Impact of strategic deficit irrigation for almonds on tree phenology, bloom, nut set and hull rot

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Final Project Report

HAL AL12010 August 2014

Karl J Sommer and Dave Monks

Department of Environment and Primary Industries

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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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August 2014

Contents

List of Figures

List of Tables

Media Summary

Economic success of the Australian almond industry increasingly depends on the adoption of strategies that ensure the most effective and efficient use of irrigation water including strategies of deficit irrigation.

Prior to this work there was little or no local information on the potential for irrigating almonds under moderate to low irrigation volumes including various strategies of deficit irrigation.

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

A field experiment was established in a commercial orchard. Eight irrigation treatments were compared; full irrigated control (100%) and three levels of deficit irrigation (55, 70 and 85%) applied as regulated (RDI) or sustained (SDI) deficits and a high irrigation level (120%).

Initially the project focused on the impact of deficit irrigation on annual production but after three seasons widened its scope to include yield components like pollination effectiveness, fruit set and spur growth.

Overall, the experiment concluded that irrigation with a moderate deficit of 85% or more of 100% ET_c has good potential to alleviate water shortages without loss of production. Specifically, results showed:

- 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.
- In seasons with above average rainfall, deficit irrigation mitigated infection with hull rot in line with the level of deficit.
- Water deficits had a stimulating effect on fruit set.
- Water deficits had no impact on the timing of flowering or fruit set but tended to accelerate hull split in line with the level of deficit.
- Water deficits showed a trend toward increasing the proportion of flowers and fruit per spur in line with the applied level of deficit.

Technical Summary

Lack of water in conjunction with a variable and unreliable water supply is one of the biggest challenges to the viability and sustainability of the $2.4 billion Victorian horticultural industry. The almond industry has recognised that its future success will increasingly depend on strategies that ensure the most effective and efficient use of irrigation water and therefore has, in collaboration with The Victorian Department of Environment and Primary Industries, initiated a research project toward the following objectives:

- Determine minimum levels of irrigation to maintain productivity and crop survival.
- Develop irrigation strategies with the potential to make industries more resilient in the face of an increasingly variable water supply.

An experimental site was established in June 2009 at Lake Powell near Robinvale, Victoria. Five levels of irrigation were tested: a fully irrigated control (100%), three levels of deficit irrigation (55, 70 and 85%) applied as regulated (RDI) or sustained (SDI) deficits and a high irrigation level (120%). Full irrigation (100%; control) was defined as the level of irrigation that meets plant water requirement (i.e. non-stressed crop evapotranspiration, ET_c) and was estimated according to the standard protocol developed by the Almond Board of Australia. The five year average estimate of the water requirement of control trees was 12.4 Ml/ha, ranging between 11-14 Ml/ha. The impact of the different irrigation strategies on agronomic performance and tree physiology were investigated and key agronomic and physiological variables were monitored throughout the growth period.

The study concluded that irrigating at 85% or more of full irrigation, which represents a moderate deficit, has good potential to alleviate water shortages without loss of production. Specifically the results showed:

- Irrigating at 85% or more of full irrigation had no negative impact on kernel size and yield but irrigating at 70% or less decreased kernel yield regardless of strategy.
- 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.
- Deficit irrigation had a stimulating effect on fruit set and there was a positive correlation between set and the level of deficit. However, the higher set possibly was compensation for a lower flower number in water deficient relative to control trees.
- Water deficits had no impact on the timing of flowering or fruit set but tended to accelerate hull split in line with the level of deficit.
- Annual increase in stem circumference was the most accurate indicator of the cumulative effect of irrigation deficit on tree growth.

Introduction

This report for the main part summarises the results of two additional seasons of a field experiment carried out in a previous project (see report AL08009, Sommer, 2012). It should therefore be read in conjunction with previously reported results.

Information was lacking on the potential for irrigating almonds under moderate to low irrigation volumes and with variable irrigation strategies such as deficit irrigation.

To address this shortcoming a field experiment was established to explore the potential for deficit irrigation of almond orchards. The work aimed 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

In the final two seasons, in addition to the objectives of the previous work, there was a focus on the impact of deficit irrigation on other important yield components including pollination effectiveness, flowering, fruit set, hull split and impacts on hull rot. In the final season the project also included a pilot study on spur growth. Spurs are considered an important yield component (Heerema et al., 2008) that strongly interacts with environmental and management factors (Tombesi et al., 2011). An understanding of their growth dynamics is therefore essential to achieve consistent production.

The report will present results of the additional seasons against the stated objectives and will discuss outcomes. To maintain continuity between the current and previous work results will include the entire five year period from 2009-2010 to 2013-2014 of the field experiment.

Materials and methods

Site

The research site was located near Lake Powell in north west Victoria (-34.706° S, 142.874° E), 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. 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).

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 and the position of each soil survey pit is shown in the map depicted in Figure 1 on page 8. The survey included an estimate of the root zone readily available soil water (RAW) which is defined

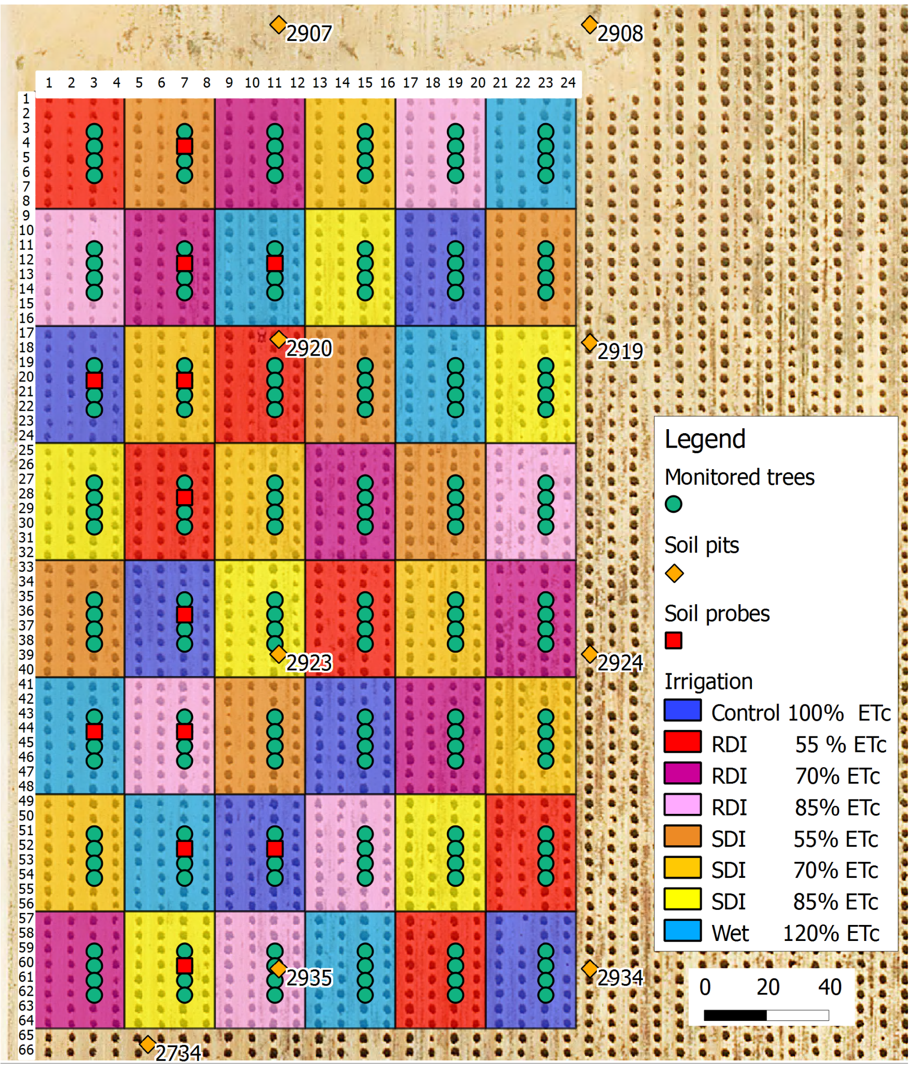

Figure 1: Experimental layout of irrigation treatments at Lake Powell including positions of monitored trees, soil moisture probes, soil survey pits; the numbers next to the survey pit locations correspond to those given in Table 1 on page 9.

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.

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 irriga-

Table 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

tion (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 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 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 on page 10. 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.

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

Table 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

ment was met. Each irrigation treatment was equipped with a flow meter and applied volumes were recorded daily.

For the remainder of the trial period 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 2 and 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). For further detail regarding the irrigation treatments see also HAL report AL08009 (Sommer, 2012).

$$ET_c = C_f \times E_{pan} \tag{1}$$

$$ET_c = C_f \times 1/K_{pan} \times ET_o \tag{2}$$

$$ET_c = K_c \times ET_o \tag{3}$$

Soil moisture monitoring

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 on page 8. 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. 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.

Table 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

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 on page 8). 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 (see Figure 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).

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 *1:0.13:1.25*, with rates of approximately 320, 40 and 400 kg/ha/season respectively.

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 4 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 harvested with a commercial shaker on 17 February 2010 (1st season), on 2 March 2011 (2nd season), on 15 February 2012 (3rd season), on 20 February 2013 (4th season) and on 12 February 2014 (5th season). Prior to shaking, irrigation was withdrawn for 2 days to

Figure 2: Light interception measurement using a ceptometer.

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, 16 days in 2011, 7 days in 2012, 5 days in 2013 and 12 days in 2014. 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 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, between 14 October 2011 and 1 March 2012, between 2 October 2012 and 20 March 2013 and between 2 October 2013 and 11 March 2014. g_s was measured using a leaf porometer (Decagon®, model SC-1; see Figure 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.

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 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.

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 of the 2010-2011, on 17/04/2012 of the 2011-2012, on 22/04/2013 of the 2012-2013 and on 30/04/2014 of the 2013-2014 seasons.

Figure 3: Stomatal conductance (g_s) measurement using a Decagon leaf porometer.

Measurements were recorded from the four central trees of each plot at a distance of 40 cm from the soil surface and were averaged for each plot before conducting the statistical analysis. On the first sampling occasion the circumference of each recorded tree was marked with white paint for easy identification on subsequent recordings. Seasonal trunk growth was calculated from the difference between the trunk circumference recorded at the end of each season.

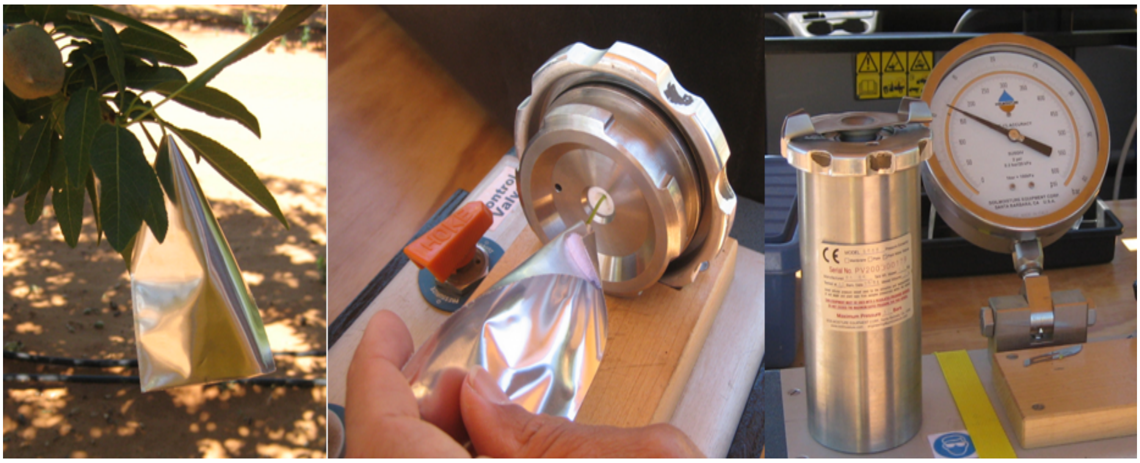

Figure 4: Pressure bomb assembly to measure stem water potential.

