit irrigation scheduling using maximum daily shrinkage. But other than this, data provided in other works is limited and unclear. Nortes et al (2005) concluded that the MDS was not suitable for young almond crops and suggested the trunk growth rate as a continuous indicator. Puerto et al (2013), for mature almond trees, confirmed the data obtained by Goldhamer and Fereres (2004), but in both papers, deficit treatments presented similar MDS values, even with different water potential values. On the other hand, McCutchan and Shackel (1992) suggested a water potential baseline for prunus that has been used in several almond irrigation works (Shackel et al., 2011). The aim of this work was to design an irrigation scheduling using MDS data in order to compare the current effect of different water stress levels on the yield components.

MATERIAL AND METHODS

Site description and experimental design

The experiment was performed during the 2017 season at the commercial farm "La Florida" (37.23ºN, -5.91ºW, Dos Hermanas, Seville, Spain). The almond (*Prunis dulcis* (Mill) DA Webb) orchard, was 7 years-old at the moment of performing the experiment. There were 2 cultivars in the orchard in coupled lines, Guara cv and Vayro cv, and the tree spacing for both cultivars was 6m x 8m. The experimental plots had 4 lines of 3 trees and measurements were performed in the central trees of the Vayro cv. The trees were irrigated with a line of drips (3.8l h^{-1}) separated 0.4 m. The soil was clay loam with over 1m depth, a high percentage of carbonate (higher than 30%) and pH around 8. The percentage of organic matter in the 0-30cm layer is approximately 1.6%, with adequate levels of P_2O_5 and K_2O.

The statistical design used randomized complete blocks with 4 repetitions and 4 irrigation treatments. Two trees per plot were measured and these trees were surrounded by a line guard. The tree phenological stage and the water stress level were the two factors defining the irrigation treatments. In the current work, the phenological stages were divided into three phases in order to simplify those suggested by Nortes et al (2009). Phase I run from full bloom until the beginning of the kernel filling (31st May in this work). Phase II stretched from kernel filling to harvest (7th August in this work). Phase III covered the postharvest harvest. According to Nortes et al (2009), a sharp increase of kernel dry weight indicated the beginning of the kernel filling period. The irrigation season started on 17th March and finished on 2nd October. Irrigation scheduling methods varied according to the treatment considered:

Control. Covering 100% of crop evapotranspiration (ETc). ETc was estimated according to Steduto et al (2012). The crop coefficients (Kc) were those suggested by Girona et al (2006 cited in Goldhamer and Girona, 2012). The reduction coefficient (Kr) value was 0.45, estimated according to Steduto et al (2012).

RDI-1. Regulated deficit irrigation (RDI) with a period of water stress during kernel filling (phase II) and full irrigated conditions for the rest of the season. The irrigation scheduling was estimated according to the midday stem water potential (SWP) and the maximum daily shrinkage (MDS) of the trunk. During phases I and III, the baseline of McCutchan and Shackel (1992) was used to estimate the optimum SWP. The baseline of MDS was estimated according to Goldhamer and Fereres (2004) around 15 days before kernel filling (31st May). In order to minimize the environmental effect on MDS values, the ratio between measured MDS and optimum MDS (hereinafter, the MDS signal (signal)), was calculated (Goldhamer and Fereres (2001)). Full irrigated conditions were considered when the signal was equal to 1. During phase II, the SWP threshold was -1.5MPa (Garcia-Tejero et al 2018) and the signal threshold was 1.75 (Goldhamer and Fereres, 2004).

RDI-2. Regulated deficit irrigation for the same period that RDI-1, but with 100mm of maximum seasonal water applied. The average irrigation needs were estimated using the seasonal average (10-years' average) of 230mm. This reduction was used to estimate the yield response with severe limitations of available water. The irrigation scheduling during phases I and III was the same. The water stress level in phase II was increased to -2.0MPa (SWP) and 2.75 (signal).

SDI. Sustained deficit irrigation throughout the experiment with 100mm maximum seasonal water applied.

The irrigation was changed daily and the water applied in the RDI treatments was estimated according to the difference between measured indicator and threshold value at each phenological stage. When the SWP and the signal were not in agreement, the most distant to the threshold was selected. The daily irrigation was based on the estimated maximum daily ETc (3mm) when a difference of more than 30% of the threshold was measured, and it was reduced to 1.5mm and 0.75 when differences were between 20-30% and 10-20%, respectively. If differences were lower than 10% or the measured value indicated a better-than-expected water status, trees were not irrigated.

Meteorological conditions throughout the experiment

The seasonal weather data were obtained from the "IFAPA Los Palacios" station, in the Andalusian weather stations network (Fig. 1). This station is about 6km away from the experimental orchard. The data for 2017 were typical of Mediterranean zones, with null rainfall during summer period and warm winters. Reference evapotranspiration values (ETo) higher than 6mm day^{-1} were measured from the end of Spring until mid-August. The average ETo during the kernel filling period was 6.3mm day^{-1} with null rainfall. During phase I, from full bloom until the kernel filling period, the average ETo was 3.5mm day^{-1} and the total rainfall was 94mm. But during the recovery period, from harvest until the end of October, rainfall was very scarce, 14.3mm, while ETo was still high, with a daily average of 4.2mm day^{-1}. The total rainfall this year was very low, 366.3mm, according to the seasonal average (539mm, AEMET, 2018).

Measurements

The water relations of the trees were studied in combination with the soil moisture, leaf gas exchange and midday stem water potential measurements. The soil moisture was measured with a portable FDR sensor (HH2, Delta-T, U.K.). Measurements were made in four plots per treatment. The access tubes for the FDR sensor were placed in the irrigation line, about 30cm from an emitter (Fernández et al., 1991). Data were obtained at 1m depth and 10cm intervals. The leaf gas exchange was measured with the midday leaf net photosynthesis using an infrared gas analyzer (CI-340, CID BioScience, USA) in one fully expanded sunny leaf per tree. The water potential was measured at midday in one leaf per tree, using the pressure chamber technique (Scholander et al., 1965). The leaves near the main trunk were covered with aluminium bags at least one hour before measurements were taken and a pressure bomb was used (PMS model 1000). In order to describe the cumulative effect of the water deficit, the water stress integral (SI) was calculated using the midday stem water potential data (Equation 1, Myers, 1988) from the beginning of kernel filling until harvest, postharvest period and total season. The expression used was:

$$SI=|\sum(SWP -c)*n| \qquad (1)$$

where: SI is the stress integral

SWP is the average midday stem water potential for any interval

c is the maximum value of SWP

n is the number of the days in the interval

At the beginning of each season, ten shoots per tree were selected randomly and marked. For each shoot, the total length and number of nuts in the first 10cm were measured periodically. The nut length was measured with a randomized survey of ten fruits per tree on each measured date. The kernel dry weight was measured periodically throughout the experiment taking a sample of 6 nuts per plot.

The trunk diameter fluctuations were measured in one tree per repetition using a band dendrometer (5µm accuracy, D6, UMS, Germany) attached to the main trunk. The band dendrometer works like a beam when bending. The trunks were measured using the nodes of a wireless sensor with a network topology for easy installation and maintenance. The band rested on a part of the trunk surface. The ends of the band were joined with Invar steel, an alloy of Ni and Fe with a thermal expansion coefficient close to zero (Katerji et al., 1994), the band circled the trunk. A Teflon net below the steel prevented friction with the bark surface. Each band dendrometer was plugged into a node (Widhoc smart solution SL, Spain) near the sensor. These nodes were integrated by two different parts. One being the measurement interface and the other the processing, recording and communication system. The nodes generated a stabilized power supply of 10Vdc to the band dendrometer. The data from each sensor node were sent wirelessly to the cloud. Ten measurements of each band dendrometer were taken every fifteen minutes.

Trunk diameter fluctuations are a daily cycle of shrinkage and swelling in which different indicators can be estimated. The most common ones are the maximum daily shrinkage (MDS) and the trunk growth rate (TGR) (Ortuño et al., 2010). The MDS is the difference between the daily maximum diameter, at the beginning of the day, and the minimum daily diameter that occurs at the end of the afternoon (Goldhamer et al., 1999). The TGR is the difference between two consecutive daily maximums (Goldhamer and Fereres, 2001), the TGR on day "n" is the difference between the maximum daily diameter for day "n+1" and for day "n". The MDS signal was used to reduce the environmental effect on the MDS measured. The MDS signal is the ratio between the measured and the estimated full irrigated MDS (Goldhamer and Fereres, 2004). The full irrigated MDS was estimated using the baseline obtained before the kernel filling period (Goldhamer and Fereres, 2004).

