Optimising water use of Australian almond production through deficit irrigation strategies

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Victorian Department of Primary Industries (VICDPI)

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Final Project Report

HAL AL08009 September 2012

Karl J Sommer

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DEPARTMENT OF PRIMARY INDUSTRIES | future farming systems research

AL08009
Optimising water use of Australian Almond Production through deficit irrigation strategies

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Purpose of Report
This final report has been prepared following the conclusion of a large field experiment. It summarizes its results and provides a number of recommendations to the almond industry.

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Media Summary

Horticulture in the Murray Darling basin in recent years has seen a steady erosion of a historically secure and readily accessible water supply and during drought this trend has led to a near unsustainable cost of irrigation water.

The almond industry has recognised that its successful future will increasingly depend on the adoption of strategies that ensure the most effective and efficient use of irrigation water including the use of deficit irrigation.

As a consequence the industry in collaboration with the Victorian Department of Primary Industries (DPI) in 2009 established a research project that evaluated the potential of strategic deficit irrigation in almond production.

A large field experiment on a commercial property gave important insights into the performance of Nonpareil under deficit irrigation.

- Trees with deficits applied throughout the irrigation cycle adapted more readily to reduced water than those receiving deficits where the stress was biased toward pre-harvest.
- Irrigating at 85% or more of normal practice had no negative impact on kernel size and yield but irrigating at 70% or less decreased kernel yield regardless of strategy.
- Irrigating at 85% or more of normal practice, which represents a moderate deficit compared to fully irrigated trees (100% ET_c), has good potential to alleviate water shortages without loss of production.

Technical Summary

Horticultural industries in the Murray Darling Basin are facing a rising challenge due to the steady erosion of a formerly secure water supply for irrigation. The almond industry in particular has recognised this dilemma and knows that its future success will increasingly depend on the adoption of strategies that ensure the most effective and efficient use of a limited resource.

As a consequence the almond industry in collaboration with the Victorian Department of Primary Industries (DPI) established a field experiment at Lake Powell near Robinvale at the end of season 2008-2009. It aimed to develop irrigation strategies with the potential to make the almond industry more resilient in the face of increasingly variable water supplies.

The field experiment tested five levels of irrigation, a 100% watered control, three levels of deficit irrigation (55, 70 and 85%) applied as regulated (RDI) or sustained (SDI) deficits and a high irrigation level (120%).

After three seasons of field experimentation results were as follows. In the first season (2009-2010) of the experiment deficit irrigation led to readily observable tree water stress.

- Trees with deficits applied throughout the irrigation cycle (SDI) adapted more readily to reduced water than those receiving deficits where the stress was applied pre-harvest (RDI)
- Irrigating at 85% or more of normal practice had no negative impact on kernel size and yield but irrigating at 70% or less decreased kernel yield regardless of deficit strategy.

In the second seasons (2010–2011) with repeated and heavy rainfall no plant water stress was measured despite the imposed irrigation deficits. Wet conditions caused a delay in harvest and hull rot infections and a delay in harvest with a lower average kernel yield than in the previous season.

- Treatments with high irrigation (120%), control (100%) and RDI 85% had a reduced kernel yield relative to RDI 70%, suggesting that deficit irrigation conferred a yield advantage under wet conditions.

Plant monitoring for the third and final season (2011–2012) found similar results to those seen in the first season. Water stress due to deficit irrigation treatments was readily observable but generally was less severe than during the first season because of milder weather.

- Irrigating at 85% either as SDI or RDI or at 70% SDI had no negative impact on kernel size and yield but irrigating at 70% RDI or at 55% RDI or SDI decreased yield and kernel size.
- Trees under an SDI regime appeared more resilient and for deficits equal to or below 70% were also more productive than those under an RDI regime.
- A higher percentage of nut damage due to carob moth was seen compared with previous seasons. Damage was greater on trees under deficit irrigation because their nuts split sooner and therefore were exposed for a longer period of potential infection and damage.

Reducing irrigation application by 15% below normal plant requirement using either an RDI or SDI strategy had no negative effect on kernel size and yield over the three seasons of investigation. Deficits that reduced normal plant water requirement by more than 15% are likely to reduce both kernel size and yield. Trees appear to better adapt to a sustained (SDI) rather than regulated deficit irrigation (RDI) strategy where deficits are imposed before harvest.

Optimising water use of Australian Almonds *(Prunus dulcis)* through deficit irrigation strategies

1.1 Abstract

The work reported here summarizes the results of three seasons of a deficit irrigation experiment carried out in a commercial almond [*Prunus dulcis* (Mill.) Webb cv. Nonpareil] orchard near Lake Powell in north west Victoria. Three levels of deficit irrigation were applied in two patterns, either as sustained deficit irrigation (SDI), where the deficit was evenly applied throughout the irrigation cycle or as regulated deficit irrigation (RDI), where the deficit was biased toward pre-harvest. Deficit levels were 55, 70 and 85 percent of a fully irrigated control treatment (approx. 12 Ml/ha of irrigation and effective rainfall). A "wet" treatment receiving 120 percent of the fully irrigated control was also included. Midday stem water potential (Ψ_w) was used as the stress indicator. In the first season it approached -3.0 MPa with the RDI pattern at the lowest applied water level and -3.2 MPa with the SDI pattern at the same irrigation level. The second season was much milder with frequent rains and therefore Ψ_w never dropped below -1.2 MPa. Ψ_w in the third season was more in line with observations made in the first season approaching -2.5 MPa with the SDI and -2.0 MPa with the RDI pattern at the same irrigation level. In the first and third seasons kernel yield at harvest was significantly reduced for the 55% RDI and SDI and the 70% RDI treatments relative to the control but in the second season yields between treatments were similar. Additional irrigation beyond the control did not increase kernel yield in either season. From early January in 2009-2010 kernel size was significantly reduced at the 55 percent level of either the RDI or SDI patterns relative to the control but no such differences were seen in 2010-2011. Canopy size in either season was not affected except for a short period in mid January when the 55 percent treatments of either pattern suffered some defoliation as a result of the imposed stress. The seasonal growth in trunk circumference was an accurate indicator of the cumulative water stress experienced by the trees.

1.2 Introduction

The majority of almond production in Australia is located along the lower Murray River where irrigators have experienced substantially reduced water allocations over recent years. The growing scarcity of water makes it imperative that almond growers apply "best irrigation management practice" by using water in the most efficient and effective way.

The need to optimize water use should include the consideration of deficit irrigation, a practice rarely applied by Australian almond growers. Historically, almond research in Australia has focused on how to irrigate almonds under moderate to high irrigation volumes. Information is lacking on the potential for irrigating almonds under moderate to low irrigation volumes and with variable irrigation strategies such as deficit irrigation.

Various deficit irrigation trials in almond have been conducted overseas (Goldhamer et al., 2006; Goldhamer & Viveros, 2000; Romero et al., 2004) but results are not immediately applicable to the soil and climatic conditions of inland Australia. To address this shortcoming the Department of Primary Industries Victoria (DPI) and the Almond Board of Australia (ABA) have recently established a field experiment that aims to explore the potential for deficit irrigation of almond orchards in inland Australia. The work aims to achieve the following objectives.

- Establish benchmarks for deficit irrigation of almonds under inland climatic conditions in Australia
- Investigate the yield response to deficit irrigation
- Establish minimum irrigation levels for almond production
- Establish optimum timing to apply deficits
- Monitor the potential for deep drainage

This article will briefly describe some of the experimental methods used in this work and will summarize the results from three growing seasons of imposing the experimental deficit irrigation treatments.

1.3 Materials and Methods

1.3.1 Site

The research site was located near Lake Powell in north west Victoria (Lat: -34.706° and Long: 142.874°), just south of the Murray River and about 20 km east of Robinvale. The experimental orchard comprised 5.2 ha of almond trees that were planted in mid 2004 and presently are coming into full bearing. Trees were spaced at a distance of 4.65 m within the rows and 7.25 m between rows. The varieties were Nonpareil and Carmel planted in alternate rows in a north south direction (see Figure 1.1).

1.3.2 Soil type

The physical characteristics of the soil of the experimental area at Lake Powell were derived from a statutory soil survey carried out shortly before the orchard was planted (Yandilla Park Services, 2004). The survey results concerning the experimental area are listed in Table 1.1 and the position of each soil survey pit is shown in the map depicted in Figure 1.1 on page 9. The survey included an estimate of the root zone readily available soil water (RAW) which is defined as the reservoir of soil water within the topsoil or estimated root zone stored between -8 and -40 kPa. The topsoil depth ranged from 95 to 200 mm while the root zone depth was estimated at 130 cm throughout the site resulting in a quite uniform RAW of between 68 - 77 mm across the experimental area. The soil texture also was found to be uniform across the site ranging from a fine sandy loam (FSL) to a sandy loam (SL) or a loamy sand (LS) with increasing depth. The presence of a carbonate layer at depths beyond 1 m was noted on some soil profiles.

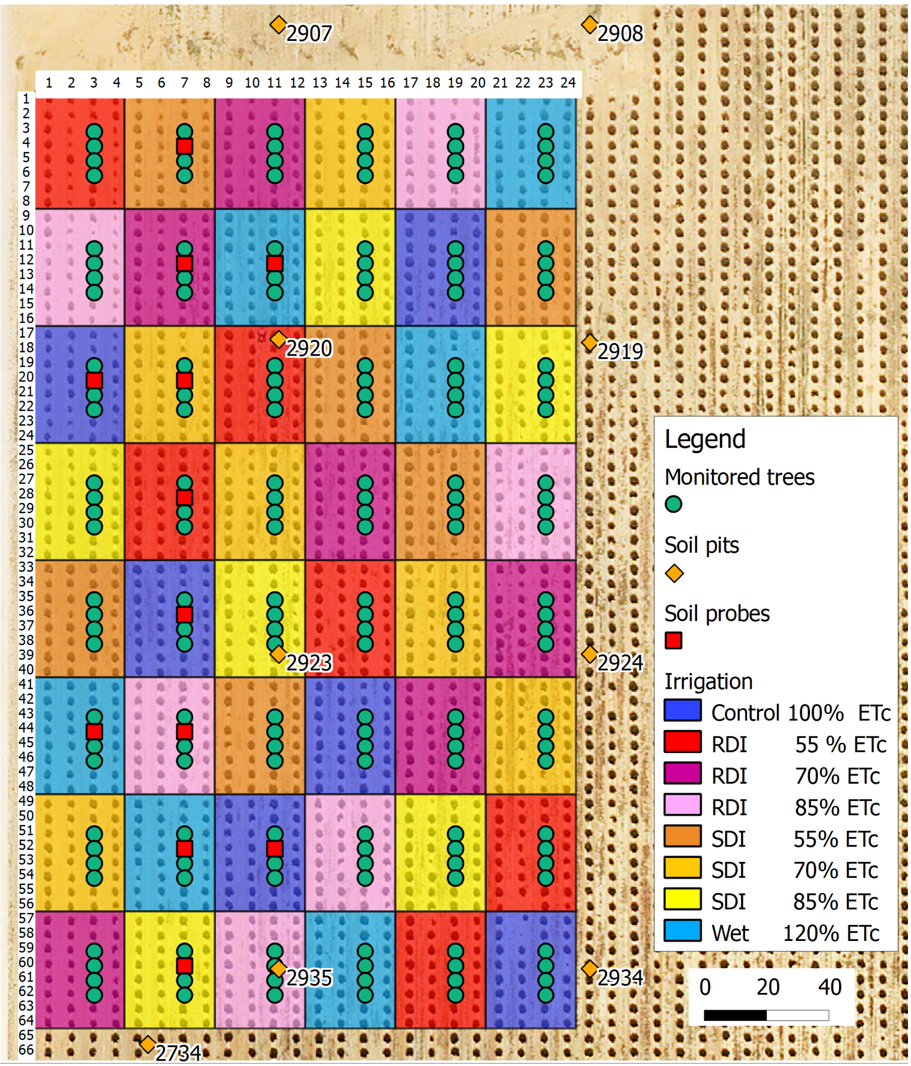

Figure 1.1: Experimental layout of irrigation treatments at Lake Powell including positions of monitored trees, soil moisture probes, soil survey pits; the numbers next to the survey pit locations correspond to those given in Table 1.1 on page 10.

1.3.3 Irrigation treatments

Trees were irrigated using a drip system where each tree row was equipped with dual irrigation lines, one either side of the row at a distance of around 1 m from the tree. Emitter spacing was 0.7 m and emitter flow was 2.1 l/h resulting in an application rate of 0.83 mm/h.

Three levels of deficit irrigation were applied in two patterns. either as sustained deficit irrigation (SDI), where the deficit was evenly applied throughout the irrigation cycle or as regulated deficit irrigation (RDI), where the deficits were biased toward pre-harvest (Table 1.2. No post-harvest deficit irrigation was applied because it has been shown to severely reduce flower bud differentiation and thus cropping potential during the subsequent season (Goldhamer & Viveros, 2000).

Deficit levels were 55, 70 and 85% of a fully irrigated control treatment, where the latter was equal to approx. 12 Ml/ha per season of irrigation and effective rainfall. Effective rainfall was

Table 1.1: Soil profile information for the Lake Powell almond trial site from a statutory soil survey (Yandilla Park Services, 2004) conducted before planting. SL = sandy loam; FSL = fine sandy loam; LS = loamy sand; RAW = readily available soil water.

Survey pit number	Topsoil depth (cm)	Topsoil RAW (mm)	Root zone depth (cm)	Root zone RAW (mm)	Layer depth (cm)	Texture classes	Carbonate layer
2907	200	99	130	77	0 - 20	FSL	nil
					20 - 200	SL	nil
2920	135	72	130	69	0 - 20	SL	nil
					20 - 135	LS	nil
					135 - 215	SL	yes
2923	200	99	130	69	0 - 25	SL	nil
					25 - 160	LS	nil
					160 - 200	SL	nil
2935	115	68	130	77	0 - 20	FSL	nil
					20 - 115	SL	nil
					115 - 180	SL	yes
2734	170	88	130	68	0 - 170	LS	nil
2908	170	90	130	69	0 - 30	LS	nil
					30 - 55	SL	nil
					55 - 170	LS	nil
					170 - 200	SL	yes
2919	145	77	130	69	0 - 20	SL	nil
					20 - 145	LS	nil
					145 - 200	SL	nil
2924	110	65	130	77	0 - 15	SL	nil
					15 - 110	SL	nil
					110 - 180	FSL	nil
2934	95	56	130	77	0 - 10	FSL	nil
					10 - 95	SL	nil
					95 - 195	SL	yes

defined as 50 percent of the precipitation equal to or above 12 mm within a 24 hour period. The design layout also comprised a "wet" treatment receiving 120% of the fully irrigated control with the aim to generate drainage beyond the root zone. Thus, the experiment had a total of eight irrigation treatments.

Full irrigation was defined as the level of irrigation that meets plant water requirement (ET_c) as depicted in equation 1.1 on page 11. It was estimated daily, according to a standard protocol developed by the Almond Board of Australia (2011). The protocol utilises historically developed crop factors (C_f) which were multiplied with daily readings from a standard class A evaporation pan (E_{pan}) located near the experimental site.

Before setting up the trial the current ABA irrigation protocol (Almond Board of Australia, 2011) was applied to long term historical evaporation records from Mildura Airport (Bureau of Meteorology, 2012) using the crop factors given in Table 1.3 on page 12. The aim was to assess the potential water requirement for the experimental treatments. The resulting long term estimate (1990-2007) of 1594 mm/season for the ABA protocol was considered to be excessive in comparison with 1124 mm/season based on published almond crop factors by Allen et al. (1998), a well recognised standard for crop and tree water use. After careful consideration, the ABA based plant requirement estimates were therefore discounted by a factor of 0.75, 0.80 and 0.85 respectively in the first, second and third season of the trial. The discount took into account the lower requirement given by Allen et al. (1998) relative to that of the ABA protocol (Almond Board of Australia, 2011) while the increase over time allowed for the fact that trees were not fully mature at the beginning of the trial and were expected to grow over its duration.

During the first season of the experiment the daily irrigation requirement was thus estimated as

Table 1.2: Timing of sustained (SDI) and regulated deficit irrigation (RDI), control and 'wet' irrigation treatments applied at Lake Powell between July 2009 and June 2012.

	RDI	SDI	RDI	SDI	RDI	SDI	Control	Wet
Period	% of control							
Aug 15-31	100	55	100	70	100	85	100	120
Sep 01-10	100	55	100	70	100	85	100	120
Sep 11-30	50	55	100	70	100	85	100	120
Oct 01-31	50	55	100	70	100	85	100	120
Nov 01-12	50	55	100	70	100	85	100	120
Nov 13-30	50	55	50	70	100	85	100	120
Dec 01-31	50	55	50	70	100	85	100	120
Jan 01-10	50	55	50	70	100	85	100	120
Jan 10-31	50	55	50	70	50	85	100	120
Feb 01-15	50	55	50	70	50	85	100	120
Feb 01-15	50	55	100	70	100	85	100	120
Feb 16-28	100	55	100	70	100	85	100	120
Mar 01-31	100	55	100	70	100	85	100	120
Apr 01-30	100	55	100	70	100	85	100	120
May 01-31	100	55	100	70	100	85	100	120

follows. The current day's irrigation hours for each treatment were estimated from long term evaporation records or short term forecasts, after adjusting the estimated value for the previous day's irrigation tally (previous day's evaporation - previous day's irrigation application). The required hours for each treatment were entered into an automatic irrigation control unit as hourly pulses with water being applied for one hour and turned off for the subsequent hour until the full requirement was met. Each irrigation treatment was equipped with a flow meter and applied volumes were recorded daily.

At the beginning of the second season E_{pan} readings were substituted with estimates of reference crop evapotranspiration (ET_o) obtained from a nearby automatic weather station and calculated according to the procedure outlined by Walter et al. (2000). The existing ABA based crop factors (C_f) were converted to equivalent crop coefficients (K_c) using a locally derived pan coefficient (K_{pan}), where $K_c = C_f \times 1/K_{pan}$ as shown in equations 1.2 and 1.3. K_{pan} was derived by correlating local E_{pan} readings with local ET_o estimates available from the "SILO Data Drill" facility of the Australian Bureau of Meteorology (data not presented, Bureau of Meteorology 2012).

$$ET_c = C_f \times E_{pan} \tag{1.1}$$

$$ET_c = C_f \times 1/K_{pan} \times ET_o \tag{1.2}$$

$$ET_c = K_c \times ET_o \tag{1.3}$$

1.3.4 Statistical design and analysis

The trial was a randomised block design with 6 blocks (replicates). Each block contained 8 plots corresponding to the 8 irrigation treatments outlined earlier (see Figure 1.1 on page 9). Each plot was 8 trees long and 4 rows wide and consisted of alternating rows of pollinator (Carmel) and non-pollinator (Nonpareil) trees. Four centre trees (sample trees) of the second Nonpareil row in each plot (counting from west to east) were used for regular monitoring of tree physiological

Table 1.3: Average monthly crop factors and equivalent crop coefficients of FAO 56 irrigation and drainage paper (Allen et al., 1998) and ABA (Almond Board of Australia, 2011).

	Crop factors (C_f)		Crop coefficients (K_c)	
Month	FAO 56	ABA	FAO 56	ABA
Jul	0.00	0.00	0.00	0.00
Aug	0.00	0.18	0.00	0.24
Sep	0.28	0.56	0.43	0.75
Oct	0.46	1.00	0.71	1.32
Nov	0.60	1.00	0.92	1.33
Dec	0.64	1.00	0.98	1.33
Jan	0.64	0.98	0.98	1.31
Feb	0.64	0.80	0.98	1.07
Mar	0.63	0.77	0.97	1.02
Apr	0.55	0.55	0.85	0.73
May	0.44	0.46	0.68	0.61
Jun	0.00	0.06	0.00	0.08

and production related indicators (see Figure 1.1). The main variables were analysed as a one-way randomised complete block design. Least Significant Difference test was used to compare treatment means ($p<=0.05$). Statistical analyses and graphing were done in R (R Development Core Team, 2011).

1.3.5 Plant nutrition

Nutrients were applied as fertigation according to the current industry standard based on outcomes from the almond optimisation trial (Almond Board of Australia, 2011). All irrigation levels received the same quantity of nutrients injected into the final irrigation pulse of the day. Nitrogen (N), phosphorus (P) and potassium (K) were applied at a ratio of *1:1.25*, with rates of approximately 320, 40 and 400 kg/ha/season respectively.

1.3.6 Soil based measurements

Soil moisture was continuously monitored with logging capacitance probes (MAIT Industries, Bayswater, Victoria 3153). One probe per deficit treatment was located in block 2 and 3 probes per control and wet treatment were located in blocks 1, 2 and 3 respectively. The probe locations are shown on the map depicted in Figure 1.1 on page 9. Each capacitance probe was equipped with 12 sensors spaced at 10 cm intervals thus covering soil depths from 10 - 120 cm. Each probes was housed in a PVC tube and each tube was positioned in line with but at a 1 m distance east of a monitored tree as indicated in Figure 1.1. The irrigation line at each probe was pegged in place such that an emitter was located at a distance of approximately 10 cm from each probe. All probes were installed by MAIT personnel 6 months prior to imposing the experimental treatments.

Wetting front detection

This method relied on the hourly change in soil moisture measured by the capacitance probes. It was calculated by differentiating successive readings for each depth increment and by estimating the rate of change between readings. Daily average values were plotted as a time series for each depth increment. A positive value indicates an increase in water content and thus a positive flux while a decrease indicates either drainage or water uptake by the trees. Plotting the changes for each depth increments provided a visual impression of the wetting front as it moved in the soil profile and thus is an indicator of the potential for drainage beyond the root zone.

Figure 1.2: Light interception measurement using a ceptometer.

1.3.7 Plant measurements

Hull and kernel development was monitored throughout the season. Four fruit per tree were collected from the six centre trees of each plot every week in the first season and fortnightly in the following 2 seasons. Samples were immediately stored in plastic bags and placed in a cooler. In the laboratory each fruit was separated into kernel, hull and shell and their fresh weight was recorded. Subsequently samples were dried in an oven at a temperature of 65° C and were re-weighed. Trees were shaken commercially on 17 February 2010 and on 2 March 2011 and on 15 February 2012. Prior to shaking, irrigation was withdrawn for 2 days to minimise shaker damage to the trunk. Nuts were left to dry on the ground until the hull moisture reached 14%, after approximately 9 days in 2010 and 16 days in 2011 and 7 days in 2012. Nuts were then swept into windrows and picked up into bulk bags. Bags were weighed and 3 kg sub-samples collected. Sub-samples were dried to a constant weight. Kernel weight and percentage crack out were determined. Nuts left on the trees after shaking were counted.