Pollination and fruit set

This work aimed to assess the inter-seasonal impact of water deficits on the course of flowering and on pollination effectiveness and fruit set. Selected shoots were hand pollinated and their subsequent fruit set was compared to bee pollinated shoots. In the spring of 2012, before flowering, 2 branches per plot in close proximity to each other, each being around 300 flowers, were selected and their flowers were counted before they opened. One of each pair of the selected branches was hand pollinated while the other was bee pollinated. Fruit number on each branch was counted on 17 Sep. and was recounted on 7 Nov to determine the percentage of fruit set on the basis of the flower number of each shoot. Analysis of variance was conducted to assess treatment differences.

Spur observations

Tagging

Four irrigation treatments were selected for tagging in late July 2013. Treatments included the control and each of the 3 sustained deficit irrigation treatments (SDI 55, 70 and 85%). Each of the four centre trees of 6 replicate treatment plots were selected. Each tree was divided into four quarters of the compass and six spurs per quarter were tagged resulting in a total of 2304 tagged spurs. It took 8 person days to select and attach the tags (approx. 32 orchard hours). Each tag consisted of a bar code laminated in plastic and was attached around the shoot just below the selected spur by copper wire.

Barcode tags were made using the Bartender program, printed on Avery L7156GU labels and laminated with 80 μm laminating pouches. Tags were attached to spurs with 20 cm of 0.71 mm diameter copper wire sourced from Murray Valley Electrics.

Data collection

The number of floral and vegetative buds was recorded at flowering. This took 2 people 3 days. The number of leaves, the length of the longest leaf and the number of fruit per spur were determined in the months of November to December. Because there was insufficient time to complete the task, measurements were only collected from 4 instead of 6 replicates.

Issues with the hand held barcode readers resulted in loss of some of the leaf and nutset data. Each spur was re-assessed for the number of flowers (return bloom) in June and July 2014. Dead spurs were noted.

Results and discussion

The following section describes the main findings after five seasons (2009-2010 to 2013-2014) of imposing the experimental treatments and briefly summarises and discusses the results in the light of other research.

Irrigation summary

Table 4 gives a summary of the irrigation volumes, effective rainfall and timing of the irrigation treatments applied during the five seasons. The volume of applied irrigation varied considerably between seaons. On average it was lowest in the second season because the evaporative demand was reduced as a result of persistently humid and overcast weather with frequent, often heavy rainfall. Higher average volumes were applied in the fourth and fifth season. Reasons were a relatively higher evaporative demand and higher crop factor to adjust for an increase in canopy size. In addition, during December and January of the 2012-2013 season reference crop evaporation (ET_o) values used for irrigation scheduling of the trial were significantly higher than comparative values obtained from the Bureau of Meteorology (data not presented). The discrepancy was not noted at the time but all treatments received more irrigation than required during the months of December to early February probably due to an overestimation of ET_o by the Lower Murray Water (LMW) weather station located nearby at Lake Powell and Boundary Bend.

The situation had improved in the 2013-2014 season although there was still a tendency toward higher estimates by the LMW station relative to comparable records from the BoM (Bureau of Meteorology) particularly in mid-season. The reasons for the discrepancy are not clear. The weather stations of the LMW network were provisioned by MEA, an engineering company based in Adelaide, specializing in soil and climatic measurements. Their weather stations' ET_o calculations are based on the "ASCE-standardized Penman-Monteith" method (ASCE-EWRI, 2005). It provides estimates for two reference crops, a short crop, equivalent to a clipped-grass 0.12 m high and a tall crop, similar to a full cover alfalfa 0.5 m high. The short crop reference is equivalent to ET_o estimates based on "FAO-56 Penman-Monteith method" (Allen et al., 1998). Some of the observed differences are possibly attributable to differences in the calculation methods, but are more likely related to sensor calibration and maintenance. Neither DEPI nor Select Harvests have any direct access to the weather stations apart from the publicly accessible data downloads of daily weather data including ET_o estimates.

The issue is of concern to the irrigation industry because many irrigators along the Murray River rely on data provided by the LMW network of automatic weather stations. The current experience highlights the importance of maintaining the automatic weather stations to a similar standard as those of the Bureau of Meteorology in order to ensure reliable and consistent operation.

Table 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
2012-2013	1 Control	1549	231	52	1601	1582	1755	–
	2 Wet	1777	231	52	1829	1899		–
	3 SDI 85	1333	231	52	1386	1343		all season
	4 SDI 70	1111	231	52	1163	1106		all season
	5 SDI 55	887	231	52	939	868		all season
	6 RDI 85	1348	231	52	1400	1368		10/01/13 - 17/02/13
	7 RDI 70	1061	231	52	1113	1051		12/11/12 - 17/02/13
	8 RDI 55	914	231	52	967	902		10/09/12 - 17/02/13
2013-2014	1 Control	1375	126	97	1408	1438	1554	–
	2 Wet	1626	126	97	1659	1724		–
	3 SDI 85	1165	126	97	1199	1223		all season
	4 SDI 70	952	126	97	985	1005		all season
	5 SDI 55	737	126	97	770	789		all season
	6 RDI 85	1184	126	97	1217	1249		10/01/14 - 17/02/14
	7 RDI 70	950	126	97	984	1012		12/11/13 - 17/02/14
	8 RDI 55	776	126	97	810	832		10/09/13 - 17/02/14

Water relations

Midday stem water potential

Midday stem water potential (Ψ_w) was used as the indicator of tree stress. In the first season, Ψ_w approached -3.0 and -3.2 MPa in the RDI 55% and SDI 55% treatments, respectively. The second season (2010-2011) was much milder with frequent rains, Ψ_w therefore never dropped below -1.2 MPa. In 2011-2012, Ψ_w was more in line with observations made in the first season approaching -2.5 MPa and -2.0 MPa in the RDI 55% and SDI 55% treatments, respectively. Despite an early onset of stress in 2012-2013, especially with SDI 55%, there was little treatment response in mid-season, extending well into February, when trees under SDI 55 and 70% showed mild stress. In 2013-2104 mild levels of stress were apparent in December and early January but thereafter all trees, except the control, wet and SDI 85% reached significant levels of stress below -2.0 MPa. RDI 70 and 85% were more severely stressed than SDI treatments.

Ψ_w was a sensitive indicator of the stress imposed by the irrigation deficits. Under SDI trees were 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 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 severe plant water stress and may explain why Goldhamer et al. (2006) saw similar stress levels using either SDI or RDI strategies.

A lack of stress response in the fourth season was mostly attributable to excessive irrigation rates applied during the months of January and February when all treatment received higher rates than required due to excessive reference crop ET_o estimates obtained from a nearby automatic weather station.

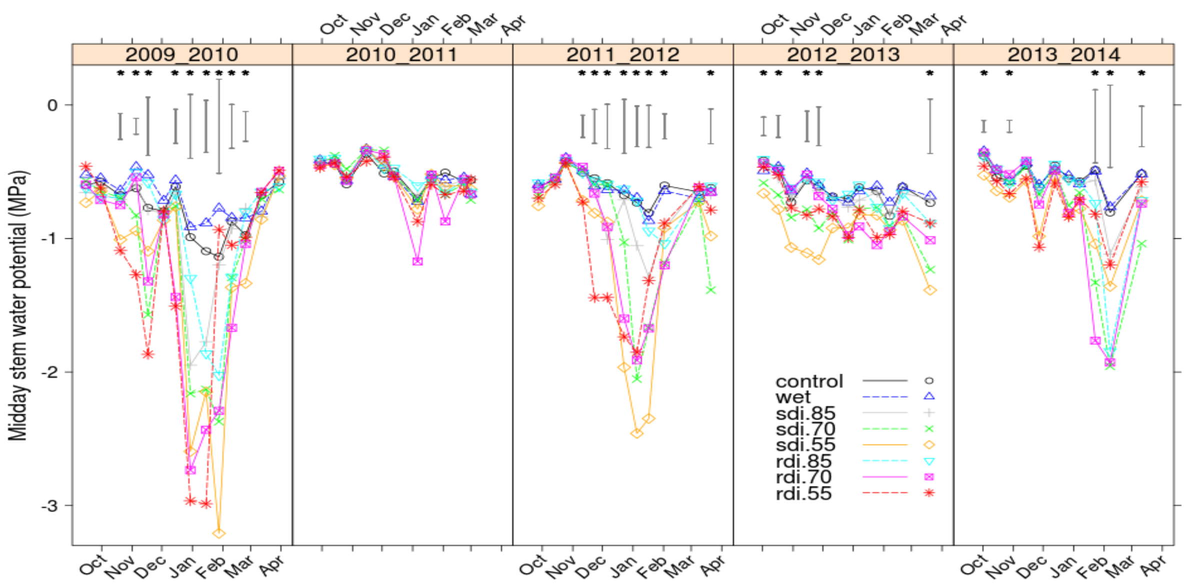

Figure 5: Ψ_w potential of irrigation treatments during the respective seasons of 2009-2010 to 2013-2014 at Lake Powell. Vertical bars indicate least significant difference between treatment means. The stars above the vertical bars indicate statistical significance (5% level).

Stomatal conductance (g_s)

Stomatal conductance (g_s) is an indication of the degree of opening of the leaf stomata which mediate the exchange of water vapour and carbon dioxide between the leaf interior and the atmosphere. Its seasonal course (Figure 6) was similar to that of Ψ_{pd} (see Figure 5 with low values indicating stomatal closure due to water stress.

Differences in most seasons were indicative of the imposed irrigation deficits especially in seasons 2009-2010; 2011-2012 and 2013-2014. In many instances g_s for SDI trees remained higher than for RDI trees during periods of peak evaporative demand. Little stress response due to irrigation treatment was apparent in seasons 2010-2011 and 2012-2013 and was mostly due to the same reasons outlined earlier for stem water potential.

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 periods of severe water stress throughout December and the beginning of January. SDI and RDI 55% and also RDI 70% temporarily 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, 2011-2012 and to a lesser extent in the 2013-2014 seasons. Not so the RDI nor SDI 85% whose g_s did not deviate much from that of control trees (100%).

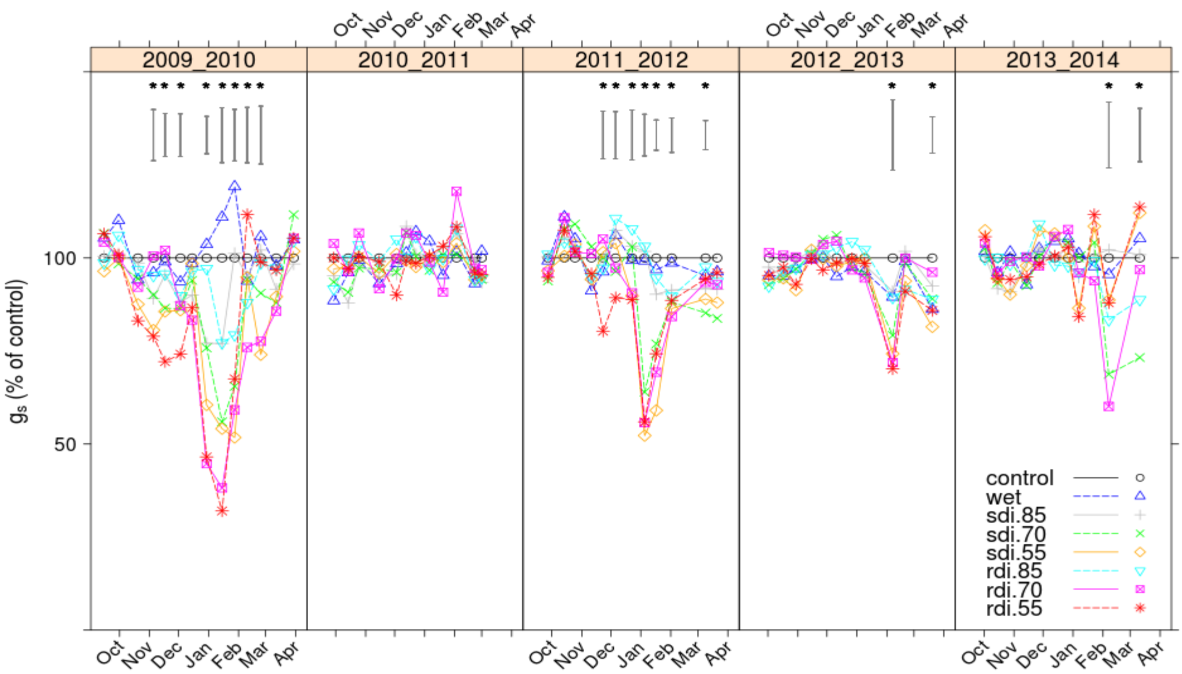

Figure 6: Influence of irrigation treatments on g_s during the respective seasons of 2009-2010 to 2013-2014 at Lake Powell. Vertical bars represent least significant difference between treatment means. The stars above the vertical bars indicate statistical significance (5% level).