The irrigation treatments were also evaluated from the point of view of quantity and quality of yield. Yield and nut relative humidity of two trees in each plot were measured. Nuts were dried until values lower than 5% relative humidity were reached (commercial reference). Then, a sample of 10 nuts per tree were obtained and the ratio kernel vs kernel plus shell was measured. The yield was expressed as kernel weight at 5% of relative humidity. The water use efficiency (WUE) was estimated as the ratio between yield and water applied in each plot.

Data analyses were performed with ANOVA and the mean separation was made using a Tukey's test with the Statistix (SX) program (8.0). Significant differences were considered when $p\text{-level}<0.05$ in both tests. Calculations of the p-level were performed considering the F-test of variance equality. When conditions of variance equality could not be obtained, a decrease in the degree of freedom and, therefore, a more restrictive p-value was calculated. The number of samples measured is specified in the text and figures.

RESULTS

The pattern of total water in the soil at 1m depth throughout the experiment is shown in Fig. 2. During the full bloom/nut set, there were no significant differences between treatments and the total amount of water in the soil was approximately 290mm. The kernel filling period started on day of the year (DOY) 151. In this period, from DOY 151 to 221, the water in soil for the RDI-1 and RDI-2 treatments was reduced continuously until values close to 250mm were reached. Trees in SDI also reduced the soil water but at a slower pace, until values nearing 280mm were reached. There were no significant differences between these treatments in this period, only Control trees presented a clear and significant higher amount of water in soil than the rest, with values close to 320mm. The period of soil moisture reduction during DOY 217-221 for Control trees was due to the dry period before harvest. In these two weeks, the deficit treatments were almost constant. After harvest, during the recovery period, the Control trees reached maximum values in three weeks (around 320mm), while the rest of treatments presented a delay and uncompleted rehydration. Only RDI-1, at the end of the irrigation season (DOY 269, 48 days after harvest), presented values similar to the ones obtained in preharvest for Control. The increase in the soil water in RDI-2 and SDI was smaller than in RDI-1, and it stopped around DOY 269 because the maximum amount of irrigation was reached in some plots. During the recovery period, only the Control treatment presented significant differences with the rest of treatments.

Three different soil moisture profiles are presented in Fig. 3. At the beginning of the experiment (Fig. 3a) the soil moisture was similar in all treatments. On this date (DOY

95, full bloom/nut set phase), maximum values were measured from 100cm (around 40% v/v) and the soil moisture decreased from this depth, down to 10cm, where it reached a minimum of approximately 10%. At the end of the deficit period (Fig. 3b, DOY 207), the soil moisture profiles were different. The Control plots presented the highest values at all depths, with a maximum at 60 and 100cm (approximately 40%) and a minimum at 10cm (approximately 25%). On this date, RDI-1 and RDI-2 presented a clear trend of being drier near the surface (10 and 20cm) with significant differences with Control at 10cm. These decreases were smaller for the treatments at depths between 30 and 60cm, but still significant in RDI-1 and almost null at 100cm. The SDI was an intermediate treatment with no significant differences with Control or the other two deficit treatments, but with clear reductions at 10cm and 60cm. At the end of the postharvest period (DOY 269), only the deeper horizons showed clear differences between Control and the rest of treatments. This was significant at 60cm depth, with values of approximately 45% in Control and 35% in the deficit treatments. In the surface, from 10 to 40cm, there were no significant differences and the soil moisture was very similar.

Midday stem water potential data are shown in Fig. 4, where the three periods considered for regulated deficit irrigation (RDI) are presented. At the beginning of the irrigation season (full bloom and nut set), there were no significant differences between values of water potential. All treatments were near the baseline suggested. Irrigation restrictions were applied from day of the year (DOY) 151 (Phase of kernel filling). During this period, there were significant differences between Control and the rest of treatments from DOY 159 until DOY 204, almost the entire period. From DOY 204, there was a dry period before harvest in all the treatments and it reduced water potential. This decrease was greater in the Control treatment than in the rest, which had higher water stress levels. In the period DOY 159-204, there were some significant differences between SDI and

RDI-1 and 2, but the general trend was that the former showed higher values. RDI-1 and RDI-2 trees presented an almost equal water potential in this period. Minimum values of water potential reached -2MPa in the RDI-1 and RDI-2 treatments. Minimum values of the Control trees were around -1.5MPa just before harvest and higher than -1.2MPa before the drying period. The pattern of the baseline during this period was similar to the pattern of Control trees. Maximum differences between Control and baseline were approximately 0.4MPa lower in the former. In the last period there were two parts; at the beginning, the recovery was delayed at least 4 weeks (the shortest period for Control trees) and even more for the rest of treatments. RDI-1 reached similar water potential values to Control on DOY 261, while RDI-2 and SDI were clearly and significantly lower. From DOY 261, some plots in RDI-2 and SDI treatments were not irrigated because they used the maximum amount of water for these treatments (100mm). The irrigation season finished by DOY 276 for the treatments and by DOY 298, after some rains, the stem water potential was almost equal for all treatments.

The stress integral (SI) during the entire experiment was significantly lower in Control (approximately 130MPa*day) than in the rest of treatments (approximately 200MPa*day), without significant differences between deficit irrigations (Fig. 5). About 85% of the SI values were measured in phase II and phase III due to water status conditions. In phase II, the Control trees presented values significantly lower than the rest, and the SDI was also statistically lower than RDI-1 and RDI-2. The SI values obtained in the phase III were very similar to the ones obtained in the phase II. In this period, only the Control trees showed a value significantly lower than the rest of treatments. RDI-1 was slightly lower than RDI-2 and SDI (12% less) but such differences were not significant.

The pattern of midday net photosynthesis throughout the experiment is showed in Fig. 6. Maximum seasonal midday Pn values were measured in the phase of full bloom/nut set and, from DOY 151, there was a slight decrease in all treatments until the middle of the kernel filling phase. There were a few dates with significant differences between treatments. On DOY 193, RDI-1 was significantly lower than the rest of treatments and, from this date until DOY 256, the trends showed lower values in deficit treatments than in Control. Such differences were significant only on DOY 235 and 256. From DOY 256, the Pn values were very similar for the different treatments. No differences were measured between deficit treatments.

The pattern of maximum daily shrinkage signal (Signal) is presented in Fig. 7. Most of the values measured throughout the experiment were almost equal for the different treatments and only a few significant differences were found. The seasonal pattern of the Signal showed values close to 1 during the phase of full bloom/nut set (Table 1). There was a slightly increase of the Signal during stage II, higher in the deficit treatments than in the Control one, but lower than the threshold considered (1.75 and 2.75, Table 1 and Fig. 7). The greatest increase of the Signal for all the treatments occurred during the postharvest period (Table 1, Fig 7), mainly until DOY 242, when Signal values of approximately 2 were measured. Only in the period between DOY 247-257, the Signal for SDI was significantly higher than for the rest of treatments.

The pattern of maximum diameter is presented in Fig. 8. In all the treatments, there was a continuous growth throughout the experiment. But trunk growth rate (TGR). The slope for maximum diameter data (Fig. 8) was clearly different under water stress conditions (Table 2). At the beginning of the experiment, phase I, although two significant differences were measured, the TGR average was very similar without a significant divergence (Table 2). During the kernel filling phase the greatest differences between treatments appeared, mainly at the end of the period because there some data were lost for the Control treatment, during DOY 162-167. Differences in TGR were significant between Control and the RDI-1 and RDI-2 from DOY 201 to 214, when sensors were removed for harvest. Trees of SDI were an intermediate treatment with no significant differences or just a few days showing different values (Fig. 8). The TGR average for this period showed this pattern. The TGR in RDI-1 and RDI-2 was significantly lower in this treatment than in the Control one, but SDI was in between, although values in this latter treatment were half those of the Control one (Table 2). The average TGR in the Control treatment was similar for phase I and II, but it was clearly reduced in phase III. In this latter phase, TGR values were significantly different for most dates (slope in the Fig. 8) with higher values in the Control treatment than in the rest. All the treatments presented an almost constant TGR during postharvest, only on DOY 260, RDI-1 showed a slight increase. The TGR average during this period was significantly different between Control and the rest (Table 2). In all the deficit treatments, the average TGR was approximately half the ones measured during phase II (Table 2).

