Citrus Drought Survival and Recovery Trial

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South Australian Research and Development Institute (SARDI)

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This report provides a summary of the methodology and outcomes of research into citrus survival of, and recovery from, drought and reduced irrigation availability. The scope of the work encompassed both a controlled research trial and a broad scale on-farm monitoring program.

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Media Summary

In response to drought conditions and reduced water availability in the Murray Darling Basin, a research project was undertaken to investigate the impact and management of deficit irrigation in tree crops, including citrus and almonds.

This event was an ideal opportunity to collect valuable information for tree crop industries which will need to manage future drought events.

A number of research trials were conducted into the effects of deficit irrigation on citrus trees. In addition, a large on-farm monitoring program tapped into the experiences of citrus and almond irrigators during the drought and subsequent recovery.

Effective strategies for coping with reduced water availability included:

- Reducing the size of citrus tree canopies by hedging;
- Skeletonising trees (very severe cutting back), although recovery time was extended;
- Reworking citrus trees (cutting back to bud in a new variety), which gave added benefits of variety renewal;
- Hedging immediately following a sustained period (at least a full season) of deficit irrigation, to assist in tree recovery;
- Purchasing water, where the cost of water was less than the value of produce lost by withholding that volume of water.

Strategies which proved less effective included:

- Cultural management techniques (mulching, “sunscreen” films applied to the canopy, and soil polymers);
- Reducing the proportion of the ground wetted by irrigation, which negatively impacted recovery once normal irrigation was reinstated.

Other factors which affected crop response to deficit irrigation included:

- Irrigation system type and coverage;
- Duration and severity of irrigation reduction, for example more than 1 season of deficit increases the time required for recovery;
- Rootstock, for example the citrus rootstock Cleopatra Mandarin was superior to Sweet Orange, and Troyer Citrange and Swingle Citrumelo also performed well in other trial work conducted by the author.

Recommendations for Future Research:

- Further investigation of the impact of deficit irrigation under different irrigation systems, and different wetted area scenarios;
- Further investigation of drought management in other tree crops, especially almonds.

Recommendations for Industry:

- Current recommendations for the use of Swingle Citrumelo and Citrange rootstocks in citrus replant situations are appropriate;
- Canopy reduction is an appropriate tool for managing reduced water availability in tree crops, with severity of reductions being proportional to severity of water shortage;
- The water market can be a valuable management tool, especially where crop returns are high, making water purchase economically viable.

Technical Summary

The 2006/07 to 2010/11 drought resulted in dramatically reduced water allocations across the Murray Darling Basin, even for irrigators holding high security allocations, and growing permanent plantings of tree and vine crops.

This event was an ideal opportunity to collect valuable information on the response of these crops to deficit irrigation, in order to inform government, community and irrigator responses during future drought events.

A number of research trials were conducted into the effects of deficit irrigation on citrus trees, including a comparison of the response of navel orange trees on different rootstocks to severe water deficit, an assessment of the impact of hedging applied after an extended period of deficit irrigation (18 months), and a comparison of a range of cultural management strategies designed to minimise the impact of deficit on mildly and more severely stressed trees. In addition, a large on-farm monitoring program was instigated, which tapped into the experiences of citrus and almond irrigators during the drought and subsequent recovery.

Effective strategies for coping with reduced water availability included:

- Reducing the size of citrus tree canopies by hedging;
- Skeletonising trees (very severe cutting back) when water was severely restricted, although recovery time was extended;
- Reworking citrus trees (cutting back to bud in a new variety), which gave added benefits of variety renewal and improved profitability once full irrigation was resumed;
- Hedging immediately following a sustained period (at least a full season) of deficit irrigation, to assist in tree recovery and improve fruit quality;
- Purchasing water, where the cost of water was less than the value of produce lost by withholding that volume of water (appropriate in almonds during this period).

Strategies which proved less effective included:

- Cultural management techniques (mulching, “sunscreen” films applied to the canopy, and soil polymers), where no significant differences were detected;
- Reducing the proportion of the ground wetted by irrigation, which negatively impacted recovery once normal irrigation was reinstated.

Other factors which affected crop response to deficit irrigation included:

- Irrigation system type and coverage, where a smaller wetted area resulted in lower ability to cope with drought, but drip at high wetted area (30%) was similar to full cover sprinkler;
- Duration and severity of irrigation reduction, with trees recovering rapidly from a single season of moderate to severe reduction, whilst trees subjected to extreme deficit irrigation (10% of normal levels) for 1 ½ seasons took a number of seasons to recover;
- Rootstock, for example the citrus rootstock Cleopatra Mandarin was superior to Sweet Orange, and Troyer Citrange and Swingle Citrumelo (key replant rootstocks in the Australian citrus industry) also performed well in other trials carried out by the author.

Recommendations:

- Current recommendations for the use of Swingle Citrumelo and Citrange rootstocks in citrus replant situations are appropriate, and Cleopatra Mandarin is the most appropriate rootstock for citrus in virgin soil, given the likely future variability in water supplies;
- Canopy reduction is an appropriate tool for managing reduced water availability in tree crops. Where possible, the severity of reductions should be proportional to the severity of the water shortage expected;
- The water market can be a valuable management tool, but only where the marginal cost of water is less than the marginal cost of yield loss resulting from reduced irrigation.

Future work:

- Some results suggest that a very low wetted area under drip irrigation can reduce the resilience of trees exposed to water stress. Further comparisons of tree performance under different irrigation levels, applied through different irrigation systems, with different wetted area scenarios are recommended;
- Positive market conditions (i.e. high returns for product) in almonds meant that the marginal cost of water was less than the marginal cost of yield loss as a result of water stress during the years of the drought when the on-farm monitoring was conducted. As a result water purchase was the management option of choice amongst almond growers, and few data were collected on other management options in this important crop. Price reductions for almonds since the drought suggest that the option of purchasing water is no longer so straight forward. Other drought management strategies, such as crop removal and canopy management (by pruning or irrigation management) should be investigated, as well as the drought tolerance of commonly used rootstocks and varieties.

Introduction

The Murray Darling Basin (MDB) is the largest river basin in Australia. Water from its rivers has been used to irrigate a wide range of crops, including pastures for meat and milk production, cotton, rice, vegetables, vines and fruit trees.

Historically, irrigation allocations high in the basin and along the tributaries of the river system have been of lower reliability than allocations in the lower reaches of the system, where reliability of supply has traditionally been high. This led to a tiered system of allocations, with High Security allocations enjoying first priority to any available water, and General Security allocations sharing the remaining water. General Security allocations were traditionally used to produce annual crops and pasture, whilst permanent plantings of fruit trees and vines are predominantly restricted to High Security allocations in the lower reaches of the system.

During the period from 2006 to 2011, drought conditions in the catchments of the MDB dramatically reduced water storage levels within the basin, with the result that most General Security allocations within the basin received no water at all for a number of consecutive seasons, and High Security allocations were drastically reduced.

Allocations of water for irrigation in the Riverland and Sunraysia regions are not determined by local rainfall and runoff, but by runoff in diverse regions on the eastern and northern boundaries of the MDB, and by carryover of water in storages. The drought was a very wide spread phenomenon, and inflows to storages were dramatically reduced in the early seasons of this work. Storage volumes coming into the drought event were critically low, and the combination of low storage volumes and dramatically reduced inflows resulted in major reductions in allocations for irrigation across the Basin.

Irrigation allocations are generally declared early in the financial year, which coincides with the water year. However, the policy is to only allocate water that is available at the time of announcement of the allocations. Allocations are then revised (generally upward) as storage conditions change during the season, for example as more inflow to the storages occurs.

Table 1 details the allocations declared at the opening of each season, as well as the final allocation reached in each season, and the dates when these allocation levels became effective, for the South Australian River Murray Prescribed Watercourse. These allocations are illustrative of the allocations experienced in the other affected jurisdictions in New South Wales and Victoria. In most seasons there were other allocation increases between these dates, but for clarity only the opening and final allocations are displayed here.

Prior to this event, allocations for High Security water had been less than 100% only once in 100 years.

Table 1: Opening and final allocations for irrigators on the SA Murray River during monitoring program

Season	Opening Allocation (%)	Effective Date	Final Allocation (%)	Effective Date
2007/08	4	1 Jul. 2007	32	14 Dec. 2007
2008/09	2	1 Jul. 2008	18	1 Feb. 2009
2009/10	2	1 Jul. 2009	62	15 Mar. 2010
2010/11	21	1 Jul. 2010	67	1 Oct. 2010
2011/12	100	1 Jul. 2011	100	1 Jul. 2011

The impact on permanent fruit tree and vine plantings of such a reduction in allocations was severe. Removal of older and/or less economically viable plantings freed up some water for transfer to other plantings, and interstate trade of water assisted growers to maintain water supplies to some level. However, many plantings were subjected to reduced irrigation applications, with uncertain effects on short term survival and production, and long term recovery.

The research carried out under this project fell into 2 separate compartments: a citrus research trial; and an on-farm drought monitoring program.

Citrus Drought Research Trial

A research trial was established to assess the impacts of different levels of water restriction on short and long term productivity of citrus trees. In addition, the trial assessed the potential of a range of management practices to assist in maintaining productivity, and in promoting rapid recovery when full irrigation was again available.

This trial was established at Solora Estate, between Loxton and Berri in the South Australian Riverland. The property was owned and operated by Agri-Exchange Pty. Ltd., who co-invested in the research project, and managed the site.

On-Farm Drought Monitoring Program

The on-farm drought monitoring trial sought to tap into the experiences of almond, avocado, citrus and grape growers in the Riverland and Sunraysia, in coping with reduced irrigation allocations. The primary aim of the trial was to monitor on-farm managerial and production responses to reduced allocations, and in particular to document the range of irrigation application practices and cultural techniques applied to plantings, and to assess the impact of these practices on production, survival and recovery of effected plantings.

The aim of this particular trial was not to apply controlled treatments, but to simply document practices put in place by growers. Some growers were found to be applying a range of treatments to different patches, in order to improve their own knowledge, while other growers were using one or two particular approaches across their whole property.

Additional Related Work

In addition to the work described above, a number of small related research trials were carried out under alternative funding, investigating the impact of rootstocks on citrus response to drought, and the use of hedging as a tool to assist citrus trees to recover from drought. Although not part of this project, and therefore not described in detail here, outcomes from this work are included amongst the recommendations in this report, for completeness.

Literature Review

Citrus Short Term Deficit Studies

Many citrus deficit irrigation studies have investigated the impact of water deficits at certain stages of crop development (Ballester et al., 2011; Ballester et al., 2013a; Domingo et al., 1996; Goldhamer & Arpaia, 1998; Gonzalez-Altozano & Castel, 2000ab; Hutton et al., 2007; Perez-Perez et al., 2008). These studies apply deficit only at certain stages, with water being fully available at other times.

A major conclusion of all of these studies is that the timing of the deficit is critical to its impact on yield. However, the critical timing seems to vary between species, and maybe even between varieties. For example:

- In Lemons a 30% water saving was realised without any yield loss by applying only 25% of full irrigation requirement throughout the season except during the rapid fruit growth stage (equivalent to mid-December to early May in Australia) (Domingo et al., 1996);
- For Clementina de Nules Mandarins, January and February were suitable for the application of deficit, but any deficit during autumn (March to May) resulted in significant yield loss (Gonzalez-Altozano & Castel, 2000a);
- Deficit in late summer and autumn (February to May) gave slight reduction in yield, but a significant increase in water use efficiency in Navel Oranges (Hutton et al., 2007). It was noted, however, that this strategy resulted in an increase in flowering and fruit set in the following season, which generally led to higher crop load and smaller fruit, with similar total yield in tonnes per tree.
- Goldhamer and Arpaia (1998) indicate that slow-down in fruit growth due to water stress at any stage of the season is not fully compensated for once water availability returns to normal in Frost Nucellar Oranges, resulting in yield reduction at harvest.
- Other authors found similarly that fruit growth and final yield were compromised when water was reduced at various stages during the season, in Clementina de Nules mandarins (Ballester et al., 2011), Navel Oranges (Ballester et al., 2013a; Perez-Perez et al., 2008) and Valencia Oranges (Hilgeman & Sharp, 1970).

There is general agreement that water stress is to be avoided during spring, as this will have the greatest impact on crop load, through flowering and fruit drop (Burdette & Dring, 2007; Cummins, 1998; Doorenbos & Kassam, 1979). Cummins (1998) further warns of the impact of stress during spring on the growth of spring flush foliage, and the potential impact of restricted spring flush on the following season's flowering and fruiting sites, leading to reduced crop load in the subsequent season.

Citrus Whole Season Deficit Studies

Studies have been carried out on sustained deficit irrigation (reduced irrigation across the whole season), with two major methods used to apply treatments. Some treatments were applied by extending the interval between irrigations (Bielorai, 1977; du Plessis, 1985; Hilgeman, 1977; Kanber et al., 1999; Syvertsen et al., 1988). In other trials, smaller amounts of water were applied at each irrigation (Gonzalez-Altozano & Castel, 2000ab; Kirda et al., 2007; Treeby et al., 2007). The first method results in rapid oscillation of soil water tension between irrigation events, whilst the second method generates a more gradual decrease in soil water availability over the course of the season.

The reduction in irrigation amount across the season varied between studies, from only 20% reduction below "full" (Menge et al., 1990), to 50% reduction (Gonzalez-Altozano & Castel, 2000ab; Kirda et al., 2007). In some of the trials with increased irrigation intervals, the total volume of water applied was the same across treatments, with the increased interval treatments receiving fewer, deeper irrigations (Bielorai, 1977; du Plessis, 1985).

For those experiments resulting in water savings, the greatest water saving and resultant yield loss are shown in Table 2.

Table 2: Water reduction and subsequent yield reduction for full season deficit studies

Reference	**Variety**	**Experiment Duration (yrs)**	**Irrigation Reduction (%)**	**Yield Reduction (%)**
Gonzalez-Altozano and Castel (2000a)	Clementina de Nules	2	50	22
Hilgeman (1977)	Valencia Orange	20	46	30
Kanber et al. (1999)	Marsh Seedless Grapefruit	3	40	5
Kirda et al. (2007)	Marisol Mandarin	2	50	30
Menge et al. (1990)	Washington Navel Orange	6	20	3
Treeby et al. (2007)	Bellamy Navel Orange	2	45	0

Most of these experiments ran for only 2 or 3 seasons. Both longer term experiments (Hilgeman, 1977; Menge et al., 1990) resulted in reports of tree decline as the experiment progressed, particularly a reduction in leaf area over the course of the experiment.

Interestingly, Menge et al. (1990) reported an increase in crop load after the initial season, and a decrease in fruit size, resulting in only a small reduction in yield (supported by Treeby et al., 2007), whereas Hilgeman (1977) reported a significant reduction in crop load in some years, such that fruit size was not affected. This may have been due to the timing of irrigation events (only 5 irrigation events were applied each season) relative to flowering and fruit set, and the impact of this on fruit drop, perhaps combined with the climatic conditions during this period in different seasons.

In this context it is worth noting that Krajewski and Rabe (1995) cite water stress as a factor in promoting flowering, and draw a quantitative link between duration and degree of water stress and flowering intensity. However, water deficit during flowering and fruit set can lead to significant flower and fruit drop, counteracting any increase in flower numbers, and reducing final yield potential (Doorenbos & Kassam, 1979; Perez-Perez et al., 2008).

The response of trees to a return to normal irrigation levels after a season or more of low irrigation does not appear to have been addressed in the literature.

The only information available for irrigation levels below 50% of normal is anecdotal evidence from South Africa (Burdette & Dring, 2007), indicating that trees survived on 27% of normal irrigation, but without any production. There was no information given about production by these trees in subsequent seasons.

Materials and Methods

Citrus Drought Research Trial

The trial was conducted in a planting of approximately 1100 Valencia orange (*Citrus sinensis* (L.) Osbeck) trees budded onto Sweet Orange rootstock, located on a large irrigated property near Berri, South Australia (34°21’S, 140°36’E). Trees were spaced 7.01 m (23 feet) between rows and 3.66 m (12 feet) within rows, forming continuous hedgerows approximately 4.0 m high and 4.0 m wide, orientated roughly North/South. The trees were planted in 1976, and have been drip irrigated since 2003, with the system consisting of two drip-tubes per tree row, with 1.75 L/h drippers spaced every 0.625 metres, giving a full cover equivalent application rate of 0.8 mm/h.

All treatments were applied to blocks of 18 trees, 6 trees in each of 3 adjacent rows. All measurements were conducted on the centre 4 trees (treatment trees), with the surrounding 14 trees acting as barriers between treatments.