Yield related variables

Dry matter accumulation

Kernel dry matter The seasonal accumulation of kernel dry matter is shown in Figure 7. Seasonal differences show a strong treatment response in the 2009-2010, 2011-2012 and 2013-2014 seasons leading to significantly lower kernel weight for both SDI and RDI 55% compared with kernels from control trees.

Persistently wet weather negated any effects of the deficit irrigation treatments imposed on the orchard in the 2010-2011 season and no treatment response was apparent throughout the season.

In 2012-2013 the average kernel weight regardless of treatment was around 30% smaller than in any other season. The decline in kernel growth relative to previous seasons was probably due to a high set and nut number but was also strongly exacerbated by a lack in nutrient supply early in the seasons due to a management error.

In the final season (2013-2014) kernel growth and dry matter were much larger than in any previous season except for SDI and RDI 55%. The large increase was mostly due to a lower fruit and kernel number per tree relative to previous years and hence greater partitioning of dry matter toward each kernel except for SDI and RDI 55% where water stress compromised kernel growth early in season.

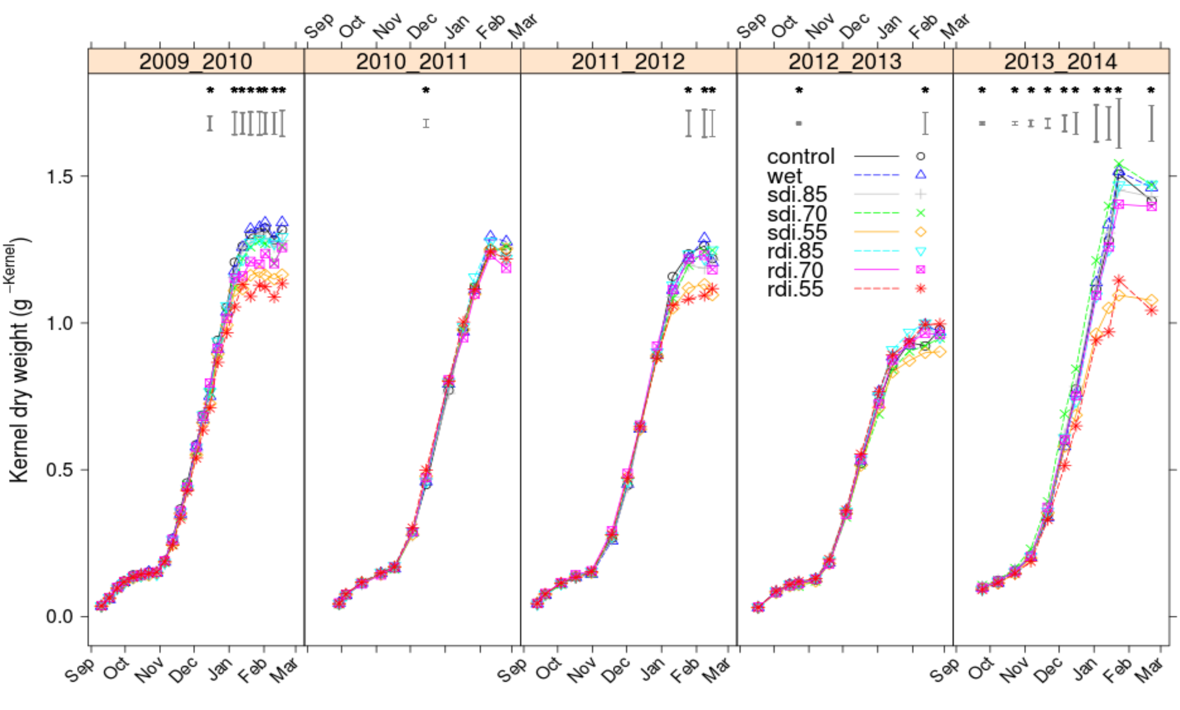

Figure 7: Kernel dry matter accumulation for all irrigation treatments during the respective seasons of 2009-2010 to 2013-2014 at Lake Powell. Vertical bars indicate least significant difference between treatment means. Stars above bars indicate statistical significance (5% level).

Generally, a reduction in kernel growth correlated with the imposed stress levels. RDI tended to reduce kernel growth more than SDI, particularly for irrigation volumes below 70%. Many of the observed patterns 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 application 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.

Hull and shell dry matter Dry matter accumulation of the hull and shell over 5 seasons is depicted in Figure 8. Unlike the kernel, most of the hull and shell dry matter was accumulated well before any significant kernel growth was apparent and its maximum dry matter was mostly reached before that of the kernels.

No treatment related 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 when fruit from trees grown with deficits of 70% and below appeared to grow heavier hulls and shells than control and even "wet" trees, although these differences had largely disappeared just prior to harvest. In 2012-2013 hull and shell dry matter was much lower than in previous years and growth rates also had dropped off much sooner. The 55% RDI had the highest growth rates while those of 55 and 70% SDI where lagging behind. In the final season (2013-2014) the overall growth rate was considerably larger than in any previous season. The large increase was mostly due to a much lower fruit number per tree relative to previous years. As a result, a higher proportion of the available dry matter per tree was partitioned toward each fruit resulting in significantly larger fruit and kernel weights. Dry weights were highest for RDI 85% a reversal from the previous seasons and probably an indication of differences in fruit number rather than growth rates.

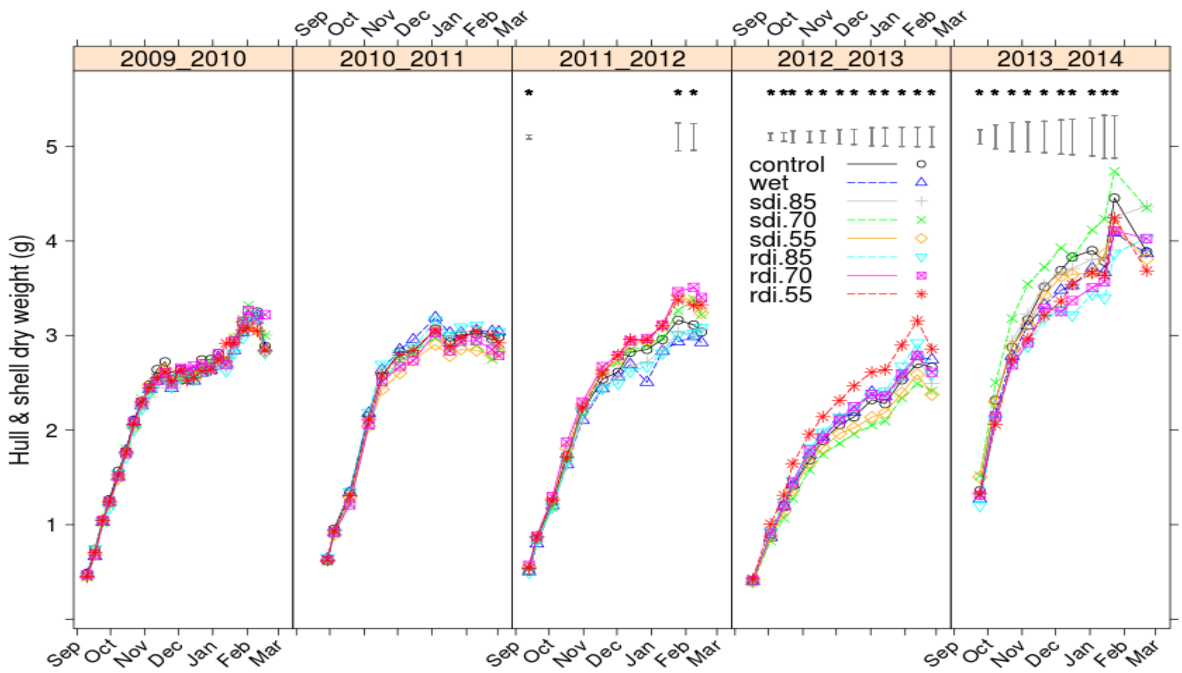

Figure 8: Hull and shell dry matter accumulation for all irrigation treatments during the respective seasons between 2009-2010 and 2013-2014. Vertical bars indicate least significant difference between treatment means. The stars above the vertical bars indicate statistical significance (5% level).

The significant drop in hull and shell dry matter in 2012-2013 was most probably caused by a lack of nutrient supply early in the seasons. The lack of sufficient nutrients in combination with a high fruit number per tree severely compromised fruit and kernel growth and most probably also interfered with flower initiation in late summer, further contributing to a depression in flower and fruit number in 2013-2014. It is therefore difficult to interpret the influence of the water deficit treatments for the final two seasons. Much of the differences appear to be related to fruit number per tree rather than a direct influence of the deficit treatments given that there was little treatment effect on hull and shell dry matter in the first three growing seasons.

Deficit irrigation clearly affected dry matter accumulation of hull and shell to a much lesser extent than that of the kernel. Goldhamer et al. (2006) also 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.

Kernel yield

The kernel yields achieved for each treatment after five seasons of investigation are depicted in Figure 9. Yield reductions relative to well watered control trees in most seasons were in line with the severity of the applied irrigation deficits.

Reducing irrigation to 70% or less decreased kernel yield in 2009-2010 but little difference was seen between the 70% and 55% deficits. Biasing the deficit toward pre-harvest (RDI 70%), imposed from 12 November, resulted in lower yield relative to a sustained deficit (SDI 70%) 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 (120% irrigation did not result in further yield gain relative to the control trees.

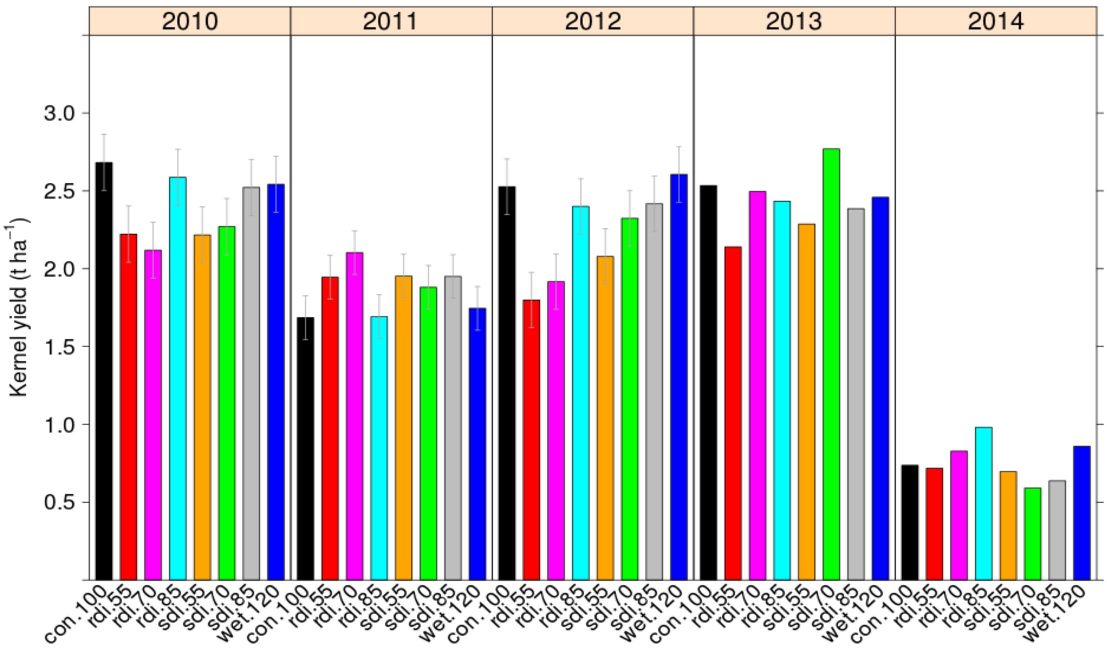

Figure 9: Kernel yield (t ha^{-1}) for all irrigation treatments at the end of the respective seasons between 2009-2010 and 2013-2014. Vertical bars indicate least significant difference between treatment means (5% level). No bars indicate lack of statistical significance.