Midday light interception was measured weekly during leaf emergence and then every month using a Decagon® AccuPAR LP-80 ceptometer (see Figure 1.2). Readings were taken from 8 sample points located on a line from the north-west corner of the tree space to the south-east corner with the tree in the centre. Measurements were taken from the fourth tree from the north end of each plot.

Leaf stomatal conductance (g_s) and midday stem water potential (Ψ_w) were monitored fortnightly between 15 September 2009 and 30 March 2010, between 29 September and 1 March 2011 and between 14 October 2011 and 1 March 2012. g_s was measured using a leaf porometer (Decagon®, model SC-1; see Figure 1.3). Measurements were taken between approximately 900 and 1500 h solar time. Two leaves, one from each of the two centre trees of each plot were recorded. On each measurement date this procedure was repeated three times during the day. The mean g_s for each plot was calculated before conducting the statistical analysis.

Figure 1.3: Stomatal conductance (g_s) measurement using a Decagon leaf porometer.

Midday stem water potential (Ritchie & Hinckley, 1975) was measured using a pressure bomb (Plant Water Status Console 3005 series, Soil Moisture Equipment Corp., Santa Barbara, CA; see Figure 1.4). One or two hours before testing, foil laminate bags (PMS Instrument Company, Albury OR) were placed over a leaf from the inner canopy of the two centre trees of each plot and measurements were taken as per Shackel (2010). On each measurement date two leaves from each plot of the three western most blocks were tested.

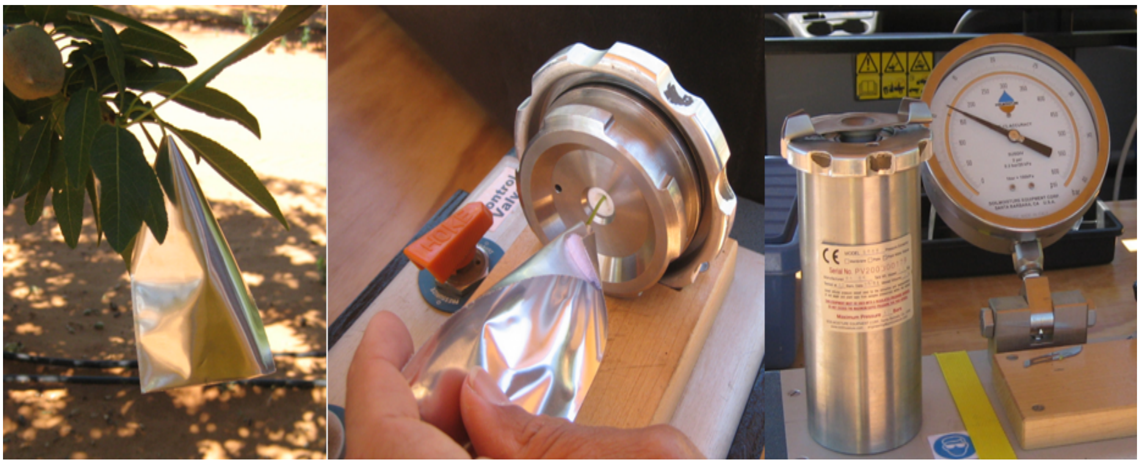

Figure 1.4: Pressure bomb assembly to measure stem water potential.

1.4 Results and Discussion

The following section describes the main findings after three seasons (2009-2010 to 2011-2012) of imposing the experimental treatments and attempts to interpret and discuss the results in the light of other research.

1.4.1 Irrigation summary

Table 1.4 gives a summary of the irrigation volumes, effective rainfall and timing of the irrigation treatments applied during the three seasons. The totals of irrigation plus effective rainfall were around 1121 mm or 11.2 Ml/ha for the first, 1011 or 10.1 Ml/ha for the second and 1122 mm or 11.2 Ml/ha for the third season. The volume of irrigation applied across all treatments was considerably lower in the second compared with the first and third seasons because the evaporative demand was reduced as a result of more humid and frequently overcast weather. Despite the considerably lower irrigation volumes applied in the second relative to the first and third seasons, the deficit irrigation treatments failed to effect any notable plant water stress and did not result in any production loss relative to well watered trees as will be discussed in following section.

Table 1.4: Seasonal irrigation, effective rain, irrigation plus effective rain and timing of deficit for the 2009-2010 and 2010-2011 seasons, respectively between 1 August and 30 June.

Season	Treatment	Irrigation	Rain	Effective rain	Irrigation + eff. rain	ET_c	ET_o	Deficit Timing
		mm						
2009-2010	1 Control	937	481	184	1121	1135	1435	–
	2 Wet	1131	481	184	1315	1362		–
	3 SDI 85	806	481	184	990	965		all season
	4 SDI 70	694	481	184	878	794		all season
	5 SDI 55	534	481	184	719	624		all season
	6 RDI 85	836	481	184	1020	1014		10/01/10 - 17/02/10
	7 RDI 70	664	481	184	848	831		12/11/09 - 17/02/10
	8 RDI 55	552	481	184	736	700		10/09/09 - 17/02/10
2010-2011	1 Control	781	618	214	1011	913	1089	–
	2 Wet	933	618	214	1170	1095		–
	3 SDI 85	677	618	214	906	776		all season
	4 SDI 70	578	618	214	807	639		all season
	5 SDI 55	476	618	214	706	502		all season
	6 RDI 85	668	618	214	900	824		10/01/11 - 17/02/11
	7 RDI 70	508	618	214	739	667		12/11/10 - 17/02/11
	8 RDI 55	488	618	214	719	561		10/09/10 - 17/02/11
2011-2012	1 Control	1082	236	40	1122	1135	1324	–
	2 Wet	1296	236	40	1336	1362		–
	3 SDI 85	916	236	40	956	965		all season
	4 SDI 70	759	236	40	800	794		all season
	5 SDI 55	686	236	40	726	624		all season
	6 RDI 85	959	236	40	1000	1014		10/01/12 - 17/02/12
	7 RDI 70	763	236	40	803	831		12/11/11 - 17/02/12
	8 RDI 55	663	236	40	703	700		10/09/11 - 17/02/12

1.4.2 Water relations

Midday stem water potential

Early in the 2009-2010 season midday stem water potential for all treatments was high (less negative). As daytime temperatures and evaporative demand began to rise, the midday stem water potential of trees receiving deficit irrigation began to decline more than those of well watered trees. The response to a heatwave in mid November (8 days above 38° C) can be clearly seen (Figure 1.5). With the onset of high evaporative demand by mid December, midday stem water potential of the deficit irrigation treatments decreased in line with the imposed deficits but was more severe for trees receiving RDI than those with SDI, indicating that RDI trees were more severely water stressed. By early March, midday Ψ_w of all trees had recovered to levels seen for well watered trees.

In the subsequent season Ψ_w of trees receiving 55% RDI fell to just below -1.2 MPa on one occasion in early January and on another in early February while trees receiving 55% SDI did not even reach -1.0 MPa on the same dates. This clearly shows that throughout 2010-2011 trees experienced very mild and infrequent water deficits because of repeated heavy rainfall from early December through to the end of February. The course of Ψ_w in the respective seasons best illustrates the strong influence climatic extremes exert on tree physiology and water status.

In the third season Ψ_w took a similar course to that seen in the first season but trees were not as severely stressed because of a milder December and January relative to the first season. Trees under SDI 55 and 70% fell to Ψ_w of -2.5 and 2.0 MPa respectively while those under RDI fell just short of -2.0 MPa. Trees of all treatments recovered readily toward late February and early March but thereafter briefly underwent a deficit period due to persistently hot and dry weather.

Ψ_w was sensitive indicator of the stress imposed by the irrigation deficits. Under SDI trees were generally less severely stressed than under an equivalent RDI strategy because RDI trees went from a fully watered to a deficient state in a relatively short time period unlike SDI trees which were able to more gradually adjust to the imposed deficits. The work of Goldhamer et al. (2006) used comparable irrigation strategies. Their most deficient trees reached pre-dawn leaf water potentials (Ψ_{pd}) of -3.5 MPa. At similar water supply Ψ_{pd} is normally less negative than midday Ψ_w (Romero et al., 2004) indicating an even more severe plant water stress. These extreme stress levels may explain why Goldhamer et al. (2006) did not see a less severe stress response in applying and SDI relative to an RDI strategy.

Stomatal conductance (g_s)

Stomatal conductance (g_s) in the 2009-2010 season (Figure 1.6) followed a similar course to that of midday stem water potential seen in Figure 1.5. The level of g_s between measurement dates was more variable than that of Ψ_wl because g_s is more closely coupled with the evaporative demand of the atmosphere. Differences between irrigation treatments became first apparent in early November during a period of above average daily temperatures. Thereafter g_s recovered and increased to a maximum in early December but then declined steadily until early February when trees were shaken. Differences seen between treatments were indicative of the imposed irrigation deficits. g_s for SDI trees remained higher than for RDI trees during periods of peak evaporative demand. By early March, g_s of all trees had recovered to levels seen for well watered trees.

In the second season of the experiment the course of g_s was totally different and extremely variable between readings with a spike observed in late November followed by a sharp decline followed by consistently high values until early February. Some of the high values were probably

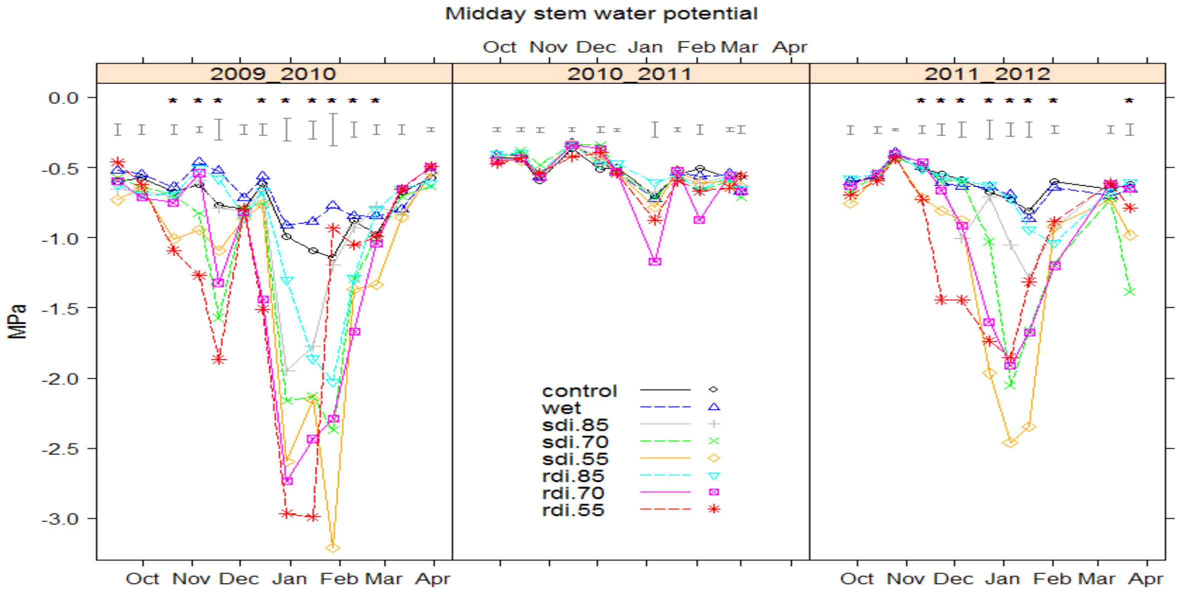

Figure 1.5: Ψ_w potential for all irrigation treatments during the 2009-2010,2010-2011 and 2011-2012 seasons at Lake Powell. Vertical bars indicate standard errors of the means. The stars above the vertical bars indicate statistical significance (5% level).

due to good soil moisture supply and high relative humidity, conditions frequently experienced in the 2010-2011 season due to frequent and heavy rainfall throughout December to February. For the same reason and unlike in the previous season no statistically significant differences were seen between irrigation treatments. Any developing water deficit as was apparent in early December was immediately negated by a significant rain event.

In the third season g_s was again quite variable between readings. However, unlike in the preceding wet year treatment differences first became apparent by late November and throughout the months of December and January g_s was always much lower under deficits equal and below 70% relative to treatments at 85% or above regardless of strategy. Tree behaviour was therefore more in line with the results seen in the first season were treatment differences were most apparent during the normally hot and dry months of December through to January.

Stomatal regulation plays an important role in controlling the balance between water loss and carbon uptake through photosynthesis. g_s and assimilation rate are therefore often closely correlated (Romero et al., 2004). So, while partial stomatal closure is likely to conserve water it is also likely to reduce the rate of assimilation and dry matter accumulation. It is therefore desirable to avoid period of severe water stress throughout December and the beginning of January. SDI and RDI 55% and also RDI 70% experienced significant reductions in g_s and probably a reduced assimilation and kernel growth rate during late December and early January of the 2009-2010 and 2011-2012 seasons. Not so the RDI nor SDI 85% whose g_s did not deviate much from that of control trees (100%).

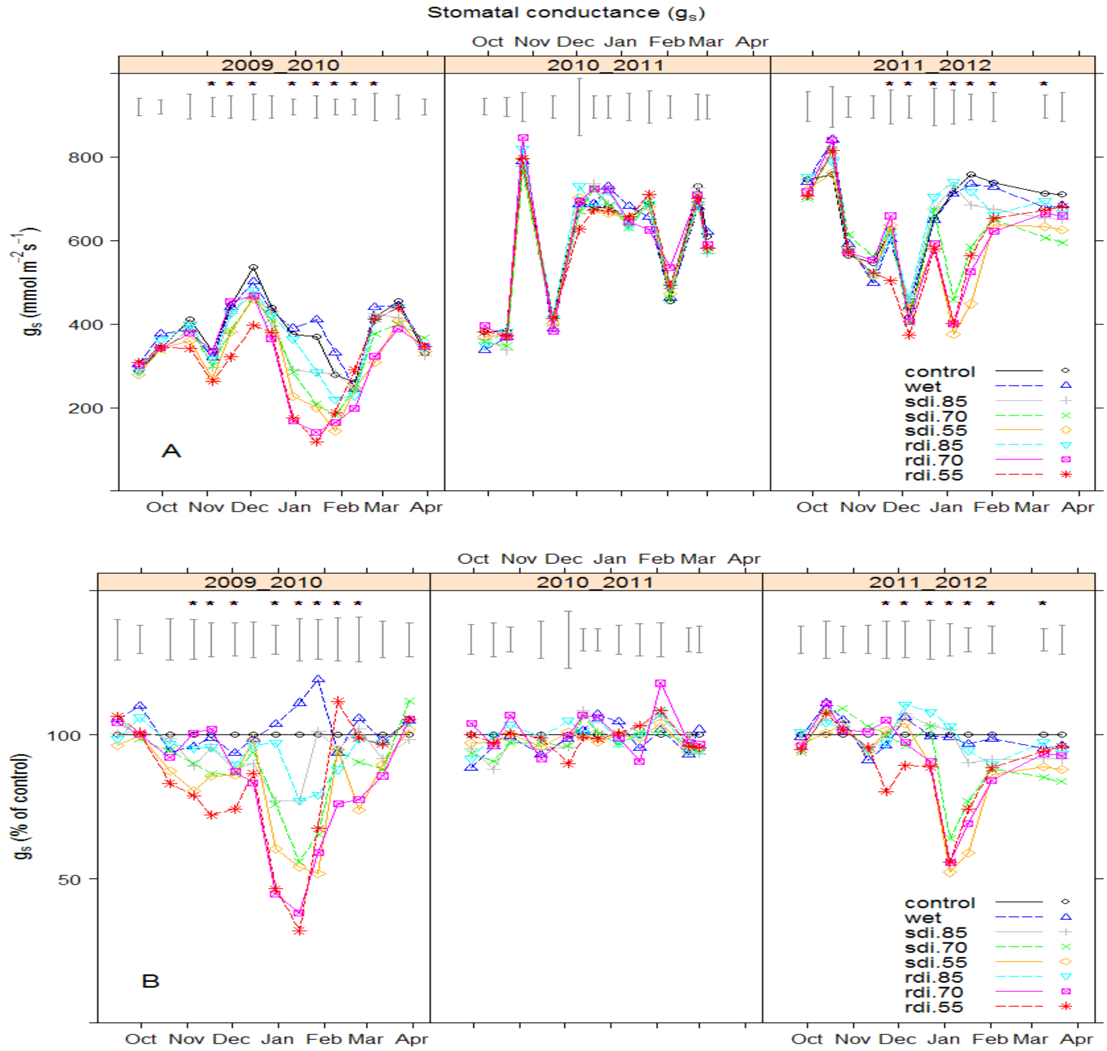

Figure 1.6: Influence of irrigation treatments on g_s during the 2009-2010 2010-2011 and 2011-20012 seasons at Lake Powell. (A) represents actual values, (B) shows g_s as a percentage of control. Vertical bars represent least significant difference. The stars above the vertical bars indicate statistical significance of treatment differences (5% level).

1.4.3 Yield related variables

Dry matter accumulation

Kernel dry matter The accumulation of kernel dry matter during the first season is shown in the top graph of Figure 1.7. It indicates when the various deficit treatments began to impact on kernel size and weight.

During the early stages of each season, until late November, kernels grew slowly, but thereafter their growth rate accelerated strongly (see bottom graph of Figure 1.7) and remained high until early in January when growth slowed and came to a halt just before harvest in mid February. Initial effects of deficit irrigation treatments were seen early in December of the 2009-2010 season when kernel weight of RDI 55% first began to fall behind the other treatments. Deficit irrigation with both SDI 55% and RDI 55% resulted in significantly lower kernel weights, a reduction of around 12%, compared with kernels from control trees. Average kernel weight for SDI 70% and RDI 70% were also lower than kernel weights of control trees but differences were not statistically significant. Kernel weights from either 55 or 70% deficits were consistently lower when irrigated under RDI relative to SDI although these differences were not statistically significant. This may indicate trees under SDI better adapted to the imposed deficits than those under RDI where the onset of the deficits was more sudden.

Below average temperatures delayed kernel growth and development by up to 3 weeks in the second relative to the first season of the experiment. Also, and very much in contrast with the first season's observations, no differences in kernel dry matter were seen throughout the second season of the experiment. This lack in response to deficit irrigation was due to frequent and heavy rainfall throughout the main growth period from late November to early March. The persistently wet weather negated any effects of the deficit irrigation treatments imposed on the orchard.

In season 2011-2012 the deficit treatment responses were similar to those seen in the first season but they impacted later and therefore had a lesser effect on kernel dry matter. Differences in kernel weight were first seen in mid to late December when both RDI and SDI 55% irrigated trees began to fall behind the other treatments. Neither 70 nor 85% deficits significantly reduced kernel weight below that of control trees regardless of irrigation strategy (RDI or SDI).

The rate of kernel dry matter accumulation is depicted in the graph at the bottom of Figure 1.7. It complements the absolute values depicted in the top graph and shows a maximum growth rate throughout the month of December. The rate in 2009-2010 was much smaller than in subsequent seasons because a weekly sampling regime was used as compared to a fortnightly regime in 2010-2011 and 2011-2012. In the first season the rate of growth in SDI 55% and RDI 55% began to decline by around mid November well before any differences in the total kernel weight were detectable. The intermediate treatment SDI 70% and RDI 70% began to respond about a month later and to a much lesser extent while SDI 85% did not deviate from control trees. In the wet season of 2010-2011 the rate of accumulation of RDI 55% and SDI 85% trees ran ahead of the other treatments from early December to mid January suggesting that deficit irrigation temporarily led to higher growth but did not result in greater kernel weights. In the final season differences in kernel growth rate became apparent in early December much later than in the fist season and the decline was consistent with the level of the imposed deficits.

The observed patterns of dry matter accumulation were similar to those described by Goldhamer et al. (2006). Like us they reported a more severe impact of an equivalent pre-harvest RDI as compared to an SDI pattern and described a similar impact of the deficits on fruit and kernel dry matter accumulation. They also reported that deficit irrigation had a greater effect on kernel than on hull and shell dry matter accumulation because hull and shell growth unlike kernel growth is mostly complete before the irrigation deficits take full effect.