Treatments

Irrigation Levels

Three levels of irrigation were applied to the trees, based on meeting apparent crop evapotranspiration (ET_C) for citrus, determined using EnviroSCAN® capacitance soil water monitoring in a neighbouring patch of identical trees:

- Nominally 100% of full ET_C, referred to as Full Irrigation (FI);
- Nominally 67% of full ET_C, referred to as Moderate Deficit Irrigation (MDI);
- Nominally 33% of full ET_C, referred to as Extreme Deficit Irrigation (EDI).

The irrigation treatments were applied for 1 season (2008/09) on half of the replicates, and for 2 seasons (2008/09 & 2009/10) on the other half, in order to assess the impact of duration of drought. This resulted in 5 irrigation treatments (FI, MDI 1Y, MDI 2Y, EDI 1Y, EDI 2Y).

Table 3: Depth of rainfall and irrigation applied and water balance components for each season

Season	Treatments	ET_0 (mm)	Irrigation (mm)	Rainfall (mm)	Tot. App. (mm)	ET_C (mm)
2008/09	EDI 1Y, EDI 2Y		230		397	394
	MDI 1Y, MDI 2Y	1494	459	167	626	596
	FI		750		917	798
2009/10	EDI 2Y		483		785	712
	MDI 2Y	1519	768	302	1070	901
	EDI 1Y, MDI 1Y, FI		1057		1359	1003
2010/11	All	1289	845	430	1275	901
2011/12	All	1398	836	294	1130	942

Irrigation events were applied as full depth applications, and the timing was stretched between irrigations according to irrigation treatment. Thus the MDI treatments received irrigation during 2 out of every 3 irrigations applied to the FI treatment, and the EDI treatments received irrigation during 1 out of every 3 irrigations applied to the FI treatment.

Seasonal totals of irrigation, rainfall and total water depth applied to each irrigation treatment for each season of the trial are shown in Table 3, along with estimated reference crop evapotranspiration (by the method of Allen et al., 1998), and actual evapotranspiration (ET_C) based on daily water balance calculations.

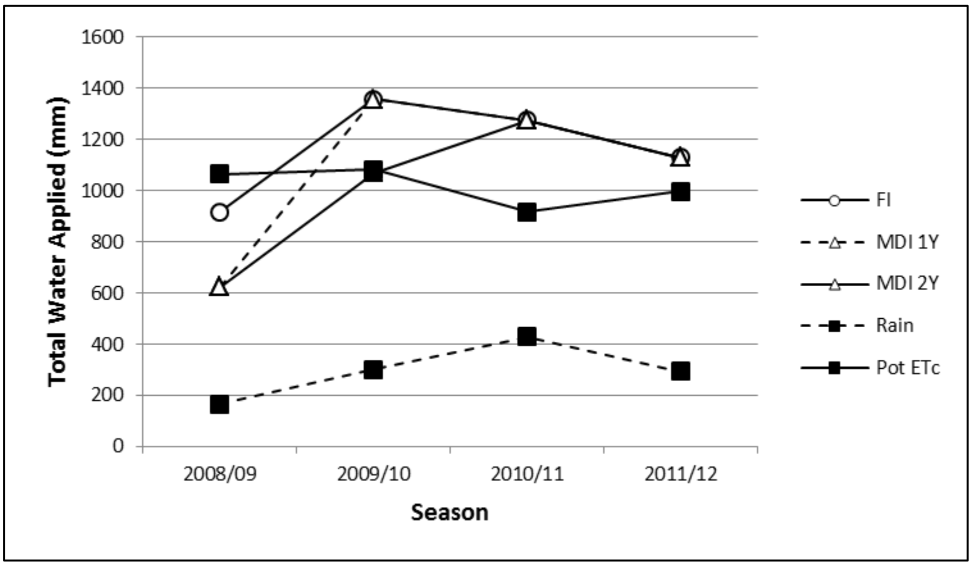


Figure 1: Water applied and potential ET_C across all seasons

As described above, irrigation treatments were determined against soil water monitoring data from a neighbouring planting. However, when seasonal total water application data are plotted against rainfall and potential citrus ET_C calculated by the method of Allen et al. (1998) (Figure 1), it is clear that the total depth of water applied in the FI irrigation treatment was slightly less than potential ET_C in the first season (2008/09), and well above potential ET_C in subsequent seasons.

More importantly, this means that the total water applied to treatment MDI 2Y in 2009/10 was very close to estimated ET_C for that season, meaning that the deficit applied to that treatment in year 2 was much lower than intended. Similarly, the level of water deficit applied to treatment EDI 2Y in 2009/10 was much less than intended, and much less than in 2008/09. This has implications for the interpretation of data, especially the differences between MDI 1Y and MDI 2Y treatments.

Management Treatments

The purpose of the different irrigation treatments applied in this trial was different. The MDI treatments were aimed at maintaining crop production, whereas the EDI treatments were aimed at survival of trees. Within each deficit irrigation treatment 3 different cultural management treatments were applied, along with a control treatment, to test the impact of different management on production maintenance (MDI) or tree survival (EDI).

MDI:

- Mulch – application of a 2m wide strip of mulch along the tree row at the beginning of the trial, to reduce evaporative water losses;
- AG30 – regular applications of AG30 polymer through the drip-tube, to hold the applied water in the root-zone and minimise drainage losses;

- Screen – regular applications of Screen® (kaolin clay film) to tree foliage, to reduce heat uptake by leaves, and reduce the level of stress experienced by the trees.

EDI:

- Hedging – trees were lightly hedged after harvest (Jan-Mar) to remove a large proportion of the developing crop;
- Ethrel – trees were sprayed with Ethrel® at 600ppm after harvest (Jan.) to remove most of the developing crop;
- GA – trees were sprayed with Gibberellic Acid (GA) prior to flowering (Sept.) to reduce flowering/fruit set.

Table 4: Treatment combinations

Irrigation Treatment	Duration	Cultural Treatment
EDI	1 Year	Control Hedge Ethrel® Gibberellic Acid
	2 Years	Control Hedge Ethrel® Gibberellic Acid
MDI	1 Year	Control AG 30 + Screen Mulch + Screen AG 30 + Mulch + Screen
	2 Years	Control AG 30 + Screen Mulch + Screen AG 30 + Mulch + Screen
FI		Control

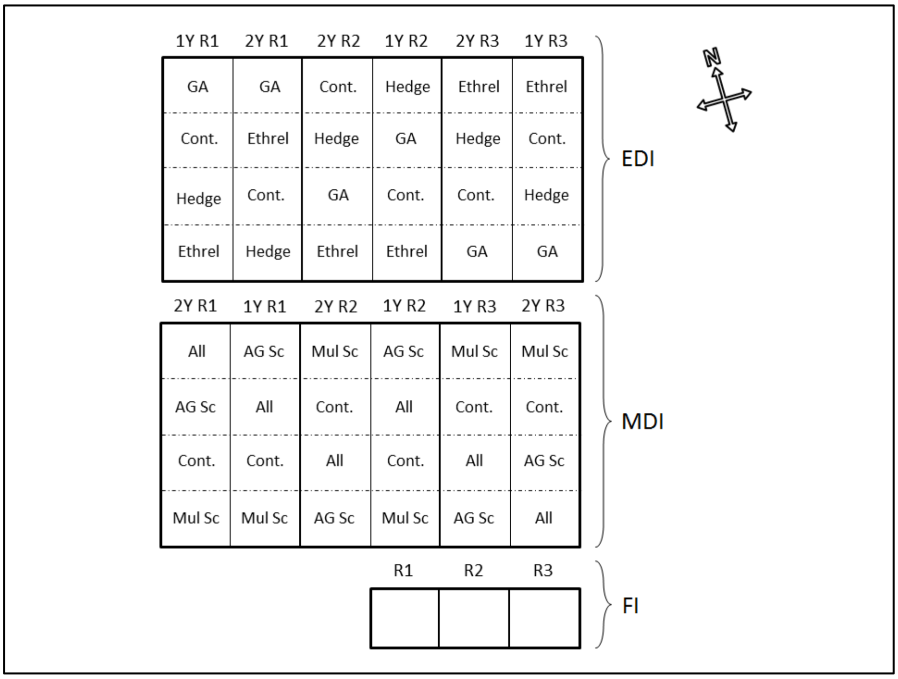
These cultural treatments were applied in combinations in the MDI treatments, and singly in the EDI treatments, and in conjunction with irrigation treatments, i.e. for only 1 season in 1 Year treatments, and for 2 seasons in 2 Year treatments (Table 4).

Each combination was replicated 3 times, giving a total of 51 blocks. The layout in the field trial site was restricted by the irrigation system layout, which meant that irrigation treatments were separated into 3 blocks (EDI, MDI and FI), with randomisation and replication of the cultural treatments within those blocks, as shown in Figure 2.

The timing of application of the various cultural treatments detailed above is laid out in Table 5. Dripper blockages led to delays in application of AG30 polymer in September to November 2009, as well as requiring the replacement of large sections of the drip-tube.

Table 5: Application timing of cultural treatments

Month	EDI Hedge	EDI Ethrel	EDI GA	MDI AG30	MDI Mulch	MDI Screen
Jul. 2008						
Aug. 2008						
Sep. 2008			✓			
Oct. 2008						
Nov. 2008				✓	✓	
Dec. 2008				✓		✓✓
Jan. 2009	✓	✓		✓		
Feb. 2009				✓		✓✓
Mar. 2009				✓		
Apr. 2009				✓		
May 2009						
Jun. 2009				✓		
Jul. 2009				✓		
Aug. 2009				✓		
Sep. 2009			✓	irrigation system issues		
Oct. 2009						
Nov. 2009						✓
Dec. 2009				✓		
Jan. 2010		✓		✓		✓
Feb. 2010				✓		✓
Mar. 2010	✓			✓		
Apr. 2010						
May 2010				✓		
Jun. 2010				✓		



EDI

1Y R1	2Y R1	2Y R2	1Y R2	2Y R3	1Y R3
GA	GA	Cont.	Hedge	Ethrel	Ethrel
Cont.	Ethrel	Hedge	GA	Hedge	Cont.
Hedge	Cont.	GA	Cont.	Cont.	Hedge
Ethrel	Hedge	Ethrel	Ethrel	GA	GA

MDI

2Y R1	1Y R1	2Y R2	1Y R2	1Y R3	2Y R3
All	AG Sc	Mul Sc	AG Sc	Mul Sc	Mul Sc
AG Sc	All	Cont.	All	Cont.	Cont.
Cont.	Cont.	All	Cont.	All	AG Sc
Mul Sc	Mul Sc	AG Sc	Mul Sc	AG Sc	All

FI

R1	R2	R3

Figure 2: Block layout for trial site

Nutrition

Nutrition treatments were not applied to the trial patch. Instead, the existing proportional fertigation protocol utilised across the property was continued. This resulted in nutrient levels in proportion to the water levels applied (e.g. MDI irrigation treatment nominally received 67% as much fertiliser as FI, EDI treatment nominally received 33% as much fertiliser). This was considered to be a reasonable approach, given that plant physiological processes were expected to slow under reduced water availability, thus reducing the demand for nutrients. This also meant that when irrigation treatment returned to Full Irrigation after 1 or 2 seasons, so too did fertiliser application.

Data Collection

Data were collected over 4 consecutive seasons:

- 2008/09 – all deficit treatments receiving deficit irrigation;
- 2009/10 – 2 year treatments receiving deficit irrigation, 1 year treatments in recovery mode;
- 2010/11 – all treatments in recovery mode;
- 2011/12 – all treatments in recovery mode.

A number of measurements were undertaken only during the first 2 seasons of the trial, whilst irrigation level treatments were in place. Other measurements were conducted throughout the 4 seasons, both under deficit irrigation, and during the recovery phase.

Soil Water Content

Soil water content was monitored weekly throughout the trial, using logging capacitance probes (Sentek® Diviner 2000®), at 10 cm intervals down to 160 cm depth. All readings were taken around mid-morning.

Plant Physiology

Canopy temperature (*Tc*) was measured weekly during the initial 2 seasons, using an infrared thermometer with a spectral response between 6.5 and 18 µm, and a 10:1 optical resolution. Readings were taken between midday and 1pm, from a distance of 2 m and in the horizontal plane, resulting in a measurement zone of 20 cm diameter (similar to the method used by Sepaskhah and Kashefipour, 1994). All 4 measurement trees in each treatment x replicate were measured. The temperature of a sheet of white paper was also measured as a standard for ambient temperature, at the beginning and end of measurements on each occasion.

Predawn and midday leaf water potential (Ψp and Ψlm) were measured monthly during the peak irrigation period of the first season (December to April) using a pressure chamber, after the method of Turner (1981). A single leaf from half of the treatment blocks was measured on each occasion, selected from amongst mature leaves in full sun. Readings were carried out immediately the leaf was excised from the tree.

Canopy leaf area index (LAI) was measured on 3 occasions (March 2009, November 2009 and July 2010), using a LI-COR® LAI 2000® Plant Canopy Analyser. A 90° shield was used on the sensor, which faced along the tree row toward North for all readings, giving a reading arc from roughly NW to NE. At each site 4 readings were taken, at equal distance across the tree row spacing, and staggered along the row as described by Strachan et al.

(2005), and illustrated in Figure 3. These 4 readings were analysed by the software package (LAI-2000 File Viewer 1.09) to determine *LAI* for each treatment block.

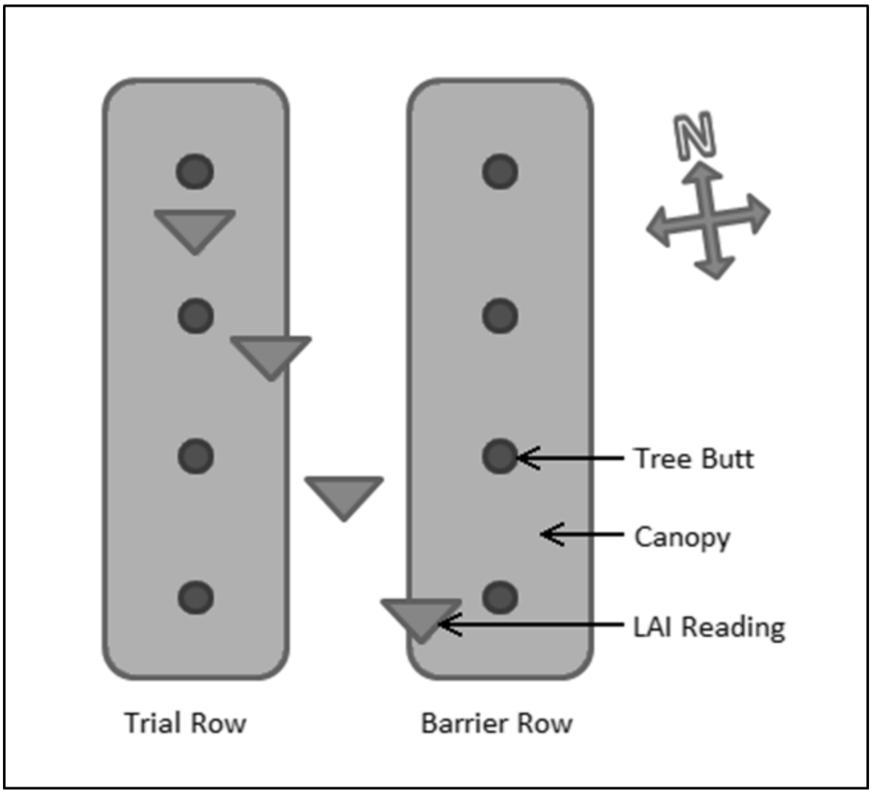


Figure 3: Leaf area index measurement positions

Crop Response

Fruit counts were conducted during the initial season (2008/09), in December 2008 (after initial fruit set, but before the second fruit drop) and March 2009 (after the second drop). Counts were taken within a cube-shaped quadrat 25 cm in each dimension, at 4 locations per tree (one each at the NW, NE, SW and SE corners). The counts from the 4 quadrats were summed for each tree, giving totals for 4 trees in each replicate block of each treatment.

Fruit growth rate was monitored weekly following final fruit set (roughly late January) until harvest (roughly December) in each season, using an Electronic Fruit Size Measure (http://www.gusstoday.com/datalogger.html), which uses a silicone loop to measure fruit circumference, and stores the result electronically, as calculated diameter. Samples of 12 labelled fruit per treatment block, consisting of 3 randomly selected fruit on each of the 4 measurement trees, were measured throughout each season.