No yield differences between irrigation treatments were discernible in 2010-2011. A lighter than average crop combined with persistently wet weather reduced the effectiveness of the imposed deficits. Wet weather also delayed harvest resulting in some hull rot infection which contributed to a further 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 yield 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.

Kernel yield in 2012-2013 was similar to the previous season but treatment differences were less apparent with no differences seen for deficits equal to 70% and above regardless of strategy. The lack of response was probably due to a relatively high nut set and nut number per tree combined with excessive irrigation in the months of January and February.

In the 2013-2014 seasons kernel yield collapsed, dropping to around 40% of that of previous seasons. There were no apparent treatment differences suggesting all trees, regardless of treatment, were affected by the depression (Figure 9). The observation is consistent with the decline in trunk expansion seen at the end of the previous season (Figures 13 and 14) Both observations were symptomatic of a weakening tree, causing a depressed flower initiation in summer and below average flower and fruit number in the following spring. Above average yields in the previous season combined with a lack of sufficient nutrients supplied in spring of that season were the main factors contributing to the depression in kernel yield.

Average yields over 5 seasons suggest no statistically significant differences between irrigation treatments. Unfortunately, results obtained for the final two seasons were atypical because insufficient fertiliser was applied in the spring of 2012-2013. This management error most likely compromised the yield potential of trees of all treatments but probably prevented those well supplied watering regimes (RDI, SDI 85%, Control and Wet) from reaching their full yield potential. Unfortunately this potential yield penalty could not be quantified by comparison to non-fertilised interrupted trees More importantly, the error most likely compromised the subsequent season's cropping potential and severely depressed yield regardless of treatment. It is therefore difficult to draw firm conclusions based on average results across all seasons.

The first and third season probably most accurately reflected the impact of strategic deficit irrigation in a average season in Sunraysia. The results suggest that irrigation deficits equal to or above 85% applied as either SDI or RDI had no negative impact on production while deficits equal to or below 70% are likely to depress kernel yield and kernel size. The observations agree with (Goldhamer et al., 2006) who suggested that pre-harvest RDI stress patterns had a more negative impact on kernel yield than from stress being applied through the season.

Conversely, in a wet seasons, deficit irrigation equal to or below 70% conferred an advantage because trees suffered a lower incidence of hull rot relative to those treatments receiving a higher irrigation volume.

Other yield components

Table 5 on page 24 lists the main yield components recorded in every season shortly before harvest. Results confirm the sensitive response of kernel dry weight to deficit irrigation seen in Figure 7. SDI and RDI 55% in most seasons significantly reduced kernel dry weight relative to control trees but deficits of 70% and less, regardless of strategy, did not. Neither fruit fresh weight or fruit dry weight (kernel+hull+shell) were affected as much by the deficit irrigation as kernel yield. A similar result was evident for the percentage of kernel per nut, either as fresh or dry weigh. The proportion of kernel per nut correlated with the imposed deficits and clearly was a more sensitive indicator of the imposed deficits than kernel dry weight alone. Results also confirm an earlier observation that hull and shell dry matter are not nearly as much affected by deficits as the kernel dry matter because a large proportion of the former is grown early during the growth cycle before any irrigation deficits become effective. Consequently, not even the most severe irrigation deficits did cause any statistically significant reduction in average dry weight per fruit.

Table 6 on page 25 includes further yield components recorded at the end of each season. Fruit or nut load per tree is an indicator of cropping potential and pollination effectiveness. Although there were big differences between seasons, fruit load within season did not strongly respond to the treatments. An exception was the wet season of 2010-2012 when control (100%) and wet (120%) trees had a lower fruit load than RDI 70% and 55% indicating a positive influence of deficit irrigation on fruit load. The yield depression seen for the 2013-2014 season was mostly attributable to a collapse in fruit load which on average was less than 1/3 of other seasons and points to the possibility that fruit bud initiation and subsequently flower number were severely compromised at the end of the 2012-2013 season due to insufficient application of nutrients.

Vegetative growth and fruiting density

The shaded area per tree is an indicator of the magnitude of vegetative growth and was calculated from the seasonal average of light interception readings between mid September and mid March (Sommer, 2012). The shaded area per tree was negatively correlated with deficit level but only the most severe deficits of 55% led to consistently and significantly smaller trees after five seasons. The more severe deficits (50 and 70%) had a greater effect when applied as RDI than an SDI strategy; on average, across all seasons, the the size of RDI 55% trees was 17% smaller than control and 21% smaller than 'wet' trees while the shaded area of the equivalent SDI 55% were respectively 12% and 16% smaller.

The shaded area was used to calculate a fruiting density per tree by dividing the fruit number per tree by the shaded area per tree. Results in Table 6 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. A pollination study (see section 'Pollination' on page 31) carried out in 2012-2013 indicated that greater deficits were positively correlated with the percentage of fruit set. 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 by inhibiting fruit bud initiation and consequently flower number.

Table 5: Fresh and dry weight per kernel, fresh and dry weight per fruit and fresh and dry kernel per nut (percent) for the respective seasons between 2009-2010 and 2013-2014 and averages across all seasons; columns followed by the same letter of 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}
2012-2013	1 Control	1.00	0.98	3.78_{abc}	3.64_{abc}	26.4	26.9
	2 Wet	0.99	0.97	3.86_{ab}	3.71_{ab}	25.6	26.1
	3 SDI 85	0.97	0.95	3.57_{cde}	3.45_{cde}	27.1	27.6
	4 SDI 70	0.97	0.95	3.48_{de}	3.36_{de}	27.8	28.3
	5 SDI 55	0.92	0.90	3.38_{e}	3.28_{e}	27.2	27.7
	6 RDI 85	0.97	0.95	3.67_{bcd}	3.55_{bcd}	26.4	26.8
	7 RDI 70	0.97	0.96	3.69_{bcd}	3.57_{bcd}	26.5	27.0
	8 RDI 55	1.01	1.00	3.99_{a}	3.85_{a}	25.5	25.9
2013-2014	1 Control	1.48_{a}	1.42_{a}	5.82	5.30	25.5_{a}	26.8_{a}
	2 Wet	1.53_{a}	1.46_{a}	5.86	5.33	26.2_{a}	27.5_{a}
	3 SDI 85	1.50_{a}	1.43_{a}	6.37	5.80	23.6_{b}	24.8_{b}
	4 SDI 70	1.54_{a}	1.47_{a}	6.38	5.82	24.2_{b}	25.3_{b}
	5 SDI 55	1.12_{b}	1.07_{b}	4.89	4.34	21.6_{c}	22.3_{c}
	6 RDI 85	1.53_{a}	1.47_{a}	6.01	5.50	25.5_{a}	26.8_{a}
	7 RDI 70	1.46_{a}	1.40_{a}	5.98	5.42	24.7_{b}	26.0_{b}
	8 RDI 55	1.08_{b}	1.04_{bc}	5.10	4.72	21.5_{c}	22.3_{c}
Mean all seasons	1 Control	1.30_{a}	1.24_{a}	4.75	4.32	27.5_{ab}	28.7_{ab}
	2 Wet	1.32_{a}	1.26_{a}	4.79	4.25	27.7_{a}	29.0_{a}
	3 SDI 85	1.29_{a}	1.24_{a}	4.83	4.40	27.1_{ab}	28.4_{ab}
	4 SDI 70	1.30_{a}	1.24_{a}	4.85	4.41	27.2_{ab}	28.5_{ab}
	5 SDI 55	1.15_{b}	1.10_{bc}	4.48	4.12	26.1_{ab}	27.1_{ab}
	6 RDI 85	1.32_{a}	1.25_{a}	4.82	4.37	27.5_{ab}	28.8_{ab}
	7 RDI 70	1.26_{a}	1.20_{a}	4.80	4.41	26.4_{ab}	27.4_{ab}
	8 RDI 55	1.16_{b}	1.11_{c}	4.60	4.24	25.4_{b}	26.5_{b}

Table 6: Weight per kernel, fruit load per tree, Kernel yield, irrgation water and total water productivity for the respective seasons between 2009-2010 and 2013-2014; 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	1.32_{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}
2012-2013	1 Control	0.98	9611	2.53	17.2_{a}	557	164_{b}	158_{b}
	2 Wet	0.97	9719	2.46	18.4_{a}	534	138_{b}	134_{b}
	3 SDI 85	0.95	8786	2.39	16.1_{a}	549	179_{b}	172_{b}
	4 SDI 70	0.95	9373	2.77	17.5_{a}	549	249_{a}	238_{a}
	5 SDI 55	0.90	8284	2.29	15.1_{b}	552	258_{a}	244_{a}
	6 RDI 85	0.95	9828	2.43	16.8_{a}	587	180_{b}	174_{b}
	7 RDI 70	0.96	8755	2.50	16.7_{a}	529	235_{a}	224_{a}
	8 RDI 55	1.00	7956	2.14	14.3_{b}	575	234_{a}	221_{a}
2013-2014	1 Control	1.42_{a}	2308	0.74	18.4_{a}	128_{b}	54_{c}	50_{c}
	2 Wet	1.46_{a}	3417	0.86	19.0_{a}	146_{b}	53_{c}	50_{c}
	3 SDI 85	1.43_{a}	2692	0.64	16.9_{a}	119_{b}	55_{c}	51_{c}
	4 SDI 70	1.47_{a}	3216	0.59	19.0_{a}	98_{b}	62_{bc}	57_{bc}
	5 SDI 55	1.08_{b}	3353	0.70	14.3_{b}	255_{a}	95_{a}	85_{a}
	6 RDI 85	1.47_{a}	1805	0.98	18.3_{a}	178_{ab}	83_{ab}	77_{ab}
	7 RDI 70	1.40_{a}	1968	0.83	17.0_{a}	163_{b}	87_{ab}	80_{ab}
	8 RDI 55	1.04_{b}	2735	0.72	14.0_{b}	242_{a}	93_{a}	84_{a}
Mean all seasons	1 Control	1.23_{a}	7308	2.03	17.1_{ab}	436	191_{ab}	168_{ab}
	2 Wet	1.26_{a}	7150	2.04	17.9_{a}	432	161_{b}	145_{b}
	3 SDI 85	1.24_{a}	6893	1.98	16.0_{ab}	451	220_{b}	189_{b}
	4 SDI 70	1.24_{a}	7577	1.97	17.3_{a}	418	254_{ab}	216_{ab}
	5 SDI 55	1.10_{b}	7260	1.85	15.1_{ab}	495	296_{a}	241_{a}
	6 RDI 85	1.25_{a}	6908	2.02	16.7_{ab}	468	215_{ab}	187_{ab}
	7 RDI 70	1.20_{a}	7086	1.89	16.0_{ab}	438	261_{ab}	217_{ab}
	8 RDI 55	1.11_{b}	7445	1.76	14.2_{b}	514	280_{ab}	228_{ab}

Sticktights

Sticktights are the proportion of fruit not removed by the harvest operation and therefore represent a yield loss and a potential hazard for infestation with carob month after harvest (Figure 10).