The vegetative growth response to the irrigation treatments was characterized using the crown volume and the shoot growth. All the treatments presented a clear increase of crown volume during the year (Fig. 9a). There were no significant differences between treatments on any of the dates. At the beginning of the season, the crown volume was approximately 22 m^3 per tree, while at the end it almost doubled. Only in RDI-1 trees, the crown volume at the end of the season was clearly lower than the rest of treatments, although the differences were not significant. The shoot expansion was very variable and there were no significant differences between treatments during the season (Fig. 9b). Most of the shoot expansion in all treatments occurred during phase I, before the kernel filling period.

The pattern of flower/nut per shoot in the first 10cm is showed in Fig. 10. The first data in this Figure were for flowers, while the rest were for nuts. There were fast decreases in the number of nuts from full bloom until one week before the end of phase I. This value decreased for all treatments until it reached a tenth of the number of nuts. Although significant differences were found during this period of decrease, the data were almost constant and not significantly different from DOY 144. During the decrease period, only RDI-1 treatments presented significantly lower number of nuts than RDI-2 (first data), RDI-2 and Control (next two data). At the end of the experiment, the number of nuts was very low, around 0.6 per 10cm shoot in Control, RDI-2 and SDI, but in RDI-1 it was even lower, approximately 0.3 nuts per 10cm shoots.

Nut development was described using measurements of the nut length, kernel dry weight and percentage of split hull (Fig. 11). The seasonal pattern of nut length growth was equal for all the treatments (Fig. 11a). There was a short period of fast growth, around 4 weeks, until DOY 109. After that date, the nut size reached a maximum and remained unchanged throughout the experiment. There were only two significant differences in this parameter, both of them during the period of maximum nut size. Therefore, such differences were likely related to sampling mistakes and not to the irrigation treatments. The pattern of kernel dry weight showed a continuous increase throughout the experiment in all treatments (Fig. 11b). The change in the slope of dry weight accumulation in DOY 151 was considered the indicator for the beginning of the kernel filling period. No significant differences between treatments were found on any of the dates. In the last measurement, just before harvest, the Control treatment showed a trend to increase over the rest of treatments and Control kernels were approximately 10% heavier than the RDI-2 nuts. The pattern of split nuts was clearly different between irrigation treatments (Fig. 11c). Only on the first date, Control trees presented a significantly lower number of split nuts (approximately 40%) than RDI-1 (approximately 70%). However, there was a clear delay trend in Control trees over those in deficit treatments, mainly RDI-1 and RDI-2. By DOY 207, the percentage of split nuts in these latter deficit treatments was 100%, while in the Control it was still lower than 80%.

The irrigation scheduling varied the volume of water applied in preharvest stages and throughout the whole season for the treatments, but it did not reduce the yield significantly (Table 3). Neither of the yield parameters were significantly affected by irrigation treatments. In Control trees, the kernel yield (expressed at 5% of water content) tended to greater values than in the deficit treatments, the greatest differences were with RDI-2, showing a reduction of approximately 20%, but the average reduction was close to 15%. Such reductions were more related to the nut load than the kernel weight (Table 3). In terms of nut load, the greatest differences, although not significant, were measured between Control and RDI-2 (approximately 10% lower than Control) and slightly higher than the other two deficit treatments (approximately 7%). The differences in kernel dry weight were lower than in nut load for RDI-2 and SDI, approximately 3% of reduction in both treatments vs Control, although there was a greater decrease in RDI-1 (10%). The ratio kernel vs kernel plus shell was almost equal for the SDI and Control treatments, and showed a slight reduction in RDI-1 (6% lower) and RDI-2 (8% lower). There were no significant differences for any of those two parameters. The pattern of water applied varied between deficit treatments. RDI-2 and SDI received a similar seasonal amount of water (approximately 100mm) but less than 50% was applied in preharvest in RDI-2, while more than 60% was used in SDI. The seasonal water applied in RDI-1 was greater than in RDI-2 and SDI, approximately 34% of Control vs 25%. The water applied in RDI-1 during preharvest was 20% lower than in the Control treatment and for postharvest this percentage was 54%. The water use efficiency (WUE) was clearly greater in the deficit than in the Control treatments, but such differences were significant only between Control and RDI-2/SDI, more than triple in the latter than in the former. RDI-1 was a statistically intermediate treatment, but WUE was double in RDI-1 than in Control.

DISCUSSION

The maximum daily shrinkage (MDS) did not support irrigation management throughout the season (Fig. 7 and Table 1). This indicator showed no differences between treatments throughout the experiment. Only during the kernel filling period, the average MDS signal (Signal) tended to show higher values in deficit treatments than in the Control one, but the maximum value expected, 2.75, was never reached (Table 1). There are a few works that use trunk diameter fluctuations for almond crops. Goldhamer and Fereres (2004) is the reference suggesting the threshold values used in the current work. In this work, the Signal values were approximately 1.75 and 2.75, but data presented great variations for days with similar values for different treatments in some measurements, although water potential measurements were always different (Goldhamer and Fereres (2004)). Puerto et al (2013) also reported values of Signal higher than 2.75, but these data were, again, similar in other deficit treatments. In none of the two articles, data for full irrigated trees were presented. The lack of maximum Signal results in the present work could be related to trunk growth. Goldhamer and Fereres (2001) suggested that a large trunk growth could reduce the MDS. There was a continuous trunk growth during the present work (Fig. 8), which could reduce MDS values and then the Signal. Nortes et al (2005), in a three-years-old almond orchard, reported no significant differences in MDS between treatments and maximum MDS values around half those reported by Puerto et al (2013) in a twelve years-old almond orchard. In addition, although there were no data of trunk growth in Goldhamer and Fereres (2004) and Puerto et al (2013), yield and orchard age suggest that the trunk growth was likely lower than in the present work. Such decrease in MDS values could affect the relationship between MDS and water potential. Puerto et al (2013) reported an exponential equation in the relationship between MDS and water potential, with a maximum MDS around 500μm and water potential near -1.8MPa. Thus, according to the water potential values obtained in the current work (Fig. 4), the MDS should be clearly different between treatments, and so should the Signal. However, the possible reduction in MDS could also affect this relationship with an even narrower interval for the MDS value and a small slope in the relationship of water potential.

Conversely, the trunk growth rate (TGR) presented differences that were clearer than Signal throughout the experiment. (Fig. 8 and Table 2). The main problems with this indicator are that the seasonal pattern changed during the year, the TGR decreased during phase III in Control trees (Table 2), and there are no data for interannual variations. The TGR decrease during the season was likely related to the physiology of almonds as deciduous trees (García-Tejero, et al., 2018). In the inter-annual variations, the trunk growth should theoretically decrease with the increase of the tree age and nut load. Therefore, the TGR values for one year would not be valid in the next season. Nortes et al (2005) concluded that, in young almond trees, the TGR is the most useful indicator for monitoring water stress when several water relations measurements were compared. Intrigliolo and Castel (2006) reported that the TGR was strongly related to the fruit load in plum trees. Egea et al (2009) reported the TGR seasonal pattern during three consecutive years for a mature almond orchard. In their work, TGR values presented a changeable seasonal pattern, with values that tended to decrease along the season and from the first to the third year of the experiment. These TGR values in Egea et al (2009)'s work were around half those reported in the current work and in Nortes et al (2005)'s work. This also supports the idea that trunk growth invalidated the MDS data. Unfortunately, the TGR has not been used in the comparison of water stress conditions, except in the work of Nortes et al (2005); therefore its suitability for irrigation scheduling is not clear, as no reference trees have been considered.

Almond tree irrigation is affected by current and previous irrigation season (Goldhamer and Viveros (2000), Girona et al., 2005). The current work was focused on the first season of the experiment and then effects of the water management in the previous season were likely negligible. The level of water stress during the kernel filling period was similar between deficit treatments, with a short period showing a clear reduction of the gas exchange (Fig. 6), but a significant decrease in the water potential during most of phase II (Fig. 4 and 5) in comparison to Control. Such conditions tended to reduce yield, and the main yield component affected was the nut load (Table 3). However, the number of nut per shoot is not in agreement with this reduction in nut load (Fig. 10). The lack of conclusive results, when the number of nut per shoot is considered, suggests that the nut set could be greater in the higher parts of the trees, rather than at the surveyed height. In superhigh-density olive orchards, the fruit set is greater at the top than in the bottom of the hedgerow (Cherbiy-Hoffmann, S et al., 2012). The current data suggest that the nut load is more sensitive than the kernel weight to the current water stress conditions. The effect on nut load is commonly related only to postharvest water stress of the previous season (Goldhamer and Viveros (2000); Girona et al (2005); Goldhamer et al (2006); Egea et al (2009)). These results could be underestimating the effect of the current deficit treatments during the kernel filling because part of such reductions could have been associated to the effect on nut load.