As the trees at the trial site were Valencia oranges, fruit hung on the tree for over 12 months, and harvest generally occurred in December of the season following flowering and fruit set (2009, 2011 & 2012). However, the fruit which set in the 2009/10 season was not harvested until February 2011.

Total weight of fruit per 4 tree block was measured at harvest every season (with the exception of EDI treatments in the initial season, when fruit load was extremely low), and fruit size distribution of the fruit from each block (number of fruit in each count size class) was assessed by sorting the fruit in a packing shed.

Data Analysis

The plant physiology and crop response data collected according to the description above was subjected to Randomised Complete Block Analysis of Variance (ANOVA), to identify any significant differences due to irrigation treatment, cultural treatment or duration of irrigation deficit. Differences between treatments were deemed significant at an alpha value of 0.05%.

On-Farm Drought Monitoring Program

A range of sources, including industry organisations, government officers and private consultants, were used to identify citrus and almond growers applying less than optimum levels of irrigation to at least some plantings. These growers were approached, and asked to provide information about their irrigation practices and other cultural techniques applied to those plantings. Individual plantings of consistent plant material and treatment were identified as distinct "sites" for the purpose of monitoring.

For each site, detailed information about the planting (crop type, variety, rootstock, spacing etc.) and the irrigation system (type, emitter make and model, spacing, application rate) were collected.

The cooperating growers were asked to record irrigation events applied to the site (date and duration, from which depth of water applied was calculated) for the whole season, as well as documenting their cultural practices, especially any specific treatments related to managing reduced irrigation availability, such as modifications to the irrigation system (installation of drip, or reduction in wetted area) or canopy reduction (hedging or pruning).

Yield data were collected and analysed, in order to assess the impact of the irrigation strategy on production.

Data were collected for each site over 5 irrigation seasons (2007/08 to 2011/12), to assess the immediate impact of reduced irrigation applications, as well as the degree of recovery from reductions, and the overall economic impact of the reductions over a longer time scale.

The primary aim of the project was to identify management strategies to assist irrigators to cope with periods of allocation reduction.

Data Collection and Manipulation

Data on plantings and irrigation system at each site were collected and entered into IRES (Irrigation Recording and Evaluation Software, Rural Solutions SA). Irrigation event data were collected at the end of each season for entry into IRES, and analysed against reference evapotranspiration and rainfall data from the Bureau of Meteorology (BoM) and crop coefficients based on Allen et al. (1998), using a daily water balance approach.

Irrigation event data incorporated soil water monitoring data, where available, and the final outcomes of this analysis included annual irrigation depth, summed drainage, and timing and degree of water stress across the season at each site.

Stress coefficient (K_S) is a measure of the degree to which water use is reduced due to lack of available water in the soil (Allen et al., 1998), with K_S equal to 1 when soil water content was calculated to be within the readily available range (soil water tension between -8 kPa and -60 kPa), and declining towards 0 as soil water content declined towards permanent wilting point (soil water tension declining from -60 kPa to -1500 kPa). The water balance calculations determined K_S on every day of the season, with seasonal K_S equal to the average over the whole season, and critical K_S equal to the average for the critical period around flowering and fruit set (from 1st August to 31st October for Almond, Avocado and Citrus sites, and from 1st October to 31st October for Grapevine sites).

Detail about the cultural treatments that were applied to each site, such as hedging, pruning, anti-transpirant sprays etc. was collected. It is noted that some of these treatments were applied to very few sites, making statistical interpretation of their impacts difficult (see Table 12 & Table 13).

The outcomes of the irrigation management strategies at each site were measured as yield from each site. Fruit quality was initially requested, but the response from participating irrigators proved very disappointing, with very few able to provide meaningful data (e.g. percent packout and size classes).

Data Presentation

Yield was the dependent variable, plotted against applied water (irrigation plus rainfall), crop evapotranspiration (ET_C) and the degree of stress (average stress coefficient, K_S; full season and critical period). A further comparison was made between Irrigation Water Use Index (IWUI, tonnes of fruit per megalitre of irrigation water applied) and applied water.

These results were presented graphically, revealing a cloud of data points. A boundary line designating the edge of each data cloud was derived by the method of Schnug et al. (1996). This boundary line indicates the apparent upper limit of the response of the dependent variable (Yield or IWUI) at any level of the independent variable (applied water, ET_C, stress days or K_S).

The boundary lines for this work were drawn as 3rd order polynomials. Schnug et al. (1996) have recommended using 4th order polynomials, but the small volume of data in this work results in some apparently spurious relationships, which are rendered far more reasonable by using more robust 3rd order polynomials.

Statistical Analysis

Regression analysis on productivity was carried out in order to identify significant relationships between variables collected as part of the Drought Monitoring Program. Wide ranging parameters were regressed against Yield and IWUI (Table 6). Regression analysis was carried out for each season of monitoring, and for parameters averaged across all 5 seasons, with results displayed as t-statistics.

Natural logarithm and square root transformations were applied to Yield to produce more reliable regression results. Only sites with data for all 5 seasons were included in the analyses. In addition, sites were excluded when yield was low (<1 t/ha for Almonds, <10 t/ha for Citrus), and multiple sites with identical applied water and recorded yield were reduced to a single site (occurred in later years as a result of a reduction in specificity of data supplied by participating growers). Some possible combinations of “independent” variables were absent or represented by only one site, resulting in lack of balance and reliability.

Regression analyses were carried out sequentially, with least significant parameters being progressively removed from the model in order to increase the power and relevance of the regression on the remaining parameters. The inclusion of rootstock and/or variety in regression analyses, with their multiplicity of levels, produced serious over-fitting in the model, and such analyses are for informal inspection only.

Table 6: Parameters included in regression analysis against yield

Planting Parameters	**Irrigation System Parameters**	**Cultural Management**	**Irrigation Management**
Variety Rootstock Age	System Type Partial Cover Converted to Drip Converted to PRD RAW % Wetted Area	Crop Removal Anti-transpirant Hedging/Topping Topworking Skeletonising	Applied Water Critical Period Stress Seasonal Stress

Results

Citrus Drought Research Trial

Soil Water Content

Soil water content data over the course of the trial are shown in Figure 4, as monthly averages for irrigation treatment. Units are percentage of maximum, as the absolute values varied between treatments, most likely due to differences in soil type.

Vertical dashed lines indicate the transition between seasons, the times at which irrigation treatments were modified according to the duration of treatment. So for example, 1Y treatments were modified to receive full irrigation from the end of June 2009 (first dashed line). All treatments received full irrigation from the 2010/11 season onwards.

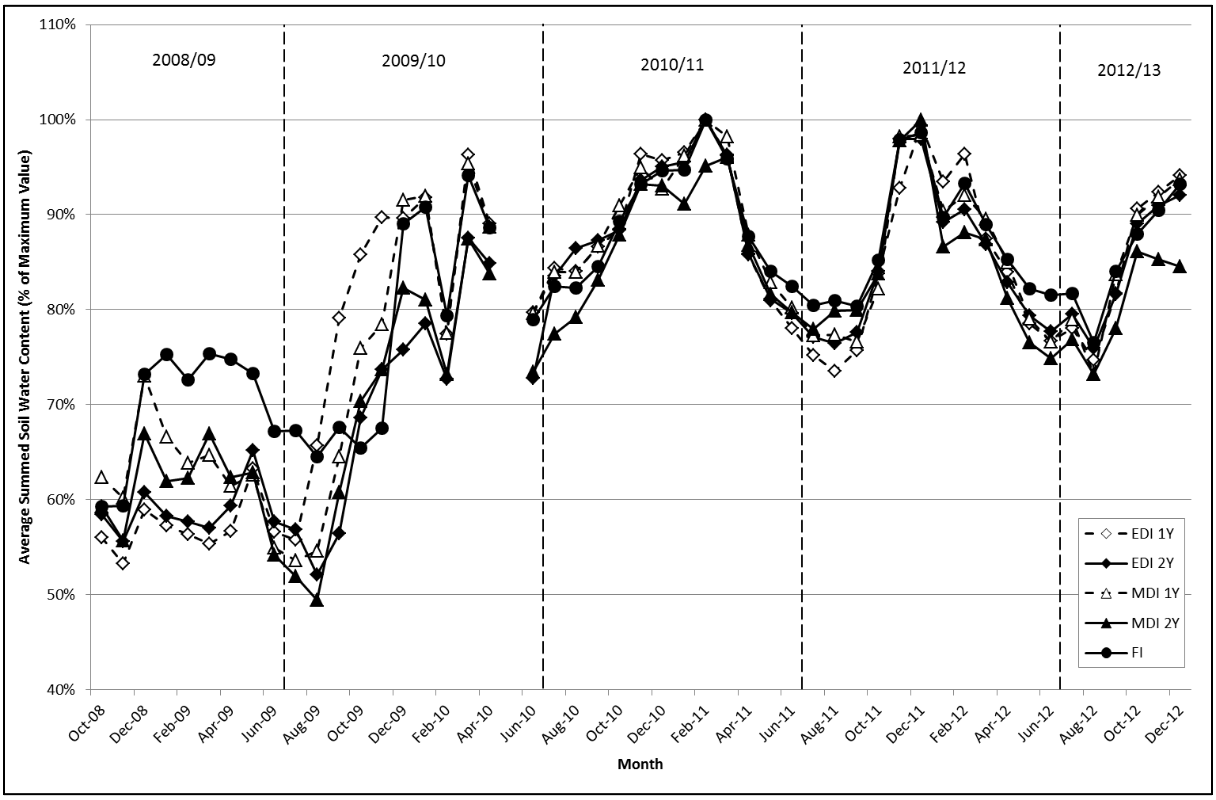


Figure 4: Soil water content of irrigation/duration treatments across all seasons (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, see Table 3, 1Y & 2Y refer to the duration of deficit irrigation)

Soil water content during 2008/09 was lower than during later seasons in all treatments, including FI. This reflects problems with the irrigation system and irrigation scheduling during this initial season, and the resultant lower water volumes applied (Figure 1, Table 3).

Even so, the difference in soil water content between irrigation treatments is clear through the middle of the season, with EDI treatments exhibiting the lowest water content, MDI treatments showing mid-range water content, and the FI treatment having the highest water content.

In the 2009/10 season water content in the 1Y treatments rose rapidly from the commencement of irrigation in August, in fact showing higher soil water content than FI, likely due to the reduced canopy in these trees at this time (Figure 8), and consequently lower water use. The 2Y treatments maintained soil water content in proportion to their relative irrigation treatments, but higher than in 2008/09, reflecting the increased irrigation applied in this second season.

From 2010/11 onward the soil water content in all treatments followed a similar path, being high during the active irrigation season and lower during winter. This annual pattern reflects the location of the soil water monitoring sensors, which were located under the canopy and adjacent to the drip-tube, making them very sensitive to drip irrigation applications, and relatively insensitive to rainfall. Interestingly, the EDI treatments showed higher soil water content than MDI treatments in the winter of 2009 (May, June and July), possibly as a result of their reduced canopy intercepting less rainfall.

The pattern of soil water content measurements confirms that the irrigation and duration treatments created a greater deficit in year 1 than year 2; and the greatest deficit in EDI, a moderate deficit in MDI, and the least deficit in FI.

Plant Physiology

Canopy Temperature

Canopy temperature (*Tc*) averaged across 4 trees by 9 irrigation and cultural treatments, 2 durations and 3 replicates (n = 216), for 6 selected dates in early 2009 is shown in Table 7. Standard deviation within treatments on the same date varied between 0.63 and 2.77, of a similar magnitude to the differences between treatments. Duration treatments are not shown, as these data are from the initial season when all deficit irrigation treatments were active. Groupings of no significant difference are indicated by the same letter.

The data demonstrates the large variability in *Tc* between dates, mostly as a result of weather conditions on the day of measurement, and the much lower variation between treatments on any particular date.

Table 7: Canopy temperature (Tc, average of 6 replicates) on selected dates (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, additional wording refers to the cultural treatments, see Table 4, letters indicate groups of no significant difference within each date)

Treatment	18/12/08	20/01/09	19/02/09	20/03/09	17/04/09	21/05/09
EDI GA	25.9^{AB}	45.6^{A}	36.9^{AB}	26.4^{ABCD}	24.6^{A}	25.1^{AB}
EDI Ethrel	26.1^{AB}	44.4^{B}	37.1^{A}	26.4^{ABC}	24.4^{AB}	25.3^{A}
EDI Hedge	25.3^{AB}	44.2^{BCD}	37.0^{A}	26.9^{A}	24.1^{ABC}	24.6^{AB}
EDI Cont.	25.7^{AB}	44.6^{AB}	37.0^{A}	26.6^{AB}	24.4^{AB}	25.2^{A}
MDI AgSc	24.9^{B}	43.3^{CD}	35.9^{C}	25.3^{CDE}	23.4^{BCD}	24.8^{AB}
MDI MulSc	25.3^{AB}	43.3^{CD}	36.2^{BC}	25.7^{BCDE}	23.0^{CD}	24.3^{B}
MDI All	25.7^{AB}	43.1^{D}	35.8^{C}	25.2^{DE}	23.2^{CD}	24.5^{AB}
MDI Cont.	24.7^{B}	$43.4B^{CD}$	36.1^{C}	25.2^{E}	22.4^{D}	24.8^{AB}
FI Cont.	27.7^{A}	42.8^{D}	35.7^{C}	25.4^{BCDE}	22.7^{CD}	24.9^{AB}

Water stress and the resultant reduction in transpiration should reduce evaporative cooling of the canopy, resulting in a warmer canopy in stressed trees. Bearing in mind that all treatments received less water than the target during this season, and therefore all trees were more stressed than intended, there is no true unstressed treatment. However, the EDI treatments tended to be warmer (more stressed) than the FI treatment on most dates, with the MDI treatments generally lying between these extremes.

What these data fail to demonstrate is any consistent impact of cultural treatments on water stress, and therefore *Tc*. There is only one date amongst the displayed data when there is a significant difference between 2 of the EDI treatments (EDI GA warmer than EDI Hedge on 20/01/09), and no dates where there is a significant difference between any of the MDI treatments. Analysis of the full set of data (29 dates) failed to reveal any consistent significant effect.

Leaf Water Potential

Predawn and midday leaf water potential (Ψp and Ψlm) for the 2008/09 season are displayed in Figure 5 and Figure 6 respectively, for irrigation and cultural treatments. Duration treatments are not shown, as these data were collected during the initial season, when all deficit irrigation treatments were active.

Significant differences in Ψ were found between treatments on one date for predawn readings (Figure 5), and 2 dates for midday readings (Figure 6). The dates of significant differences did not overlap, however.

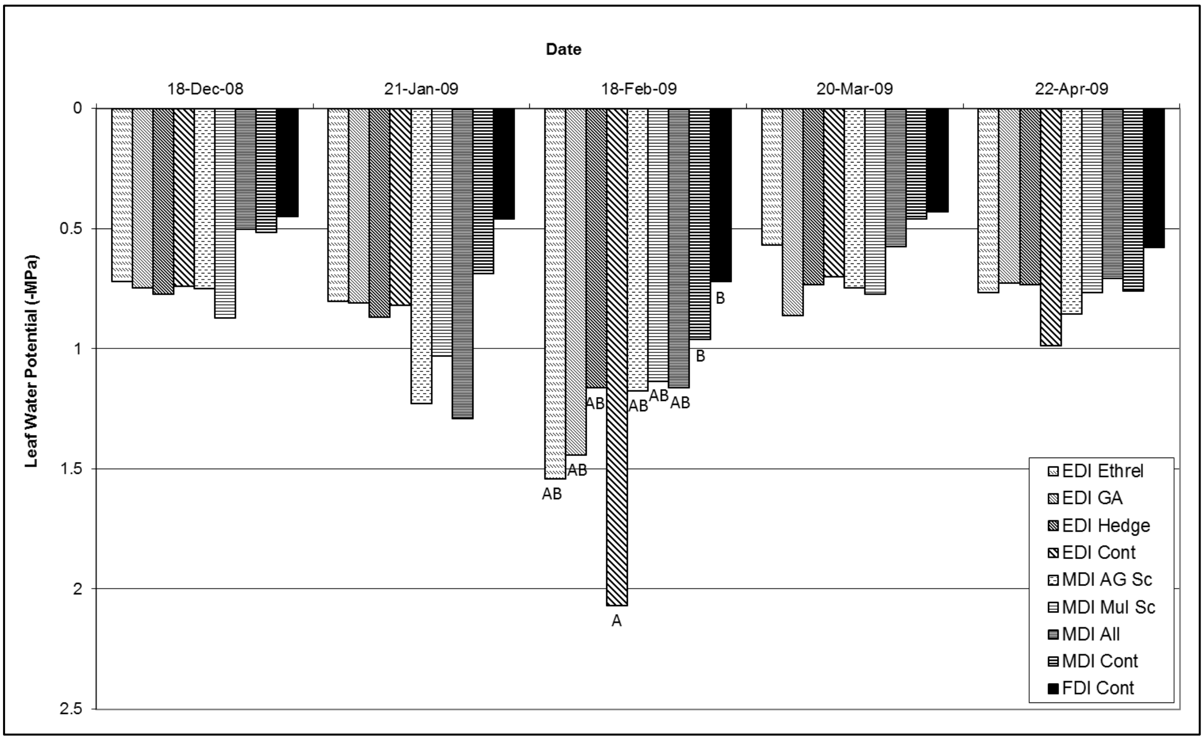


Figure 5: Predawn leaf water potential (Ψp) on selected dates (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, letters indicate groups of no significant difference within each date)

Results for 2 dates (predawn on 18 Feb 09 and midday on 03 Dec 08) show the FI treatment is significantly less stressed (Ψ less negative) than one of the EDI treatments, as might be expected. However, on 22 Apr 09 the midday measurement shows 2 MDI treatments as significantly more stressed (Ψ significantly more negative) than FI treatment, while all EDI treatments are not significantly different to the FI treatment. It is not clear why this is so.