In most seasons deficit irrigation led to a significant reduction in the proportion of sticktights. Also, the more severe the applied deficit the lower the proportion of sticktights remaining on the trees.

The proportion of sticktights showed a marked seasonal trend. In the wet and humid season of 2010-2011 a much higher proportion of sticktights (>4%) remained on the trees regardless of treatment, while the proportion was generally lower than 0.5% in 2012-2013 and was not even evaluated in 2013-2014 because of below average yields and a negligible proportion of sticktights.

It appears that fruit on trees with less negative Ψ_w is always more difficult to dislodge than from trees under mild stress and the level of retained fruit or sticktights is positively correlated with that of irrigation volume (Goldhamer et al., 2006). In wet seasons with humid weather, application of strategic deficit irrigation can significantly reduce the proportion of sticktights.

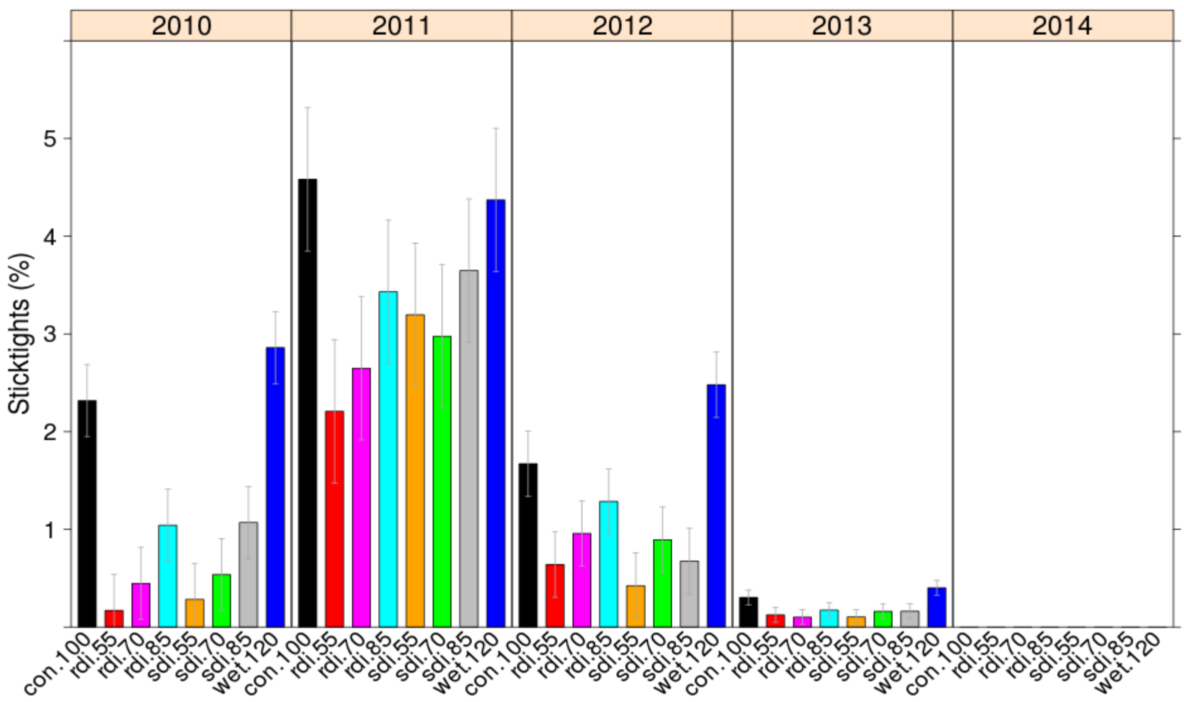

Figure 10: Percent sticktights for all irrigation treatments at the end of the respective seasons of 2009-2010 to 2013-2014. Vertical bars indicate least significant difference between treatment means (5% level). No sticktights were recorded in 2014.

Hull split

The proportion of split fruit was assessed throughout the ripening period of each season and is shown in Figure 11. The onset of hull split typically extended from late December to late February and there were clear differences between seasons.

In most seasons deficit irrigation accelerated hull split and the degree of acceleration was correlated with the level of the imposed deficits. Full hull split in control and "wet" treatments in most seasons was delayed by around 2 - 3 weeks relative to the most water deficient treatments SDI and RDI 55%. The progress of hull split in 2010-2011 showed no discernible treatment differences, probably because of the persistently wet and humid weather and a lack of split-inducing water stress.

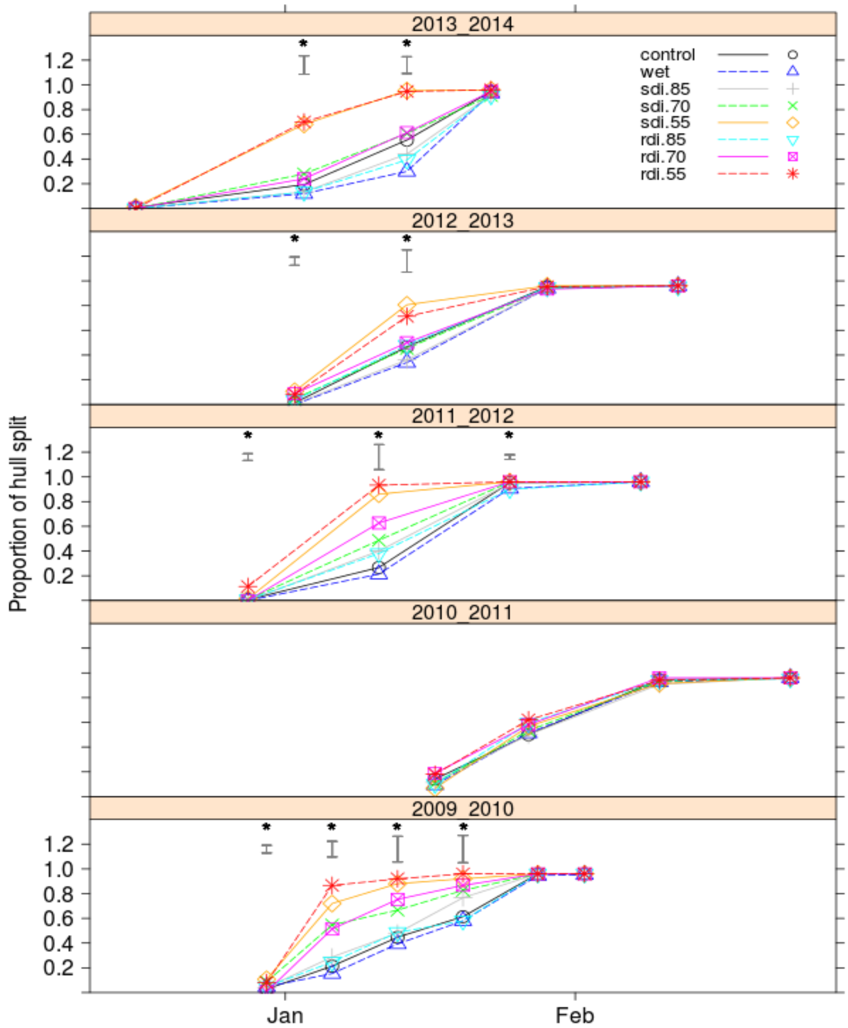

Figure 11: Percent hull split for all irrigation treatments throughout the ripening period of the respective seasons between 2009-2010 and 2013-2014. Vertical bars indicate least significant difference between treatment means. The stars above bars indicate statistical significance (5% level).

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. The work of Goldhamer et al. (2006) also 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 under RDI or SDI 55%, probably because our trees never reached such severe levels of plant water stress (see section 'Stem water potential' on 17).

Light interception

Light interception (LI) measurements were generally indicative of the size of the leaf canopy as the seasons progressed (Figure 12), with a sudden rise in LI after leaf emergence in early September due to rapid canopy fill in spring.

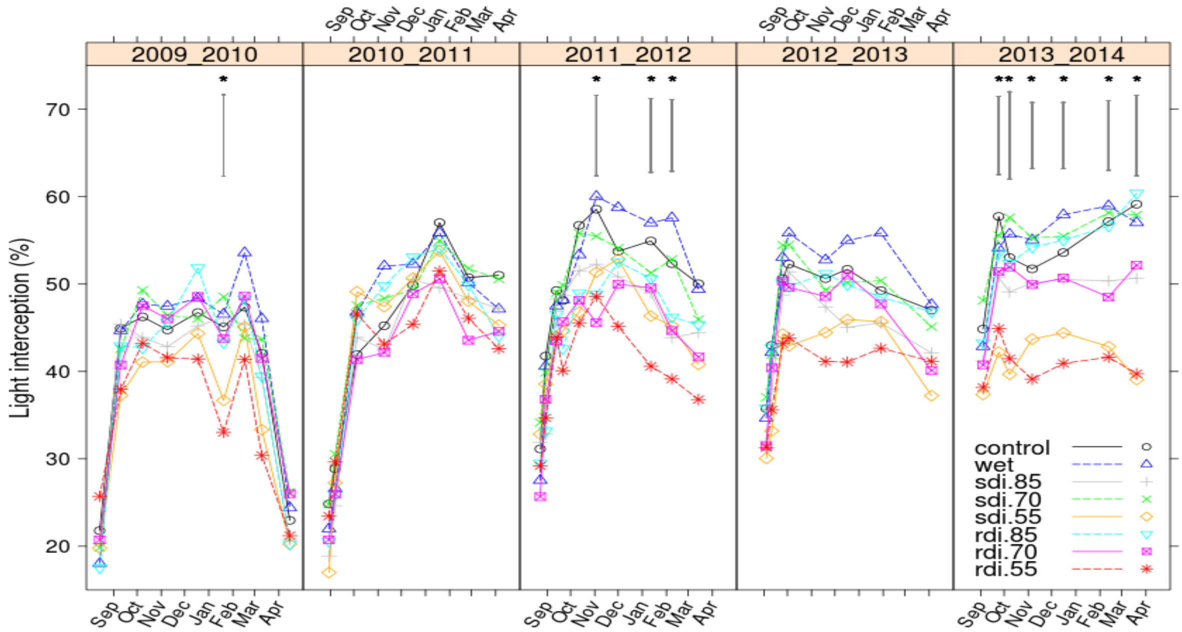

Figure 12: Influence of irrigation treatments on midday light interception during the respective seasons between 2009-2010 and 2013-2014 at Lake Powell. Vertical bars indicate least significant difference between treatment means. The stars above the vertical bars indicate statistical significance (5% level).

LI of most treatments increased progressively until the end of the third seasons, reaching a maximum of around 60% for control trees. The 55% treatments were an exception in that their LI remained static or even decreased slightly after season three. Difference in LI between control and strongly water deficient trees (55%) grew progressively larger from season to season. The fourth, relative to the previous seasons, indicated a slight decline in LI regardless of treatment but further growth was seen in the final year except for the 55% treatments.

Imposing deficits of 55% strongly retarded tree growth such that the 55% treatments after the fifth season still were of similar size as when the experiment began but were about 35% smaller than control trees. Growth retardation of the other deficit treatments was less apparent and temporary rather than ongoing.

Trunk circumference

The seasonal expansion in trunk circumference (Figure 13) represents a quantitative estimate of the long term impact of the various irrigation treatments on tree growth.

In most seasons tree trunk growth was closely aligned with the imposed deficits with the exception of the 2010-2011 and the 2012-2013 seasons. In the former, despite a high seasonal growth rate, persistently wet weather rendered the deficit irrigation ineffective resulting in small treatment differences. Conversely, in the latter (2012-2013), despite relatively high irrigation volumes, seasonal trunk growth of all treatments was equally and severely depressed. The most likely cause was a shortfall in the supply of nutrients combined with the potential for high yield that led to a diversion of resources from structural to fruit and kernel growth.

Despite the observed irregularities long term trunk growth aligned closely with the level of the imposed deficits and thus is a very reliable indicator of tree stress (Figure 14). 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).