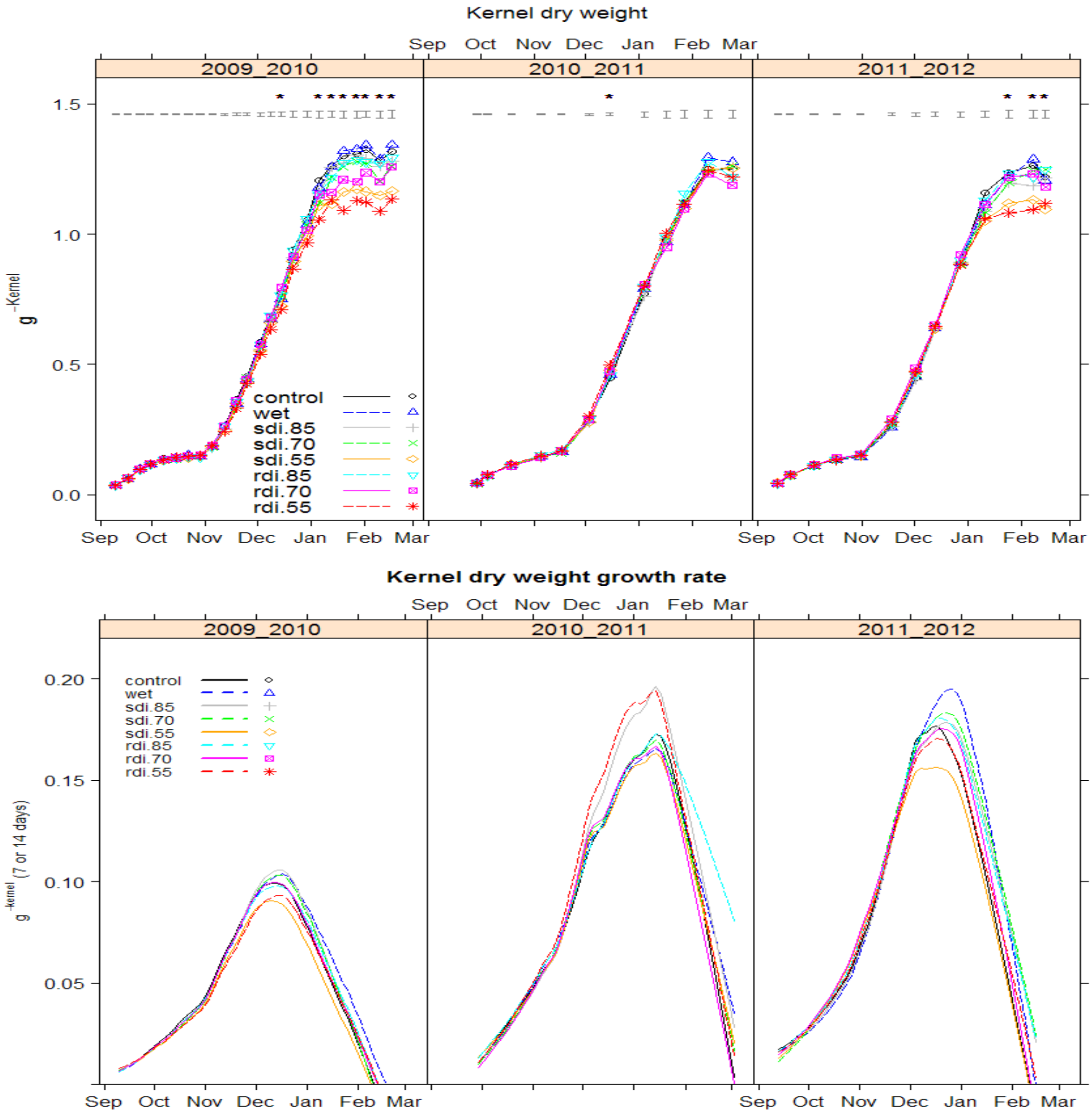

Figure 1.7: Top: kernel dry matter accumulation for all irrigation treatments during the 2009-2010, 2010-2011 and 2011-2012 seasons. Vertical bars indicate standard errors of means. The stars above the vertical bars indicate statistical significance (5% level). **Bottom**: rate of kernel dry matter accumulation for all irrigation treatments during the 2009-2010, 2010-2011 and 2011-2012 seasons. Note: Sampling interval in 2009-2010 was weekly while in 2010-2011 and 2011-2012 it was fortnightly

Hull and shell dry matter Dry matter accumulation of the hull and shell over 3 seasons is depicted in Figure 1.8. Unlike the kernel, most of the hull and shell dry matter was accumulated well before any significant kernel growth was apparent, because, there was no obvious lag phase as was seen in the development of the kernels, and maximum dry matter was reached well before that of the kernels. No treatment effects on hull and shell growth were seen in 2009-2010 and 2010-2011. Some differences were seen at the very beginning and at the end of 2011-2012. Surprisingly, fruit from trees grown with deficits of 70% and below appeared to grow heavier hulls and shells than control and even "wet" trees, although at the final sampling date just prior to harvest these differences had largely disappeared.

As was indicated earlier, Goldhamer et al. (2006) also found that deficit irrigation affected the dry matter accumulation of hull and shell to a lesser extent than that of the kernel but reported a more severe influence of pre-harvest RDI than SDI. We did not see such a difference possibly because our stress levels were less severe than theirs. Their measured pre-dawn leaf water potentials often were more negative than our Ψ_w suggesting that their trees experienced considerably more severe water stress (see section 1.4.2).

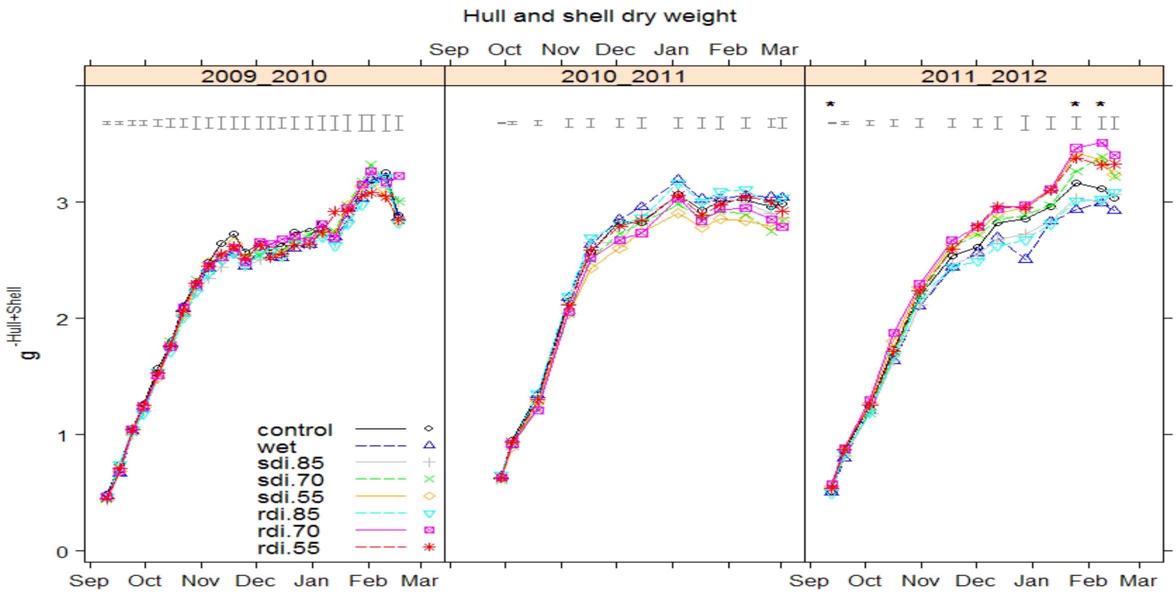

Figure 1.8: Hull and shell dry matter accumulation for all irrigation treatments during the 2009-2010, 2010-2011 and 2011-2012 seasons. Vertical bars indicate standard errors of means. The stars above the vertical bars indicate statistical significance (5% level).

Kernel yield

The kernel yields achieved for each treatment after three seasons of investigation are depicted in Figure 1.9. The average kernel yield across all irrigation treatments was 2.39, 1.87 and 2.17 t ha^{-1} in 2009-2010, 2010-2011 and 2011-2012 respectively. Below average temperatures during the pollination period in the spring of 2010-2011 possibly contributed to a reduction in nut set and therefore a lower yield potential than in the previous and subsequent seasons.

Yield reductions relative to well watered control trees after the end of the first seasons (2009-2010) were a reflection of the severity of the applied irrigation deficits over the season. Results suggest that reducing irrigation to 70% or less decreased kernel yield. Little difference in kernel yield was seen between the 70% and 55% deficits. There is a suggestion that biasing the deficit toward pre-harvest (RDI 70%, imposed from 12 November) resulted in lower yield relative to a sustained deficit (SDI 70%, imposed throughout the season). Reducing irrigation by 15% or less, regardless of the deficit strategy did not reduce yield relative to control trees. Applying additional irrigation in the "wet" treatment did not result in further yield gain relative to the control trees.

No yield differences between irrigation treatments were discernible in the subsequent season of 2010-2011. This suggests that the applied irrigation deficits did not cause any or only very mild tree water deficits during the course of the season. A number of factors probably contributed to this outcome. Firstly, the yield potential at the start of the season was below average. Tree development was delayed due to persistently cool weather leading to poor conditions for successful pollination and nut set. Whole tree nut counts in an adjacent orchard had indicated a 30% reduction compared to an average season. This lighter than average crop combined with the persistently wet conditions further reduced the effectiveness of the imposed deficits in causing tree water stress readily observed in the previous season. The wet conditions of 2010-2011 also delayed harvest and resulted in some hull rot infection which further contributed to a depression in yield.

Kernel yield at the end of 2011-2012 was higher than in the previous season but was marginally lower than in the first season. The treatment effects were similar to those seen in the first season. Deficit irrigation with 55 or 70% RDI reduced kernel most strongly followed by 55% SDI and to lesser degree by 70% SDI. Neither 85% SDI or RDI reduced kernel yield relative to control trees.

The first and the third season of the experiment were probably more typical of an average season in Sunraysia than the wet and humid second season. Yield results for the former suggest that an irrigation deficit of equal to or above 85% applied as either SDI or RDI has not negative impact on production while any deficits below 85% are likely to depress kernel yield and kernel size. Conversely, in a wet season, deficit irrigations equal to or 70% the tree irrigation requirement conferred an advantage because trees suffered a lower incidence of hull rot relative to those treatments receiving a higher irrigation volume.

Other yield components

The fresh and dry matter of the main yield components recorded just before harvest (see Table 1.5) confirm the sensitive response of kernel weight to deficit irrigation seen in Figure 1.7. SDI and RDI 55% significantly reduced kernel weight relative to control trees but deficits of 70% and higher regardless of strategy did not. It is also interesting to note that neither fresh nor dry fruit yield (kernel + hull + shell) were not nearly affected as much by the deficit irrigation as was kernel yield. This also is evident when the kernel dry and fresh weight are expressed as a percentage of the whole nut. The kernel percentage of the nut weight clearly drops in proportion to the imposed deficits and clearly is a more sensitive indicator of the imposed deficits than kernel dry matter alone. Results also indicate that the hull and shell components of the nut are not nearly as much affected by deficits as the kernel because a large proportion of the hull dry matter is grown early during the growth cycle before trees are severely stressed by the imposed irrigation deficits. So, despite the quite severe irrigation deficits imposed on the trees for part or all of the season they led to only small differences in the nut dry matter without statistical significance.

The nut load or the number of fruit per tree represents another component of yield listed in Table 1.6. Nut load did not respond to the imposed treatments except in the wet season of 2010-2012 when control (100%) and wet (120%) trees had a lower fruit load than RDI 70%. Fruit load was generally lower during the wet season compared with the preceding or subsequent season.

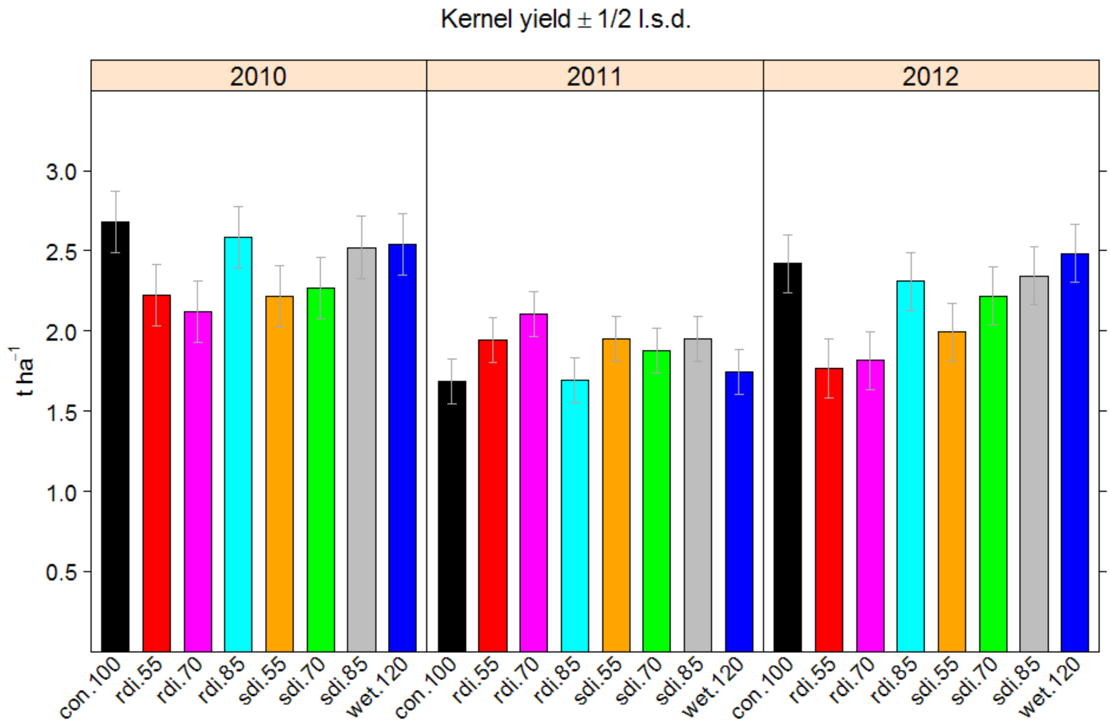

Figure 1.9: Kernel yield (t ha^{-1}) for all irrigation treatments at the end of the 2009-2010, 2010-2011 and 2011-2012 seasons. Vertical bars indicate ± 1/2 least significant differences of means (5% level).

The within season treatment differences seen in the wet season are difficult to explain. Results suggest that trees under RDI 55% and 70% for some reason had a greater number of nuts than control trees. Both water deficient treatments also had fewer sticktights, which represent fruit that cannot be dislodged from the tree easily. A high proportion of sticktights is often associated with the presence of hull rot. However, the fruit load estimates already included the number of sticktights and they therefore do not explain the remaining differences. It is possible that not all the sticktights were included in the tally because some were dislodged naturally between harvest in late February and their removal in June. However the contribution of the missed sticktights to the total weight was probably very small. Overall, deficit irrigation had little effect on nut load per tree suggesting that neither fruit bud initiation in mid season nor set in spring were greatly influenced by the imposed deficits.

Vegetative growth and fruiting density

The shaded area per tree is an indicator of vegetative growth and was calculated from the seasonal average of light interception readings between mid September and mid March (see section 1.4.5). Within season treatment differences were never statistically significant but shaded area in general was always negatively correlated with the severity of the applied deficits. The treatment means across all seasons indicated that the size of RDI 55% trees on average was 14% smaller than control and 18% smaller than 'wet' trees while the shaded area of the equivalent SDI 55% with respectively 12% and 7% was reduced less severely. Apparently, the more severe water deficits (50 and 75%) had a greater affect when applied as an RDI than an SDI strategy.

Table 1.5: Fresh and dry weight per kernel, fresh and dry kernel per nut (percent) for the seasons 2009-2010, 2010-2011 and 2011-2012 and averages across all seasons; columns followed by the same letter or by no letter are not significantly different; least significant difference; p<=0.05.

Season	Treatment	Kernel fresh weight g kernel^{-1}	Kernel dry weight g kernel^{-1}	Fruit fresh weight g nut^{-1}	Fruit dry weight g nut^{-1}	Kernel per nut fresh %	Kernel per nut dry %
2009-2010	1 Control	1.37$_{a}$	1.32$_{a}$	4.51	4.20	30.5$_{ab}$	31.5$_{ab}$
	2 Wet	1.39$_{a}$	1.34$_{a}$	4.53	4.20	30.8$_{a}$	32.0$_{a}$
	3 SDI 85	1.33$_{a}$	1.28$_{a}$	4.60	4.29	28.9$_{bcd}$	29.9$_{bcd}$
	4 SDI 70	1.31$_{a}$	1.26$_{a}$	4.56	4.27	28.7$_{cd}$	29.7$_{cd}$
	5 SDI 55	1.21$_{b}$	1.16$_{b}$	4.28	4.00	28.2$_{d}$	29.2$_{d}$
	6 RDI 85	1.34$_{a}$	1.29$_{a}$	4.42	4.11	30.4$_{abc}$	31.5$_{abc}$
	7 RDI 70	1.31$_{a}$	1.26$_{a}$	4.81	4.48	27.2$_{d}$	28.2$_{d}$
	8 RDI 55	1.18$_{b}$	1.13$_{b}$	4.25	3.98	27.7$_{d}$	28.5$_{d}$
2010-2011	1 Control	1.37	1.26	5.04	4.24	27.3	29.7
	2 Wet	1.44	1.32	5.19	4.36	27.9	30.4
	3 SDI 85	1.42	1.31	4.97	4.17	28.5	31.5
	4 SDI 70	1.41	1.28	5.01	4.12	28.3	31.0
	5 SDI 55	1.38	1.28	4.77	4.11	29.0	31.2
	6 RDI 85	1.44	1.30	5.34	4.34	27.2	30.0
	7 RDI 70	1.31	1.21	4.57	3.99	28.6	30.2
	8 RDI 55	1.37	1.27	4.87	4.19	28.2	30.3
2011-2012	1 Control	1.27$_{a}$	1.22$_{a}$	4.60	4.26	27.7$_{a}$	28.9$_{a}$
	2 Wet	1.26$_{a}$	1.21$_{ab}$	4.49	4.13	28.0$_{a}$	29.2$_{a}$
	3 SDI 85	1.26$_{a}$	1.21$_{a}$	4.63	4.28	27.2$_{a}$	28.4$_{a}$
	4 SDI 70	1.29$_{a}$	1.25$_{a}$	4.82	4.47	26.8$_{a}$	27.9$_{a}$
	5 SDI 55	1.14$_{b}$	1.10$_{c}$	4.68	4.34	24.3$_{b}$	25.3$_{b}$
	6 RDI 85	1.30$_{a}$	1.25$_{a}$	4.69	4.33	27.7$_{a}$	28.9$_{a}$
	7 RDI 70	1.23$_{ab}$	1.18$_{abc}$	4.97	4.59	24.8$_{b}$	25.8$_{b}$
	8 RDI 55	1.16$_{b}$	1.12$_{bc}$	4.81	4.44	24.2$_{b}$	25.2$_{b}$
Mean all seasons	1 Control	1.34$_{ab}$	1.26$_{abc}$	4.72	4.23	28.5$_{ab}$	30.0$_{ab}$
	2 Wet	1.36$_{a}$	1.29$_{a}$	4.74	4.23	28.9$_{a}$	30.6$_{a}$
	3 SDI 85	1.34$_{ab}$	1.27$_{abc}$	4.74	4.25	28.2$_{ab}$	29.9$_{ab}$
	4 SDI 70	1.34$_{ab}$	1.26$_{abc}$	4.80	4.28	28.0$_{ab}$	29.6$_{ab}$
	5 SDI 55	1.24$_{b}$	1.18$_{bc}$	4.58	4.15	27.2$_{ab}$	28.6$_{ab}$
	6 RDI 85	1.36$_{ab}$	1.28$_{ab}$	4.81	4.26	28.5$_{ab}$	30.1$_{ab}$
	7 RDI 70	1.28$_{ab}$	1.22$_{abc}$	4.78	4.35	26.9$_{ab}$	28.1$_{ab}$
	8 RDI 55	1.24$_{b}$	1.17$_{c}$	4.64	4.21	26.7$_{b}$	28.0$_{b}$

The shaded area was used to calculate a fruiting density per tree by dividing the fruit number per tree by the shaded are per tree. Results show that smaller trees generally tended to have a greater nut density probably because nut load was less affected by the deficit treatments than tree leaf area. Goldhamer et al. (2006) also reported a correlation between fruiting and deficiency level except for their post-harvest deficit which appeared to reduce fruiting density because it probably inhibited fruit bud initiation and nut number.

Sticktights

Sticktights are the proportion of fruit not removed by the harvest operation and therefore represent a yield loss and a potential hazard for later infestation with carob month (Figure 1.10).

In the first season of the trial the percentage of sticktights was strongly influenced by the level of the applied deficits. Full irrigation and over-irrigation (120%) both increased the percentage of sticktights as compared to any of the deficit treatments. Conversely, the more severe the applied deficit the lower the number of sticktights remaining on the trees. The observed gradient was

Table 1.6: Weight per kernel, fruit load per tree, Kernel yield, irrgation water and total water productivity for the seasons 2009-2010, 2010-2011 and 2011-2012;columns followed by the same letter or by no letter are not significantly different; least significant difference; p<=0.05.

Season	Treatment	Kernel weight g kernel^{-1}	Fruit load No. tree^{-1}	Kernel yield t ha^{-1}	Shaded area m^{-2} tree^{-1}	Fruiting density nuts m^{-2}	Irrigation water productivity kg Ml^{-1}	Total water productivity kg Ml^{-1}
2009-2010	1 Control	1.31_{a}	9652	2.68_{a}	15.3	638	286_{b}	239_{a}
	2 Wet	1.34_{a}	8919	2.54_{ab}	16.3	568	225_{c}	193_{c}
	3 SDI 85	1.28_{a}	8827	2.52_{ab}	14.8	601	313_{b}	255_{b}
	4 SDI 70	1.26_{a}	8321	2.27_{b}	15.6	549	327_{b}	259_{b}
	5 SDI 55	1.16_{b}	9142	2.22_{b}	13.6	704	415_{a}	309_{a}
	6 RDI 85	1.29_{a}	9608	2.59_{a}	15.2	644	309_{b}	254_{b}
	7 RDI 70	1.26_{a}	8029	2.12_{bc}	15.5	519	319_{b}	250_{b}
	8 RDI 55	1.13_{b}	9730	2.22_{bc}	13.0	766	309_{a}	302_{a}
2010-2011	1 Control	1.26	5993_{c}	1.69_{b}	16.5	365_{b}	216_{de}	169_{c}
	2 Wet	1.32	6222_{bc}	1.75_{b}	17.3	370_{b}	187_{e}	152_{cd}
	3 SDI 85	1.31	7096_{abc}	1.95_{ab}	15.8	452_{ab}	288_{bc}	219_{bc}
	4 SDI 70	1.28	6849_{abc}	1.88_{ab}	17.0	412_{b}	325_{b}	237_{b}
	5 SDI 55	1.28	7059_{abc}	1.95_{ab}	16.8	422_{b}	410_{a}	283_{a}
	6 RDI 85	1.30	6198_{bc}	1.69_{b}	17.0	365_{b}	253_{cd}	192_{c}
	7 RDI 70	1.21	8042_{a}	2.10_{a}	15.3	526_{a}	414_{a}	291_{a}
	8 RDI 55	1.27	7215_{ab}	1.95_{ab}	15.7	465_{ab}	399_{a}	277_{a}
2011-2012	1 Control	1.22_{a}	8974	2.53_{a}	18.0	495	234_{de}	225_{cd}
	2 Wet	1.21_{ab}	9629	2.61_{a}	18.5	544	201_{e}	195_{d}
	3 SDI 85	1.21_{a}	8752	2.42_{ab}	16.4	536	264_{bcd}	253_{bc}
	4 SDI 70	1.25_{a}	8195	2.32_{ab}	17.6	483	306_{a}	291_{a}
	5 SDI 55	1.10_{c}	8464	2.08_{b}	15.8	541	303_{ab}	286_{ab}
	6 RDI 85	1.25_{a}	9034	2.40_{ab}	16.1	565	250_{cd}	240_{c}
	7 RDI 70	1.18_{abc}	6946	1.92_{c}	15.7	454	251_{c}	239_{c}
	8 RDI 55	1.12_{bc}	7432	1.80_{c}	14.2	521	271_{abc}	256_{abc}
Mean all seasons	1 Control	1.26_{abc}	8207	2.30	16.6_{ab}	499	245_{bc}	211_{bc}
	2 Wet	1.29_{a}	8126	2.30	17.4_{a}	494	204_{c}	180_{c}
	3 SDI 85	1.27_{abc}	8225	2.30	15.7_{ab}	530	288_{b}	242_{b}
	4 SDI 70	1.26_{abc}	7788	2.16	16.7_{ab}	481	319_{ab}	262_{ab}
	5 SDI 55	1.18_{bc}	8222	2.08	15.4_{ab}	555	376_{a}	293_{a}
	6 RDI 85	1.28_{ab}	8280	2.23	16.1_{ab}	525	271_{bc}	229_{bc}
	7 RDI 70	1.22_{abc}	7672	2.05	15.5_{ab}	500	328_{ab}	260_{ab}
	8 RDI 55	1.17_{c}	8126	1.99	14.3_{b}	584	357_{ab}	278_{ab}

possible due to a heavier crop load in the well-watered treatments which in turn caused a delay in ripening and thus a greater proportion of sticktights. The overall percentage of sticktights in 2010 was between 2 and 3 percent for non-water deficient trees and was around 1 or less than 1% for those irrigated under a water deficit regime.