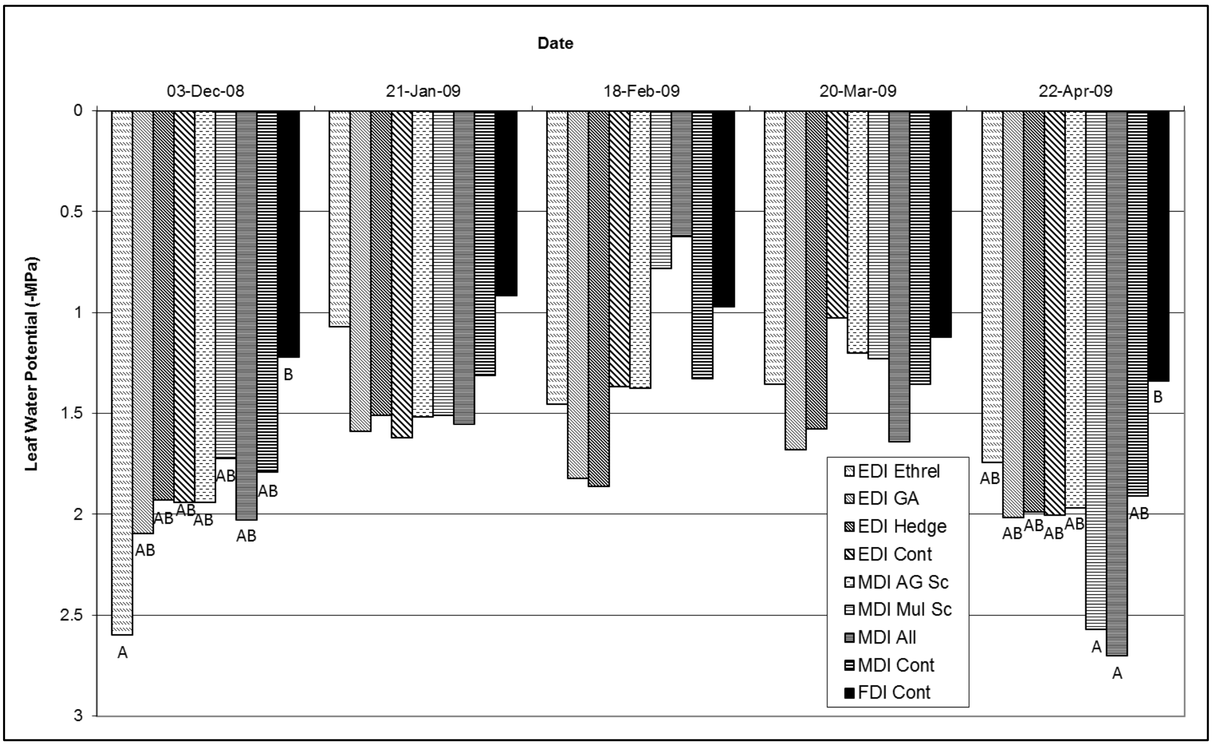


Figure 6: Midday leaf water potential (*Ψlm*) on selected dates (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, letters indicate groups of no significant difference within each date)

Leaf Area Index

Leaf Area Index (*LAI*) measured on 3 different dates is displayed in Figure 7 for duration treatments, and in Figure 8 for cultural treatments. It shows an initial decline in *LAI* in trees under deficit irrigation treatments (from March 2009 to November 2009), followed by a partial recovery by July 2010. During the same period the full irrigation treatment trees suffered a gradual decline in *LAI*, to finish in a similar condition to the droughted trees.

Deficit irrigation was applied from July 2008, so at the first measurement date (March 2009) the trees had been under deficit for 9 months. At this time the reduction in *LAI* below the FI treatment was only significant for the EDI Hedged treatment (Figure 8), which had not only suffered deficit irrigation, but had also had its canopy trimmed to remove the crop.

By November 2009 both MDI duration treatments had significantly lower *LAI* than the FI treatment, and both EDI duration treatments had lower *LAI* than MDI (Figure 7), demonstrating a clear impact of deficit irrigation on leaf retention.

The responses were less clear amongst the cultural treatments (Figure 8), but there was a clear difference between FI and the deficit treatments. In addition, the MDI All treatment, which had received mulch, polymer and sunscreen cultural treatments had significantly lower *LAI* than the MDI control treatment, suggesting that the not only were the cultural treatments not effective in reducing stress, they may in fact have had a negative influence on canopy retention during the spring and early summer.

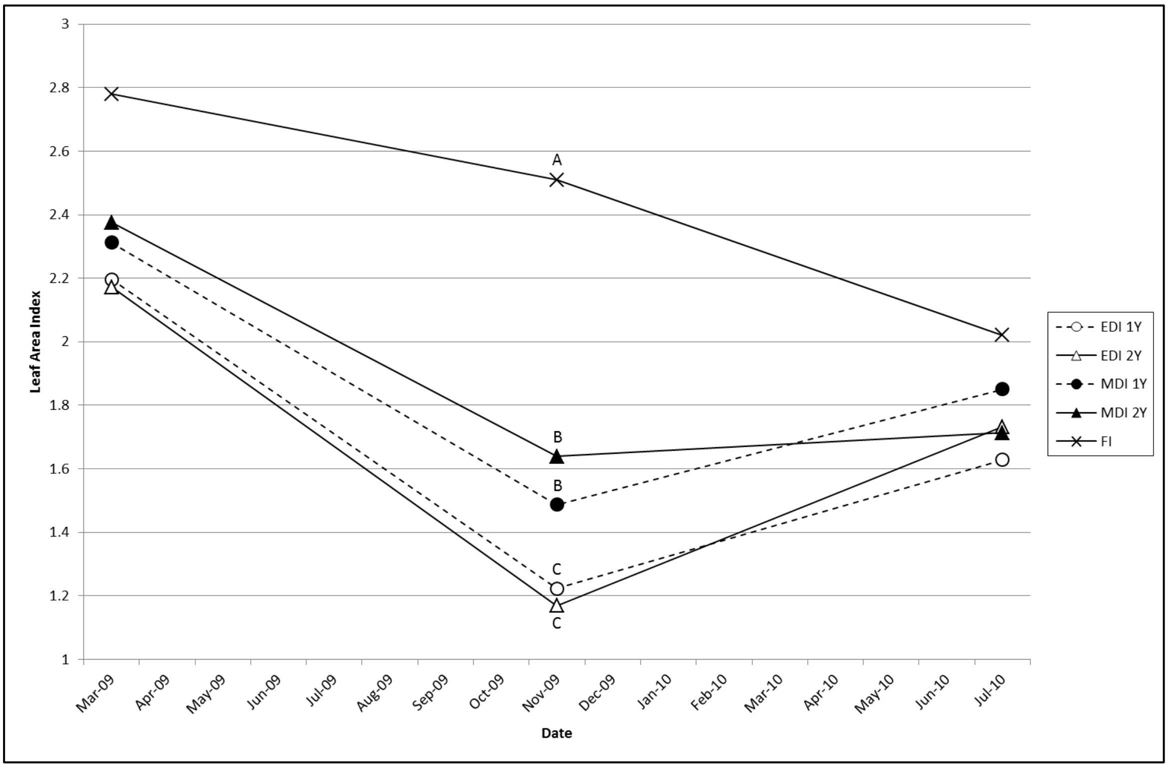


Figure 7: Leaf area index by irrigation and duration on selected dates (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, 1Y & 2Y refer to the duration of deficit irrigation, letters indicate groups of no significant difference within each date)

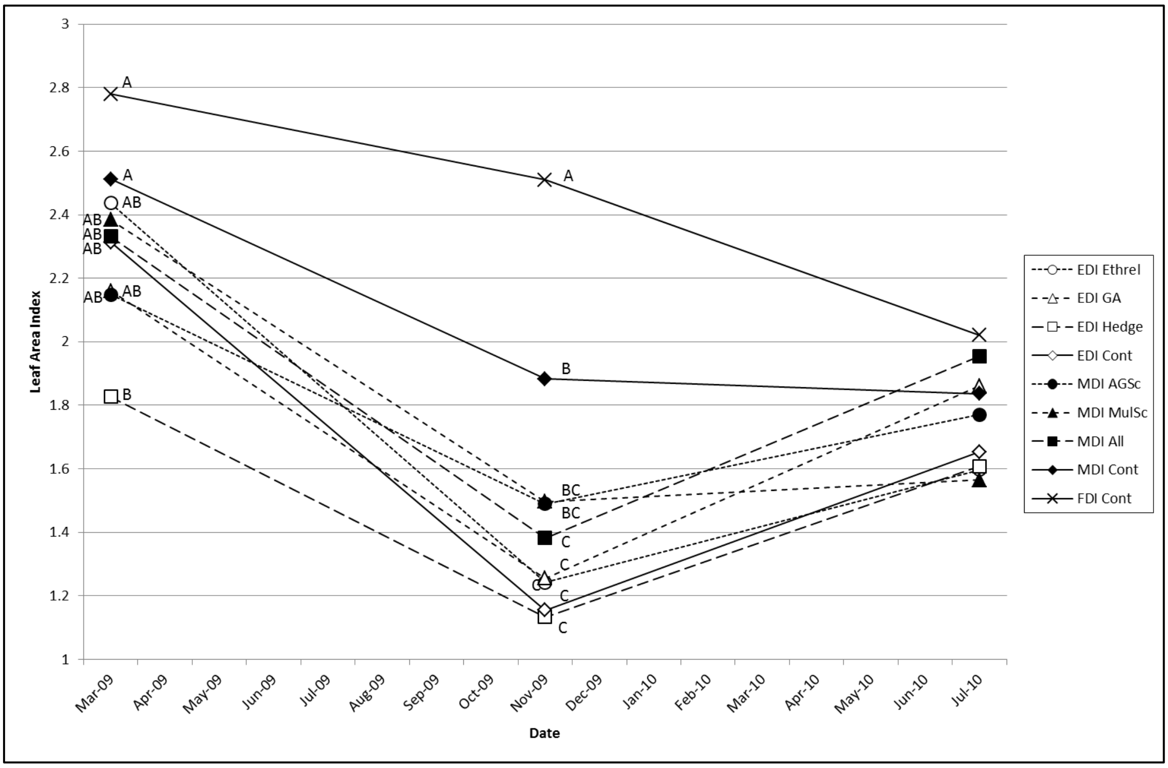


Figure 8: Leaf area index by cultural treatment on selected dates (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, additional wording refers to the cultural treatments, see Table 4, letters indicate groups of no significant difference within each date)

By July 2010 there was no significant difference in *LAI* between any of the treatments (Figure 7 & Figure 8), suggesting a significant autumn flush (growth of new leaves) in the deficit irrigated treatments, in response to the high soil water levels experienced during March and April 2010 across all treatments.

Interestingly there is no significant difference between 1Y and 2Y treatments within either the EDI or MDI irrigation treatments (Figure 7). At the March 2009 measurement all treatments were still under deficit, but the 1Y treatments returned to full irrigation soon after this (July 2009), however *LAI* followed a similar path despite this change.

Crop Response

Crop Load

Figure 9 presents fruit count data from quadrat counts at each of the 4 corners of each tree, measured in December and March in the initial season of the trial (2008/09), following the first and second fruit drop periods respectively.

There was no significant difference between counts in December 2008, even when testing at the level of irrigation treatment only (not shown), mostly due to the wide range in counts from individual trees. The data suggest a small influence on fruit count due to irrigation treatment, with EDI trees responding to early stress by flowering heavily and setting more fruit in the initial fruit set period (Krajewski & Rabe, 1995).

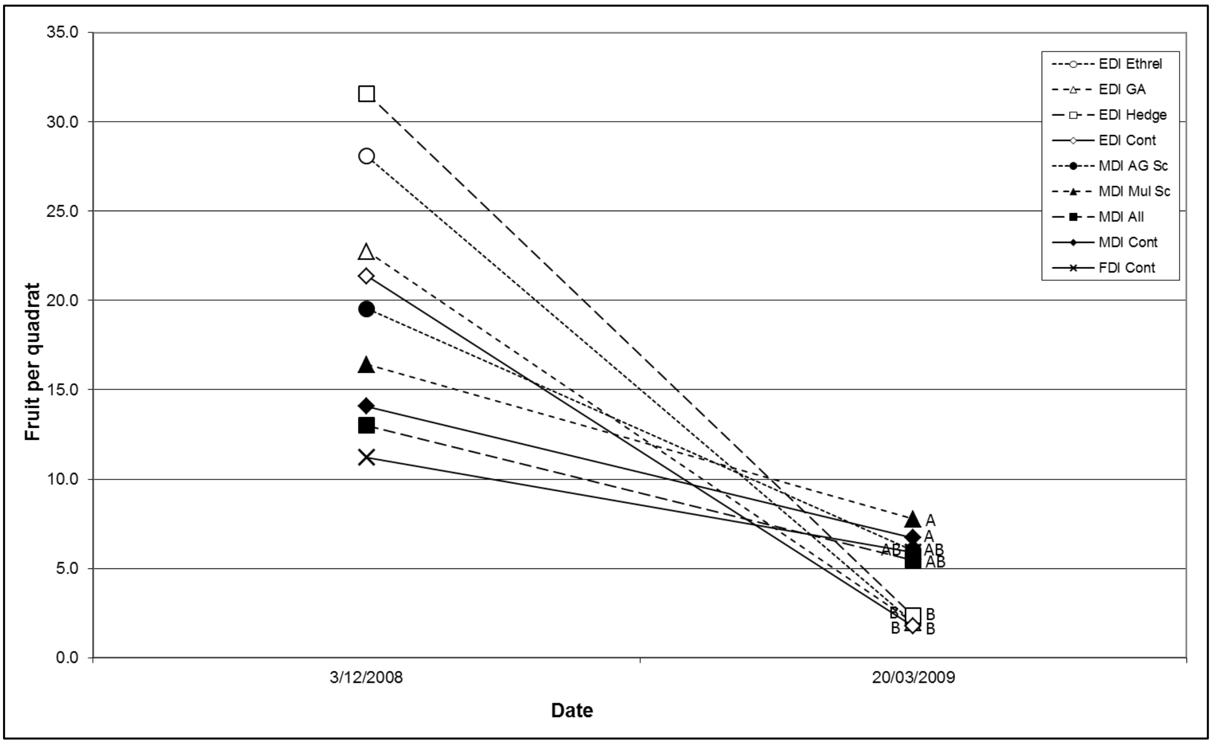


Figure 9: Fruit count (4 quadrats) displayed by irrigation and cultural treatment (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, additional wording refers to the cultural treatments, see Table 4, letters indicate groups of no significant difference within each date)

A significant difference emerged after the summer fruit drop period, when the EDI treatments experienced heavy shedding of fruit, with the result that all EDI treatments carried significantly less fruit in March than 2 of the MDI treatments (Figure 9). When analysed just at the level of irrigation treatment, EDI had significantly fewer fruit than MDI and FI on this later date (data not shown). This lower crop load in the highest irrigation deficit treatments mirrors the findings of Perez-Perez et al. (2008).