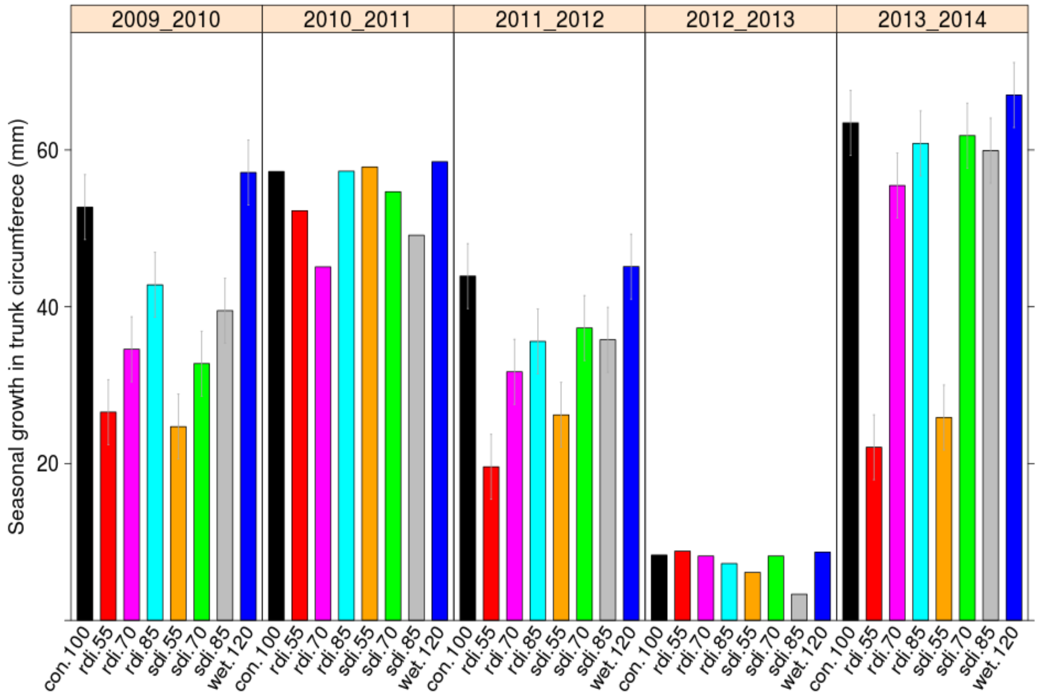

Figure 13: Influence of irrigation treatments on the seasonal growth in trunk circumference assessed for the respective seasons between 2009-2010 and 2013-2014 at Lake Powell. Vertical bars indicate least significant differences between treatment means (5% level). No bars indicate lack of statistical significance.

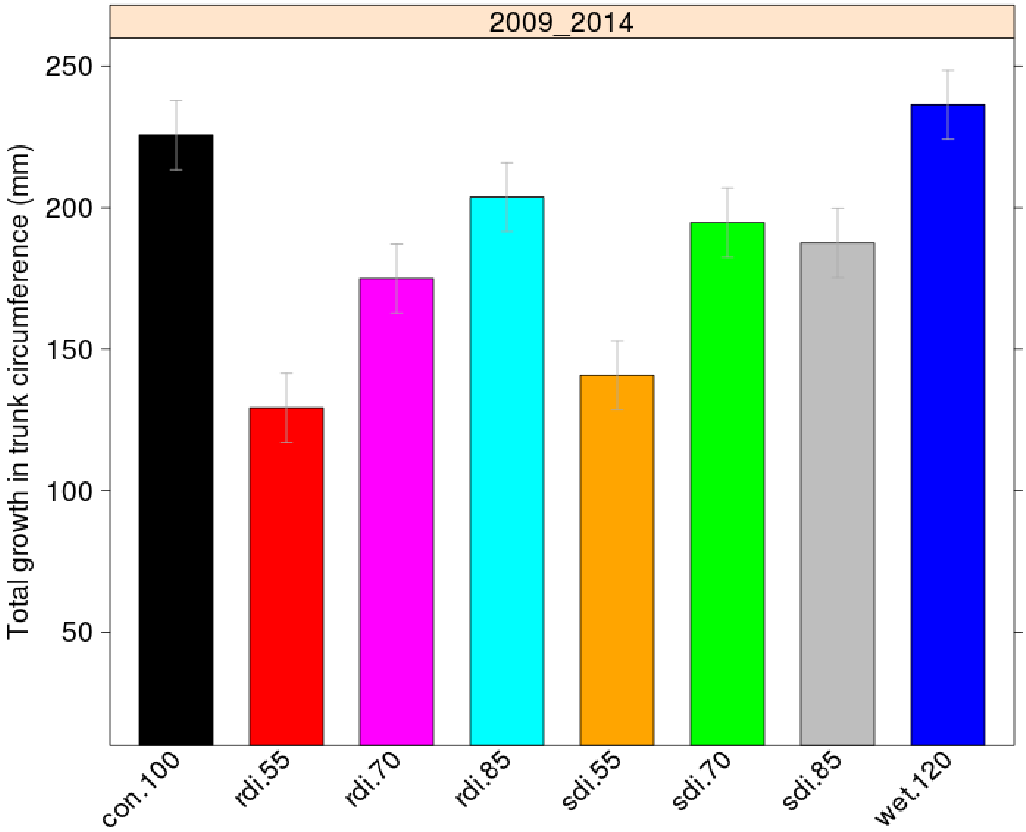

Figure 14: Influence of irrigation treatments on total growth in trunk circumference between 22/10/2009 and 30/04/2014 season at Lake Powell. Vertical bars indicate least significant difference between treatment means (5% level).

Fruit set, phenology, hull rot

These measurements aimed to to assess the inter-seasonal impact of water deficits on the course of flowering and on pollination effectiveness and fruit set. To that end, selected shoots were hand pollinated and their subsequent fruit set was compared to bee pollinated shoots (Table 7).

Results suggest that on 17 September 2012, hand pollination led to a superior fruit set although the difference between hand and bee pollination was small. On the second count (7 November 2012) fruit had reduced by a further 10% and, although there was still a difference between bee and hand pollination, it was not statistically significant.

Table 7: Effect of deficit irrigation on fruit set of bee and hand pollinated almonds in the 2012-2013 season; columns followed by no letter are not significantly different; least significant difference; p<=0.05.

Pollination	Treatment	Fruit set (%)	
		17-Sep-12	07-Nov-12
Bee	1 Control	38.6	25.6
	2 Wet	42.1	29.9
	3 SDI 85	49.6	34.2
	4 SDI 70	42.5	29.0
	5 SDI 55	56.8	38.1
	6 RDI 85	41.9	30.4
	7 RDI 70	41.9	32.2
	8 RDI 55	43.8	39.9
Hand	1 Control	48.6	33.3
	2 Wet	49.1	33.0
	3 SDI 85	41.2	31.9
	4 SDI 70	49.6	32.9
	5 SDI 55	60.2	41.2
	6 RDI 85	51.1	34.1
	7 RDI 70	56.3	37.0
	8 RDI 55	58.3	42.9
Pollination average	1 Control	43.6	29.5
	2 Wet	45.6	31.4
	3 SDI 85	45.5	33.1
	4 SDI 70	46.0	31.0
	5 SDI 55	58.5	39.6
	6 RDI 85	46.5	32.2
	7 RDI 70	49.1	34.6
	8 RDI 55	51.0	41.4
Bee	Treatment average	43.6_b	32.4
Hand		45.6_a	35.8

The difference in fruit set due to irrigation treatment, although not statistically significant, suggested a positive correlation between fruit set and deficit level. Both SDI and RDI 55% had consistently higher fruit set than those treatments with a less severe or no deficit. It is possible that this trend was due to a smaller flower number per tree as a result of deficit irrigation. Water deficient trees presumably compensated for a relative shortage in flower number by setting more fruit. Unfortunately, we don't have a direct measurements of the flower numbers per tree and therefore cannot test this hypothesis.

The fruit load per tree calculated from kernel yield per tree and weight per kernel indicated that nut number per tree was negatively correlated with deficit level. This suggests indeed that the higher set found in stressed trees is a compensation mechanism for a lower flower number per tree. If it were otherwise we would expect a higher, not lower fruit number per tree as a result of deficit irrigation.

The course of flowering for different irrigation treatments was similar and most flowers opened within a two week period between August 13 and August 27. Flowering peaked around 20 August. The course of flowering for the different irrigation regimes suggests little or no phenological shift in response to differential irrigation, neither with regard to leaf-out nor flowering.

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 (see section 'Hull split' on page 27).

Hull rot was assessed in conjunction with hull split. Significant infection was only recorded in the persistently wet season of 2010-2011 but not in any other. Deficit irrigation in line with the applied deficit did reduce the level of infection. The number of sticktights is often correlated with the level of hull rot infection and the number of sticktights were negatively correlated with deficit level (see section 'Sticktights' on page 26 and Figure 10 on page 26.

Spur based observations

Spur based observations were introduced in 2013-2014, the final season of the experiment. The objective was to evaluate spur based observations against the impact of selected deficit irrigation treatments.

Fewer leaves grew on spurs irrigated under SDI 55% and the longest leaf on the spur was shorter than on the other treatments (see Table 8). The proportion of spurs with fewer leaves was greater on trees from SDI 55% relative to other treatments.

There was no difference in the number of vegetative or floral buds but the number of fruits per spur was higher on SDI 55% relative to SDI 85% and the control but not relative to SDI 70%, suggesting that set tended to be higher for SDI 55% than 85% or control trees. A similar trend was seen in the previous year when fruit set was positively correlated with deficit level.

No difference in any of the observed variables was seen as a result of the spurs' position within the tree canopy, whether they came from a NE, NW, SE or SW oriented quarter of the tree canopy (data not presented).

Results confirm that trees under a water deficit regime tend to be less vegetative than well watered trees and the degree of vegetativeness is correlated with the deficit level.

Table 8: Effect of deficit irrigation on spur growth indicators in the 2013-2014 season; columns followed by the same letter or by no letter are not significantly different; least significant difference; p<=0.05.

Irrigation treatment	Longest leaf (mm)	Leaves	Vegetative buds	Floral buds	Fruits (nuts)
			per spur		
1 Control	54_a	8.8_a	1.9	2.1	$0.64_{\ b}$
3 SDI 85	56_a	9.0_a	1.9	1.9	$0.74_{\ b}$
4 SDI 70	56_a	8.2_{ab}	1.7	1.8	0.81_{ab}
5 SDI 55	45_b	$7.4_{\ b}$	1.7	2.1	0.99_a

The chosen methods of tagging individual spurs was more labour intensive than anticipated and consequently fewer spurs were tagged than originally planned. Additional difficulties were encountered with the bar code reader which malfunctioned on one occasion leading to the loss of some records. Despite those setbacks the methods appears suitable for detailed quantitative assessment of the medium to longterm fruitfulness of almond spurs.

Soil moisture monitoring

Moisture readings showed a similar seasonal course as in previous years but differences between irrigation treatments were less obvious in the final two seasons because of the higher irrigation volumes applied relative to previous years (results not presented).

Conclusions

Benchmarks for deficit irrigation based on the current ABA based irrigation protocol:

- Reducing irrigation application by 15% using either a RDI or SDI strategy had no negative effect on kernel size and yield over the five seasons of investigation. Such a reduction in most seasons represent only a moderate deficit compared to fully irrigated trees (100% ET_c) and has good potential to alleviate water shortages without loss of production.
- Deficits that reduced irrigation by more than 15% usually reduced both kernel size and yield. Trees appeared to better adapt to a sustained (i.e. SDI) rather than a pre-harvest deficit (i.e. RDI) irrigation strategy.
- Annual growth in tree circumference correlated closely with the cumulative irrigation deficit and was therefore the most sensitive indicator of cumulative water stress.

Yield response to deficit irrigation:

- Initial effects of deficit irrigation on kernel growth became apparent in early December when kernel growth was at its maximum. Only the most severe RDI deficit of 55% in some but not all years led to significant reductions in kernel weight. This suggests that trees under SDI better adapted to the imposed deficits than those under RDI where the onset of the deficits was more sudden.
- Deficit irrigation had a greater effect on kernel than on hull and shell growth because hull and shell, unlike kernel growth, was mostly complete before the irrigation deficits took full effect.