In the subsequent season, the percentage of sticktights was between 2 and 5% and thus, regardless of treatment, was much higher than in the previous season. Control (100%) and wet (120%) trees again had a higher percentage of sticktights than those under a deficit irrigation but the differences between water-deficient and non-deficient trees was smaller than in the preceding season but correlated with the severity of the imposed deficits.

Results seen in the third season were similar to those in first. Full irrigation and over-irrigation (120%) both led to a higher percentage of sticktights as compared to any of the deficit treatments and the percentage of sticktights on water deficient trees was correlated with level of the applied deficits.

It appears that fruit on well watered trees is always more difficult to dislodge than on trees with a sub-optimal water supply and the level of retained fruit or sticktights is positively correlated with that of irrigation volume. Goldhamer et al. (2006) reported a similar correlation where the percentage of sticktights was lowered in relation to the level of the imposed irrigation deficit.

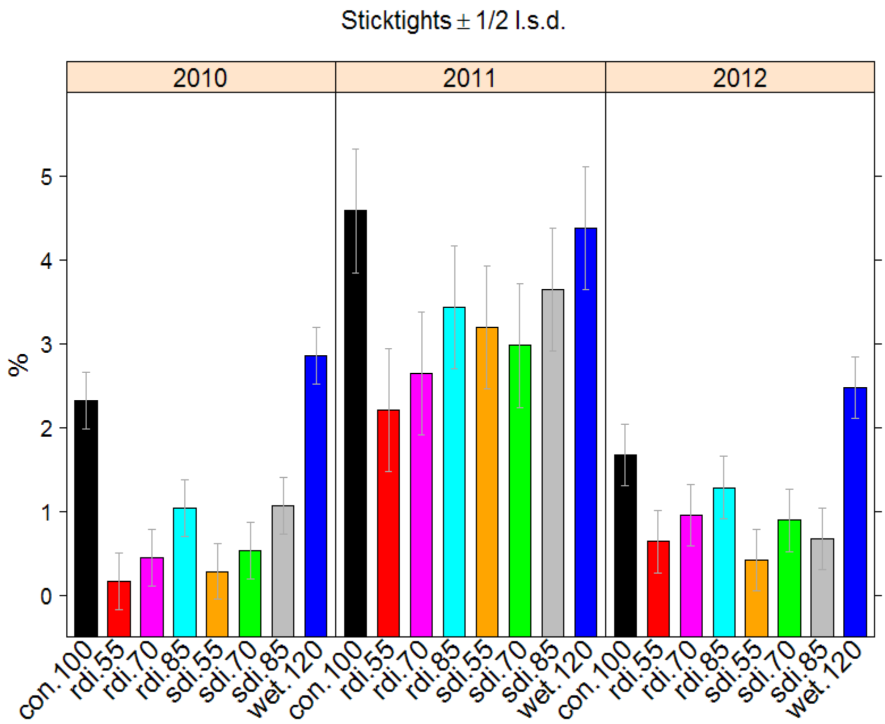

Figure 1.10: Percent sticktights for all irrigation treatments at the end of the 2009-2010, 2010-2011 and 2011-2012 seasons. Vertical bars indicate ±1/2 least significant differences of means (5% level).

1.4.4 Hull split

The proportion of split fruit was assessed throughout the ripening period of each season and is shown in Figure 1.11. Hull split extended from late December to late February depending on the predominant weather. There were clear differences in the onset of hull split between seasons. In the first (2009-2010) and last season (2011-2012) hulls began to split in early January and split progressed most rapidly in fruit from trees under deficit irrigation. In fact, the progress of hull split in both seasons appeared to be closely correlated with the level of the imposed deficits independently of either irrigation strategy. Full hull split in control and 'wet' treatments in both seasons was delayed by around 2 - 3 weeks relative to the most water deficient treatments SDI and RDI 55%. Conversely, no treatment differences in the progress of hull split were discernible in the second season (2010-2011), probably because of the persistently wet and humid weather and a lack of split inducing water stress. Hull split in all treatments was delayed by around 2 weeks relative to the preceding and subsequent season.

The onset and progress of hull split appears to be strongly influenced by tree water status such that its onset will be earlier and progress will be more rapid in line with a rising deficit. However, the work of Goldhamer et al. (2006) suggests that there is a critical threshold beyond which the level of stress may inhibit rather than promote hull split. Using pre-harvest RDI and SDI deficit regimes of similar magnitude as us they reported a comparable advance in hull split. An exception was their most water deficient pre-harvest RDI, which led to a reduction in hull split rather than an increase and was attributed to severe drought stress. We did not see such an effect neither under RDI or SDI 55%, probably because our trees never quite reached such a severe level of plant water stress (see section 1.4.2).

1.4.5 Light interception

Generally light interception readings for all seasons were indicative of the size of the leaf canopy as the seasons progressed (Figure 1.12). The sudden rise in interception after leaf emergence in early September was due to rapid canopy fill in spring.

In the first season differences between treatments were apparent in late January of 2010 when the 55% treatments experienced some stress-induced wilting and defoliation although trees had recovered by late February. Thereafter, light interception for trees of all treatments declined and trees were largely defoliated by late April. There was a trend toward smaller leaf canopies under the 55% treatment compared with the other treatments but the differences were never statistically significant except on one occasion in mid January.

The general growth in the subsequent season was similar to that of the first season but was slightly delayed due to below average spring temperatures. Overall, light interception was slightly higher for all treatments in 2010-2011 than in the previous season and trees retained their leaves for longer but deficit irrigation did not affect the tree canopy development and size, although those under a deficit had slightly smaller average light interception and therefore leaf canopies.

In season three, light interception and canopy size of control (100%) and wet (120%) trees reached maxima of around 60% interception, a much higher value than was attained in previous seasons. Differences due to irrigation treatment were first apparent in early November and remained so until harvest in early February. There was sharp decline in leaf area between mid February and early March due to defoliation which affected all trees irrespective of irrigation treatment. In the second half of February the farm's pump delivery system malfunctioned and was unable to deliver a sufficient water volume to the experimental area. This caused a shortfall in irrigation for nearly a week and resulted in a temporary irrigation deficit irrespective of water regime. As a consequence all trees suffered some defoliation but control (100% and 120%) trees

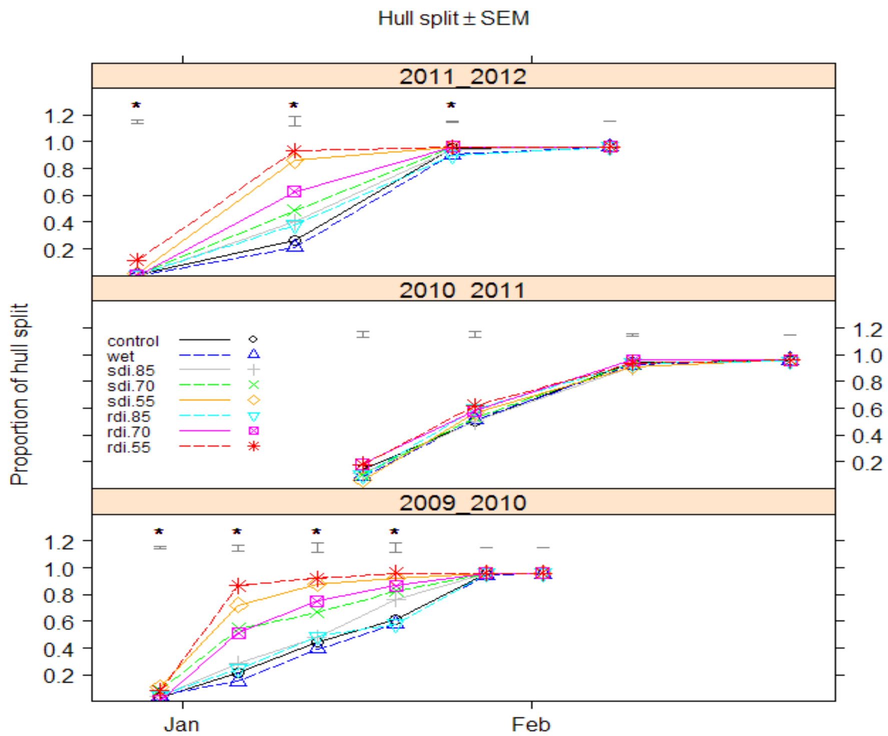

Figure 1.11: Percent hull split for all irrigation treatments throughout the ripening period of the 2009-2010, 2010-2011 and 2011-2012 seasons. Vertical bars indicate standard error of means The stars above SEM bars indicate statistical significance (5% level).

were affected more strongly than those under irrigation deficits. Consequently the previously seen differences in light interception and canopy size between well watered and water-deficient treatments decreased strongly.

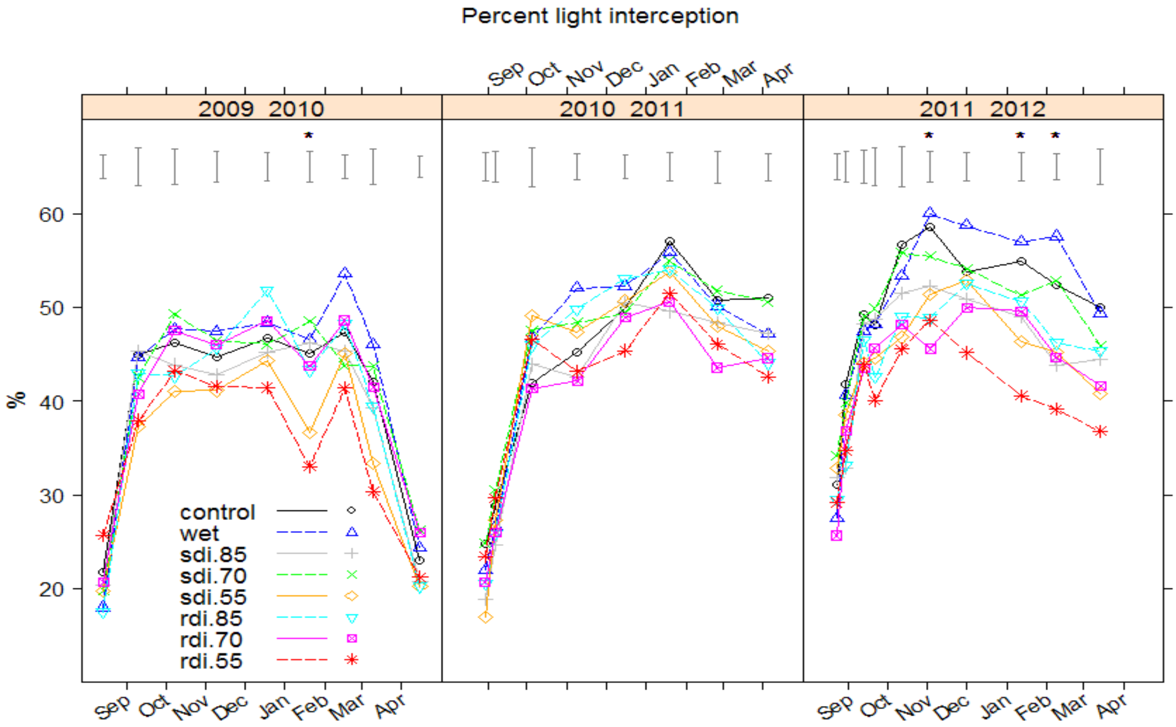

Figure 1.12: Influence of irrigation treatments on midday light interception during the 2009-2010, 2010-2011 and 2011-2012 seasons at Lake Powell. Vertical bars indicate one standard error of the mean. The stars above the vertical bars indicate statistical significance (5% level).

1.4.6 Trunk circumference

Trunk circumference was measured at the beginning (22/10/2009) and again at the end of each season respectively on 21/05/2010 of the 2009-2010, on 27/04/2011 in the 2010-2011 and on 17/04/2012 in the 2011-2012 season. The difference between the two measurements for the respective seasons is depicted in Figure 1.13 and provides a quantitative estimate of the seasonal trunk expansion as influenced by irrigation treatment.

Results suggest that reducing irrigation to 85% or less decreased trunk expansion in 2009-2010 (note, differences are not statistically significant if the grey error bars overlap).

At the end of 2010-2011 differences between irrigation treatments were negligible except for RDI 70% and this was probably so because water deficits were mild, infrequent and insufficient to retard trunk expansion compared with the preceding season.

In 2011-2012 there were again marked differences in trunk growth as a result of deficit irrigation. The effects were similar to those seen after the first season when the reduction in trunk growth was closely correlated with the imposed deficit level.

Trunk growth therefore appears to closely reflect the cumulative deficit experienced by the trees as shown in Figure 1.14 and despite the wet season there is a clear indication that all deficit treatments reduced trunk growth in line with the severity of the imposed deficit. The sensitivity of trunk expansive growth to water deficit is well documented (Goldhamer et al., 1999) and the magnitude of the diurnal trunk expansion and shrinkage have indeed been proposed as a tool for irrigation scheduling (Goldhamer & Fereres, 2004; Fereres & Goldhamer, 2003).

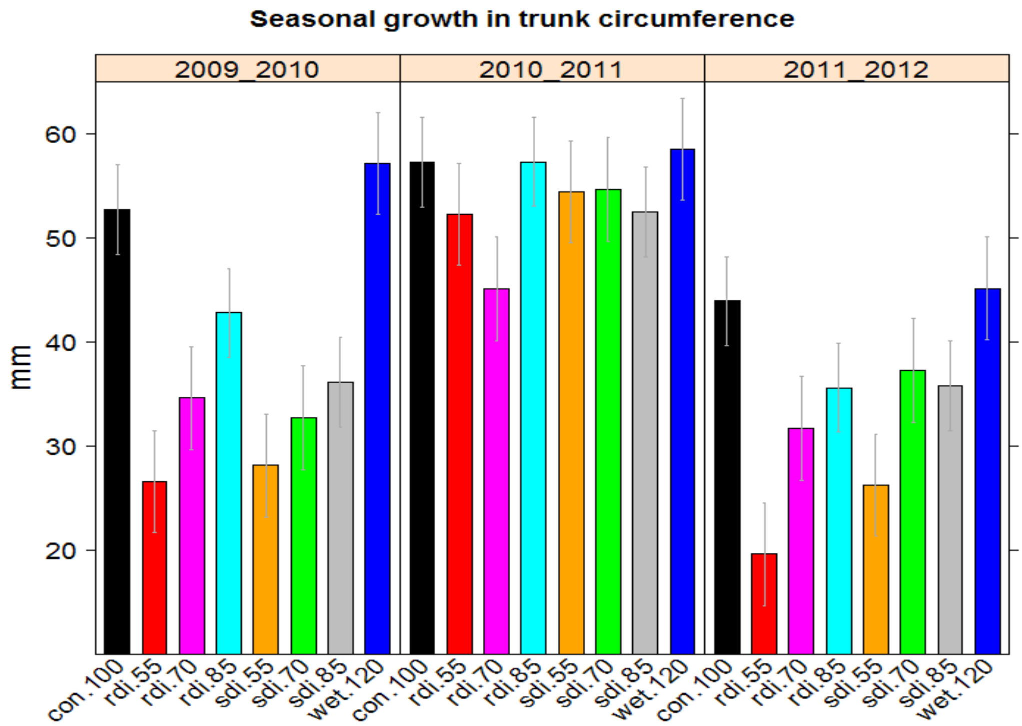

Figure 1.13: Influence of irrigation treatments on the seasonal growth in trunk circumference assessed between 22/10/2009 and 21/05/2010 in the 2009-2010 and between 21/05/2010 and 27/04/2011 in the 2010-2011 season at Lake Powell. Vertical bars indicate $\pm 1/2$ least significant differences of means (5% level).

1.4.7 Soil moisture monitoring

The soil moisture traces at 20 and 120 cm soil depth for all irrigation treatments are depicted in Figure 1.15. Their course was generally consistent with the applied water level. In water deficient treatments the moisture levels relatively deep in the profile (120 cm) declined more rapidly as the season progressed and reached lower levels than in well watered control or "wet" treatments. Near the soil surface (20 cm) soil moisture was more variable over time due to frequent re-watering events. However, in treatments with an RDI strategy moisture content near the surface tended to decline gradually after applying the deficit regime. A gradual and steady decline of the respective treatments was most obvious at 120 cm because the applied volume was insufficient to reach the deeper soil layers but moisture continued to be depleted by the trees until RDI were discontinued around harvest in mid to late February. Subsequently, RDI trees again received the same volume of water as control trees and this resulted in a steady refill of the profile at 120 cm depth. An exception was the 2010-2011 season when a temporary moisture depletion during the

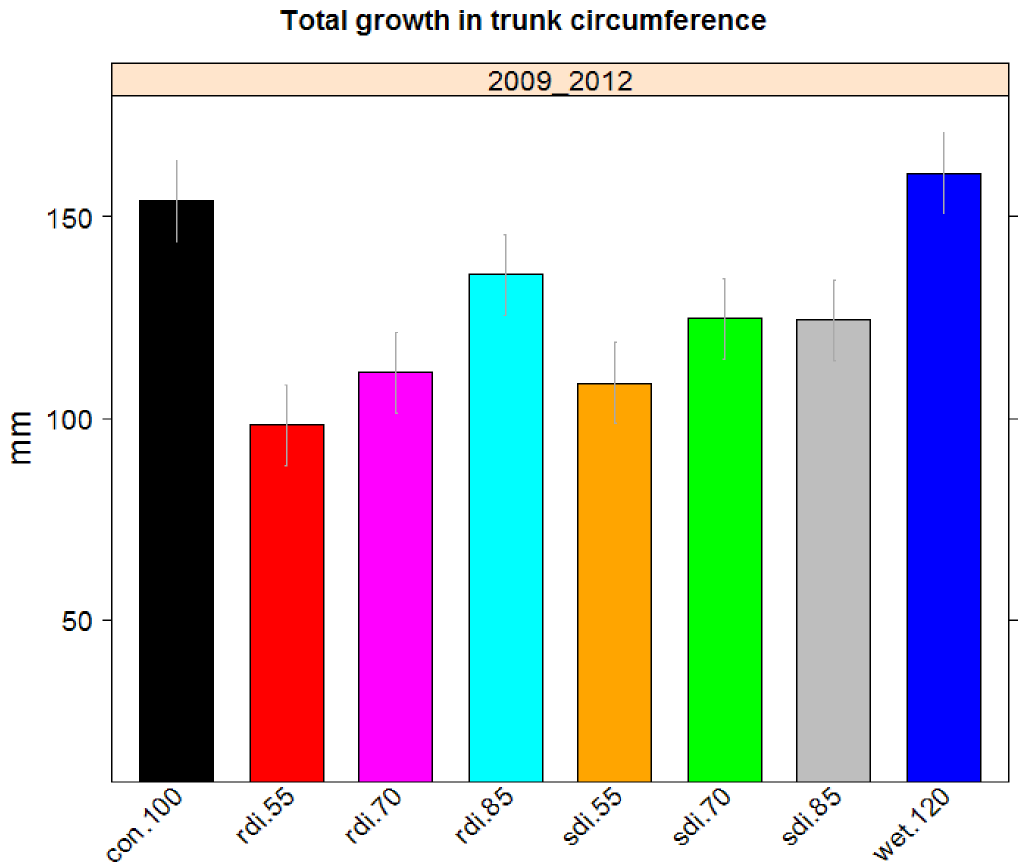

Figure 1.14: Influence of irrigation treatments on total growth in trunk circumference between 22/10/2009 and 17/04/2012 season at Lake Powell. Vertical bars indicate ±1/2 least significant differences of means (5% level).

RDI deficit period did not eventuate because of frequent rainfall, which was sufficient to refill the soil reservoir to a depth of 120 cm several times during that season.

Moisture readings near the soil surface of treatments with SDI showed a similar seasonal course as those of control trees due to frequent irrigation applications. However, deeper in profile (120 cm), SDI appeared to readily deplete the plant available moisture which then remained at relatively low levels for the rest of the season. An exception was 85% SDI for which an obvious depletion was restricted to the mid season period when plant water use was at its maximum. Under the more severe SDI deficits (55 and 70%), the applied irrigation was almost entirely intercepted by the surface roots while deeper roots had largely depleted the plant available soil moisture season (see section 1.4.8).

A short period of overlap or near overlap of the shallow and deep moisture readings in the RDI and SDI 55% treatment late in 2011-2012 are believed to erroneous and were caused by malfunctioning sensor probes.