Water stress conditions were accurately described with soil moisture and water potential (Figs. 2,3,4,5). Soil moisture data are difficult to use as a reference indicator in different orchards because it is not easy to define an absolute value and the locations for the sensors. However, these data suggest that the main root activity is located 40-60cm deep. Then, a small amount of irrigation during the recovery will delay the tree rehydration because the soil moisture at these depths would not increase enough. The midday stem water potential (SWP) could define different indicators to evaluate the water stress level, minimum value and stress integral, which includes the effect of duration and level of water stress. The baseline of McCutchan and Shackel (1992) could be a useful tool in fully irrigated conditions because the SWP values were close for most of the season (Fig. 4). The minimum SWP value was below -1.5MPa in SDI and near -2MPa in RDI-1 and RDI-2, before the dry preharvest period. According to the gas exchange data (Fig. 6), these levels of water stress were moderate but lasted a long period. The reduction in net photosynthesis was approximately 40% for almost 2 months (Fig. 6), most of them during the recovery period. Different authors reported effects on net photosynthesis, but with more severe water potential values (-1.5MPa predawn, Romero et al., 2006; -2.5/-3.5MPa midday Gomes-Laranjo et al., 2006). An SWP of approximately -2MPa has been suggested as the threshold value to reduce yield (Hutmacher et al (1994); García-Tejero et al (2018)). This level of water stress was also reached by Control trees just before harvest (Fig. 4), but the gas exchange was not affected at any point in time (Fig. 6). Therefore, the minimum SWP for the period is probably not a good water stress indicator to consider. The stress integral near 50MPa*day during the kernel filling phase could also be a possible threshold to considered for future works. The current one cannot evaluate the yield response because it is a single-season experiment, but it could suggest these values as possible thresholds for nut load reduction.

CONCLUSIONS

The MDS Signal was not a useful indicator for irrigation scheduling because of the great trunk growth. On the contrary, the TGR was a sensitive water stress indicator. Such results are in agreement with the response of young almond orchards. However, the suitability of the TGR is restricted to the current season and only for reference trees, because there is no approach yet that can estimate this indicator throughout the orchard's life. The nut load was the main yield component affected by the current water stress. A SWP below -1.5MPa and a stress integral below 50MPa*day during kernel filling could be the threshold value to minimize this effect. The SWP baseline is useful for full irrigation conditions.

Acknowledgement

This research was supported by the Agencia Española de Investigación (AEI) and the Fondo Europeo de Desarrollo (FEDER) project AGL2016-75794-C4-4-R. Authors thank to Finca La Florida for their helpful assistant during the experiment, specially to Mr Carlos Angulo.

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Figure Captions

Fig. 1. Annual pattern of potential evapotranspiration (ETo) and rainfall. Vertical lines indicate the period of kernel filling. Data were obtained from the "IFAPA Los Palacios" station which is approximately 6km away from the experiment site. This meteorological station in part of the Andalusian agroclimatic stations network (Junta de Andalucía).

Fig. 2. Pattern of total soil water at 1m depth throughout the experiment. Each point is the average of 4 values. Vertical bars represent the standard error. Vertical lines indicate the period of kernel filling. Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. Stars indicate the date when significant differences were measured ($p<0.05$, Tukey Test). Circles around DOY 95, 207 and 269 mark the dates when data of the amount of water in the soil profile are presented in Fig. 3.

Fig. 3. Soil moisture in the 1m profile on three different dates throughout the experiment (dates are indicated with a circle in Fig. 2). (a) DOY 95 (full bloom/nut set phase), (b) DOY 207 (kernel filling phase), (c) DOY 269 (postharvest phase) Each point is the average of 4 values. Horizontal bars represent the standard error. Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. Stars indicate the depth where significant differences were measured ($p<0.05$, Tukey Test).

Fig. 4. Pattern of midday stem water potential throughout the experiment. Each point is the average of 4 values. Vertical bars represent the standard error. Vertical lines indicate the period of kernel filling. Solid lines represent the baseline of McCuhan and Shackel (1992). Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. Stars indicate the date when significant differences were measured ($p<0.05$, Tukey Test).

Fig. 5. Stress integral for the whole experiment, in phase II (kernel filling) and in phase III (postharvest). Each column is the average of 4 values. Vertical bars represent the standard error. Different letters indicate significant differences in the period considered ($p<0.05$, Tukey Test).

Fig. 6. Pattern of midday net photosynthesis (Pn) throughout the experiment. Each point is the average of 4 values. Vertical bars represent the standard error. Vertical lines indicate the period of kernel filling. Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. Stars indicate the date when significant differences were measured ($p<0.05$, Tukey Test).

Fig. 7. Pattern of signal of maximum daily shrinkage (Signal) throughout the experiment. Each point is the average of 4 values. Vertical lines indicate the period of kernel filling. Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. Stars indicate the date when significant differences were measured ($p<0.05$, Tukey Test).

Fig. 8. Pattern of maximum diameter throughout the experiment. Each point is the average of 4 values. Vertical lines indicate the period of kernel filling. Solid line, Control; long dash line RDI-1; dotted line and line, RDI-2; short dash line SDI. Stars indicate the date when significant differences in the trunk growth rate (TGR, the slope of this graph) were measured ($p<0.05$, Tukey Test).

Fig. 9. Vegetative growth response to irrigation treatments. (a) Crown volume at the beginning (January, black bars) and at the end (December, grey bars) of the experiment. (b) Shoot expansion throughout the experiment. Vertical lines represent the standard error. Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. No significant differences were found between treatments on the same dates ($p<0.05$, Tukey Test).

Fig. 10. Pattern of number of flower (only first data) or nuts in the first 10cm of the shoot throughout the experiment. Each point is the average of 40 values. Vertical bars represent the standard error. Vertical lines indicate the period of kernel filling. Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. Stars indicate the date when significant differences were measured ($p<0.05$, Tukey Test).

Fig. 11. Pattern of nut length (a), kernel dry weight (b) and split nuts (c) throughout the experiment. Each point is the average of 40 values. Vertical bars represent the standard error. Vertical lines indicate the period of kernel filling in a and b. Solid square, Control; empty square, RDI-1; solid triangle, RDI-2; empty triangle, SDI. Stars or different letters indicate the date when significant differences were measured ($p<0.05$, Tukey Test).

Table 1. Average maximum daily shrinkage signal (Signal) and standard error in the three phenological stages considered in the experiment. Phase I, from full bloom until kernel filling, Phase II from kernel filling until harvest, Phase III, postharvest. No significant differences were found (Tukey Test, $p<0.05$).

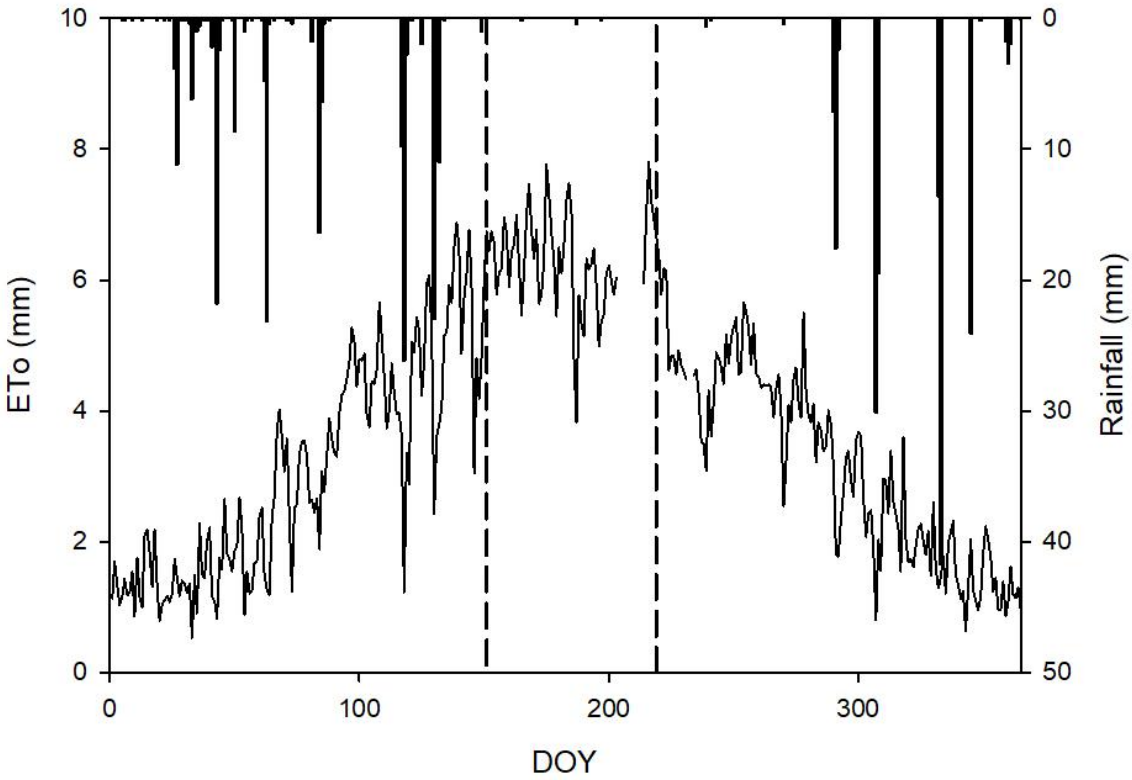
	Phase I	**Phase II**	**Phase III**
Control	1.13±0.11	1.13±0.15	1.58±0.07
RDI-1	1.00±0.13	1.24±0.11	1.50±0.17
RDI-2	1.11±0.11	1.37±0.24	1.41±0.19
SDI	1.14±0.03	1.32±0.10	1.84±0.04