Establish minimum irrigation levels for almond production:

- The minimum irrigation level that may be applied without any significant trade off in yield is equal to or above 85% of plant water requirement. An irrigation level of between 70% and 85% is likely to reduce yield but not by a large percentage. Anything below 70% will strongly reduce yield and the medium to long-term tree productivity.

Establish optimum timing to apply deficits:

- Sustained deficits applied throughout the seasons (SDI) were less detrimental to tree productivity than pre-harvest deficits (RDI). Even mild and medium pre-harvest deficits of 85 or 70% led to significant defoliation events and resulted in a setback in growth in most years.
- If application of a strategic deficit is part of the seasonal irrigation strategy, it is preferable to apply it throughout the growing period.

Technology transfer

Table 9: Project field days and workshops

Activity	Audience	Attendance
Field day and seminar by visiting international scientist (Ted DeJong). Ted spoke about his work with almond and peach tree physiology, presenting work from his UC Davis pomme fruit team.	Scientists, industry	25
Annual workshop with Select Harvest to present update on the project outcomes. The sessions are used to bring the technical teams up to speed with the work, to talk about practice outcomes from the work and to answer questions about the direction and future of the project.	Technical staff	15
Annual (2013 and 2014) attendance and project results summary delivered to growers, industry representatives and industry advisory committee members.	Scientists, industry, technical staff, HAL staff	75-110

- An article was published in April 2014 by Irrigation Australia on the strategic irrigation of almonds. The article highlighted the results from the experiments at Lake Powell, namely that reducing irrigation application by 15% below normal plant requirements using either an RDI or SDI strategy had no negative effect on kernel size or yield. It also showed that trees appeared to adapt better to a sustained (SDI) rather than regulated (RDI) deficit irrigation strategy. The article is attached in the Appendix.

- Three key papers are in preparation from this work. One, submitted to Agriculture and Water Management in April 2014, addresses the effects of drought on fatty acid and tocopherol concentrations in almonds. The second, in preparation for submission to Tree Physiology, compares the sensitivity of different water status indicators in almonds to deficit irrigation treatments. The third, in preparation for submission to Irrigation Science or Water Management, addresses the effect of irrigation strategy and water application on tree performance.

- Conference presentations have twice been delivered at the Almond Board Conference, with the most up to date results and interpretation from the experiment. In June 2014, the final presentation was made to the Almond Board's Activated Almonds Research and Development Forum, with over 110 people attending from the Industry Advisory committee, plant improvement sub-committee, production sub-committee and the processing sub-committee. Representatives from HAL were also in attendance. That presentation, delivered as Milestone 105, is available on the ABA website (as all ABA conference presentations are).

Table 10: Project publications

Activity	Number
Conference abstract	2
Conference poster	2
Journal articles	1 submitted, 1 in preparation
Newsletter/pamphlet/flyer	1
Industry articles	1 published, 1 in preparation including the attached, recent publication in Irrigation Australia
Agnotes	1 in preparation for ABA regarding irrigation scheduling using crop factors and crop coefficients
Press release	interview with local ABC Radio Renmark (June 2013)

Recommendation

Our results suggest that a mild deficit of 15% below full plant water requirement, a potential saving of 1 – 1.6 Ml/ha, does not adversely affect production after 5 seasons. A number of shortcomings regarding the agronomic management of the trial were encountered in the fourth season highlighting the downside of having to rely on a commercial orchard environment for field experimentation. The experience suggested a need for ongoing education and training in the area of irrigation management.

Another issue of concern was the reliability of the automatic weather stations the trial relied upon. In the 2012-13 season, and to a lesser extent in following season, the trial received more irrigation than required during the months of December, January and February probably due to an overestimation of ET_o by the Lower Murray Water (LMW) weather stations at Lake Powell and at Boundary Bend. The issue is of concern because many irrigators along the Murray River now rely on the output of automatic weather stations. A comparison of modelled weather data from the Bureau of Meteorology for the same geographic location suggests that the quality of the data produced by the automatic weather stations was not optimal. Unfortunately, neither the research team nor Select Harvests' irrigation mangers had any control over the weather stations and had to rely on LMW for their maintenance. In addition data errors are often not immediately obvious and therefore difficult to remedy.

Among irrigators there appears to be a lack of a clear understanding of some of the concepts of reference crop evaporation relative to pan evaporation and the application of crop factors versus crop coefficients. In many cases confusion over the correct application of these terms can lead to substantial over- or under-estimation of crop water requirement. Opportunities for further training in this area provided by the industry would be a worthwhile investment.

The almond industry has developed their own in-house standards regarding irrigation scheduling. The standards are based on pan evaporation readings in combination with crop factors to estimate tree water requirement. It would be an advantage to clearly align these standards with those of other well established and widely used protocols for the estimation of reference crop evaporation and tree water use.

This project initiated a pilot study to develop a method for assessing spur growth from season-to-season. The aim was to gain a better understanding of the physiological principles that determine yield formation from season-to-season and its interaction with tree management. Preliminary results were in line with published results suggesting that dominance in vegetative growth (more leaves and buds per spur) was negatively correlated with flower and fruit number. Results also suggested that a given proportion of spurs are growing predominantly in a vegetative mode while others are more generative. This area of research has potential to gain a better understanding of the management factors most likely to optimise yield and economic return and should be further developed.

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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

Monks, M., & Taylor, C. (2014). Growing spurs not trees. Should we start thinking about growing spurs rather than growing trees. Poster presentation, 62^{th} Mildura Field Days, 23-24 May. See Att. 3 on page 41

Monks, D, & Taylor, C. (2014). Should we start thinking about growing spurs rather than growing trees? *In a Nutshell*, *Winter 2014* See Att. 5 on page 44

Sommer, K. J. & Taylor, C. (2014). Using deficit irrigation strategies to optimise water use of almonds. Irrigation Australia, *Autumn 2014, 10–11.* See Att. 4 on page 42

Sommer, K. J., Taylor, C. O'Connell, M. Abuzar, M. Fitzgerald, G. & Perry, E. (2012). Remote sensing applications to diagnose tree size and nutrient status in almond. Poster presentation, Australian Almond Conference, Barossa Valley, 8-10 October. See Att. 1 on page 39

Taylor, C., Sommer, K. J., & Downey, M. (2013). Influence of irrigation strategies on pollination and fruit set in almond. Poster presentation, 61^{th} Mildura Field Days, 24-25 May. See Att. 2 on page 40

Remote sensing applications to diagnose tree size and nutrient status in almond

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Introduction and Objectives

High resolution remote sensing data from satellites or unmanned aerial vehicles is becoming increasingly accessible. Appropriate analysis of the data potentially enables almond producers to identify orchard problem areas affected by nutrient and/or water stress. The timely recognition of water or nutrient stress in susceptible orchard areas is most important in avoiding production losses.

This poster demonstrates the potential usefulness of remotely sensed information as part of an ongoing deficit irrigation experiment jointly run by the ABA, HAL and DPI Victoria (see other poster).

Methods

Satellite based measures of the ***"Normalised Difference Vegetation Index"*** (NDVI) and ***"Canopy Chlorophyll Content Index"*** (CCCI) were sourced from RapidEye acquired on 16-Jan-2012. NDVI and CCCI are indicators of tree vegetative growth and nitrogen supply respectively (Barnes et al. 2000; Rouse et al. 1973).

The experiment was established in 2009 with the objective to test **regulated (RDI)** and **sustained (SDI)** deficit irrigation strategies and compare them to well watered control trees (100% ETc; 11-12 Ml/ha).

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 (Figure 1a).

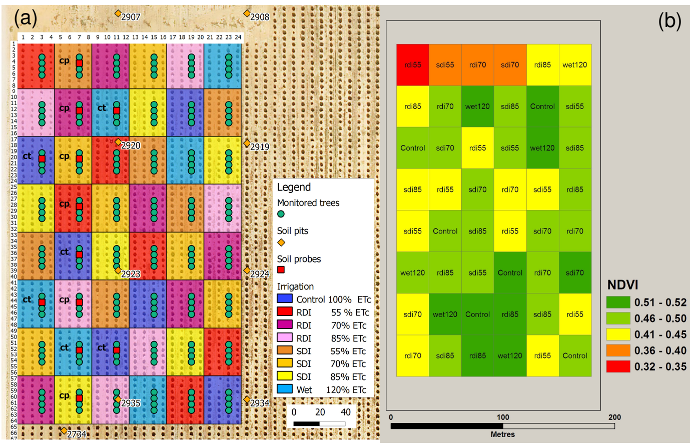

Figure 1: (a) Experimental treatment layout of deficit irrigation experiment at Lake Powell. (b) NDVI map of experimental area (16-Jan-12), an indicator of tree canopy cover and growth.

Results

Vegetative cover and NDVI

NDVI readings of the experimental plots on 16-Jan-12 are shown in Fig 1b. NDVI values of treatment means were also related to the ground-based radiation interception (see Fig. 2a). The close correlation between the two independent variables suggests that the satellite-based NDVI is an accurate indictor of tree size (canopy cover). NDVI data showed that deficit irrigations (<70% ETc) led to a significant reduction in vegetative cover and tree growth (Fig. 2 b).

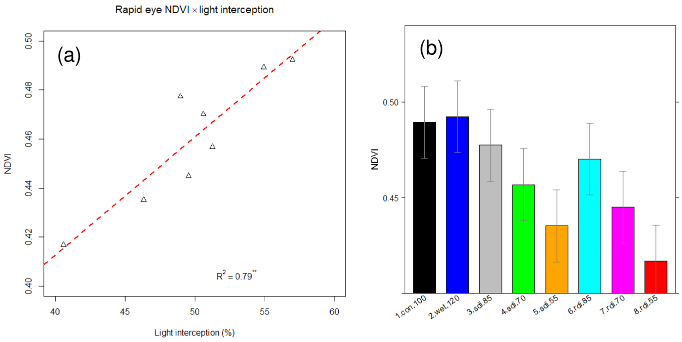

Figure 2: (a) Regression of NDVI derived from satellite data (16-Jan-12) vs. radiation interception (%) measured on the ground (12-Jan-12) using a ceptometer. (b) Mean NDVI per deficit irrigation treatment, vertical bars represent +/- 1/2 l.s.d.; (p=<0.05).

CCCI

CCCI is an indicator of tree nitrogen status. Results show that water deficient plots (RDI 55%) had a low nitrogen status (Fig 3a). By mid January RDI 55% trees were suffering from severe water stress leading to partial defoliation and consequently were unable to maintain sufficient nitrogen uptake. This was so despite an identical fertigation regime for all irrigation treatments and suggests that severely water deficient trees were unable to realise the nitrogen supply.

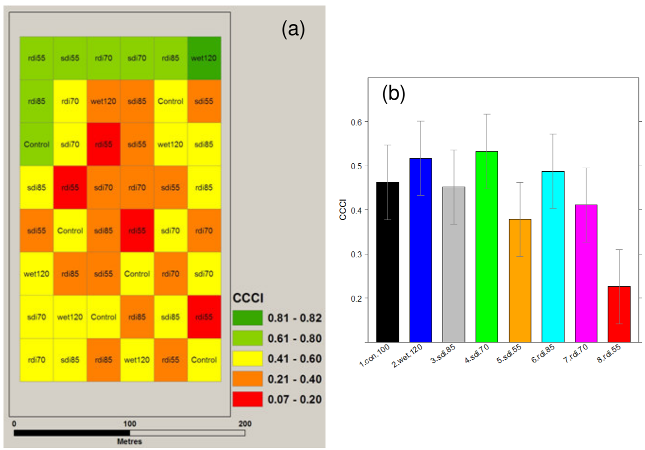

Figure 3: (a) CCCI map of experimental area (16-Jan-12), an indicator of tree nitrogen status. (b) Mean CCCI per deficit irrigation treatment; vertical bars represent +/- 1/2 l.s.d.; (p=<0.05).