Of particular interest was the consistent low fruit count across the EDI cultural treatments. The cultural treatments applied were designed to enhance the natural fruit drop, to minimise the stress experienced by trees from carrying too high crop load. However, it appears that the stress on the trees was sufficient to cause such a large fruit drop that there was no difference between the EDI control and those trees receiving enhanced fruit drop treatments.

Fruit Growth

The growth of individual tagged fruit over the course of the season is illustrated in Figure 10 for irrigation and duration treatments. The X-axis of each graph shows the same portion of the season, although from different years, and the Y-axes show the same diameter scale, allowing good comparison of growth between seasons as well as within each season.

Note that in 2008/09 and 2009/10 fruit growth data were only collected from FI and MDI treatments.

The general shape of the growth curve is similar for all seasons and all treatments, with rapid growth during spring and summer after final fruit set, slow growth through winter, and a second spurt of growth in the following spring. Being Valencia oranges the fruit was harvested between December and early February of the season after the fruit was set.

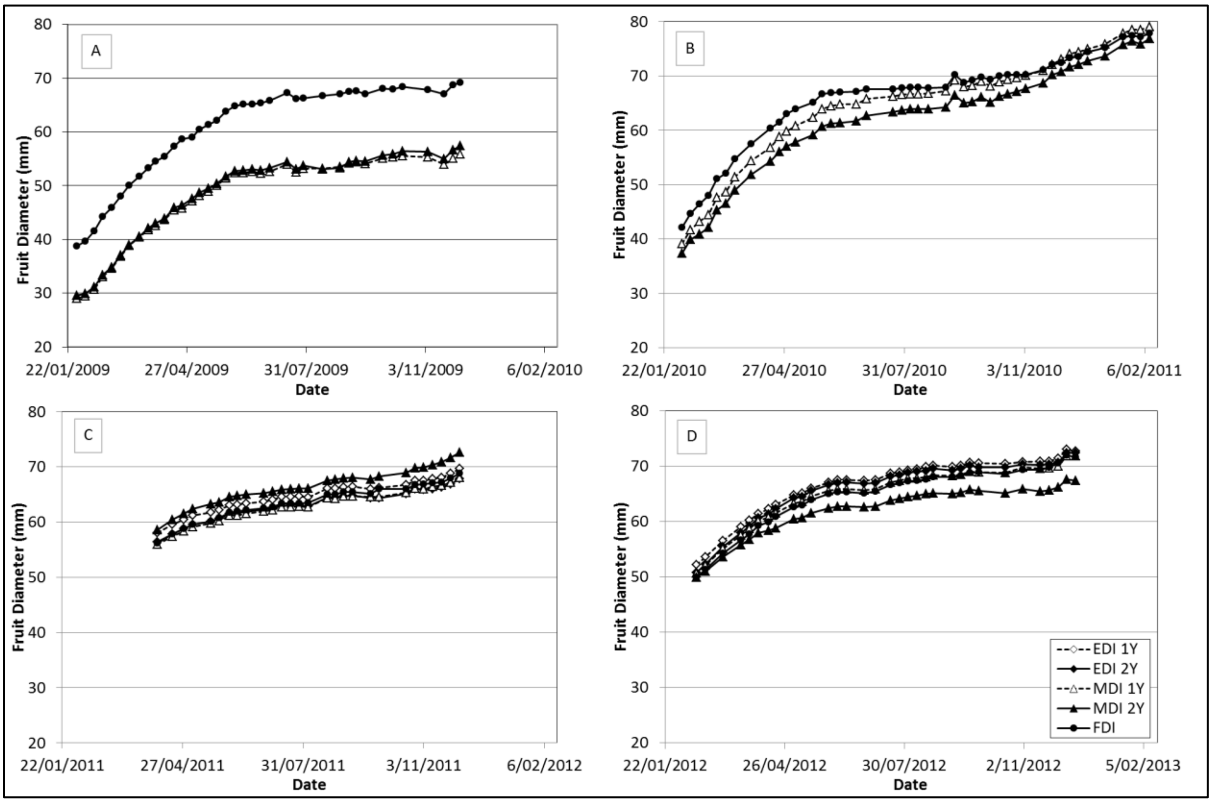


Figure 10: Change in fruit diameter over each season, displayed by irrigation and duration (A = 2008/09, B = 2009/10, C = 2010/11, D = 2011/12, EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, see Table 3, 1Y & 2Y refer to the duration of deficit irrigation)

Similar curves and separation between irrigation treatments as seen in 2008/09 (Figure 10a) were also found by Gonzalez-Altozano and Castel (2000a).

Average fruit size for different treatments on 3 days each season (early, mid and late season) is shown in Table 8 (irrigation by cultural treatment) and Table 9 (irrigation by duration). Groups of no significant difference are indicated for each date by letters.

The data in the figure and tables illustrate the change in fruit size across each individual season, and also the difference in fruit size at the same stage in different seasons. This difference between seasons is in large part due to the difference in crop load between seasons, which in turn influenced fruit growth rate (higher crop load leading to reduced fruit growth rate).

Table 8: Average fruit diameter (mm) on 3 similar dates across 4 seasons for irrigation by cultural treatment (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, see Table 3, additional wording refers to the cultural treatments, see Table 4, letters indicate groups of no significant difference within each date)

Date	EDI Eth	EDI GA	EDI Hed	EDI Cont	MDI AgSc	MDI MuSc	MDI All	MDI Cont	FI
02/04/09					41.2^{C}	45.3^{B}	39.2^{C}	45.3^{B}	54.5^{A}
29/07/09					52.0^{C}	55.3^{BC}	50.5^{C}	56.2^{B}	66.3^{A}
25/11/09					54.1^{B}	57.9^{B}	54.2^{B}	57.4^{B}	68.7^{A}
01/04/10					53.0^{B}	53.8^{B}	57.0^{B}	52.6^{B}	57.5^{A}
29/07/10					65.3	65.3	63.6	66.2	67.7
25/11/10					71.4	71.2	69.8	72.1	72.1
07/04/11	56.8^{AB}	56.1^{B}	58.9^{A}	57.0^{AB}	57.3^{AB}	57.0^{AB}	57.7^{AB}	57.0^{AB}	56.2^{AB}
28/07/11	63.6^{AB}	62.7^{B}	65.6^{A}	63.6^{AB}	64.5^{AB}	64.0^{AB}	65.0^{AB}	64.2^{AB}	63.4^{AB}
24/11/11	67. 6	67.0	69.6	67.1	69.9	68.7	70.3	68.9	67.9
05/04/12	61.2^{A}	61.0^{AB}	61.0^{AB}	61.2^{A}	58.4^{B}	59.3^{AB}	59.0^{AB}	59.5^{AB}	59.3^{AB}
26/07/12	69.1^{A}	68.6^{ABC}	68.1^{ABC}	69.1^{A}	64.9^{C}	66.2^{ABC}	65.9^{BC}	66.3^{ABC}	67.0^{ABC}
22/11/12	70.9^{A}	70.9^{A}	70.0^{AB}	70.9^{A}	67.0^{B}	67.8^{AB}	68.1^{AB}	68.0^{AB}	69.8^{AB}

Table 9: Average fruit diameter (mm) on 3 similar dates across 4 seasons for irrigation by duration (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, see Table 3, 1Y & 2Y refer to the duration of deficit irrigation, letters indicate groups of no significant difference within each date)

Date	EDI 1Y	EDI 2Y	MDI 1Y	MDI 2Y	FI
02/04/09			42.5^{B}	43.0^{B}	54.5^{A}
29/07/09			53.2^{B}	53.8^{B}	66.3^{A}
25/11/09			55.1^{B}	56.7^{B}	68.8^{A}
01/04/10			54.4^{B}	51.8^{C}	57.5^{A}
29/07/10			66.5^{A}	$63.\ 7^{B}$	67.7^{A}
25/11/10			72.1	70.2	72.1
07/04/11	58.0^{A}	56.4^{AB}	55.9^{B}	58.6^{A}	56.2^{AB}
28/07/11	64.7^{AB}	63.1^{BC}	62.8^{C}	66.1^{A}	63.4^{ABC}
24/11/11	68.8^{B}	66.9^{C}	67.2^{BC}	71.7^{A}	67.9^{BC}
05/04/12	61.5^{AB}	60.7^{AB}	60.1^{AB}	57.9^{C}	59.3^{BC}
26/07/12	69.0^{AB}	68.4^{AB}	67.4^{AB}	64.2^{C}	67.0^{BC}
22/11/12	70.9^{A}	70.4^{A}	69.7^{A}	65.7^{B}	69.8^{A}

Few significant differences were observed between cultural treatments within each irrigation level on any particular dates (Table 8). Some differences emerged between irrigation and duration treatments (Table 9).

Of particular interest was the significant difference between MDI 1Y and MDI 2Y on 01/04/10 and 29/07/10 (Table 9). This season saw MDI 1Y receive full irrigation, whilst MDI 2Y was still on restricted watering until the beginning of July 2010. Thus the differences on the two dates noted above coincided with this difference in water applied. However, on the final comparison date (25/11/10) the difference had disappeared, and Figure 10b shows fruit size in MDI 2Y catching up to the other treatments after June 2010, under full irrigation.

Yield

Annual yield from each trial block of 4 trees is shown in Figure 11, for irrigation by duration treatments. Cultural treatments are not shown, as there was no difference between treatments.

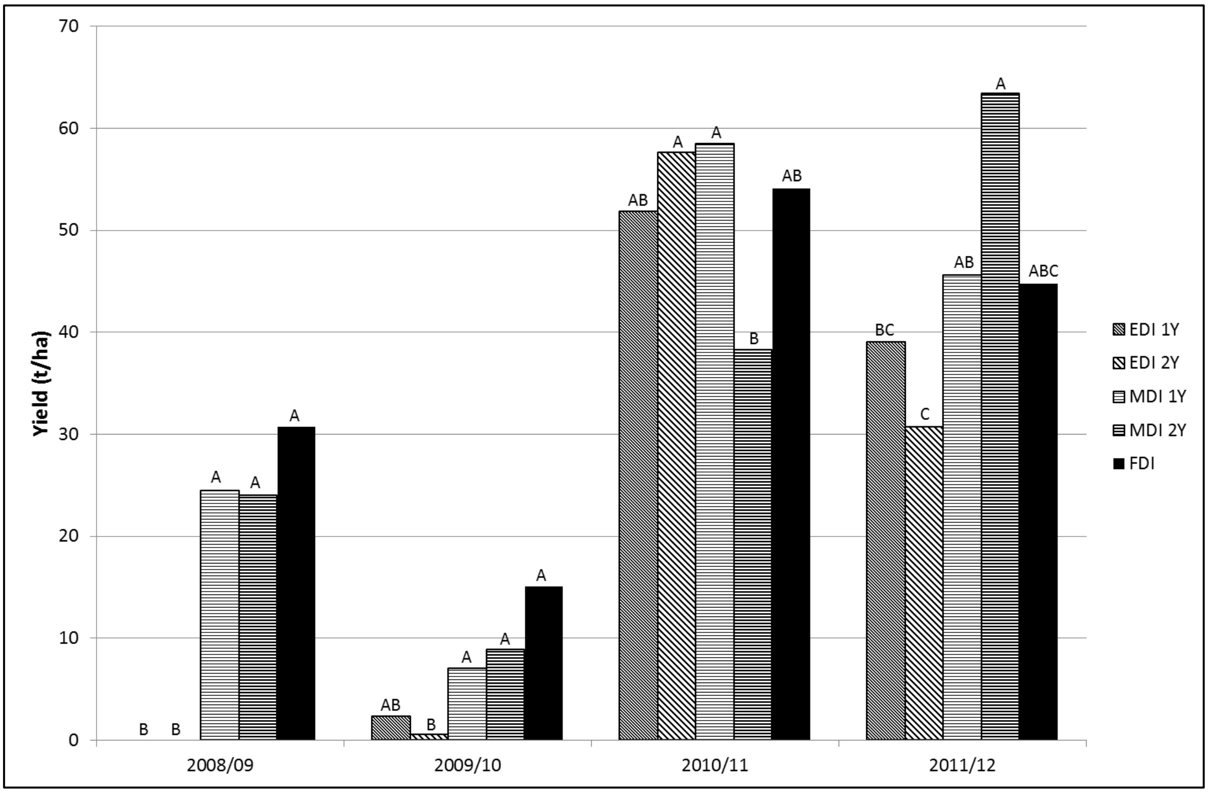


Figure 11: Annual yield per trial block for 4 seasons (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, see Table 3, 1Y & 2Y refer to the duration of deficit irrigation, letters indicate groups of no significant difference within each year)

The EDI irrigation treatments were not harvested in season 1 (2008/09) due to the very low fruit numbers present. They were harvested in 2009/10, but the yields were still very low, especially in the 2Y treatment. Interestingly, yield was down in all treatments in 2009/10, perhaps due to the reduced irrigation applied to all treatments in 2008/9 (see Figure 1).

Biennial bearing is apparent in Figure 11, with most treatments having relatively lower yields in 2009/10 and 2011/12, and higher yields in 2010/11. The exception to this rule is the MDI

2Y treatment, which increased in yield between 2009/10 and 2010/11, and then increased again in 2011/12. The key could be in analysis of water applied and yield in 2009/10.

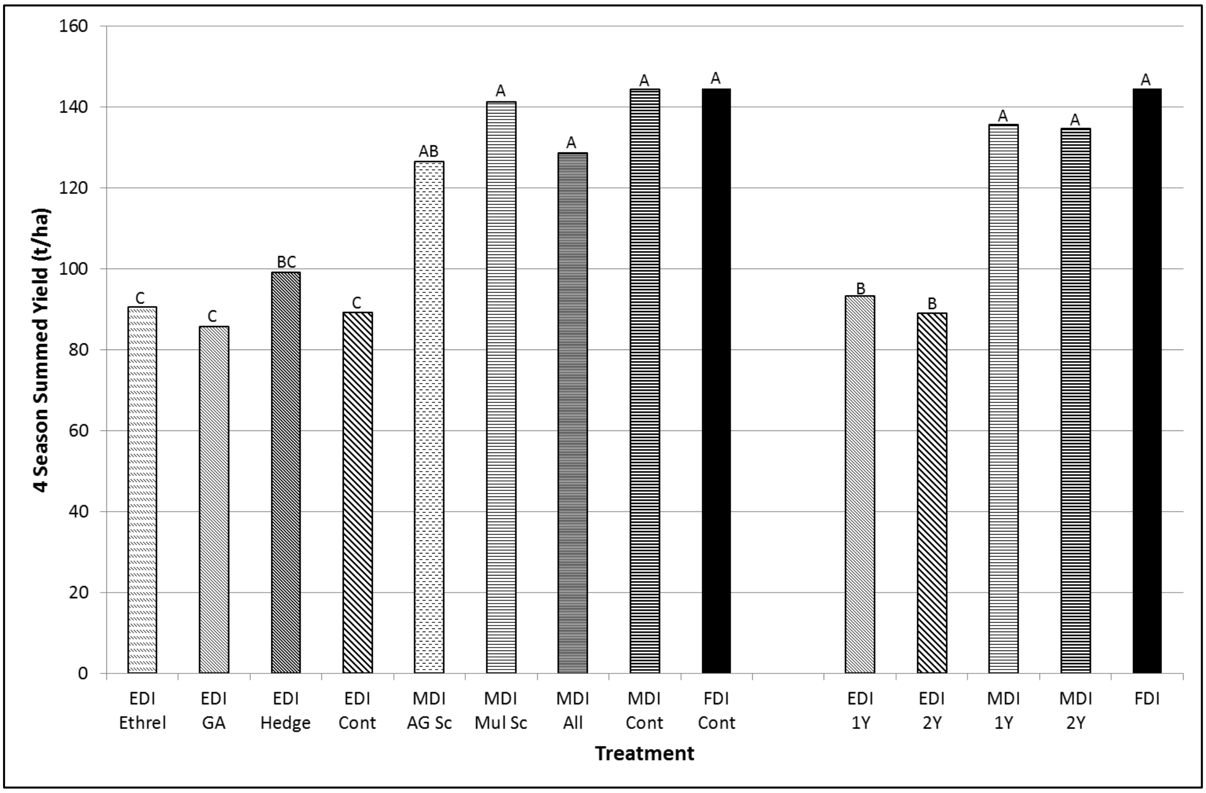


Figure 12: Yield totals over 4 seasons, irrigation by cultural treatment and irrigation by duration (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, 1Y & 2Y refer to the duration of deficit irrigation, additional wording refers to the cultural treatments, see Table 4, letters indicate groups of no significant difference within each year)

Figure 12 presents total yield summed over all 4 seasons of the trial, for irrigation by cultural treatment, and irrigation by duration. It illustrates that the moderate reduction in irrigation to MDI did not result in a significant reduction in total yield over the life of the trial, but the more severe reduction to EDI did. It also demonstrates that duration of irrigation reduction did not have a significant impact over the life of the trial (possibly due to the very moderate reductions applied in 2009/10), nor did any of the cultural treatments.