Table 2. Average trunk growth rate (TGR, mm day^{-1}) and standard error in the three phenological stages considered in the experiment. Phase I, from full bloom until kernel filling, Phase II from kernel filling until harvest, Phase III, postharvest. Each value is the average of 4 values. Different letters within the column indicate significant differences (Tukey Test, $p<0.05$).

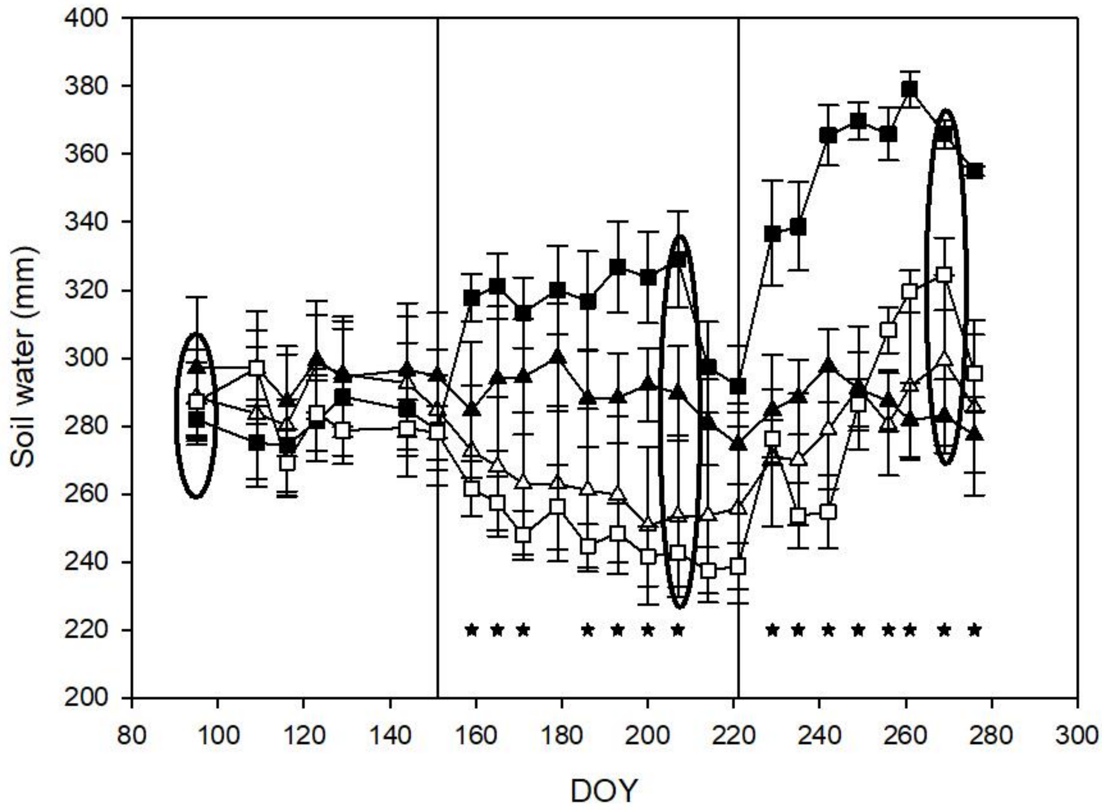
	Phase I	**Phase II**	**Phase III**
Control	0.34±0.10	0.29±0.08 a	0.18±0.03 a
RDI-1	0.24±0.03	0.07±0.03 b	0.04±0.00 b
RDI-2	0.37±0.04	0.06±0.02 b	0.01±0.01 b
SDI	0.43±0.11	0.15±0.05 ab	0.07±0.03 b

Table 3. Yield and water applied during the experiment (average ± standard error). Each data is the average of 4 trees. Kernel dry weight (g), kernel yield (expressed at 5% water content, Kg/ha), ratio between Kernel and kernel plus shell (%), nut load, applied water during preharvest and in the whole season (mm), water used efficiency (kg m^{-3}). Different letters indicate significant differences (Tukey Test, $p<0.05$).

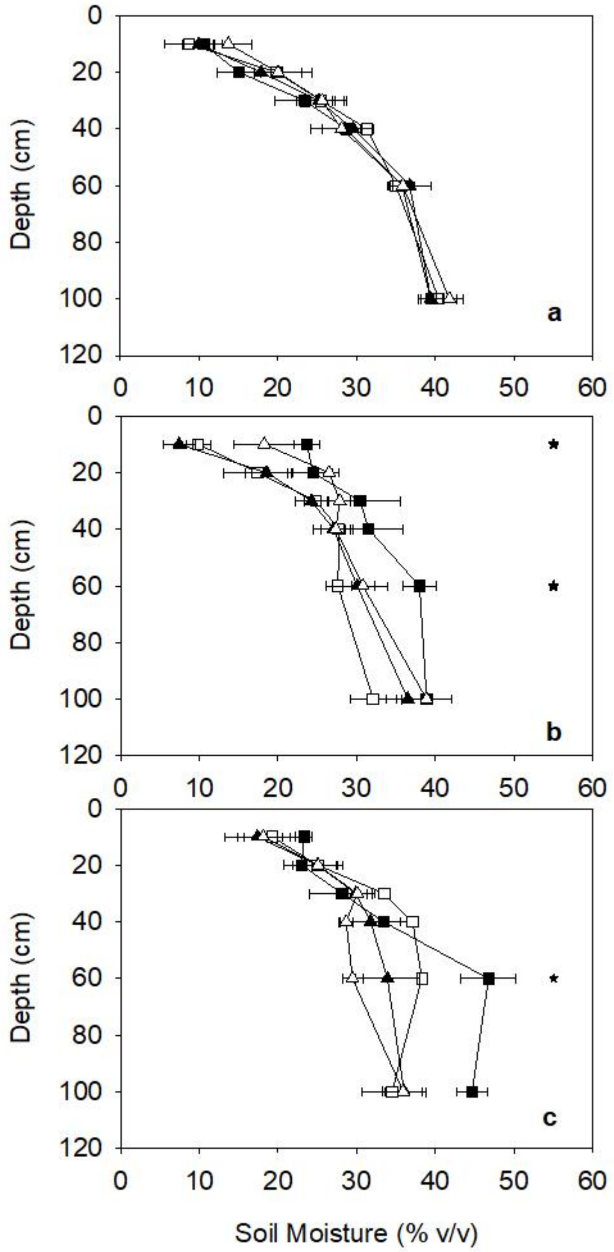
	Control	**RDI-1**	**RDI-2**	**SDI**
Kernel dry weight (g)	1.54±0.07	1.39±0.05	1.49±0.00	1.51±0.06
Kernel yield (Kg/ha)	664±183	548±167	533±137	573±207
Kernel/Kernel+Shell (%)	31.0±0.3	29.2±0.4	28.4±1.2	30.5±0.1
Nut load	2578±736	2414±764	2331±585	2369±887
Preharvest Applied Water (mm)	250±18.8a	49±15b	43±9b	73±1b
Total Applied Water (mm)	433±26a	148±25b	103±3b	114±13b
Water Used Efficiency (Kg/m^3)	0.15±0.05b	0.35±0.13ab	0.51±0.20a	0.46±0.16a