1.4.8 Wetting front detection

The graphs depicted in Figures 1.16, 1.17 and 1.18 on pages 35, 36 and 37 respectively show the relative daily change in soil moisture to a profile depth of 120 cm during each of the 3 seasons under investigation. A positive value indicates profile refill, a negative, indicates drainage or tree water uptake.

The measurements are a good indicator of the seasonal course of the soil wetting front induced by irrigation and rainfall events. Each chart is a graphical representation of the relative daily changes in soil moisture for each 10cm depth increment between 10 and 120 cm depth and for the duration of each season.

Results in the first season show clear differences between irrigation treatments. The presence of a wetting front to a depth of at least 100 cm and mainly during the months of October to April is clearly evident for control (100%), high watering ("wet" 120%) and both SDI and RDI 85%. Progressively less wetting and drying was seen for both the SDI and RDI 70% 55% with increasing soil depth. Little irrigation water or rain appeared to penetrate below 60 cm for SDI 70% and below 50 cm for SDI 55%. Probably because the roots in shallower soil (10-80 cm) intercepted most of the irrigation or rain preventing it from penetrating any deeper. The profile wetting at the beginning of the growing period is visible in all treatments and values indicate that there was some drainage beyond the root zone. There appeared to be deeper wetting in RDI 70 and 55% than in the equivalent SDI treatments but this was true mostly after the end of January when RDI treatments were returned to full irrigation. Although some drainage beyond the roots zone is evident for treatments of 85% and wetter, it does not appear excessive.

A similar wetting pattern as in 2009-2010 was seen in the subsequent season (Figure 1.17). Again the irrigation levels are clearly distinguishable and the depth of penetration of a regular wetting front was correlated with the volume of irrigation or rain. Results suggest that drainage beyond the root zone was evident for those treatments that received irrigation equal to or in excess of 85% plant water requirement.

The wetting front patterns of 2011-2012 were again similar to those seen in previous seasons with an obvious wetting front throughout the profile for most of the season in treatments receiving 85% or more of plant requirement. Wetting at depths beyond 70 cm was clearly reduced in SDI 55 and 70% and in RDI 55 and 70% during deficit periods. For deficits equal to and smaller than 75% the RDI pattern had more frequent and deeper wetting events than the SDI pattern.

The lack of a clear wetting front for most of the season under and SDI 55% and to a lesser extent the SDI 75% strategy may be associated with a buildup of salt which, in the medium to long term, could lead to inhibited root function and may also cause soil structural problems. Any strategic deficit irrigation strategy should therefore apply sufficient irrigation to allow leaching of excessive salt probably in early spring at the time of profile refill.

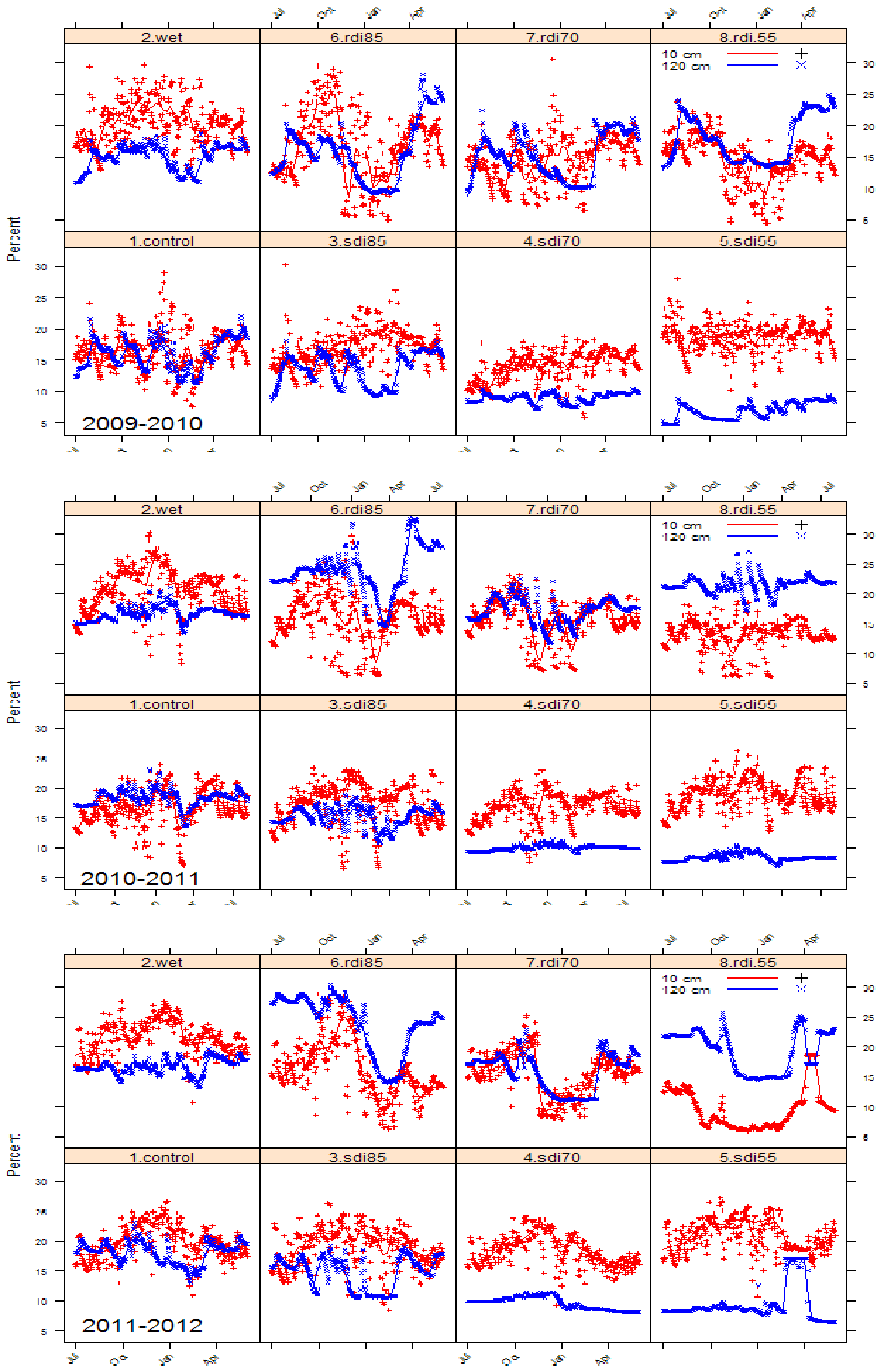

Figure 1.15: Seasonal course of soil moisture at 10 and 120 cm soil depth under the respective irrigation treatments in seasons 2009-2010, 2010-2011 and 2011-2012.

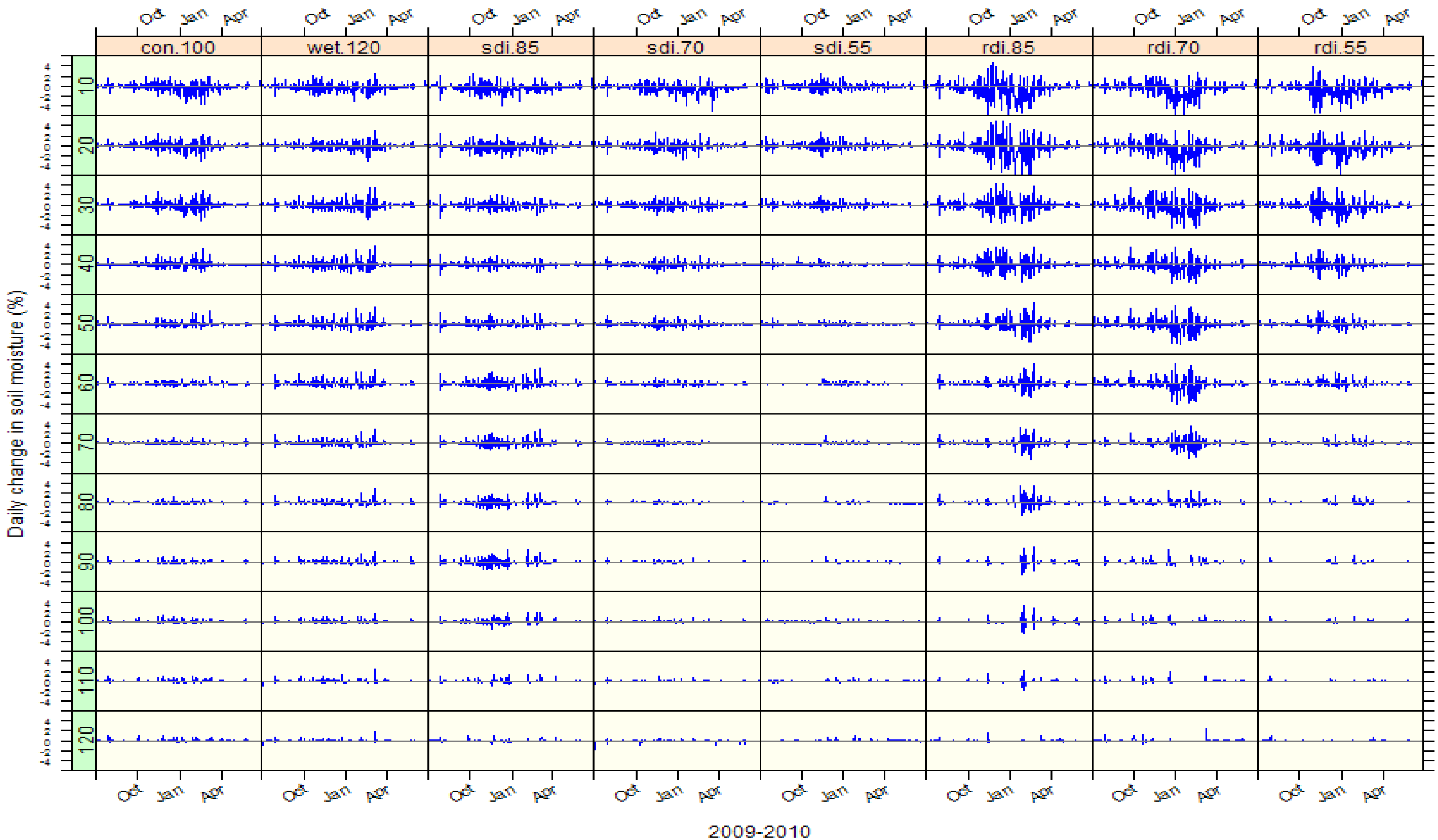

Figure 1.16: Daily soil moisture fluctuations between 10 and 120 cm soil depth during the 2009-2010 season.

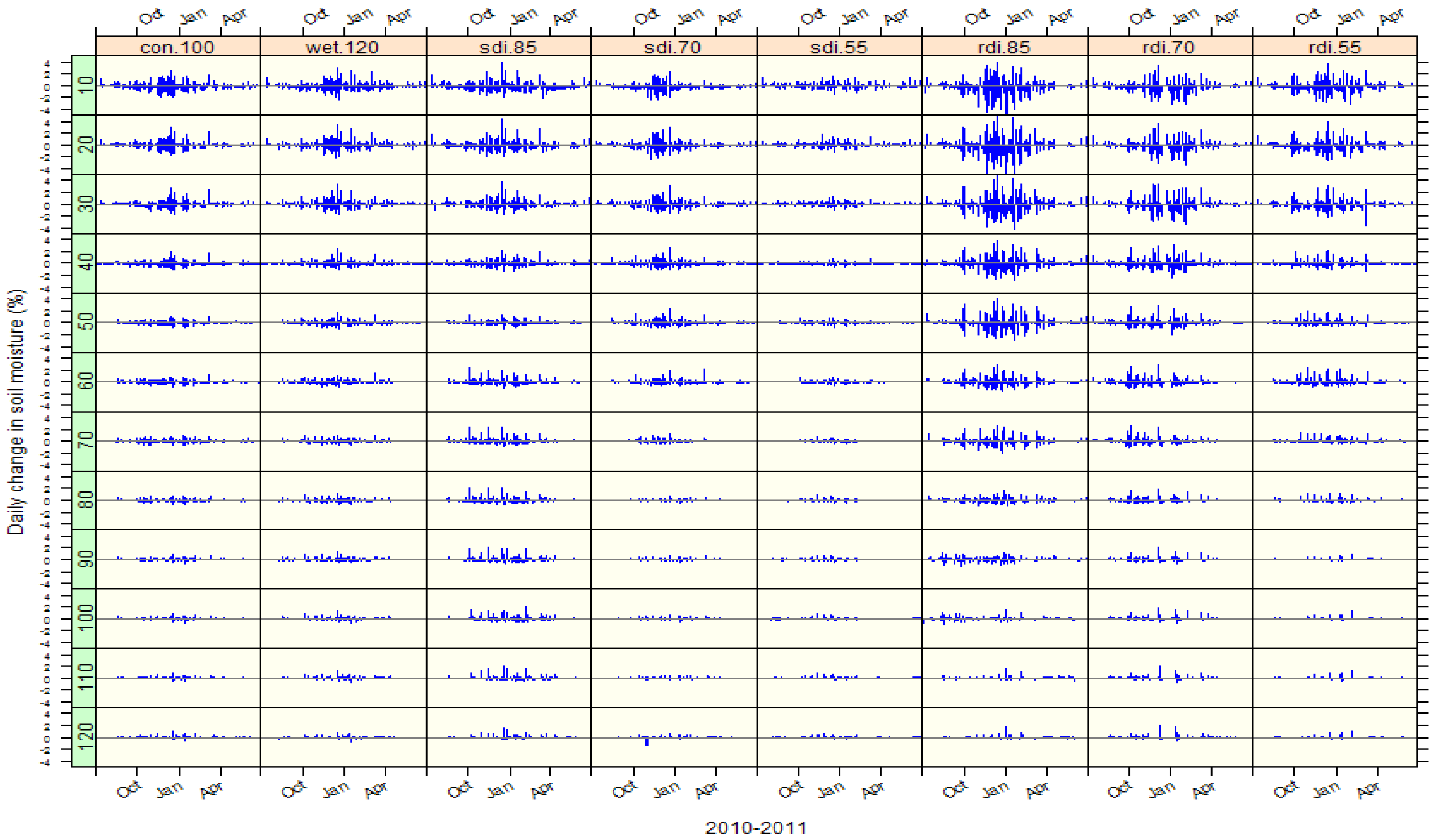

Figure 1.17: Daily soil moisture fluctuations between 10 and 120 cm soil during the 2010-2011 season.

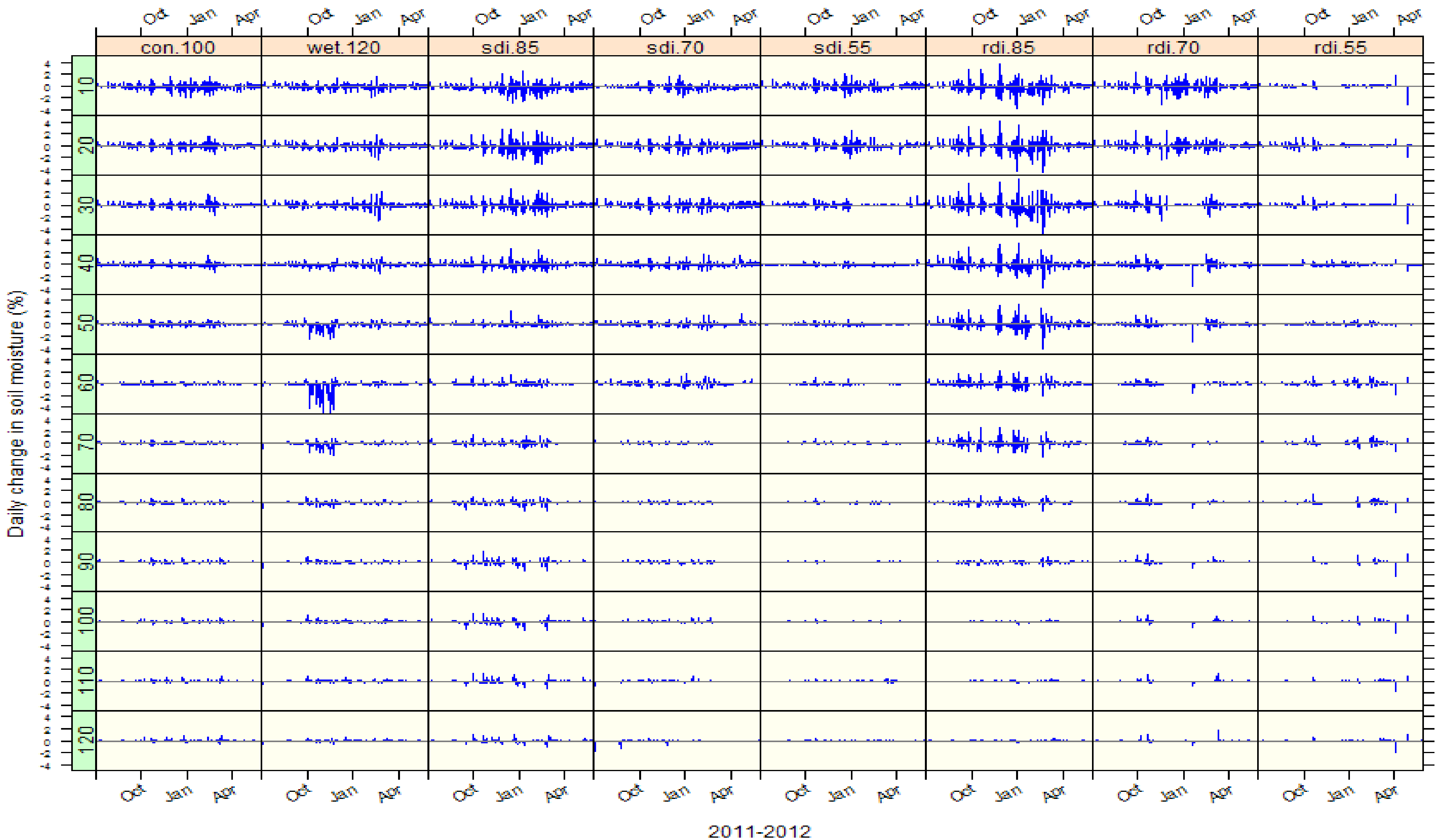

Figure 1.18: Daily soil moisture fluctuations between 10 and 120 cm soil during the 2011-2012 season.

1.5 Summary

The experimental site was established at the end of season 2008-2009 at Lake Powell near Robinvale, Victoria, with the aim to test five levels of irrigation, a 100% watered control, three levels of deficit irrigation (55, 70 and 85%) applied as regulated (RDI) or sustained (SDI) deficits and a high irrigation level (120%). The impact of the various irrigation treatments on tree physiology, growth and productivity was assessed.

The most important findings after three seasons of field experimentation were as follows:

In the first season (2009-2010) of the experiment deficit irrigation led to readily observable tree water stress.

- Trees with deficits applied throughout the irrigation cycle (SDI) adapted more readily to reduced water than those receiving deficits where the stress was biased towards pre-harvest (RDI)
- Irrigating at 85% or more of normal practice had no negative impact on kernel size and yield but irrigating at 70% or less decreased kernel yield regardless of strategy. Irrigating at 55% decreased kernel size and kernel yield. (see Figs. 3-4).

In the second season (2010-2011) with repeated and heavy rainfall no plant water stress was measured despite the imposed irrigation deficits. Wet and comparatively cool conditions caused a delay in harvest and led to hull rot infections with a lower average kernel yield than in the previous season.

- Treatments with high irrigation (120%), control (100%) and RDI 85% had a reduced kernel yield relative to RDI 70%, suggesting that deficit irrigation conferred a yield advantage under wet conditions.

Results from the third and final season (2011-2012) were similar to those seen in the first season. Water stress due to deficit irrigation treatments was readily observable but generally was less severe than during the first season because of milder weather.

- Irrigating at 85% either as SDI or RDI or at 70% SDI had no negative impact on kernel size and yield but irrigating at 70% RDI or at 55% RDI or SDI decreased yield and kernel size.
- Trees under an SDI regime appeared more resilient and for deficits equal to or below 70% were also more productive than those under an RDI regime.
- A higher percentage of nut damage due to carob moth was seen compared with previous seasons. Damage was greater on trees under deficit irrigation because their nuts split sooner and therefore were exposed for a longer period of potential infection and damage.

1.5.1 Conclusion

Reducing irrigation application by 15% below normal plant requirement using either an RDI or SDI strategy had no negative effect on kernel size and yield over the three seasons of investigation.

Deficits that reduced normal plant water requirement by more than 15% are likely to reduce both kernel size and yield.

Trees appear to better adapt to a sustained (SDI) rather than regulated deficit irrigation (RDI) strategy where deficits are imposed before harvest.

Limited profile wetting and root water extraction was seen at depth beyond 70-80 cm in SDI 55 and 70% and may lead and accumulation of salt in the root zone. Drainage beyond the root zone was apparent in irrigation regimes receiving 85% or more of plant water requirement.

1.5.2 Recommendation

Our results suggest that a mild deficit of 15% below full plant water requirement does not adversely affect production after 3 seasons. Some uncertainty remains around the long term productivity of trees under mild water deficits given the quite variable weather over the 3 seasons under investigation.

For maximum certainty regarding definitive industry guidelines we are therefore recommending to extend the experiment by an additional two seasons.

This will consolidate the current results and, in addition, will allow us to address a number of research questions that arose during the course of the work. They include the impact of deficit irrigation on the timing and duration of key phenological events, the quantity of bloom and fruit set and the impact of strategic irrigation management on the potential for hull rot.

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Appendix

The results of this work have been published in a number of articles in industry journals and have been presented as posters at conferences and field days. A copy of each listed article or poster is attached.