Fruit Size Class

The weight of fruit in each of a range of fruit size classes is shown in Figure 13 for each of the 4 harvests. There was no harvest in EDI treatments in 2008/09 (Figure 13a), and fruit from duration treatments were not measured separately in this year as there was no difference in water received or cultural treatment up to that point. Cultural treatments are not shown, as there was no difference between treatments.

Differences in the distribution of fruit size classes between seasons reflect differences in yield between seasons (Figure 11). In particular, in 2009/10 (Figure 13b) all treatments produced low yields, and the fruit size class distribution was skewed dramatically toward larger fruit sizes (lower count per carton) as a result.

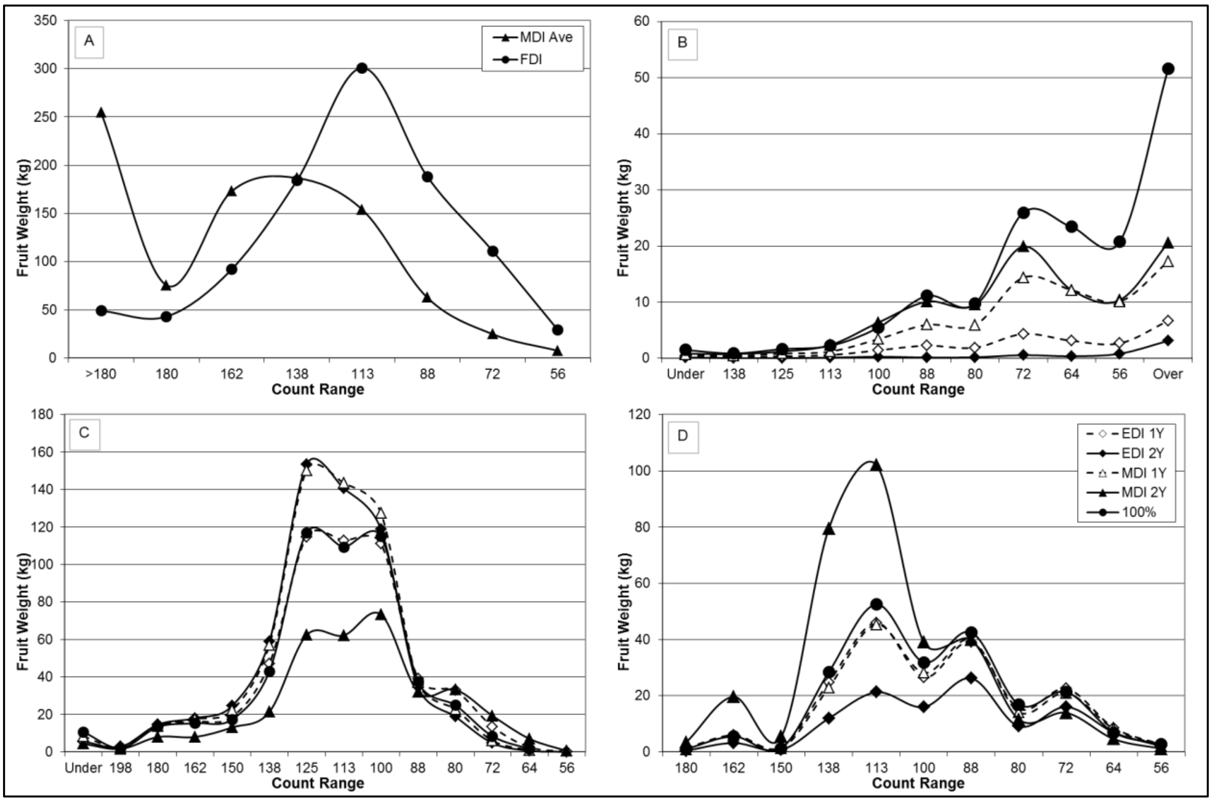


Figure 13: Fruit size class distribution at harvest for each season (A = 2008/09, B = 2009/10, C = 2010/11, D = 2011/12) (EDI = Extreme Deficit Irrigation, MDI = Moderate Deficit Irrigation, FI = Full Irrigation, see Table 3, 1Y & 2Y refer to the duration of deficit irrigation)

Results for 2008/09 (Figure 13a) indicate that the combination of reduced water and no appreciable stress in the preceding season (prior to the establishment of the drought trial) resulted in slower fruit growth and therefore smaller fruit sizes in MDI than in FI treatment. Other authors (Ballester et al., 2011; Ballester et al., 2013a) found similar results in mandarins and ‘Lanes Late’ Navel oranges, with an increase in relative weight of smaller size classes in the most extreme Regulated Deficit Irrigation (RDI) treatment.

Results for the other 3 seasons indicate a similar distribution of fruit sizes between treatments (allowing for different weights due to higher or lower overall yield), with the exception of MDI 2Y in 2011/12 (Figure 13d). This is the season when this treatment carried a higher crop load than other treatments (Figure 11), and this is reflected in the higher weight of smaller fruit (counts 162, 138 and 113), and lower weight of larger fruit (counts 80, 72, 64, 50).

On-Farm Drought Monitoring Program

Climate and Water Allocations

The 5 seasons during which the monitoring program took place were climatically diverse, reflecting the drought event and subsequent recovery. Table 10 illustrates climatic conditions experienced in each season, compared with the long term average for Loxton, South Australia.

The data illustrate the low rainfall and high evaporation during the first 3 seasons, leading to higher than average water deficit, followed by a major turnaround in conditions in the 4th season (2010/11), with very high rainfall and lower than average evaporation.

Table 10: Climate parameters at Loxton, South Australia

Parameter	Long Term Average	2007/08	2008/09	2009/10	2010/11	2011/12
Mean Max. Temp. (^{o})	23.9	25.1 (+5%)	24.2 (+1%)	25.1 (+5%)	22.9 (-4%)	24.1 (+1%)
Mean Min. Temp. (^{o})	9.0	9.0	9.0	10.2 (+13%)	9.3 (+3%)	9.4 (+4%)
Total Rainfall (mm)	269	175 (-35%)	175 (-35%)	306 (+14%)	542 (+102%)	290 (+8%)
Rain Days	79	67 (-16%)	85 (+7%)	83 (+5%)	100 (+26%)	83 (+5%)
Mean Daily Solar Radiation (MJ/m^2)	18.4	20.3 (+10%)	20.4 (+11%)	20.6 (+12%)	19.6 (+7%)	18.2 (-1%)
Mean Daily Class A Pan Evap. (mm)	5.2	6.0 (+16%)	5.7 (+10%)	5.6 (+7%)	4.4 (-16%)	5.2
Annual Water Deficit [Evap. – Rain] (mm)	1629	2033 (+25%)	1911 (+17%)	1733 (+6%)	1047 (-36%)	1616 (-1%)

Number of Monitoring Sites

At the beginning of the project, a number of property owners agreed to participate in this research, and a large number of sites (planting patches) were identified for ongoing monitoring. However, the number of monitored sites declined over the term of the project, due to the long term nature of the research, and in many cases as a direct result of the impact of the drought (Table 11).

The inclusion of an additional property in the second season boosted the number of citrus sites, but over the course of the research there was a decrease in the number of sites in all crop types except Avocadoes, which were planted on only 2 properties.

Table 11: Number of sites monitored for each crop type by season

Season	Almond	Avocado	Grape	Citrus	Total
2007/08	149	28	33	130	339
2008/09	134	28	20	147	329
2009/10	132	28	20	139	319
2010/11	132	28	14	121	295
2011/12	132	28	14	99	273

Drought Management Strategies

Almond Drought Management Strategies

A very limited range of strategies were used by almond growers, many fewer than seen amongst citrus growers.

In most cases only the irrigation management was changed, and the trees were left to adjust to the reduced water availability. One reason for this is the deciduous nature of almond trees, contrasted with evergreen citrus trees. As a result, the reduced availability of water in the early season resulted in the development of a smaller canopy in almonds, which then demanded less transpiration. This was reflected in greatly reduced shoot extension growth reported by these almond growers.

Some growers removed the crop from some trees, to reduce the demand, but only when water available for a given patch was extremely limited (around 30% of normal). Most growers, however, still attempted to produce a crop, at whatever yield they could achieve with the available water.

Interestingly, most Almond growers independently identified 10ML/ha as an appropriate reduced irrigation allocation, and all indicated that their reason for aiming at this irrigation level was in order to grow a commercial crop and therefore generate return from the orchard, albeit a reduced return from what they would normally expect. This contrasts with normal irrigation practice in the region resulting in annual irrigation applications of between 12 and 15ML/ha.

Table 12: Almond monitoring trial site summary

Property	**No. Sites**	**Crop Removal**	**Hedging &/or Topping**	**Skeletonising**	**Top-working**	**Anti-transpirant**	**Partial Cover Sprinklers**	**Drip Irrigation**
Almond 1	24							✓
Almond 2	12							✓
Almond 3	15	✓						✓
Almond 4	8					✓		✓
Almond 5	3							
Almond 6	7							✓
Almond 7	4							
Almond 8	18							
Almond 9	4							✓
Almond 10	54							

A summary of the strategies used at the different almond sites is shown in Table 12.

Citrus Drought Management Strategies

A wide range of management strategies were used by citrus growers to nurse trees through reduced allocations. The strategies varied according to the degree of restriction of allocations, as well as the philosophy of the grower.

Canopy reduction was a common strategy, although there were those who believed that the canopy should not be reduced during the water restriction period, but should be allowed to naturally defoliate, and any dead wood resulting from the restriction should be cleaned out when full irrigation allocations are once again available.

Amongst those who reduced canopy, hedging and/or topping was most popular, as they were able to be applied mechanically, and were therefore relatively quick and cheap (Falivene et al., 2006). The amount of canopy removed ranged from as little as around 10% to as much as 80% on some very large mature trees.

An alternative strategy used by some growers was topworking. These growers took healthy trees with a scion of an undesirable variety, and topworked the trees to a more desirable variety (Sanderson et al., 2007). As this practice involved initial removal of up to 75% of the existing canopy, and the eventual removal of all of the original variety, there was an immediate reduction in water requirement. In addition, these trees were expected to come back into production much more rapidly than could be achieved by removing the trees and replanting with seedling trees.

A comparable strategy was skeletonising, which is similarly to topworking, but does not involve budding a new variety, instead allowing the existing variety to regrow. This strategy was not widely practiced, but there were 2 sites within this trial where this was done.

Table 13: Citrus monitoring trial site summary

Property	No. Sites	Crop Removal	Hedging &/or Topping	Skeletonising	Top-working	Anti-transpirant	Partial Cover Sprinklers	Drip Irrigation
Citrus 1	2							✓
Citrus 2	14							✓ (PRD)
Citrus 3	17							✓
Citrus 4	1		✓				✓	
Citrus 5	9		✓				✓	✓
Citrus 6	4		✓				✓	
Citrus 7	1		✓				✓	
Citrus 8	4		✓					
Citrus 9	19							✓ (PRD)
Citrus 10	15	✓	✓		✓		✓	
Citrus 11	2							
Citrus 12	3		✓	✓				✓
Citrus 13	2		✓			✓	✓	
Citrus 14	5				✓		✓	
Citrus 15	12							✓
Citrus 16	9							✓
Citrus 17	6							✓
Citrus 18	1						✓	
Citrus 19	3		✓	✓				✓
Citrus 20	5		✓	✓	✓		✓	
Citrus 21	3	✓						
Citrus 22	2							✓
Citrus 23	3		✓				✓	
Citrus 24	6						✓	✓

Removal of the developing crop was another strategy, usually combined with hedging. In some cases this was done intentionally to reduce the transpiration demand of the trees, and to minimise the impact of water deficit on fruit growth (Bevington et al., 2003). In other cases it happened unintentionally due to the level of stress trees came under during flowering and fruit set. In the case of some Lemon sites, the initial crop was sacrificed in favour of a second, out of season crop, made possible by increases in allocations as the season progressed. This out of season crop was in fact more valuable than the normal season crop that was sacrificed, due to the ability to market lemons at a time when they were rare in the market.

A fairly common strategy was conversion of the irrigation system, in many cases to drip irrigation, but also to partial cover sprinkler systems. A number of sprinkler manufacturers released alternative spinners for their undertree sprinkler products in response to the drought conditions, which reduced the distance of throw of the sprinklers, and resulted in only a fraction of the ground in the orchard being wetted. Combined with the movement of the sprinklers into the tree row, this strategy resulted in water being applied predominantly under the tree canopy, where shading assisted in reducing evaporation losses from the soil.

Conversion to drip irrigation was also accompanied in some cases by establishment of Partial Root-zone Drying (PRD) (Kriedemann & Goodwin, 2003). This strategy requires specific irrigation infrastructure, which allows irrigation application to be switched between each side of the tree row. This creates “drying” in a portion of the root-zone, which stimulates a hormonal response from the trees, reducing transpiration, and therefore reducing stress resulting from water shortage.

Finally, some growers combined heavy hedging with Kaolin Clay, which was sprayed over the remaining foliage to reduce transpiration, and thus reduce the stress on the trees, as well as helping to prevent sunburn damage to the trunk and major branches.

The range of strategies used at the different citrus properties where sites were located is summarised in Table 13.

Yield Response Data

Almond Yield Response

The Australian almond industry is built primarily on the variety Non Pareil, essentially the same as California Paper Shell. In all of the sites monitored for this project this was the target variety, and all other varieties planted were used primarily as pollinators for Non Pareil.

Yield response relationships for Non Pareil almonds are shown in Figure 14 to Figure 18. In these and subsequent similar graphs, fitted upper boundary lines determined by the method of Schnug et al. (1996) are shown. The graphs contain data points for all sites for all years, even where sites became inactive in later years. Similar graphs were derived for pollinator varieties, but are not presented here.

Yield against total water applied (rainfall plus irrigation) is shown in Figure 14. The graph indicates that the volume of applied water was generally lowest in 2007/08, and increased in later seasons as growers’ water allocations increased. The boundary line suggests maximum yield was achieved at around 1500 mm of applied water (15.0 ML/ha).

The relationship of yield to crop evapotranspiration (ET_C) was similar (Figure 15), but the numbers for ET_C were smaller, reflecting the loss of some applied water to evaporation, runoff and deep drainage. As a result, the boundary line indicates maximum yield was achieved around 1300 mm (13.0 ML/ha)

Figure 16 displays Irrigation Water Use Index (IWUI), that is tonnes of product per megalitre of irrigation applied, against total water applied. This indicator focusses on production per unit of irrigation water rather than unit of land area, and thus is quite appropriate for a study of drought, where water is the most limiting factor. The boundary line suggests that the highest productivity per unit of irrigation water is achieved around 1150 mm (11.5 ML/ha) of total applied water.

Stress coefficient (K_S) averaged over the whole season is shown in Figure 17, and the same coefficient averaged over the critical period around flowering and fruit set is shown in Figure 18. Both graphs indicate greater stress occurred in the early years of the drought (2007/08, 08/09 and 09/10), when water availability was low, and when water was more available in later years less water stress was the result.

The boundary lines in Figure 17and Figure 18 indicate that any level of stress (K_S < 1) is detrimental to yield, either during the critical period, or across the season.