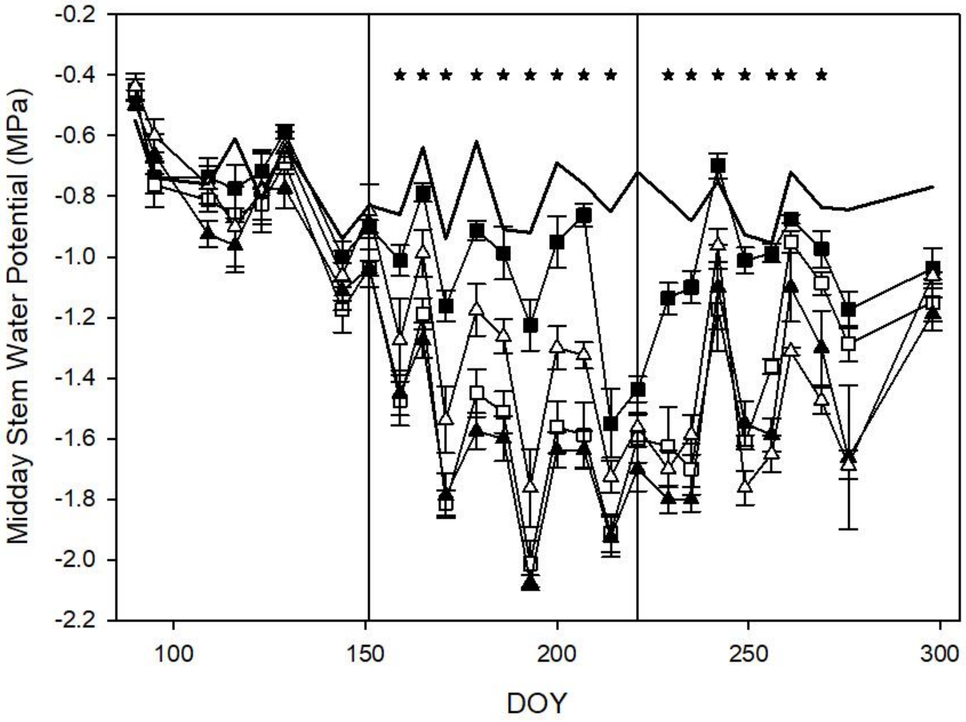
ETo (mm)
Rainfall (mm)
DOY
0
2
4
6
8
10
0
10
20
30
40
50
0
100
200
300



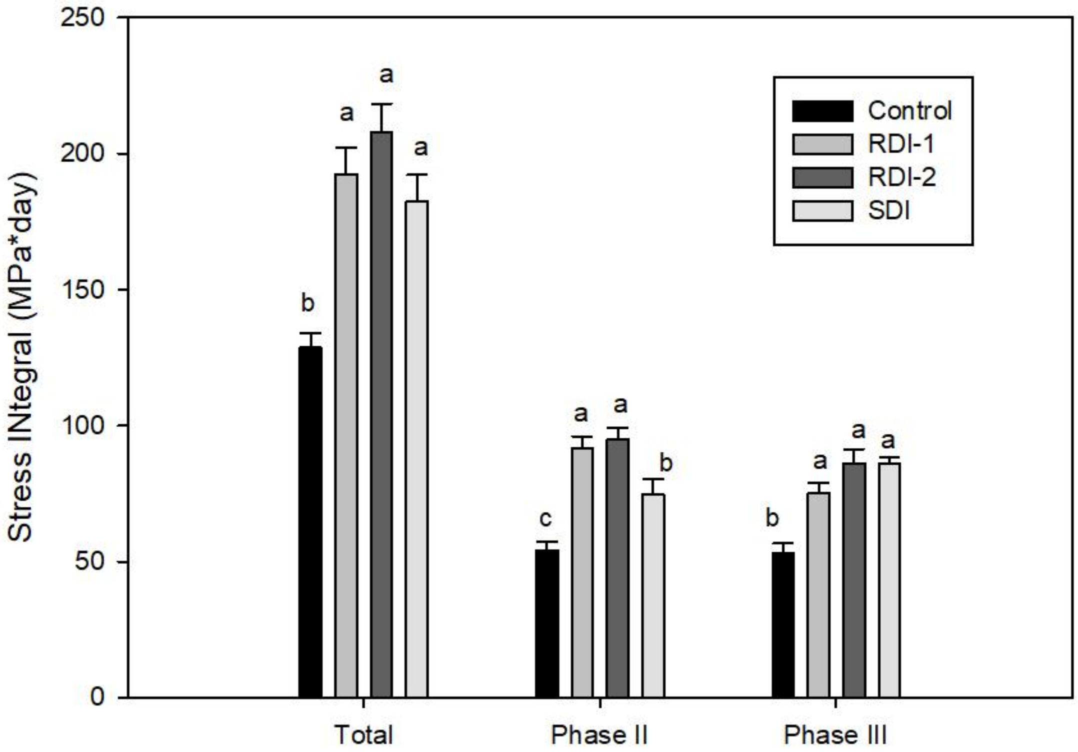
Soil water (mm)
DOY
400
380
360
340
320
300
280
260
240
220
200
80
100
120
140
160
180
200
220
240
260
280
300



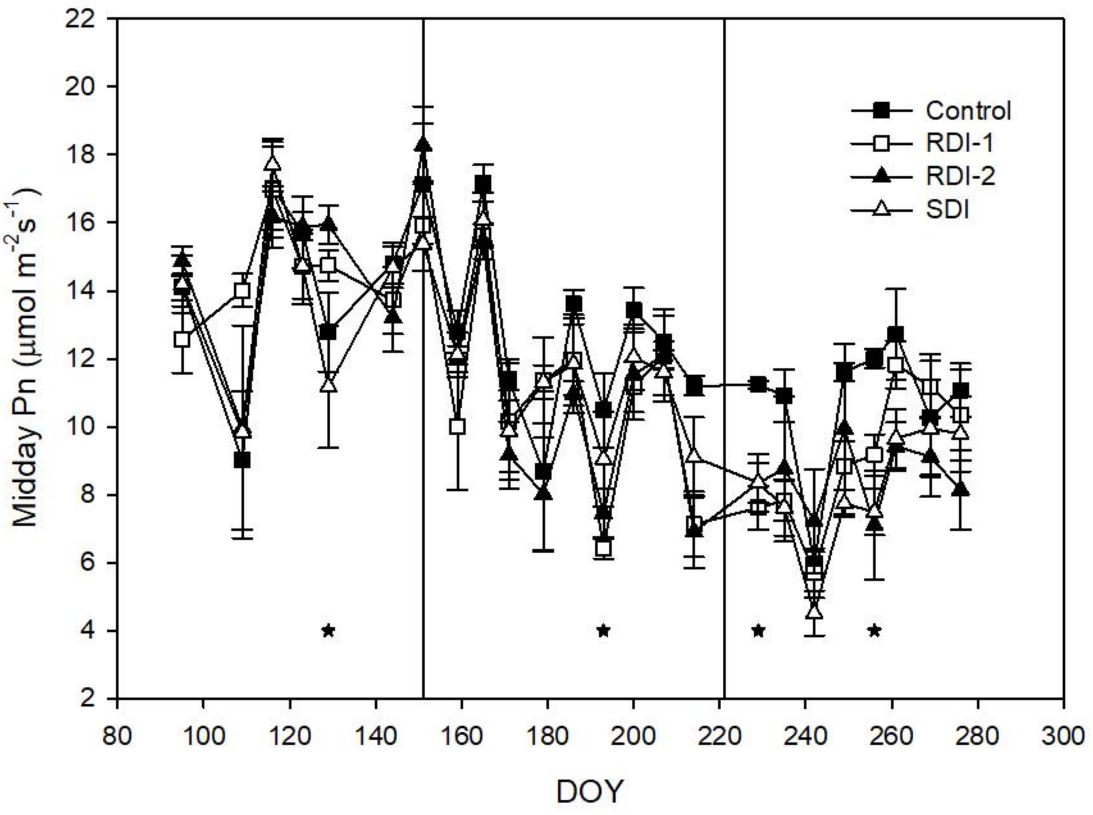
0
20
40
60
80
100
120
Depth (cm)
a
0 10 20 30 40 50 60
b
*
*
c
*
Soil Moisture (% v/v)