List of attachements

Brown, B. (2012). R & D Roundup: Optimising water use of Australian almond production through deficit irrigation strategies. *In a Nutshell*, *June*, p. 14–15. See Att. 6 on page 47

Sommer, K. (2009). Deficit irrigation in almonds. *In a Nutshell*, *September*, p. 3–3. See Att. 2 on page 43

Sommer, K. J., Taylor, C., & Ratna, R. (2010). Optimising Australian almond production through deficit irrigation strategies. *Australian Nutgrower*, *24*(3), 9–13. See Att. 7 on page 49

Sommer, K. J., Taylor, C., & Ratna, R. (2011). Deficit irrigation strategies in almond during contrasting seasons. *Australian Nutgrower*, *25*(4), 34–36. See Att. 8 on page 54

Taylor, C., Ratna, R., Sommer, K. J., & Downey, M. (2009). Optimising water use of Australian almonds through defict irrigation. Poster presentation, 58th Mildura Horticultural Field Days, 26-27 May. See Att. 1 on page 42

Taylor, C., Ratna, R., Sommer, K. J., & Downey, M. (2010). Optimising water use of Australian almonds through defict irrigation strategies. Poster presentation, 59th Mildura Horticultural Field Days, 25-26 May. See Att. 3 on page 44

Taylor, C., Ratna, R., Sommer, K. J., & Downey, M. (2011). Contrasting seasons under deficit irrigation in almond. Poster presentation, 60th Mildura Horticultural Field Days, 24-25 May. See Att. 4 on page 45

Taylor, C., Ratna, R., Sommer, K. J., & Downey, M. (2012). Optimising Australian almond production through defict irrigation strategies. Poster presentation, 61st Mildura Field Days, 29-30 May. See Att. 5 on page 46

DEPARTMENT OF
PRIMARY INDUSTRIES

Optimising water use of Australian almond production through deficit irrigation

C. Taylor, R. Ratna, K. J. Sommer and M. Downey

Department of Primary Industries, Mildura, Victoria

Introduction

The current drought and restricted water allocations along the lower Murray River make it imperative that almonds are grown according to 'best irrigation management practice' by using water in the most efficient and effective way.

The need to optimize water use requires detailed knowledge on how almond trees respond to deficit irrigation regarding both, the timing and volume of the water applied.

There is currently limited information on the potential for deficit irrigation and its effect on almond production under inland climatic conditions in Australia.

Objectives

- Establish benchmarks for deficit irrigation of almond under inland climatic conditions in Australia
- Investigate the yield response to deficit irrigation
- Establish minimum irrigation levels for almond production
- Establish optimum timing to apply deficits
- Monitor the potential for deep drainage

Progress

A field site has been established within a large commercial almond orchard near Lake Powell in northern Victoria just south of the Murray River about 35 km east of Robinvale (Figure 1).

Figure 1: Aerial image of wider area of field site location near Lake Powell, Victoria

The trial area of around 5.2 ha shown in Figure 2 was planted to almond in the 2002-2003 season and is now coming into full production. Experimental treatments will be applied from the 2009-2010 season.

Experimental

Figure 3 shows the experimental layout comprising 8 irrigation treatments with 5 levels of irrigation replicated 6 times. The level of irrigation is always expressed as the percentage of water use or evapotranspiration (%ETc) of an orchard whose demand for water is fully satisfied as in the control treatment (100% ETc). The experiment also comprises a 'wet' treatment irrigated at 120% ETc with the aim to generate drainage.

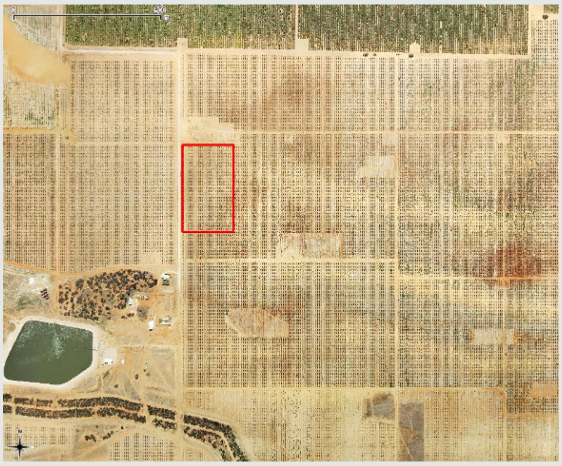

Figure 2: Aerial image of field site location near Lake Powell, Victoria

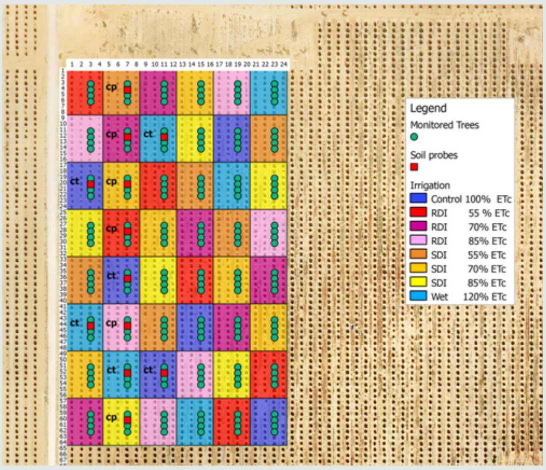

Figure 3: Layout of experimental blocks of deficit irrigation trial at Lake Powell, Victoria

Two deficit strategies will be applied:

- *Regulated Deficit Irrigation (RDI)*
- *Sustained Deficit Irrigation (SDI)*

With RDI, deficits are biased toward pre-harvest, while with SDI deficits are applied throughout the irrigation cycle as a fixed percentage of the volume applied to fully irrigated trees.

The site is equipped with logging capacitance probes and tensiometers to monitor soil moisture for each irrigation treatment. The irrigation infrastructure for the trial will be fully operational from July 2009.

Treatment effects on tree growth, development and water status will be monitored throughout the growing season.

Acknowledgments

This work is a component of a wider DPI project with the aim to *'maximise productivity of perennial horticulture during periods of reduced water allocations'*.

We acknowledge the support of Select Harvests Pty. Ltd..

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Deficit Irrigation in Almonds

by Dr Karl Sommer, DPI Victoria

Much remains to be learnt about the impact of water on almond production in Australia, so a research project was established in winter 2009, to build the industry's knowledge about the role of water deficits on yield and nut quality.

To provide the necessary data, a trial has been established at Lake Powell near Robinvale in Victoria with funding from the Department of Primary Industries Victoria (DPI), Australian Almond Industry levies and Horticulture Australia Limited (HAL).

The site has five levels of irrigation applied – a control (approximately 12 ML/Ha), three levels of deficit irrigation (55, 70 and 85 per cent) and a higher irrigation level (120 per cent).

The water deficits are being applied in two different patterns – regulated deficit irrigation, where the stress is biased towards pre-harvest, and sustained deficit irrigation, where deficits are applied throughout the irrigation cycle.

Work to date has involved the installation of the irrigation infrastructure such as flow meters, fertigation tanks, automatic controls and logging capacitance probes.

During the current season, deficit irrigation is being applied to the site and its impact on tree growth and plant/soil water status will be monitored. Yield and nut quality will be assessed post-harvest.

There will be an opportunity to inspect the trial site at a field day to be held in early 2010.

For more information contact:
Ben Brown
Industry Liaison Manager
Almond Board of Australia
bbrown@australianalmonds.com.au

Control unit in front and fertigation tank in background (Lake Powell)

Installation of irrigation infrastructure at Lake Powell trial site

Flow meters for 8 irrigation treatments at Lake Powell

Optimising water use of Australian Almond production through deficit irrigation strategies

C. Taylor, R. Ratna, K. Sommer, M. Downey
Department of Primary Industries, Mildura, PO Box 905, Mildura, Victoria, 3502

Introduction and objectives

Growing almonds using 'best irrigation management practice' is critical in the current climate of drought and restricted availability of water for irrigation. The need to optimize water use requires detailed knowledge on response of almond trees to deficit irrigation regarding both, the timing and volume of the water applied. Currently there is limited information on the response of almonds to reduced water inputs under inland climactic conditions in Australia. Here we report preliminary findings of a 3 year research trial designed to:

- Establish benchmarks for deficit irrigation of almond under inland climatic conditions in Australia.
- Investigate the yield response to deficit irrigation.
- Establish minimum irrigation levels for almond production.
- Establish optimum timing to apply deficits.
- Monitor the potential for deep drainage.

Methods

The trial is located at Lake Powell in north western Victoria and was planted in 2002-03. The experiment was established in 2009 and deficit irrigation treatments were applied from August 2009. Two deficit strategies are being tested:

- *Regulated Deficit Irrigation* (RDI)
- *Sustained Deficit Irrigation* (SDI)

With RDI, deficits were biased toward pre-harvest, while with SDI deficits were applied throughout the irrigation cycle as a fixed percentage of the volume applied to fully irrigated trees.

The following data was collected: weekly fruit dry matter samples, fortnightly mid-day stem water potential and stomatal conductance, monthly canopy light interception.

Table 1. Irrigation treatments, irrigation volumes, rainfall and timing of deficit applications. Rainfall and irrigation applied 1 August 2009 to 31 April 2010.

Treatment	ML/ha	Rainfall (mm)	Deficit timing
Control	9.04	361	-
Wet	10.92	361	-
SDI 85%	7.78	361	All season
SDI 70%	6.69	361	All season
SDI 55%	5.16	361	All season
RDI 85%	8.07	361	10/1/10-17/2/10
RDI 70%	6.38	361	12/11/09-17/2/10
RDI 55%	5.27	361	10/9/09-17/2/10

Results

Reducing irrigation to 70% or less decreased kernel yield (Figure 1).

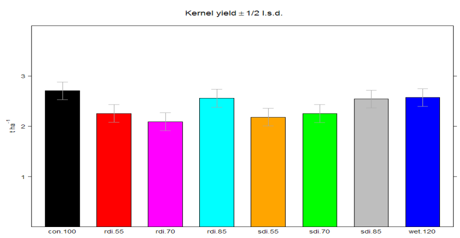

Figure 1. Effect of irrigation treatments on kernel yield, 2009-2010 season.

Deficit irrigation significantly reduced kernel weight by 12% in the treatments receiving 55% irrigation (Figure 2).

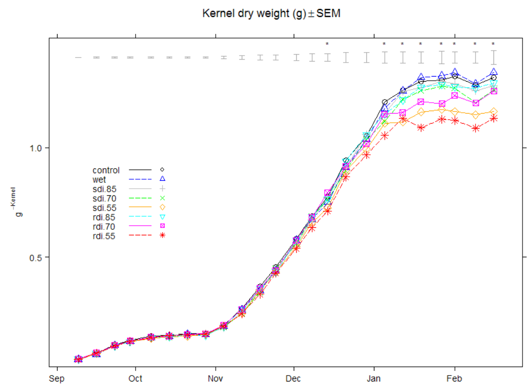

Figure 2. Effect of irrigation treatment on kernel weight over the 2009-2010 season.

Early in the irrigation season mid-day stem water potential for all treatments was high. As daytime temperatures and evaporative demand began to increase, the mid-day stem water potential of trees receiving deficit irrigation began to decline more than those of well watered trees. The response to a heatwave in mid November (8 days above 38°C) can be clearly seen (Figure 3). With the onset of high evaporative demand by mid December, mid-day stem water potential of the deficit irrigation treatments decrease in line with the imposed deficits but was more severe for trees receiving RDI than when compared with SDI, indicating that RDI trees were more severely water stressed.

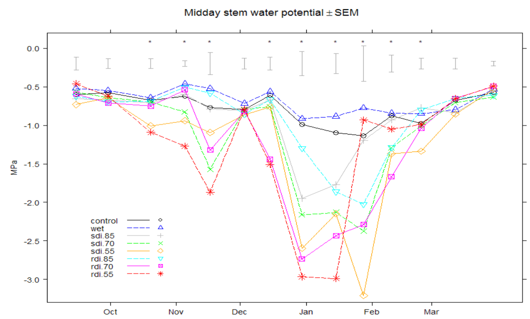

Figure 3. Effect of irrigation treatment on midday stem water potential, 2009-2010 season.

Conclusions

While only one year's data has been collected, the following trends are beginning to emerge.

- Trees receiving SDI appear to be adapting more readily to reduced water than those receiving RDI.
- Reduced irrigation results in decreased kernel weight.
- Irrigating at 70% or less decreased kernel yield.

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Contrasting seasons under deficit irrigation in Almond

C. Taylor, R. Ratna, K. Sommer and M. Downey
Department of Primary Industries, Mildura, PO Box 905, Mildura, Victoria, 3502

Introduction and objectives

Growing almonds using 'best irrigation management practice' is critical in times of drought and restricted availability of water for irrigation. DPI Victoria in collaboration with HAL and the ABA have designed a field experiment to address the following objectives:

- Establish benchmarks for deficit irrigation of almond under inland climatic conditions in Australia.
- Investigate the yield response to deficit irrigation.
- Establish minimum irrigation levels for almond production.
- Establish optimum timing to apply deficits.
- Monitor the potential for deep drainage.

Here we report results of two contrasting seasons, one hot and dry (2009-2010) the other wet and humid (2010-2011).

Methods

The trial is located at Lake Powell in north western Victoria and was planted in 2002-2003. The experiment was established in 2009 and deficit irrigation treatments were applied from August 2009. Two deficit strategies are being tested:

- *Regulated Deficit Irrigation* (RDI)
- *Sustained Deficit Irrigation* (SDI)

With RDI, deficits were biased toward pre-harvest, while with SDI deficits were applied throughout the irrigation cycle as a fixed percentage of the volume applied to fully irrigated trees.

The following data was collected: weekly/fortnightly fruit dry matter samples, fortnightly mid-day stem water potential and stomatal conductance, monthly canopy light interception.

Table 1. Irrigation treatments, irrigation volumes, rainfall and timing of deficit applications. Rainfall and irrigation applied 1 August to 31 April for each year.

Treatment	ML/ha		Rainfall (mm)		Deficit timing
	2010	2011	2010	2011	
Control	9.04	7.78	361	573	-
Wet	10.92	9.31	361	573	-
SDI 85%	7.78	6.75	361	573	All season
SDI 70%	6.69	5.76	361	573	All season
SDI 55%	5.16	4.75	361	573	All season
RDI 85%	8.07	6.66	361	573	10 Jan-17 Feb
RDI 70%	6.38	5.06	361	573	12 Nov-17 Feb
RDI 55%	5.27	4.86	361	573	10 Sep-17 Feb

Results

The 2009-2010 season, although slightly hotter than average was reasonably typical for the Sunraysia area, while the 2010-2011 season received record rainfall and was cooler but much more humid than an average season in Sunraysia.

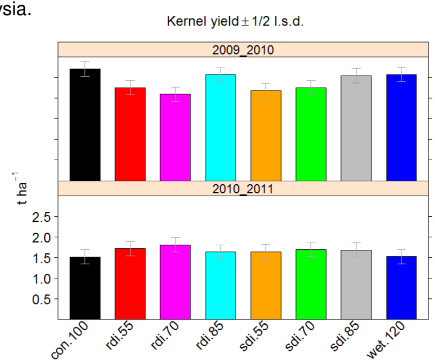

Figure 1. Effect of irrigation treatments on kernel yield, 2009-2010 and 2010-2011 seasons.

The results very much reflect those contrasting seasons. Reducing irrigation to 70% or less decreased kernel yield in the first year, In the second year treatments with high irrigation had reduced kernel yield relative to the RDI 70% treatment when wet conditions caused a delay in harvest and hull rot infections with lower average yields. (Figure 1).

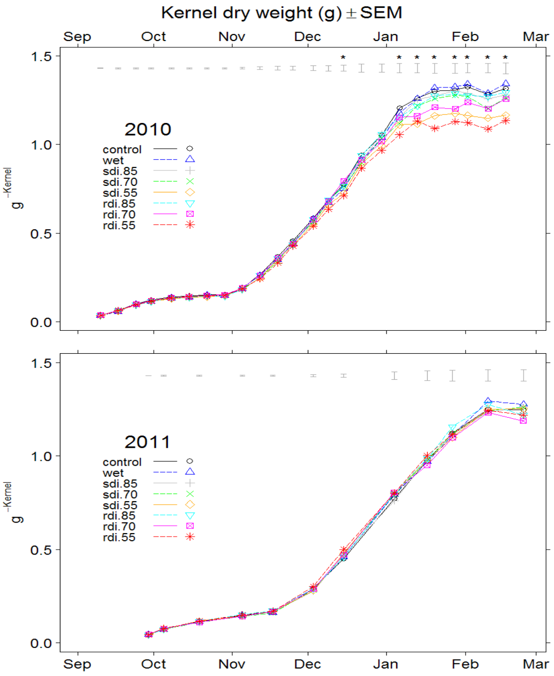

Figure 2. Effect of irrigation treatment on kernel weight during the 2009-2010 and 2010-2011 seasons.

In the 2009-2010 season, deficit irrigation significantly reduced kernel weight by 12% in the treatments receiving 55% irrigation while no differences were observed in 2010-2011 (Figure 2).

While in the first season the imposed deficits were clearly apparent from around early December, no differences where seen in the second season because in each of the hot and dry months during Dec – Feb, the orchard received frequent and heavy rainfall, immediately cancelling the developing deficits.

Conclusions

Two contrasting season showed very different trends

First season (2009-2010)

- Trees receiving SDI were adapting more readily to reduced water than those receiving RDI.
- Reduced irrigation results in decreased kernel weight.
- Irrigating at 70% or less decreased kernel yield.

Second season (2010-2011)

- Reduced irrigation results in increased kernel yield.
- Fruit development was delayed by several weeks relative to the first season.

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Optimising water use of Australian almond production through deficit irrigation strategies

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Introduction and Objectives

Growing almonds using 'best irrigation management practice' is critical in times of drought and restricted water availability for irrigation. DPI Victoria in collaboration with HAL and the ABA have designed a field experiment to address the following objectives:

- Establish benchmarks for deficit irrigation of almond under inland climatic conditions in Australia.
- Investigate the yield response to deficit irrigation.
- Establish minimum irrigation levels for almond production.
- Establish optimum timing to apply deficits.
- Monitor the potential for deep drainage.

Here we report results of three seasons, 2009-10, 2010-11 and 2011-12.

Methods

The trial orchard is located at Lake Powell in north western Victoria and was planted in 2002-03. The experiment was established in 2009 and deficit irrigation treatments were applied from August 2009. Two deficit strategies were tested:

- *Regulated Deficit Irrigation* (RDI)
- *Sustained Deficit Irrigation* (SDI)

With RDI, deficits were biased toward pre-harvest, while with SDI deficits were applied throughout the irrigation cycle as a fixed percentage of the volume applied to fully irrigated trees.

Tree growth, fruit growth and tree stress were measured throughout each season and kernel yield at the end of each season.

Table 1. Irrigation treatments, irrigation volumes and timing of deficit applications. Irrigation applied 1 August to 30 April for each year.

Treatment	Irrigation (mm)*			Deficit timing
	2010	2011	2012	
Control	937	781	1082	-
Wet	1131	933	1296	-
SDI 85%	806	677	916	All season
SDI 70%	694	578	759	All season
SDI 55%	534	476	686	All season
RDI 85%	836	668	959	10 Jan-17 Feb
RDI 70%	664	508	763	12 Nov-17 Feb
RDI 55%	552	488	663	10 Sep-17 Feb

*2009-10 effective rainfall 184mm, ETo 1435 mm,
2010-11 effective rainfall 214m, ETo 1089 mm,
2011-12 effective rainfall 40mm, ETo 1324 mm

Results

Water stress

Deficit irrigation led to readily observable water stress in 2009-10 (Figure1) when deficient trees underwent severe stress between mid December and late January. No water stress was apparent in 2010-11 due to frequent rainfall. In 2011-12 treatments receiving 70% or less of normal plant requirements had periods of severe stressed in December and January.

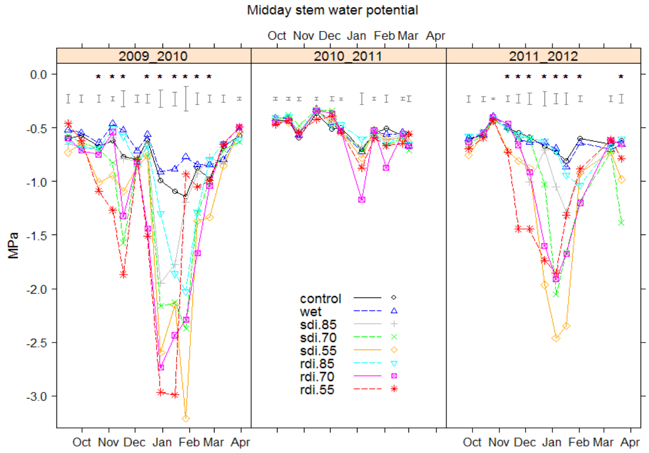

Figure 1. Midday stem water potential for all irrigation treatments for the 2009-10, 2010-11 and 2011-12 seasons.

Yield

2009-2010: Irrigating at 85% or more of normal plant requirements either as SDI or RDI had no negative impact on kernel size or yield but irrigating at 70% or less decreased kernel yield.
2010-2011: No differences were seen between treatments except for the 70% RDI which had a higher yield than the control and wet treatments.
2011-2012: Irrigating at 85% either as SDI or RDI or at 70% SDI had no negative impact on kernel size and yield but irrigating at 70% RDI or at 55% RDI or SDI decreased yield and kernel size.

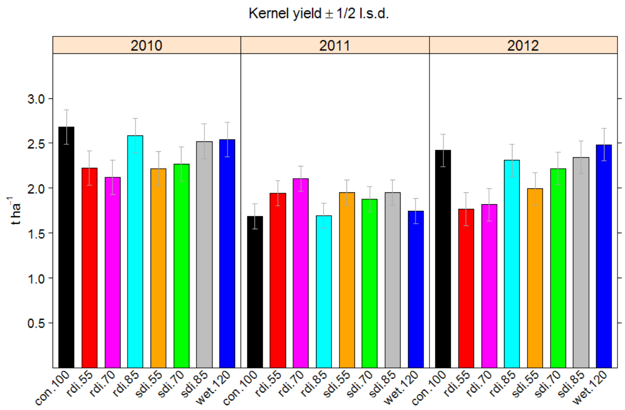

Figure 2. Effect of irrigation treatments on kernel yield, 2009-10, 2010-11 and 2011-12 seasons.

Conclusions

Deficits of 15% below normal plant requirements over 3 years had no negative effect on kernel size or yield regardless of irrigation strategy.

Deficits that reduced normal plant water requirement by more than 15% are likely to reduce both kernel size and yield.

Trees appear to better adapt to a SDI rather than a RDI strategy.

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R&D Roundup

Ben Brown - Industry Liaison Manager

With the 2012 harvest complete it provides a good opportunity to summarise the key points from two of our key Research & Development projects: AL08009 – Optimising water use of Australian almond production through deficit irrigation strategies (aka "RDI trial"); and AL11003 – Enhancing almond pollination efficiency. The pollination project is a new project, whereas you should be aware of the RDI trial if you have read industry publications such as the Australian Nutgrower, or attended recent conferences and field days. If you have not participated in these events, or are not a current member of the ABA and receiving its publications, I would strongly encourage you to do so. These publications provide you the opportunity to be kept up to date with all the latest information from your R&D levy investment.