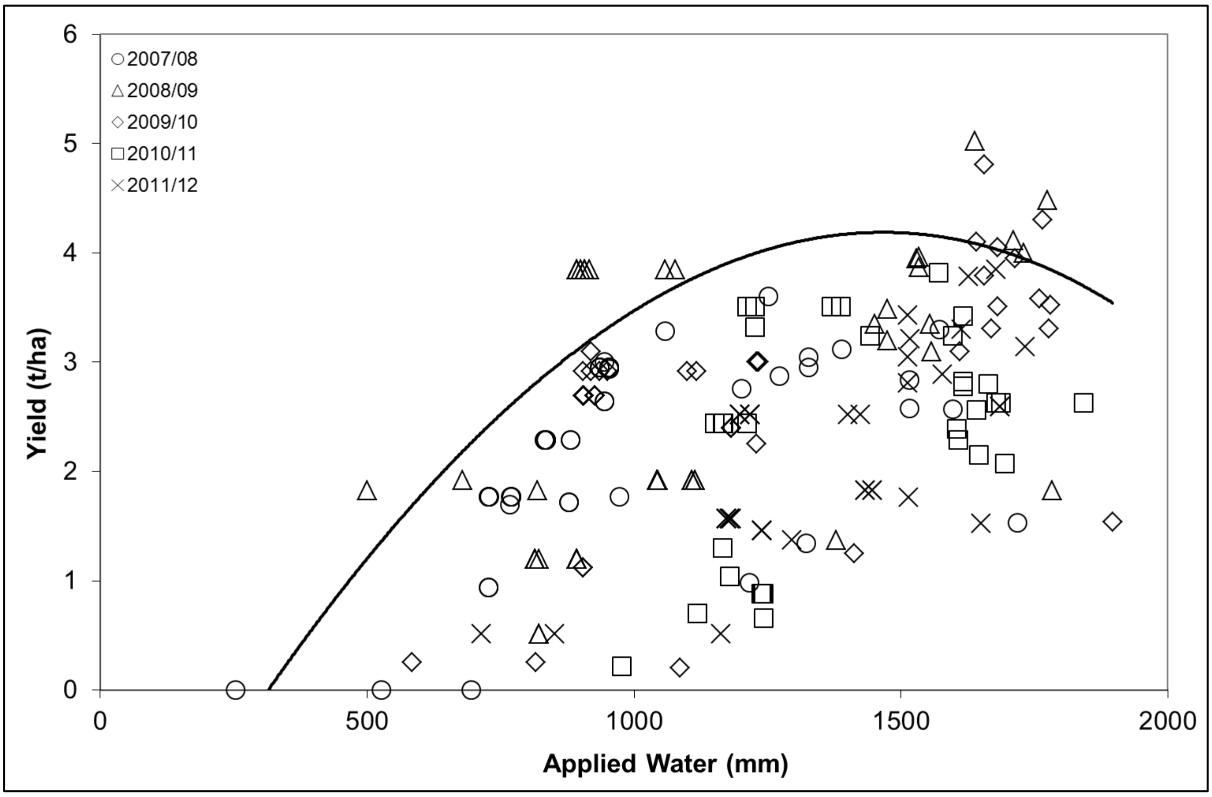


Figure 14: Yield by applied water for Non Pareil Almonds

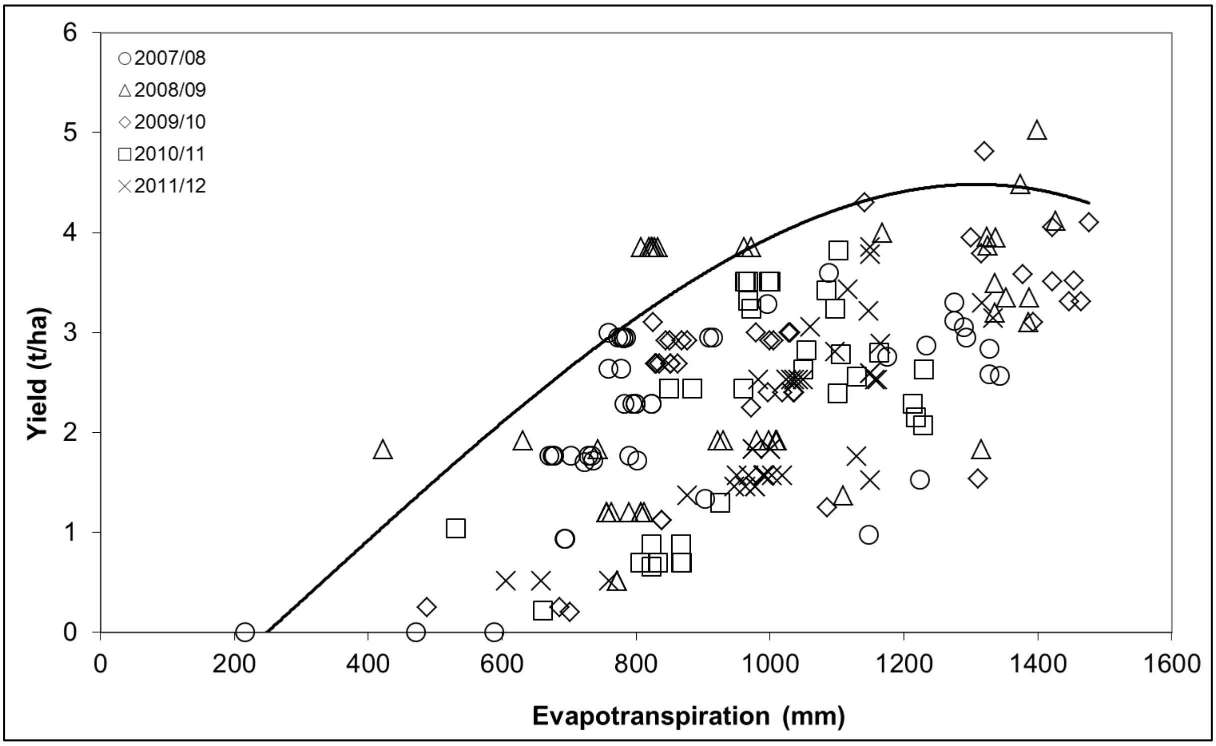


Figure 15: Yield by evapotranspiration for Non Pareil Almonds

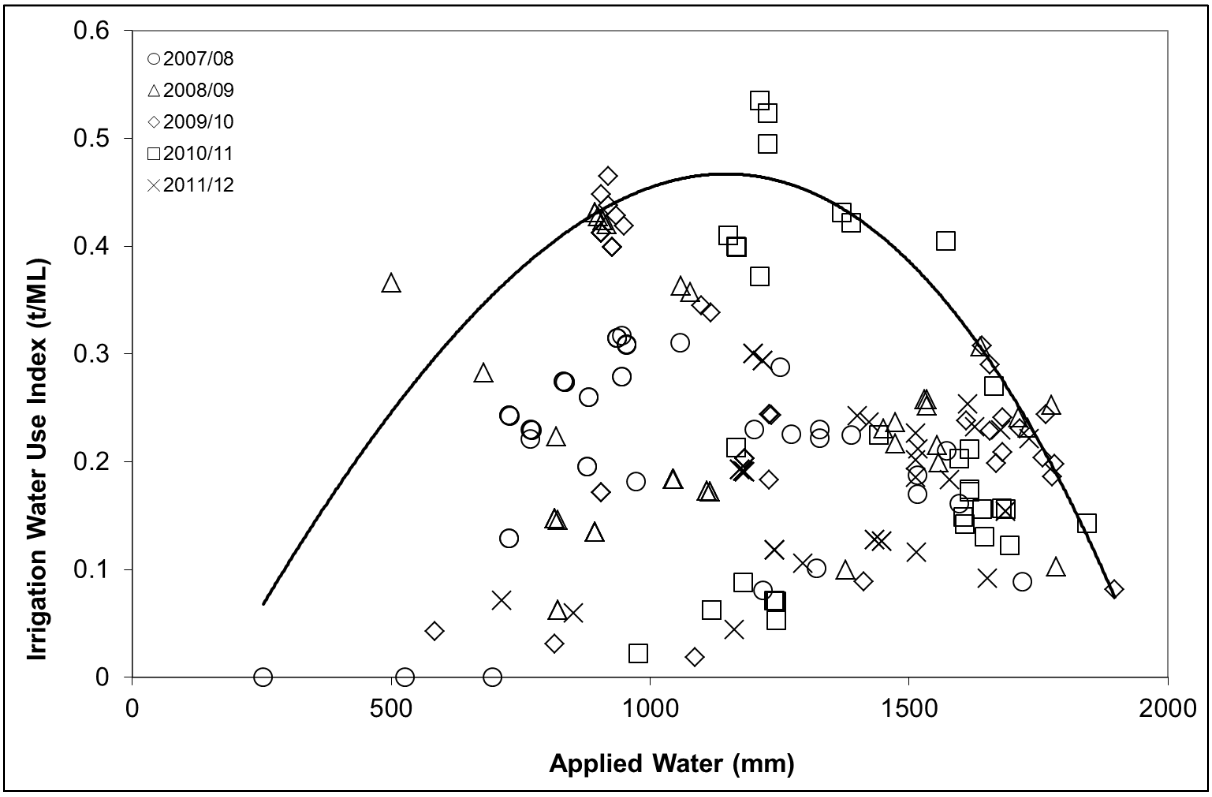


Figure 16: Irrigation Water Use Index by applied water for Non Pareil Almonds

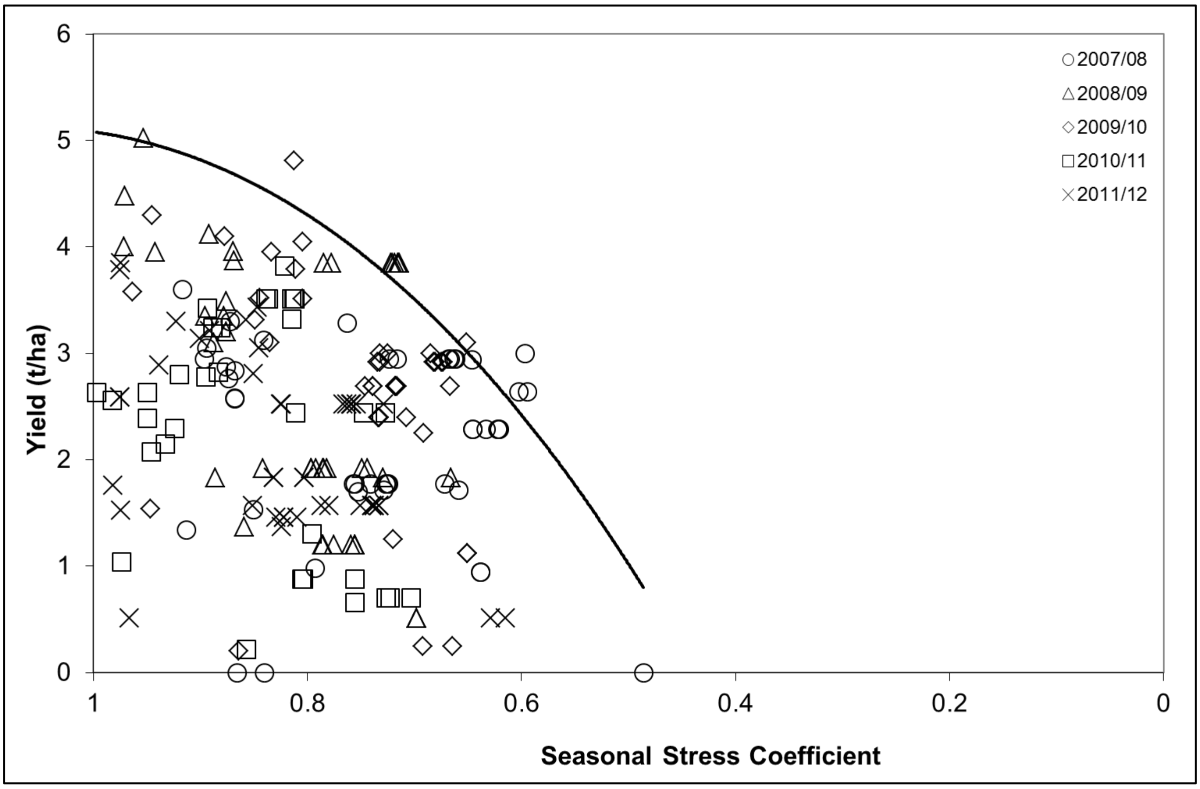


Figure 17: Yield by seasonal water stress coefficient for Non Pareil Almonds

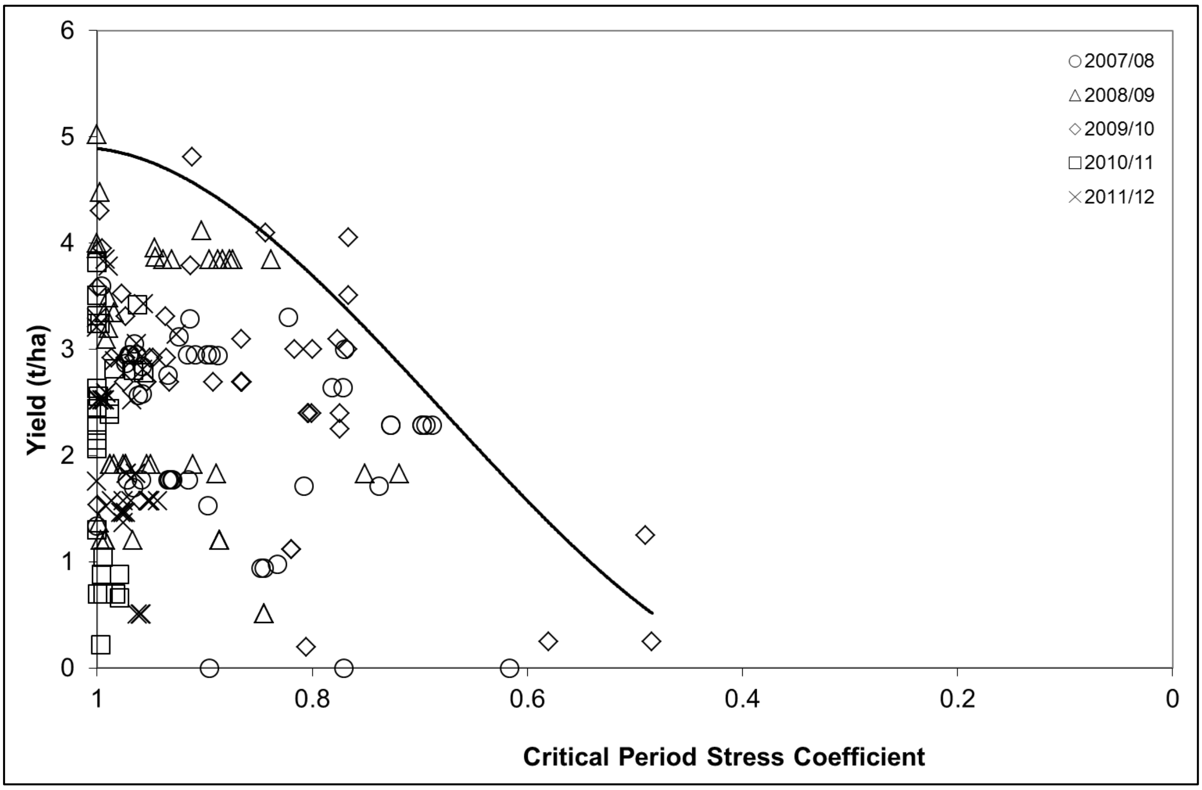


Figure 18: Yield by critical period water stress coefficient for Non Pareil Almonds

Table 14: Summary t-statistics, and linear regression against square root of almond yield (sites with 5 Year Ave Y > 1 t/ha) (bold designates p < 0.05, bold and italic designates p < 0.1)

	07/08		**08/09**		**09/10**		**10/11**		**11/12**		**Average**	
Mean Yield	2.312		2.748		2.796		2.290		1.912		2.411	
Median Yield	2.288		3.1		2.8		2.44		1.64		2.356	
Standard Dev.	0.772		1.358		0.908		1.322		0.812		0.839	
	estimate	**p**	**estimate**	**p**	**estimate**	**p**	**estimate**	**p**	**estimate**	**p**	**estimate**	**p**
Constant	-0.484	0.588	-6.49	<.001	-2.37	0.027	0.35	0.946	-2.28	0.362	-6.47	<.001
Anti-transpirant	0.204	0.208	**1.098**	**<.001**	0.110	0.411	0.095	0.653	0.195	0.191	***0.1869***	***0.062***
Wetted Area %	0.00442	0.278	**0.02236**	**<.001**	**0.00902**	**<.001**	**0.02028**	**<.001**	**0.00900**	**<.001**	**0.01115**	**<.001**
RAW	-0.0117	0.289	**-0.0504**	**<.001**	**-0.02080**	**0.002**	**-0.0314**	**0.016**	**-0.01678**	**0.050**	**-0.02482**	**<.001**
Converted to Drip	0.077	0.569	0.038	0.759	**0.2522**	**0.001**	0.153	0.343	**0.2319**	**0.012**	**0.2008**	**0.003**
Applied Water	0.00205	0.272	**0.00924**	**<.001**	**0.00401**	**0.002**	-0.00288	0.516	-0.00026	0.923	**0.00804**	**<.001**
Applied Water2	-0.000000592	0.374	**-0.00000419**	**<.001**	**-0.00000135**	**0.003**	0.00000143	0.347	0.00000037	0.750	**-0.00000280**	**<.001**
Critical Ks	1.114	0.197	-2.24	0.309	**1.614**	**<.001**	1.87	0.622	**3.32**	**0.016**	**4.174**	**<.001**
ETc	0.000384	0.426	**0.002770**	**<.001**	0.000460	0.162	**0.001769**	**0.049**	0.000061	0.923	**0.001115**	**0.003**
Seasonal Ks	***-2.19***	***0.053***	2.45	0.289	-1.182	0.184	-2.56	0.175	-0.40	0.714	**-3.51**	**0.015**