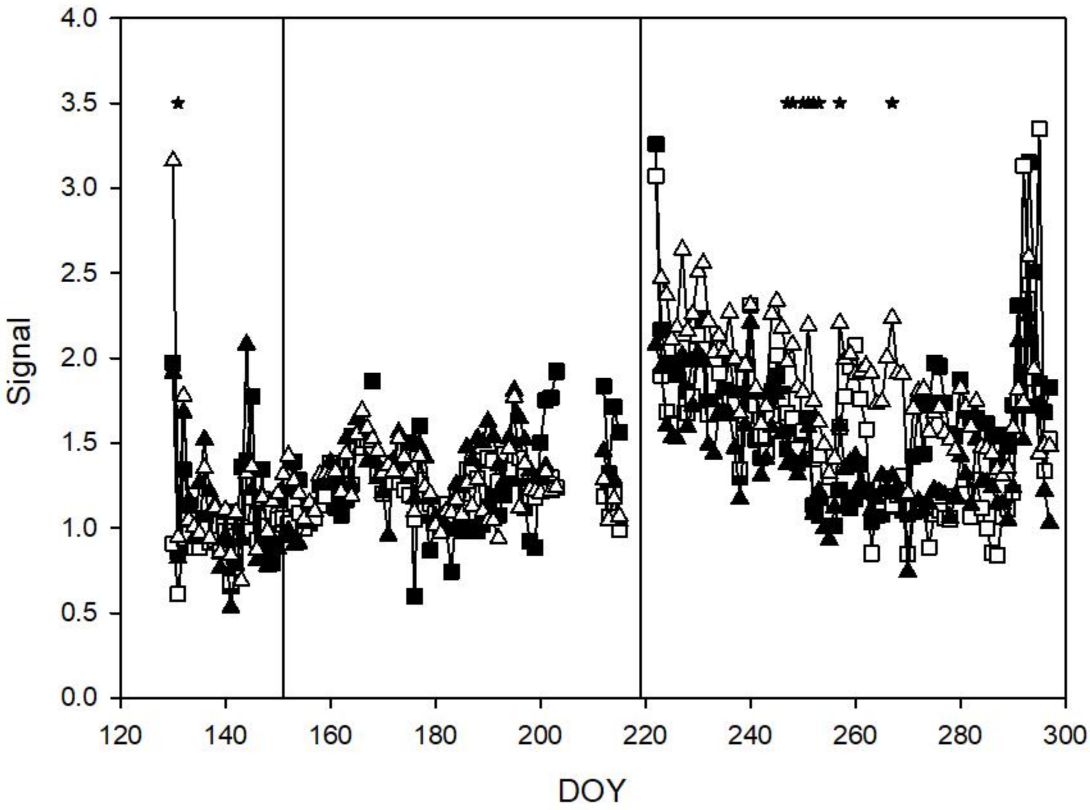
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
-2.2
Midday Stem Water Potential (MPa)
100
150
200
250
300
DOY



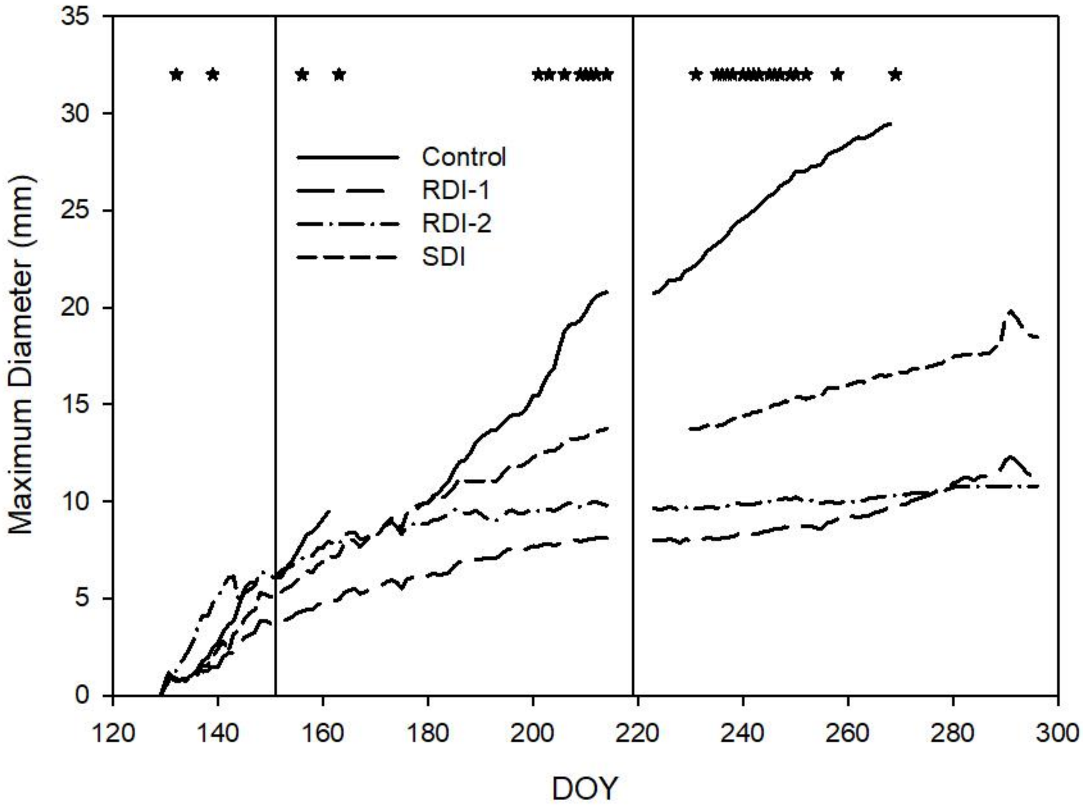
Stress INtegral (MPa*day)
250
200
150
100
50
0
Control
RDI-1
RDI-2
SDI
a
a
a
b
a
a
b
c
a
a
a
b
Total
Phase II
Phase III



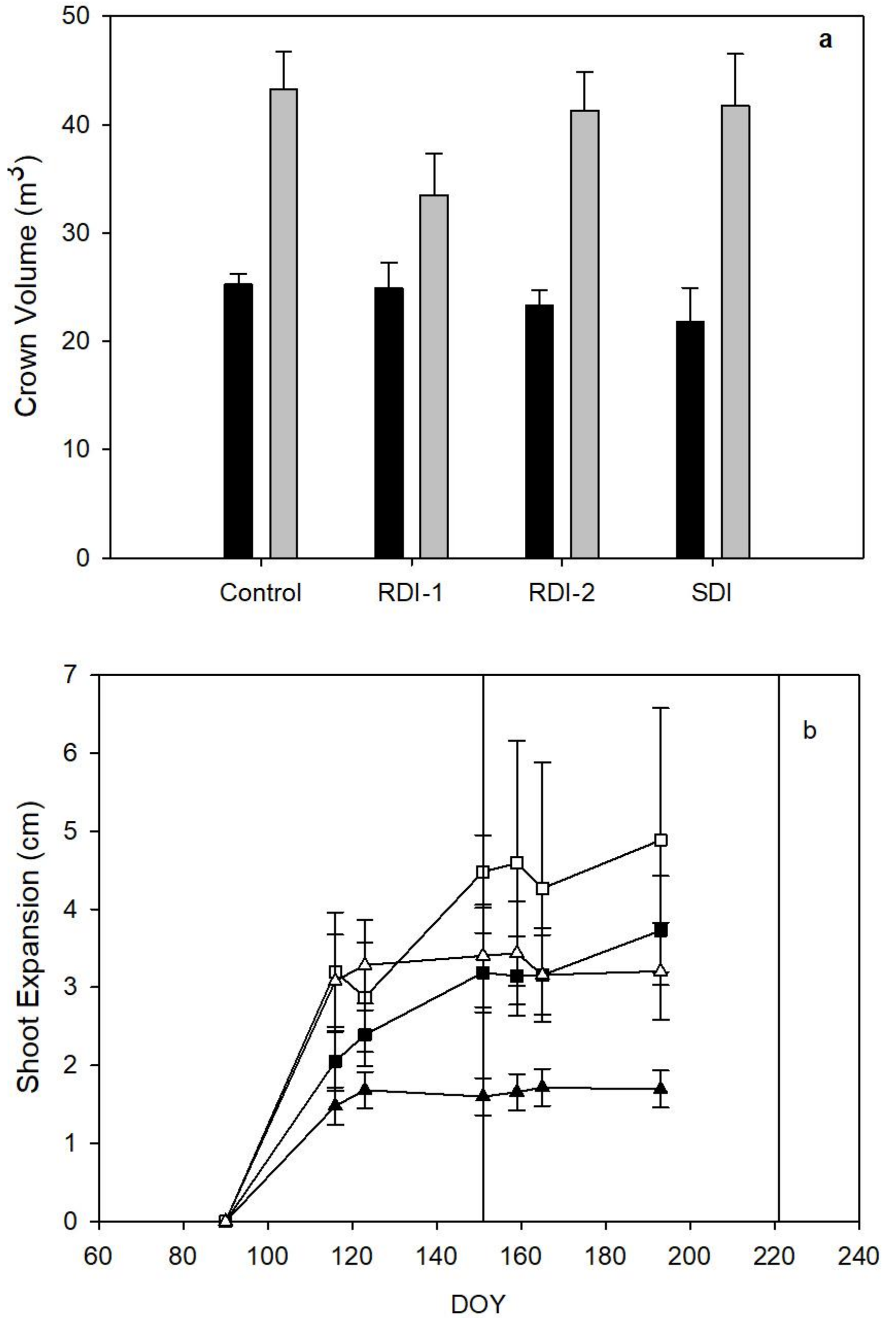
Control
RDI-1
RDI-2
SDI
Midday Pn (µmol m-2s-1)
DOY
22
20
18
16
14
12
10
8
6
4
2
80
100
120
140
160
180
200
220
240
260
280
300