Optimising water use of Australian almond production through deficit irrigation strategies (AL08009 aka "RDI trial")

Dr Karl Sommer, & Cathy Taylor, DPI Victoria

Introduction

The experimental site was established at the end of season 2008-2009 at Lake Powell near Robinvale, Victoria, to test five levels of irrigation (Figure 1) – a 100% watered control, three levels of deficit irrigation (55, 70 and 85%) applied as regulated (RDI) or sustained (SDI) deficits and a high irrigation level (120%). RDI treatments involved reduced water and increased stress, biased towards pre-harvest. SDI treatments involved reduced water and increased stress across the entire season with no bias towards any particular period.

Three seasons of field experimentation have been completed and results may be summarised as follows.

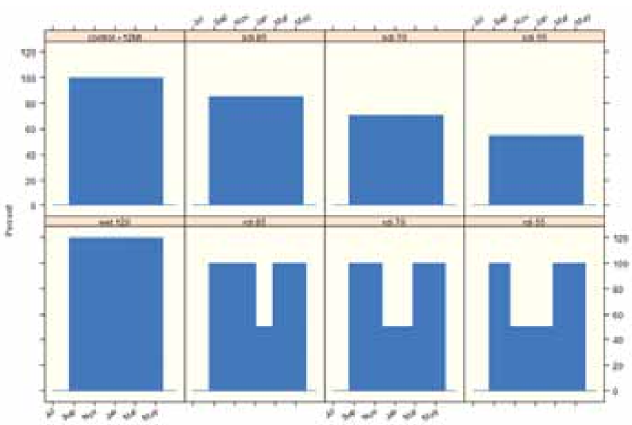

Figure 1: Conceptual diagram of the irrigation strategies investigated in AL08009

First season (2009-2010)

In the first season of the experiment deficit irrigation led to readily observable tree water stress (Figure 2).

- Trees with deficits applied throughout the irrigation cycle (SDI) adapted more readily to reduced water than those receiving deficits where the stress was biased towards pre-harvest (RDI).

Irrigating at 85% or more of normal practice had no negative impact on kernel size and yield but irrigating at 70% or less decreased kernel yield regardless of strategy. Irrigating at 55% decreased kernel size and kernel yield (Figure 3 and Figure 4).

Second season (2010 – 2011)

In the second season with repeated and heavy rainfall little or no plant water stress was measured despite the imposed irrigation deficits. Wet conditions caused a delay in harvest and increased hull rot infections with a lower average kernel yield than in the previous season.

Treatments with high irrigation (120%), control (100%) and RDI 85% had a reduced kernel yield relative to RDI 70%, suggesting deficit irrigation conferred a yield advantage under wet conditions (Figure 2 to Figure 4).

Third and final season (2011 – 2012)

Generally, results were similar to those seen in the first season. Water stress due to deficit irrigation treatments was readily observable but generally was less severe than in the first season because of milder weather (Figure 2 to Figure 4).

Irrigating at 85% SDI, 85% RDI or 70% SDI had no negative impact on kernel size and yield but irrigating at 70% RDI, 55% RDI or 55% SDI decreased yield and kernel size (Figure 3 and Figure 4).

Trees under an SDI regime appeared more resilient and for deficits equal to or below 70% were also more productive than those under an RDI regime. (Figure 2 and Figure 4).

A higher percentage of nut damage due to carob moth was seen compared with previous seasons. Damage was greater on trees under deficit irrigation because their hulls split sooner and therefore were exposed for a longer period of potential infection and damage.

Conclusion

Reducing irrigation application by 15% below normal plant requirement using either an RDI or SDI strategy had no negative effect on kernel size and yield over the three seasons of investigation.

Deficits that reduced normal plant water requirement by more than 15% are likely to reduce both kernel size and yield.

Trees appear to better adapt to a sustained (SDI) rather than regulated deficit irrigation (RDI) strategy where deficits are imposed before harvest.

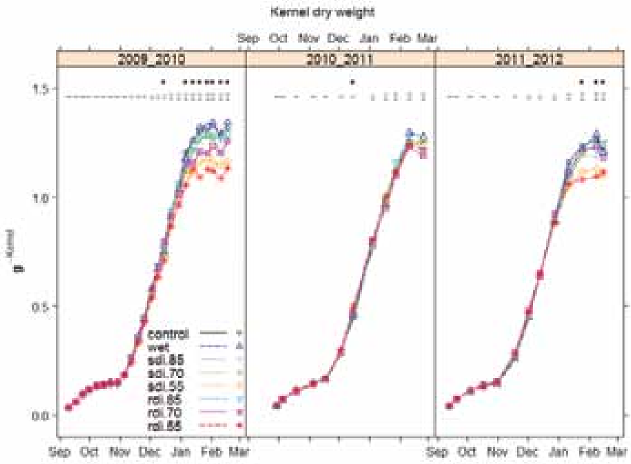

Figure 3: Influence of irrigation strategy on kernel growth during the 2009-2010, 2011-2012 and 2012-2013 growing seasons at Lake Powell

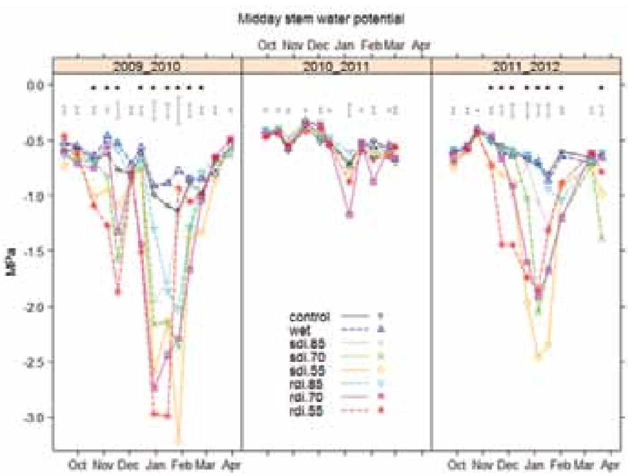

Figure 2: Influence of irrigation strategy on midday stem water potential in the 2009-2010, 2010-2011 and 2011-2012 growing seasons at Lake Powell

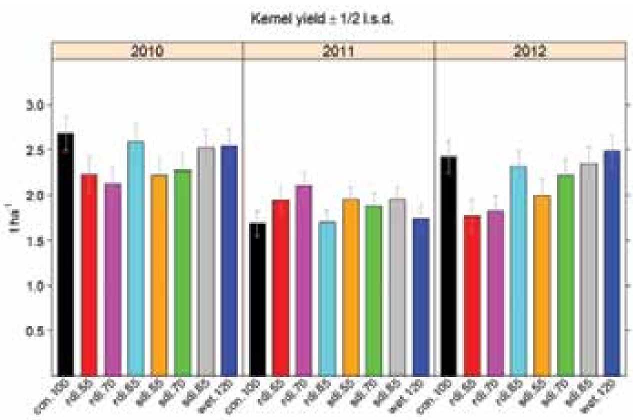

Figure 4: Influence of irrigation strategy on kernel yield at the end of the 2009-2010, 2011-2012 and 2012-2013 growing seasons at Lake Powell

Optimising Australian almond production through deficit irrigation strategies

K. J. Sommer, C. Taylor and R. Ratna,
Department of Primary Industries, Victoria.

1. Introduction

The majority of almond production in Australia is located along the lower Murray River where irrigators have experienced substantially reduced water allocations over recent years. The growing scarcity of water makes it imperative that almond growers apply "best irrigation management practice" by using water in the most efficient and effective way.

The need to optimize water use should include the consideration of deficit irrigation, a practice rarely applied by Australian almond growers. Historically, almond research in Australia has focused on how to irrigate almonds under optimal irrigation volumes with no savings through deficit strategies. Information is lacking on the potential for irrigating almonds under moderate to low irrigation volumes and with variable irrigation strategies such as deficit irrigation.

Various deficit irrigation trials in almond have been conducted overseas but the results are not immediately applicable to the soil and climatic conditions of inland Australia (Goldhamer et al., 2006, Goldhamer & Viveros, 2000, Romero et al., 2004). To address this shortcoming the Department of Primary Industries Victoria (DPI) and the Almond Board of Australia (ABA) have recently established a field experiment that aims to explore the potential for deficit irrigation of almond orchards in inland Australia. The work aims to achieve the following objectives:

- Establish benchmarks for deficit irrigation of almonds under inland climatic conditions of Australia
- Investigate the yield response to deficit irrigation
- Establish minimum irrigation levels for almond production
- Establish optimum timing to apply deficits
- Monitor the potential for deep drainage.

This article will briefly describe some of the experimental methods used in this work and will summarize the results of the first growing season after establishing the experimental treatments.

2. Materials and Methods

2.1 Site

The research site is located near Lake Powell in north west Victoria (Lat: -34.706° and Long: 142.874°), just south of the Murray River and about 15 km east of Robinvale. The experimental orchard comprises 5.2ha of almond trees that were planted in mid 2004 and are presently coming into full bearing. Trees are spaced at a distance of 4.65m within the rows and 7.25m between rows. The varieties are Nonpareil and Carmel planted in alternate rows in a north south direction. The rootstock is Nemaguard.

2.2 Irrigation treatments

Trees are irrigated using a drip system where each tree row is equipped with dual irrigation lines, one at either side of the row at a distance of around 1m from the tree. Emitter spacing is 0.7m and emitter flow 2.1 l/h, resulting in an application rate of 0.83 mm/h.

The experiment consists of three levels of deficit irrigation applied in two strategies, either as sustained deficit irrigation (SDI), where the deficit was evenly applied throughout the irrigation cycle or as regulated deficit irrigation (RDI), where the deficits were biased toward pre-harvest. No post-harvest deficit irrigation was applied because it has been shown to severely reduce flower bud differentiation and thus cropping potential during the subsequent season [Goldhamer and Viveros, 2000].

Deficit levels were 55, 70 and 85 percent of the control treatment, where the latter was equal to approximately 12 Ml/ha per season of irrigation and effective rainfall. Effective rainfall was defined as 50 percent of the precipitation equal to or above 12mm within a 24 hour period. The design layout also included a "wet" treatment receiving 120 percent of the control with the aim to determine drainage beyond the root zone. Thus the experiment had a total of eight irrigation treatments.

The control was defined as the level of irrigation that many growers and a previous experiment were applying. The plant water requirement (ETc) of the control was calculated using a standard protocol developed by the ABA by multiplying historically developed crop factors (Cf) with readings from a standard class A evaporation pan (Epan) located near the experimental site.

$$ETc = Cf \times Epan \quad (1)$$

The current day's irrigation hours for each treatment were estimated from long term evaporation records or short term forecasts, after adjusting for the previous day's irrigation tally (previous day's evaporation - previous day's irrigation application). The required hours for each treatment were entered into an automatic irrigation control unit as hourly pulses with water being applied for one hour and turned off for the subsequent hour until the full requirement was met. Each irrigation treatment was equipped with a flow meter and applied volumes were recorded daily.

2.3 Statistical analysis

The trial was a randomized block design with 6 blocks (replicates). Each block contained 8 plots corresponding to the 8 irrigation treatments outlined earlier. Each plot was 8 trees long and 4 rows wide and consisted of alternating rows of pollinator (Carmel) and non-pollinator (Nonpareil) trees. Four centre trees (sample trees) of the second Nonpareil row in each plot (counting from west to east) were used for regular monitoring of tree physiological and production related indicators.

2.4 Plant nutrition

Nutrients were applied as fertigation according to the current industry standard based on outcomes from the almond optimisation trial [Almond Board of Australia, 2010]. All irrigation levels received the same quantity of nutrients injected into the final irrigation pulse of the day. Nitrogen (N), phosphorus (P) and potassium (K) were applied at a ratio of 1 : 0.13 : 1.25, with rates of approximately 320, 40 and 400 kg/ha respectively.

2.5 Soil based measurements

Soil moisture was continuously monitored with logging capacitance sensors (MAIT) using one probe per deficit treatment in one replicate and one probe per control and wet treatment in 3 replicates.

Figure 1. Light interception measurement using a ceptometer.

2.6 Plant measurements

Hull and kernel development was monitored throughout the season. Four fruit per tree were collected every week. Samples were immediately stored in plastic bags and placed in a cooler. In the laboratory each fruit was separated into kernel, hull and shell and their fresh weight was recorded. Subsequently samples were dried in an oven at a temperature of 65°C and were re-weighed. Trees were shaken commercially on 17 February 2010.

Prior to shaking, irrigation was withdrawn for 2 days to minimise shaker damage to the trunk. Nuts were left to dry on the ground until the hull moisture reached 14%, after approximately 9 days. Nuts were then swept into windrows and picked up into bulk bags. Bags were weighed and 3kg sub-samples collected. Sub-samples were dried to a constant weight. Kernel weight and percentage crack out were determined. Nuts left on the trees (i.e. sticktights) after shaking, were counted.

Midday light interception was measured every month using a Decagon AccuPAR LP-80 ceptometer (see Figure 1). Readings were taken from 8 sample points located on a line from the north-west corner of the tree space to the south-east corner with the tree in the centre. Measurements were taken from the fourth tree from the north end of each plot.

Leaf stomatal conductance and midday stem water potential were monitored fortnightly between 15 September 2009 and 30 March 2010. Stomatal conductance was measured using a leaf porometer (Decagon, model SC-1; see Figure 2).

Measurements were taken between approximately 900 and 1500h solar time. Two leaves, one from each of the two centre trees of each plot were recorded. On each measurement date this procedure was repeated three times during the day.

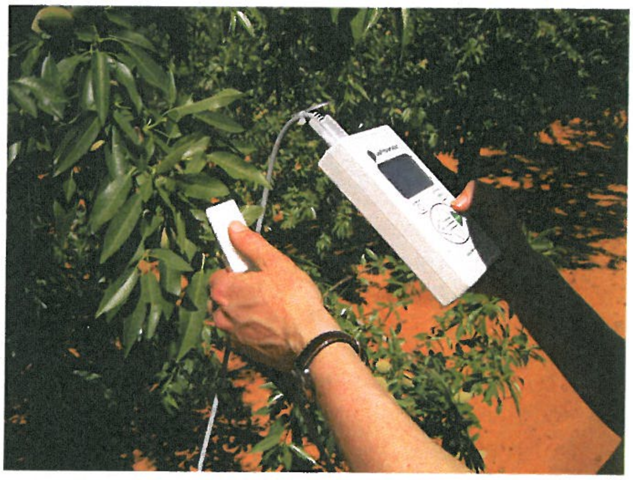

Figure 2: Stomatal conductance measurement using a leaf porometer.

Midday stem water potential was measured according to Ritchie and Hinckley, 1975 using a pressure bomb (Plant Water Status Console 3005 series, Soil Moisture Equipment Corp., Santa Barbara, CA; see Figure 3).

One or two hours before testing, foil laminate bags (PMS Instrument Company, Albury, Oregon) were placed over a leaf from the inner canopy of the two centre trees of each plot and measurements were taken as per Shackel, [2010]. On each measurement date two leaves from each plot of the three western most blocks were tested.

Figure 3: Pressure bomb assembly to measure stem water potential.

3. Results and Discussion

The following section illustrates the main findings for the 2009-2010 season and provides a brief interpretation of results obtained so far.

3.1 Irrigation summary

Table 1 gives a summary of the irrigation volumes, effective rainfall and timing of the irrigation treatments applied during the first season. Irrigation and effective rain were 1107mm or 11 Ml/ha for control trees and 1301mm or 13 Ml/ha for trees under the 120 percent treatment. The achieved deficits were reasonably close to the percentages specified at the outset.

Treatment	Irrigation (mm)	Effective rain (mm)	Irrig. + eff. rain (mm)	Deficit Timing
1 Control	937	184	1121	-
2 Control + 20	1131	184	1315	-
3 SDI 85	806	184	990	all season
4 SDI 70	694	184	878	all season
5 SDI 55	534	184	719	all season
6 RDI 85	836	184	1020	10/01/10 - 17/02/10
7 RDI 70	664	184	848	12/11/09 - 17/02/10
8 RDI 55	552	184	736	10/09/09 - 17/02/10

Table 1: Irrigation treatments, irrigation, effective rain, effective rain + irrigation and timing of deficit between 1 August 2009 and 30 June 2010.

3.2 Yield related variables

3.2.1 Kernel yield

The achieved kernel yield under the various treatments is depicted in Figure 4. The observed yield reductions were generally a reflection of the severity of the applied deficits over the season. Results suggest that reducing irrigation to 70% or less decreased kernel yield. Little difference in kernel yield was seen between the 70% and 55% deficits. There is a suggestion that biasing the deficit toward pre-harvest (RDI 70, imposed from 12 November) resulted in lower yield relative to a sustained deficit (SDI 70, imposed throughout the season). Reducing irrigation by 15% or less, regardless of the deficit strategy did not reduce yield relative to control trees. Applying additional irrigation in the 120 percent treatment did not result in further yield gain relative to the control trees.

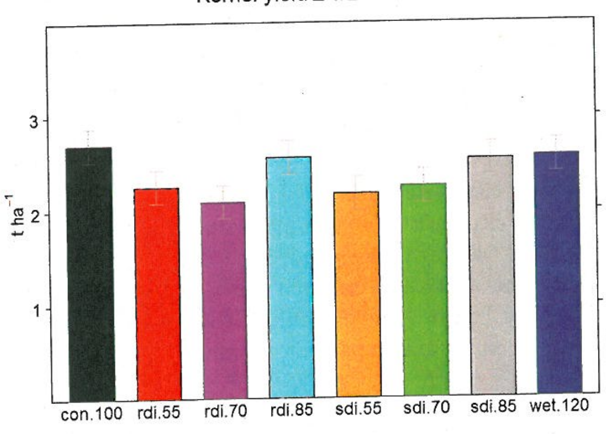

Figure 4: Kernel yield (t ha−1) for all irrigation treatments at the end of the 2009-2010 season. Vertical bars indicate ±1/2 least significant differences of means (5% level).

3.2.2 Dry matter accumulation

The accumulation of kernel dry matter during the first season (Figure 5) provided an indication at what stage in kernel development the various deficit treatments began to impact on kernel size and weight. During the early season, until late November kernels grew slowly, but thereafter their growth rate accelerated strongly and remained high until early in January when it began to decline and ceased just before harvest in mid February.

Initial effects of deficit irrigation treatments were seen early in December when kernel weight of RDI 55% first began to fall behind the other treatments. Deficit irrigation with both SDI 55% and RDI 55% resulted in significantly lower kernel weights, a reduction of around 12%, compared with kernels from control trees. Average kernel weight for SDI 70% and RDI 70% were also lower than kernel weights of control trees but differences were not statistically significant.

Kernel weights from either 55 or 70% deficits were consistently smaller when irrigated under RDI relative to SDI although these differences were not statistically significant. This may indicate trees under SDI better adapted to the imposed deficits than those under RDI where the onset of the deficits was more sudden.

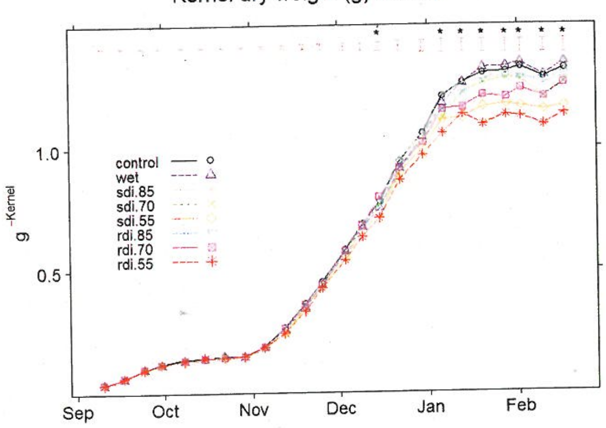

Figure 5: Dry matter accumulation for all irrigation treatments during the 2009-2010 season. Vertical bars indicate standard errors of means. The stars above the vertical bars indicate statistical significance (5% level).

3.2.3 Sticktights

The percentage of sticktights under the various treatments is depicted in Figure 6. Sticktights represent the proportion of fruit not removed by the harvest operation.

In the present experiment the percentage of sticktights was strongly influenced by the level of the applied deficits. The control and 120 percent treatments both increased the percentage of sticktights as compared to any of the deficit treatments.

Conversely, the more severe the applied deficits, the lower the number of sticktights counted on the trees. The observed gradient was possibly due to a heavier crop load in the more-watered treatments which in turn caused a delay in ripening and thus a greater proportion of sticktights.

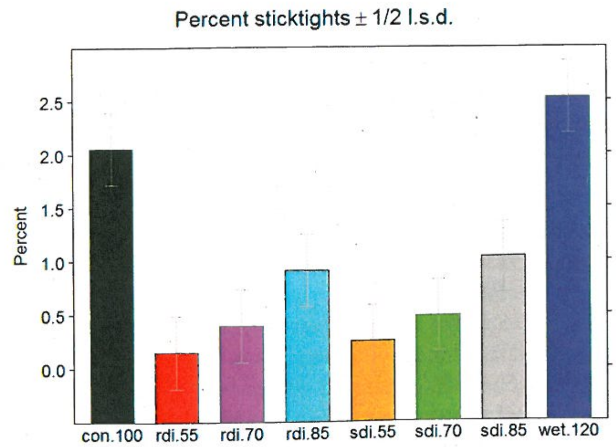

Figure 6: Percent sticktights for all irrigation treatments at the end of the 2009-2010 season. Vertical bars indicate 1/2 least significant differences of means (5% level).

3.3 Water relations

3.3.1 Midday stem water potential

Early in the irrigation season midday stem water potential for all treatments was high. As daytime temperatures and evaporative demand began to rise, the midday stem water potential of trees receiving deficit irrigation began to decline more than those of the control and 120 percent trees. The response to a heatwave in mid November (8 days above 38°C) can be clearly seen (Figure 7).

With the onset of high evaporative demand by mid December, midday stem water potential of the deficit irrigation treatments decreased in line with the imposed deficits but was more severe for trees receiving RDI than those with SDI, indicating that RDI trees were more severely water stressed. By early March, stem water potential of trees of all deficits treatments had recovered to levels seen for the control trees.