Conclusion

High resolution satellites have the potential to accurately measure vegetative growth and nitrogen status of orchard trees.

This area of research has significant potential to develop diagnostic tools for the rapid assessment and management of water and nutrient status in the field.

Acknowledgement

RapidEye imagery was provided by SunRise21

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Influence of deficit irrigation strategies on pollination and fruit set in almond

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Introduction and Objectives
The aim of this work was to assess the carry over effect of deficit irrigation on the course of pollination, flowering and fruit set in subsequent seasons.

Irrigation treatments
The trial orchard is located at Lake Powell in north western Victoria and was planted in 2002-03. Deficit irrigation was first introduced in August 2009 and two strategies have been applied since:

- *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.

Pollination and fruit set
In the spring of 2012 the flowers of 2 branches in close proximity to each other were counted before they opened. One of each pair of the branches was hand pollinated while the other was bee pollinated. Fruit number on each branch was counted on 17 Sep. and was recounted on 7 Nov. to determine the percentage fruit set.

Figure 1 Pollination was performed by hand and bees.

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

Impact of water deficit on fruit set
Table 1 shows the annual irrigation volumes applied to the various treatments since the experiment was established and Table 2 shows the percentage of fruit set under those irrigation regimes measured in the spring of 2012.

Table 2 Effect of irrigation treatments and pollination method on fruit set of Nonpareil in spring 2012 at Lake Powell.

Pollination	Treatment	Fruit set (%)	
		17-Sep-12	07-Nov-12
Bee	1 Control	38.6	25.6
	2 Wet	42.1	29.9
	3 SDI 85	49.6	34.2
	4 SDI 70	42.5	29.0
	5 SDI 55	56.8	38.1
	6 RDI 85	41.9	30.4
	7 RDI 70	41.9	32.2
	8 RDI 55	43.8	39.9
Hand	1 Control	48.6	33.3
	2 Wet	49.1	33.0
	3 SDI 85	41.2	31.9
	4 SDI 70	49.6	32.9
	5 SDI 55	60.2	41.2
	6 RDI 85	51.1	34.1
	7 RDI 70	56.3	37.0
	8 RDI 55	58.3	42.9
Pollination average	1 Control	43.6	29.5
	2 Wet	45.6	31.4
	3 SDI 85	45.5	33.1
	4 SDI 70	46.0	31.0
	5 SDI 55	58.5	39.6
	6 RDI 85	46.5	32.2
	7 RDI 70	49.1	34.6
	8 RDI 55	51.0	41.4
Bee	Treatment average	43.6_b	32.4
Hand		45.6_a	35.8

Pollination effect
Hand pollination led to a higher fruit set than bee pollination when measured on 17 Sep. Differences were small but were still evident on 7 Nov. although set had declines for all treatments due to fruit abscission.

Irrigation effect
There was a positive correlation between the severity of the deficits and fruit set for both bee and hand pollinated trees but differences were not statistically significant.

Conclusions
Fruit set in 2012 was high for both hand and bee pollination. Hand pollination improved fruit set but differences were small. Water deficits led to higher fruit set but was possibly so because water deficient trees had fewer flowers per tree .

State Government Victoria | ALMOND BOARD OF AUSTRALIA | HAL Horticulture Australia | DEPARTMENT OF PRIMARY INDUSTRIES | future farming systems research

Growing Spurs Not Trees

Should we starting thinking about growing spurs rather than growing trees?

Dr Dave Monks and Cathy Taylor

This year, DEPI is starting a new ABA/HAL funded research project to focus on spur-level responses to changing light environments, water and nutrient management. We're going to undertake field experiments investigating the effects of light, nutrients and water on spur productivity over time. This new experiment expands on a 10-year study of spurs in California (Tombesi *et al*., 2011).

To help describe the way spurs function over multiple seasons, we're going to measure the:
- number of spurs
- number of flowers
- fruit set
- fruit retention
- nut dry weight
- and light interception

The data will be used to better understand spur productivity under Australian conditions.

The main fruit-bearing shoots in almond trees are spurs. An understanding of the factors that influence spur fruitfulness and longevity is required to understand seasonal fluctuation in fruit behaviour, and to develop appropriate management practices that will deliver higher spur productivity and yield.

We will collaborate with scientists from around the world on this work—including CSIRO here is Australia and UC Davis, in the USA.

a) DEPI's Karl Sommer in the field at Lake Powell attaching barcodes to spurs for long-term assessment

b) Two spurs – the one bearing fruit last year has no flower buds, the other spur, vegetative last year, does

c) Flowers appearing on spurs with different fruiting histories

References
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Department of Environment and Primary Industries

State Government Victoria

USING DEFICIT IRRIGATION STRATEGIES TO OPTIMISE WATER USE OF ALMONDS

Most almond production in Australia is located along the lower Murray River, where irrigators have experienced substantial reductions in their water allocations over recent years. This scarcity of water makes it essential that almond growers apply best irrigation management practice by using water in the most efficient and effective way.

Although it has been shown to be a successful technique to optimise water use, deficit irrigation is 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. As a result, there is little or no information on the potential for irrigating almonds under moderate to low irrigation volumes and with variable irrigation strategies such as deficit irrigation.

The research

Various deficit irrigation trials in almond have been conducted overseas but results are not directly applicable to the soil and climatic conditions of inland Australia. To address this gap the Department of Environment and Primary Industries Victoria (DEPI) and the Almond Board of Australia (ABA) initiated research to explore the potential for deficit irrigation of almond orchards in inland Australia.

Monitoring leaf temperature and stomatal conductance using a porometer in the Almond research orchard at Lake Powell in north-west Victoria.

Almond harvest at the Lake Powell experimental orchard in late February.

The aims of this research were to:
- establish benchmarks for deficit irrigation of almonds under climatic conditions in inland Australia
- investigate the yield response to deficit irrigation
- establish minimum irrigation levels for almond production
- establish optimum timing to apply deficits.

The experimental site was established at the end of season 2008-09 at Lake Powell near Robinvale in Victoria. Five levels of irrigation were tested:

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

SDI was applied evenly throughout the irrigation cycle while RDI was applied pre-harvest, beginning on 10 September, 12 November and 10 January respectively for RDI 55, 70 and 85% and ending at harvest (late February). During RDI trees received 50% of their full water requirement. The impact of the various irrigation treatments on tree physiology, growth and productivity was assessed.

Key findings

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

Trees with deficits applied throughout the irrigation season (i.e. SDI) adapted more readily to reduced water than those receiving RDI deficits, where the stress was biased towards 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 55% decreased kernel size and kernel yield.

The second season (2010-2011) was very wet and 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 at 85% had a reduced kernel yield relative to RDI at 70%, suggesting that deficit irrigation conferred a yield advantage under wet conditions.

Results from the third season (2011-2012) were similar to those seen in the first season. Water stress due to deficit irrigation treatments was obvious 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 in the third season 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.

The bottom line

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% reduced both kernel size and yield.

Trees appeared to better adapt to a sustained (SDI) rather than regulated deficit irrigation (RDI) strategy where deficits were 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.

Our results suggest that a mild deficit of 15% below full plant water requirement does not adversely affect production after three seasons. There is some uncertainty about the long-term productivity of trees under mild water deficits given the variable weather over the three seasons under investigation.

Information

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AUSTRADE PLANS WATER SECTOR ACTIVITIES

Austrade has planned two international activities in the water sector in the UAE and Latin America for early 2014 and is inviting participation from industry stakeholders.

Trade mission to UAE 13 to 16 April

As part of this trade mission Austrade will be holding two urban water symposiums in Dubai and Abu Dhabi on 13 and 14 April. The symposiums will share Australia's extensive experience in water conservation, urban water trends, management and product development. They will also highlight how Australia has tackled a range of issues such as desalination, water recycling and flood management. This initiative builds on Austrade's green building and energy efficiency program held in 2013.

Austrade will also have a national pavilion at WETEX Dubai from 14-16 April 20. This is the key regional water show and Austrade invites Australian companies to participate. For more information contact Zareen.Hussain@austrade.gov.au

Water solution trade missions to South America 21 to 29 April.

Austrade is inviting environmental and water solutions suppliers to participate to develop business opportunities in Chile, Peru and Mexico. Delegates will participate at Expomin in Santiago in Chile as part of the Australian Pavilion, under the Visitor's Package, and will have tailored business meetings, as well as group networking events to connect to potential business partners and customers in the mining and utilities markets.

For information contact Leigh Wilmott (leigh.wilmott@austrade.gov.au), or Shelley Jackson (shelley.jackson@austrade.gov.au)

Should we starting thinking about growing spurs rather than growing trees?

Dr Dave Monks and Cathy Taylor
DEPI Mildura

The main fruit-bearing shoots in almond trees are spurs. Spurs start out growing vegetatively and then, after one or two seasons, bear fruit. Spurs bearing fruit in one season are likely to be non-bearing the next year—and may remain non-bearing for two or more years. Most spurs remain viable for 3 – 5 seasons, but then begin to lose vigour and die. The rate of spur death is variable, ranging from 5 – 25 % per season. An understanding of the factors that influence spur fruitfulness and longevity is required to understand seasonal fluctuation in fruit behaviour, and to develop appropriate management practices that will deliver higher spur productivity and yield.

Bringing it back to first principals, the yield of an almond orchard is determined by the tree's ability to grow and fill kernels. It can be broken down as simply "Yield = the number of kernels x weight of kernels". The number of kernels can be further broken down to account for the number of kernels per spur, spurs per branch and branches per tree. These components of yield are inherently influenced by genetics and are expressed through interactions with management and environment. In some crops, yield components are elastic, freely moving carbohydrate from areas of high supply to areas of high demand, for example you could remove the fruit from the top half of a tomato plant and have the remaining fruit size up and not lose much yield (Ho, 1996). However, the spurs of an almond tree operate as semi-autonomous units, and tend to only move carbohydrate supply and demand within the one structure (Heerema *et al.*, 2008).

Our new ABA/HAL funded research project will focus on the spur-level responses to changing light environments, water and nutrient management. It follows a 10-year analysis by Tombesi *et al*. (2011) in California that ultimately debunked the idea that almonds are an alternate-bearing species. Their work found that the year-to-year variation was due to factors influencing spur fruitfulness, rather than the notion that a spur population is itself intrinsically alternate-bearing. Here in Australia, we'll use controlled field experiments to take this work even further—investigating the effects of light, nutrients and water on spur productivity over time. By measuring the number of spurs, the number of flowers, fruit set, fruit retention, nut dry weight, light interception and climate variables we'll be able to describe the way these components interact over multiple seasons. The data will be used to better understand spur productivity under Australian conditions.

The project team has drawn on the experience of DEPI research staff and research partners to design the data collection approach and the research experiment. Team leader, Dr Dave Monks, is a research scientist with Victoria's DEPI. He has a PhD in crop physiology and a B. Hort Sci (Hons) from Lincoln University, New Zealand. Dave has worked in the North West of Victoria for 3 years leading a number of diverse research projects. He succeeded Dr Karl Sommer as the leader of the almond deficit irrigation project at Lake Powell, Victoria. His experience is in reproductive physiology and component of yield analysis.

Our national collaborators on this project include CSIRO's Drs Saul Cunningham and Everard Edwards and Plant and Food Australia's Drs Grant Thorp and Andrew Granger. On an international level, Dr Monks and the DEPI team will continue to maintain strong relationships with UC Davis' Drs Lampinen, DeJong, Michailides, Brown and Shackel and their technical and extension team including David Doll, Roger Duncan and Blake Sanden. The project is due to begin in the spring of 2014.

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Ho, L.C. 1996. The mechanism of assimilate partitioning and carbohydrate compartmentation in fruit in relation to the quality and yield of tomato. Journal of Experimental Botany **47**, 1239-1243.

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Plate 1: DEPI's Karl Sommer in the field at Lake Powell attaching barcoded wire-ties to identify spurs for long-term assessment of their fruiting behaviour.