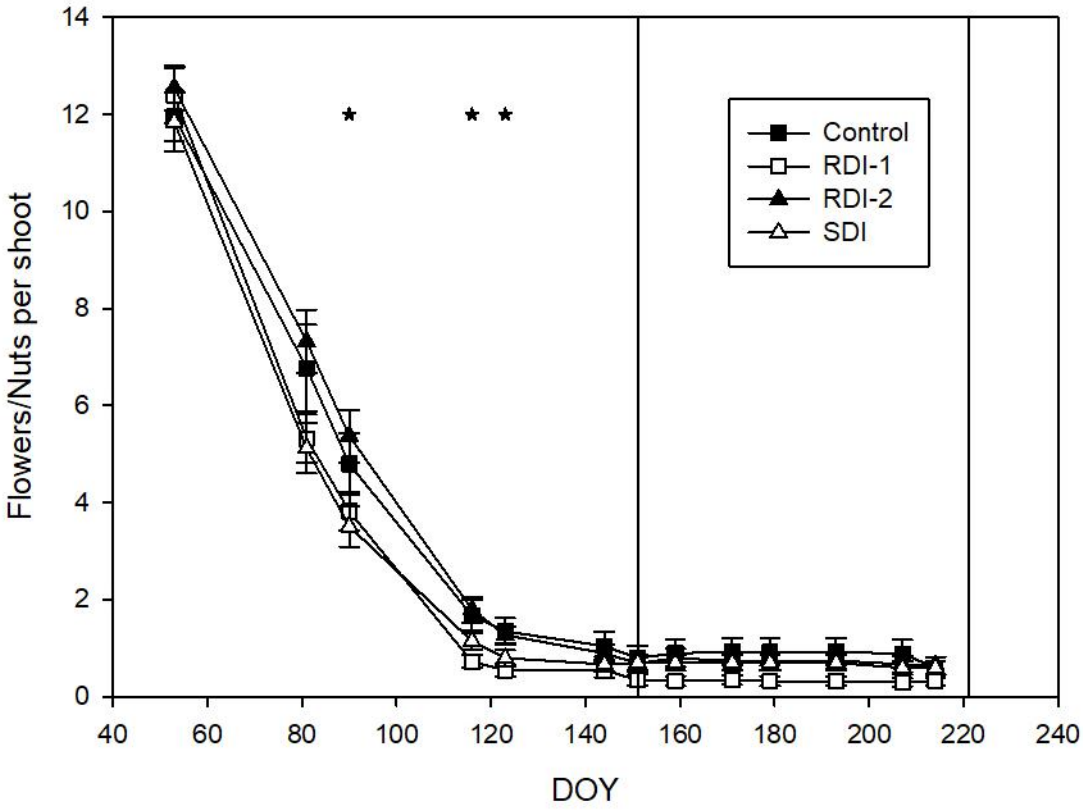
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Signal
120
140
160
180
200
220
240
260
280
300
DOY



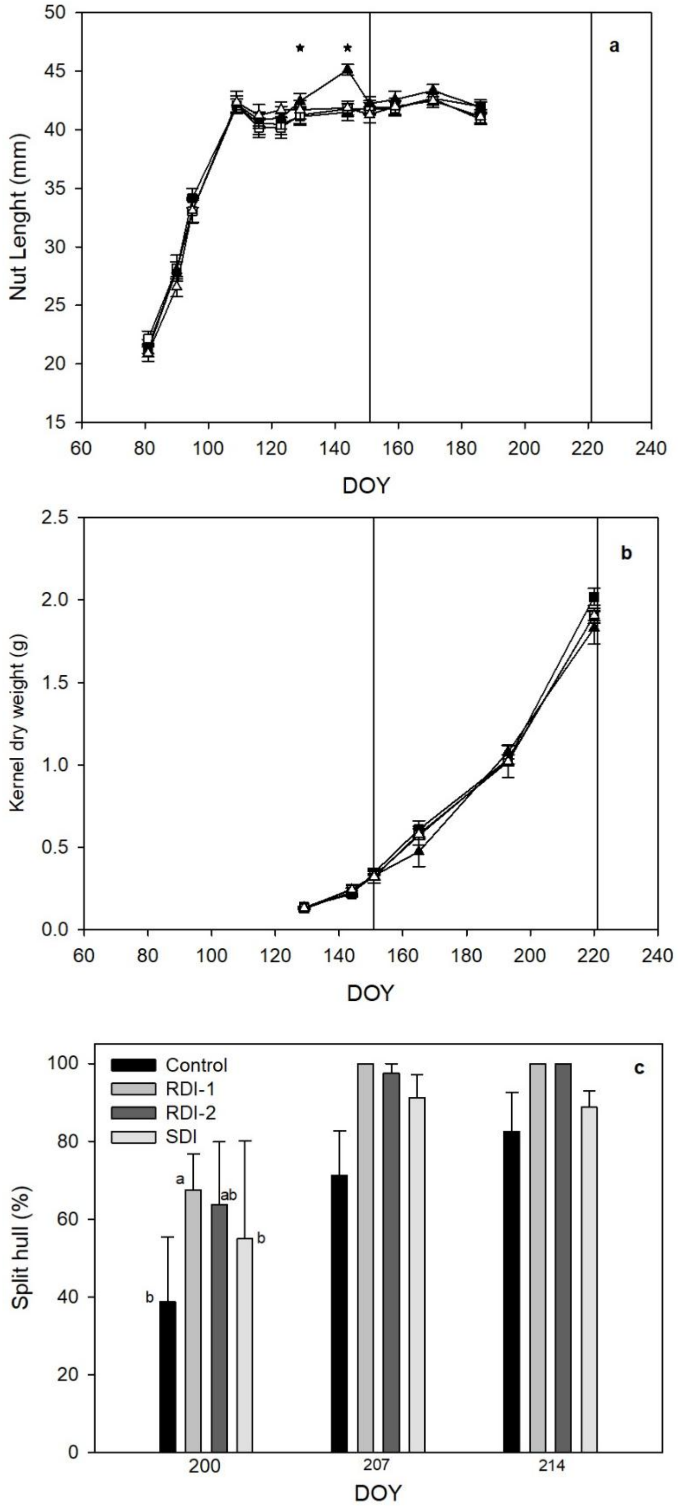
35
30
25
20
15
10
5
0
Maximum Diameter (mm)
120
140
160
180
200
220
240
260
280
300
DOY
Control
RDI-1
RDI-2
SDI



a
Crown Volume (m³)
50
40
30
20
10
0
Control
RDI-1
RDI-2
SDI
b
Shoot Expansion (cm)
7
6
5
4
3
2
1
0
60
80
100
120
140
160
180
200
220
240
DOY



Flowers/Nuts per shoot
DOY
Control
RDI-1
RDI-2
SDI
0
2
4
6
8
10
12
14
40
60
80
100
120
140
160
180
200
220
240


a
Nut Lenght (mm)
DOY
b
Kernel dry weight (g)
DOY
c
Control
RDI-1
RDI-2
SDI
Split hull (%)
a
ab
b
b
200
207
214
DOY