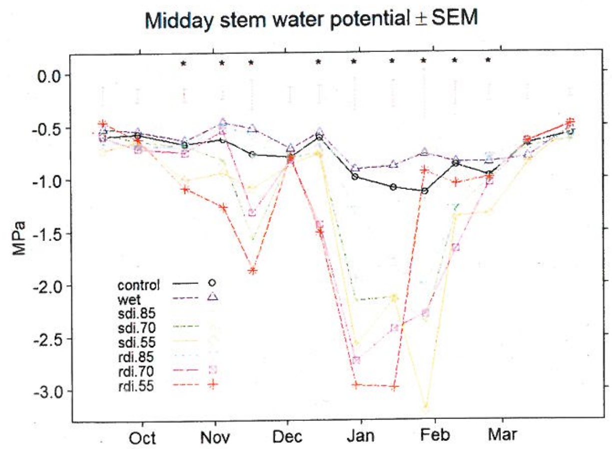

Figure 7: Midday stem water potential for all irrigation treatments during the 2009-2010 season at Lake Powell. Vertical bars indicate standard errors of the means. The stars above the vertical bars indicate statistical significance (5% level).

3.3.2 Stomatal conductance

Stomatal conductance (Figure 8) followed a similar course to that of midday stem water potential as seen in Figure 7. The level of stomatal conductance between measurement dates was more variable than that of midday stem water potential because it is more closely coupled with the evaporative demand of the atmosphere.

Differences between irrigation treatments became apparent in early November during a period of above average daily temperatures. Thereafter conductance recovered and increased to a maximum in early December but thereafter declined steadily until early February when trees were shaken. Differences seen between treatments are indicative of the imposed irrigation deficits. Stomatal conductance for SDI trees remained higher than for RDI trees during periods of peak evaporative demand. By early March, stomatal conductance of all trees had recovered to levels seen for the control trees.

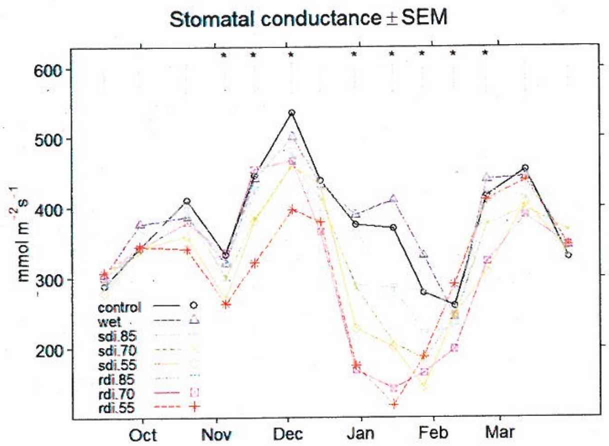

Figure 8: Stomatal conductance for all irrigation treatments during the 2009-2010 season at Lake Powell. Vertical bars indicate standard errors of the means. The stars above the vertical bars indicate statistical significance (5% level).

3.4 Light interception

Light interception readings were indicative of the size of the leaf canopy as the season progressed (see Figure 9 opposite page). The sudden rise in interception during September was due to rapid canopy fill in spring.

Differences between treatments were only apparent in late January when the 55% treatments experienced some stress-induced wilting and defoliation but trees had recovered by late February. Thereafter light interception for trees of all treatments declined and trees were largely defoliated by late April. Light interception values for the 55% treatment were consistently lower than the controls indicating a smaller leaf canopy but the differences were not statistically significant except on one occasion in mid January.

3.5 Trunk circumference

Trunk circumference was measured at the beginning (22/10/2009) and again at the end (21/05/2010) of the irrigation season. The difference between the two measurements is depicted in Figure 10 and provides a quantitative estimate of the seasonal trunk expansion as influenced by irrigation treatment.

Results suggest that reducing irrigation to 70% or less decreased trunk expansion (note, differences are not statistically significant if the grey error bars overlap). The indicator appears to closely reflect the cumulative deficit experienced by the trees to date.

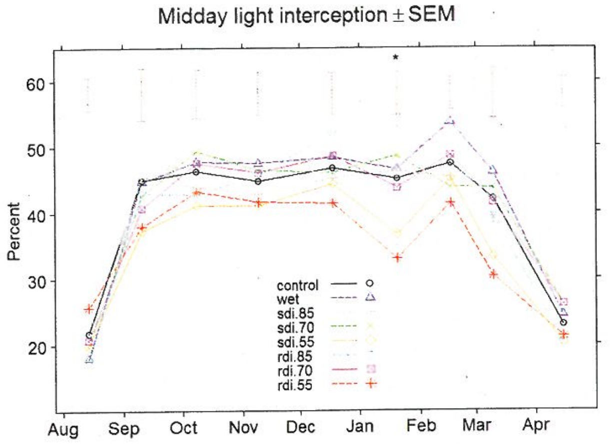

Figure 9: Light interception for all irrigation treatments during the 2009-2010 season at Lake Powell. Vertical bars indicate standard errors of the means. The stars above the vertical bars indicate statistical significance (5% level).

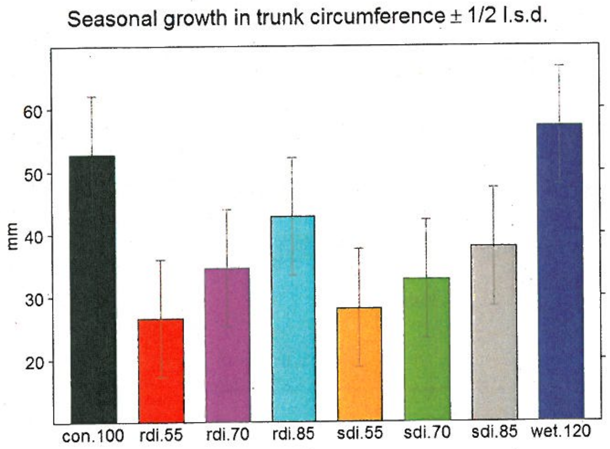

Figure 10: Growth in trunk circumference for all irrigation treatments measured between 22/10/2009 and 21/05/2010 at Lake Powell. Vertical bars indicate 1/2 least significant differences of means (5% level).

4. Conclusions

While only one year's data has been collected, the following observations were evident:

- Trees receiving SDI appeared to be adapting more readily to reduced water than those receiving RDI.
- Irrigating at 85% or more of normal practice had no negative impact on kernel size and yield.
- Irrigating at 70% or less decreased kernel yield regardless of strategy.
- Irrigating at 55% decreased kernel size and kernel yield.
- Trunk circumference was an accurate indicator of the accumulated seasonal water deficit.

Monitoring of the experiment will continue over coming seasons and should clarify the first seasons observations. Results will be used to develop firm guidelines for the sustainable minimum irrigation requirements of almond crops in Australia.

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Deficit irrigation strategies in almond during contrasting seasons

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Introduction

The background to this work was presented in the September 2010 issue of Australian Nutgrower together with results from the first season (2009-2010) (Sommer et al 2010). This article updates the trial's progress by adding the observations of the second trial season (2010-2011) which, compared with the previous season, was characterised by very different climatic conditions and results.

The work is a collaborative project between the Department of Primary Industries Victoria (DPI), the Almond Board of Australia (ABA) and Horticulture Australia (HAL) and aims to achieve the following objectives.

- Establish benchmarks for deficit irrigation of almonds under inland climatic conditions of Australia,
- Investigate the yield response to deficit irrigation,
- Establish minimum irrigation levels for almond production,
- Establish optimum timing to apply deficits, and
- Monitor the potential for deep drainage.

Methods

An abbreviated version of the experimental methods described in Sommer et al. (2010) is included here for clarification.

The research site was located near Lake Powell in north-west Victoria. It comprised 5.2 ha of almond trees that were planted in alternate rows in mid 2004 with the varieties Nonpareil and Carmel on Nemaguard rootstock. Three levels of deficit irrigation were applied in two patterns, either as sustained deficit irrigation (SDI), where the deficit was evenly applied throughout the irrigation cycle, or as regulated deficit irrigation (RDI). Deficit levels were 55, 70 and 85% of a fully irrigated control treatment, where the latter was equal to approx. 12 Ml/ha per season of irrigation and effective rainfall.

The design layout also comprised a "wet" treatment receiving 120% of the fully irrigated control with the aim to generate drainage beyond the root zone. Tree water use was estimated daily and was based on evaporation records from either a locally situated evaporation pan or a nearby weather station.

Hull and kernel development was monitored throughout the season. Trees were shaken commercially on 17 February 2010 and 2 March 2011. Nuts were left to dry on the ground until the hull moisture reached 14%, after approximately 9 days in 2010 and 16 days in 2011.

Midday light interception was measured every month using a Decagon AccuPAR LP-80 ceptometer. Leaf stomatal conductance and midday stem water potential (SWP) were monitored fortnightly between 15 September 2009 and 30 March 2010 and between 29 September 2010 and 1 March 2011.

Results

Irrigation summary

Table 1 gives a summary of the irrigation volumes, effective rainfall and timing of the irrigation treatments applied during both seasons. The totals of irrigation plus effective rainfall were 1121 mm or 11.2 Ml/ha for the first season and 1011 or 10.1 Ml/ha for the second season. The volume of irrigation applied across all treatments was considerably lower in the second compared with the first season because the evaporative demand was reduced as a result of more humid and frequently overcast weather conditions. The considerably lower irrigation volumes in the second relative to the first season, nevertheless failed to affect any notable plant water stress in the deficit irrigation treatments, and therefore also did not result in any production loss relative to well watered trees.

Yield related variables

Kernel yield

The average kernel yield of

Season	Treatment	Irrigation	Effective rain	Irrig. & eff. rain	ETo	Deficit
		mm	mm	mm	mm	Timing
2009-2010	1 Control	937	184	1121	1435	-
	2 Wet	1131	184	1315		-
	3 SDI 85	806	184	990		all season
	4 SDI 70	694	184	878		all season
	5 SDI 55	534	184	719		all season
	6 RDI 85	836	184	1020		10/01/10 - 17/02/10
	7 RDI 70	664	184	848		12/11/09 - 17/02/10
	8 RDI 55	552	184	736		10/09/09 - 17/02/10
2010-2011	1 Control	781	214	1011	1089	-
	2 Wet	933	214	1170		-
	3 SDI 85	677	214	906		all season
	4 SDI 70	578	214	807		all season
	5 SDI 55	476	214	706		all season
	6 RDI 85	668	214	900		10/01/11 - 2/03/11
	7 RDI 70	508	214	739		12/11/10 - 2/03/11
	8 RDI 55	488	214	719		10/09/10 - 2/03/11

Table 1: Seasonal irrigation, effective rain, effective rain and irrigation, and timing of deficit for the 2009-2010 and 2010-2011 seasons respectively between 1 August and 30 June.

2.39 t/ha−1 across all treatments after the first season was considerably higher than that of 1.65 t/ha−1 achieved after the second season (Figure 1). A number of factors contributed to this outcome. Firstly, the yield potential at the start of the second season was below average. Tree development was delayed due to persistently cool weather leading to poor conditions for successful pollination and nut set. Whole tree nut counts in an adjacent orchard had indicated a 30% reduction compared to an average season. This lighter than average crop combined with the persistently wet conditions, further reduced the effectiveness of the imposed deficits in causing tree water stress which was readily observed in the previous season. The wet conditions of 2010-2011 also delayed harvest and resulted in some hull rot infection which further contributed to a depression in yield.

Yield reductions relative to well watered control trees after the end of the first season (2009-2010) were a reflection of the severity of the applied irrigation deficits over the season. Reducing irrigation by 15% or less, regardless of the deficit strategy did not reduce yield relative to control trees.

In contrast, in the subsequent season of 2010-2011, the well watered, control and RDI 85 treatments had reduced yield relative to the RDI 70. This suggests that applying irrigation deficits during the 'wet' 2010-2011 season increased yield relative to the well watered treatments.

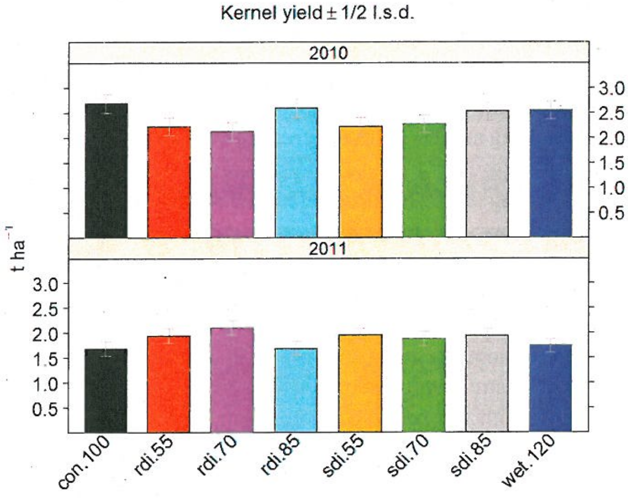

Figure 1: Kernel yield (t/ha−1) for all irrigation treatments at the end of the 2009-2010 and 2010-2011 seasons. Vertical bars indicate +/- 1/2 least significant differences of means (5% level)

Dry matter accumulation

In the first season, initial effects of deficit irrigation treatments on kernel weight were seen early in December and resulted in a 12% reduction of both SDI and RDI 55% treatments compared with kernels from control trees (Fig.2).

Below average temperatures delayed kernel growth and development by up to 3 weeks in the second relative to the first season of the experiment. No differences in kernel dry matter were seen throughout the second season of the experiment. This lack in response to deficit irrigation was due to frequent and heavy rainfall from late November to early March negating any effects of the deficit irrigation treatments imposed on the orchard.

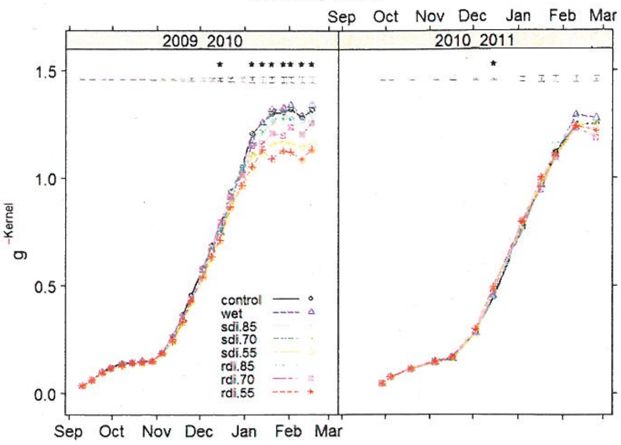

Figure 2: Dry matter accumulation for all irrigation treatments during the 2009-2010 and 2010-2011 seasons. Vertical bars indicate standard errors of means. The stars above the vertical bars indicate statistical significance (5% level)

Sticktights

Sticktights represent the proportion of fruit not removed by the harvest operation (Figure 3). In the first season the percentage of sticktights was negatively correlated with the level of the applied deficits (Sommer et al. 2010). No difference in the percentage of sticktights was seen in the second season suggesting that deficits were insufficient to cause differences and less severe than in the previous season. More sticktights were seen in the second than first season regardless of treatment, and probably resulted from the much wetter second season.

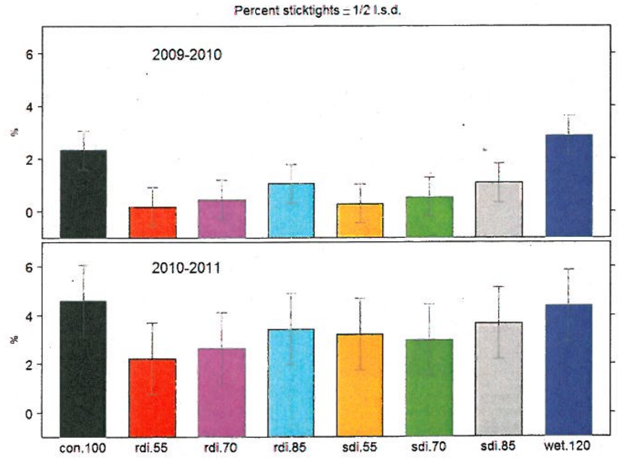

Figure 3: Percent sticktights for all irrigation treatments at the end of the 2009-2010 and 2010-2011 season. Vertical bars indicate +/- 1/2 least significant differences of means (5% level).

Water relations

Midday stem water potential

Midday stem water potential (SWP) is an accurate indicator of plant water stress (Figure 4). In line with the imposed deficits, trees in the first season underwent quite severe stress between mid December and the end of January (Sommer et al 2010). In contrast during the subsequent season, stress was infrequent and never severe because of repeated heavy rainfall from early December through to the end of February. The course of SWP in the both seasons illustrates the strong influence a variable climate may exert on tree physiology and water status.

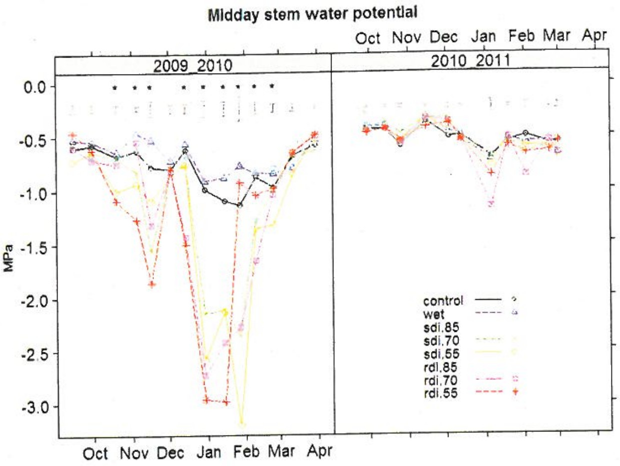

Figure 4: Midday stem water potential for all irrigation treatments during the 2009-2010 and 2010-2011 seasons at Lake Powell. Vertical bars indicate standard errors of the means. The stars above the vertical bars indicate statistical significance (5% level).

Light interception

Light interception is indicative of the seasonal course of tree leaf area (Figure 5). The first season saw a difference between treatments when in late January of 2010 the 55% treatments resulted in stress-induced wilting and partial defoliation but trees had recovered by late February. In the subsequent season the tree canopy filled in later because of below average temperatures but intercepted more light for the remainder of the season, irrespective of treatment. Trees also retained their leaves for longer than in the first season but deficit irrigation did not influence interception.

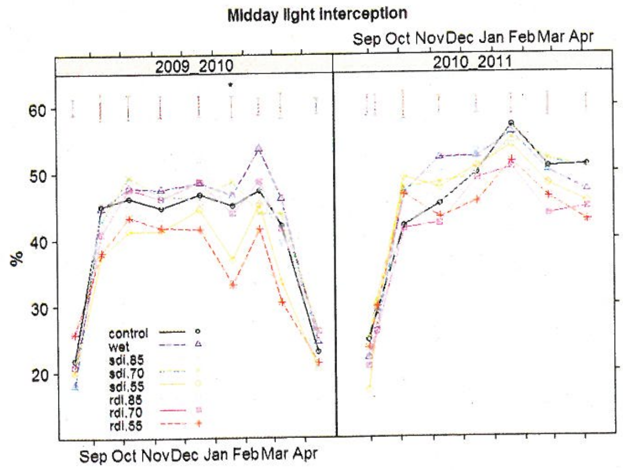

Figure 5: Influence of irrigation treatments on midday light interception during the 2009-2010 and 2010-2011 seasons at Lake Powell. Vertical bars indicate one standard error of the mean. The stars above the vertical bars indicate statistical significance (5% level).

Trunk circumference

Deficit irrigation (70% or less) decreased seasonal growth in trunk circumference in 2009-2010 but no differences were apparent in 2010-2011 probably because tree deficits were mild and infrequent compared with the preceding season (Figure 6). Trunk growth appears to closely reflect the cumulative deficit experienced by the trees to date.

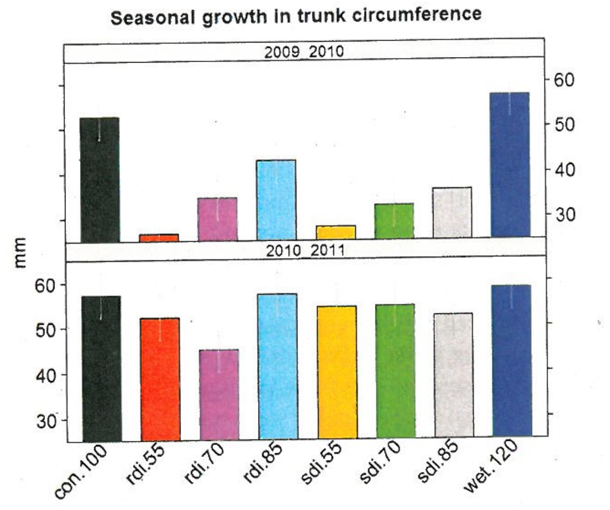

Figure 6: Influence of irrigation treatments on the seasonal growth in trunk circumference assessed between 22/10/2009 and 21/05/2010 in the 2009-2010 and between 21/05/2010 and 27/04/2011 in the 2010-2011 season at Lake Powell. Vertical bars indicate ±1/2 least significant differences of means (5% level).

Conclusions

A number of trends were seen at the end of the first season after initiating the experiment.

- Trees receiving SDI appeared to be adapting more readily to reduced water than those receiving RDI.
- Irrigating at 85% or more had no negative impact on kernel size and yield.
- Irrigating at 70% or less decreased kernel yield regardless of strategy.
- Irrigating at 55% decreased kernel size and kernel yield.
- Trunk circumference was an accurate indicator of the accumulated seasonal water deficit.

The only statistically significant difference observed in the subsequent season was a lower kernel yield in the well watered treatments (control 100% and wet 120%) relative to RDI 70% but not relative to the other treatments. None of the other variables monitored throughout the second season showed any differences. Factors contributing to this outcome were as follows:

- Delayed onset of the season due to cold weather.
- Unfavourable weather during pollination leading to poor nut set.
- Persistently wet and humid weather with frequent and heavy rain.
- Delayed harvest and hull rot infection.

Monitoring of the experiment will continue over the coming season and will be essential to clarify if the initially observed trends continue in a hopefully more representative season than the one just experienced. Results will be used to develop firm guidelines for sustainable minimum irrigation requirements in almond in Australia.

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