Table 15: Summary t-statistics, and linear regression against square root of citrus yield (sites with 5 Year Ave Y > 10 t/ha) (bold designates p < 0.05, bold and italic designates p < 0.1)

	07/08		**08/09**		**09/10**		**10/11**		**11/12**		**5 Yr Average**	
Mean Yield	16.54		36.34		22.78		25.49		36.92		27.61	
Median Yield	12.93		34.42		22.63		20.04		30.46		25.32	
Standard Dev.	16.43		17.34		14.46		15.63		19.26		10.65	
	estimate	**p**	**estimate**	**p**	**estimate**	**p**	**estimate**	**p**	**estimate**	**p**	**estimate**	**p**
Constant	3.68	0.369	3.85	0.181	2.14	0.418	-11.21	0.110	4.74	0.062	1.50	0.506
Crop Type	1.056	0.266	-0.292	0.612	0.129	0.837	0.362	0.612	***-0.645***	***0.068***	-0.017	0.951
Converted to PRD	1.258	0.206	-0.592	0.187	**1.630**	**0.005**	1.257	0.138	0.122	0.787	**0.805**	**0.002**
Hedging/Topping	-0.176	0.859	**1.405**	**0.026**	0.703	0.309	***1.670***	***0.052***	***0.732***	***0.058***	**1.041**	**0.002**
Partial Cover Sprinkler	2.63	0.359	1.21	0.421	1.36	0.406	-0.81	0.641	0.081	0.923	0.682	0.355
Irrigation System Type	0.35	0.927	-2.15	0.300	-1.27	0.559	2.45	0.314	0.53	0.641	-0.18	0.860
Wetted Area %	0.0289	0.575	-0.0011	0.968	0.0251	0.449	-0.0109	0.740	-0.0234	0.162	0.0017	0.910
Applied Water	-0.00566	0.441	0.00257	0.328	-0.00185	0.254	0.00240	0.166	**0.001975**	**0.018**	***0.00226***	***0.059***
Critical Ks	1.87	0.757	-2.65	0.668	-2.66	0.318	9.9	0.340	-1.71	0.572	-5.70	0.219
ETc	0.00369	0.533	0.00132	0.539	0.00320	0.147	-0.00165	0.280	0.00069	0.610	0.00013	0.929
Seasonal Ks	-3.51	0.703	1.37	0.877	2.46	0.602	3.4	0.769	0.58	0.881	5.91	0.340

Results of regression analysis of a range of parameters against almond yield are shown in Table 14. The estimates listed are the partial regression coefficients of square root of filtered yield (t/ha) on the various parameters. Analyses are displayed for each season of data collection, as well as for 5 year average yield. Significance levels may occasionally be optimistic in view of the unbalanced nature of the particular data set. The response in almond yield to applied water was far from linear, and thus a squared term for applied water (Applied Water 2) is included.

Citrus Yield Response

The monitoring program incorporated a range of citrus varieties, predominantly navel oranges, but also including Valencia oranges, mandarins, and a few lemon plantings (Table 16). The graphs in Figure 19 to Figure 23 display data for navel orange sites only.

Table 16: Citrus varieties included in monitoring program

Type	Variety	Number of Sites	Number of Sites
Lemon	Eureka	1	5
	Lisbon	1	
	Verna	1	
	Other	2	
Mandarin and Relatives	Ellendale	2	22
	Honey Murcott	2	
	Imperial	9	
	Minneola Tangelo	4	
	Other Tangelo	5	
Navel Orange	Barnfield	3	99
	Chislett	14	
	Hutton	2	
	Lane Late	25	
	Leng	7	
	Navelate	2	
	Navelina	13	
	Powell	1	
	Rhode	5	
	Summer Gold	1	
	Thomson	1	
	Washington	25	
Other Orange	Hamlin	1	22
	Valencia	19	
	Valencia Newton Clone	2	

The graph of yield by water applied (Figure 19) again shows a change in applied water between seasons, with the lowest on average in 2007/08, and the highest in 2010/11. The graph further indicates that maximum yield was achieved at around 1150 mm of annual applied water (11.5 ML/ha), less than the 1500 mm for almonds in Figure 14.

Figure 20 indicates that maximum yield coincided with around 750 mm of evapotranspiration (7.5 ML/ha), which was less than the 1150 mm of applied water, and would suggest that an average of 400 mm of applied water was lost (i.e. not converted into evapotranspiration) each season.

However, evaluation of the data from individual navel orange sites indicates an average of 250 mm difference between applied water and evapotranspiration. Thus the difference in the peak of the boundary line between Figure 19 and Figure 20 is the result of a combination of a difference in the base data (applied water vs. evapotranspiration) on the one hand, and in the boundary line calculation process on the other.

The boundary line for IWUI (Figure 21) indicates that the optimum yield per unit of applied water occurred at around 950 mm of total applied water (9.5 ML/ha). Interestingly, there is a cluster of sites applying around this amount, especially in seasons 2008/09 and 2009/10, at the height of the drought.

The upward curving tail at the right hand side of this figure is an anomaly, and reflects the low number of data points at the far right of the graph, which leads to a few points exerting undue influence over the boundary line.

The spread of applied water data in Figure 21 is suggestive of very different responses in the various years of the drought. In 2007/08 (circles), the first season of significantly reduced allocations, many growers appear to have over-reacted, and cut water back quite dramatically. This coincided with opening allocations in South Australia of only 4%, and although allocations eventually reached 32%, irrigations were cut back dramatically in the early part of the season.

In the following 2 seasons (triangles and diamonds) the level of irrigation clustered around the identified maximum yield per megalitre, a suitable strategy when water was limiting production rather than land.

In the final 2 seasons, when allocations were increased early in the season (2010/11, squares), or returned to 100% (2011/12, crosses), water application increased, clustering closer to the maximum yield per hectare, a suitable strategy when water was no longer limiting (especially in light of reductions in planted area which were very common across the whole region).

The pattern of water applications in the first 3 seasons is illustrative of a general trend in response to the drought across a range of crops. The drought was very much an unknown, both in that there was very little understanding of what allocations were likely to be as the season progressed, and in terms of there being extremely little experience within the grower community of operating with less than adequate allocations.

As a result, the area of plantings on most properties tended to be reduced slowly as the drought commenced, with the result that available water was distributed across a large area of plantings in 2007/08, and many growers experienced dramatic yield declines, both as a result of the low amounts of water applied, and in many cases also as a result of poor management the timing of irrigations. However, even by the second season (2008/09) growers were able to manage their water much more effectively, demonstrating a very steep learning curve.

The graphs of yield response to water stress (Figure 22 and Figure 23) reinforce that citrus is sensitive to water stress, although low levels of stress were acceptable. Again these graphs indicate differences between seasons in the levels of stress experienced by the trees, with higher stress on average in the early seasons, and less in later seasons, reflecting the annual volumes of water applied.

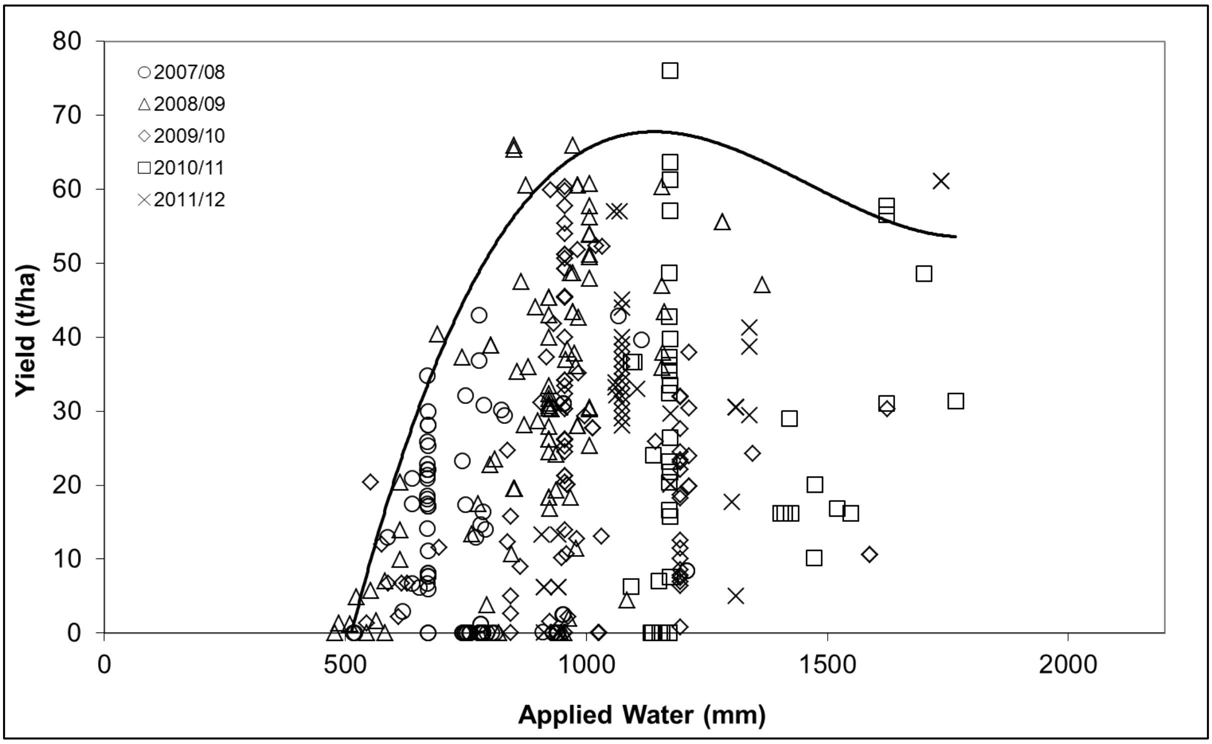


Figure 19: Yield by applied water for Navel Oranges

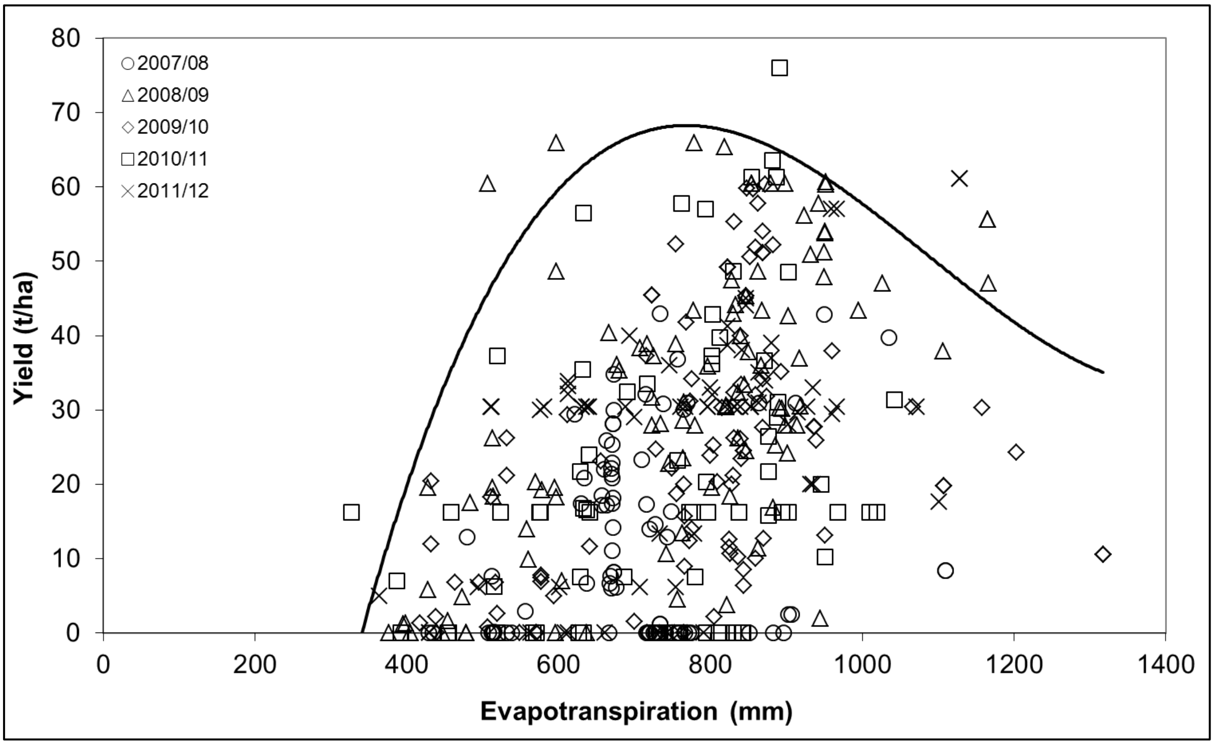


Figure 20: Yield by evapotranspiration for Navel Oranges

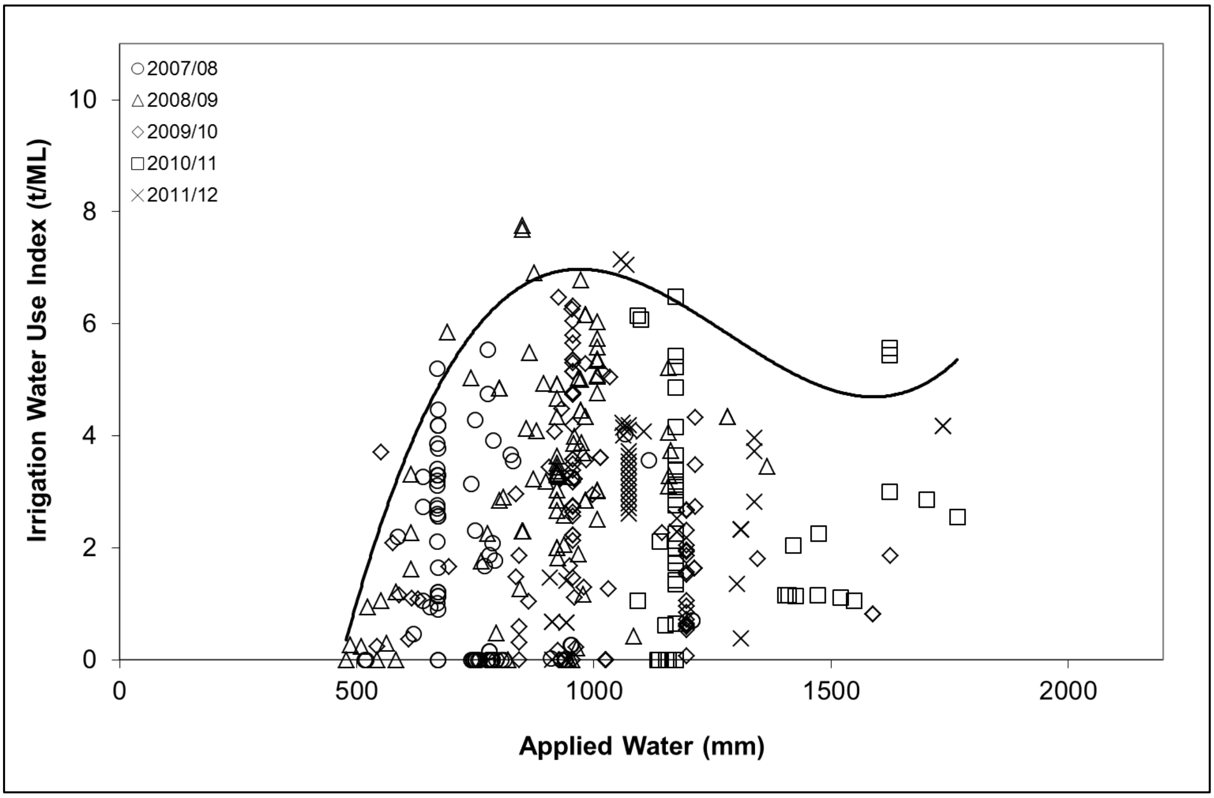


Figure 21: Irrigation Water Use Index by applied water for Navel Oranges

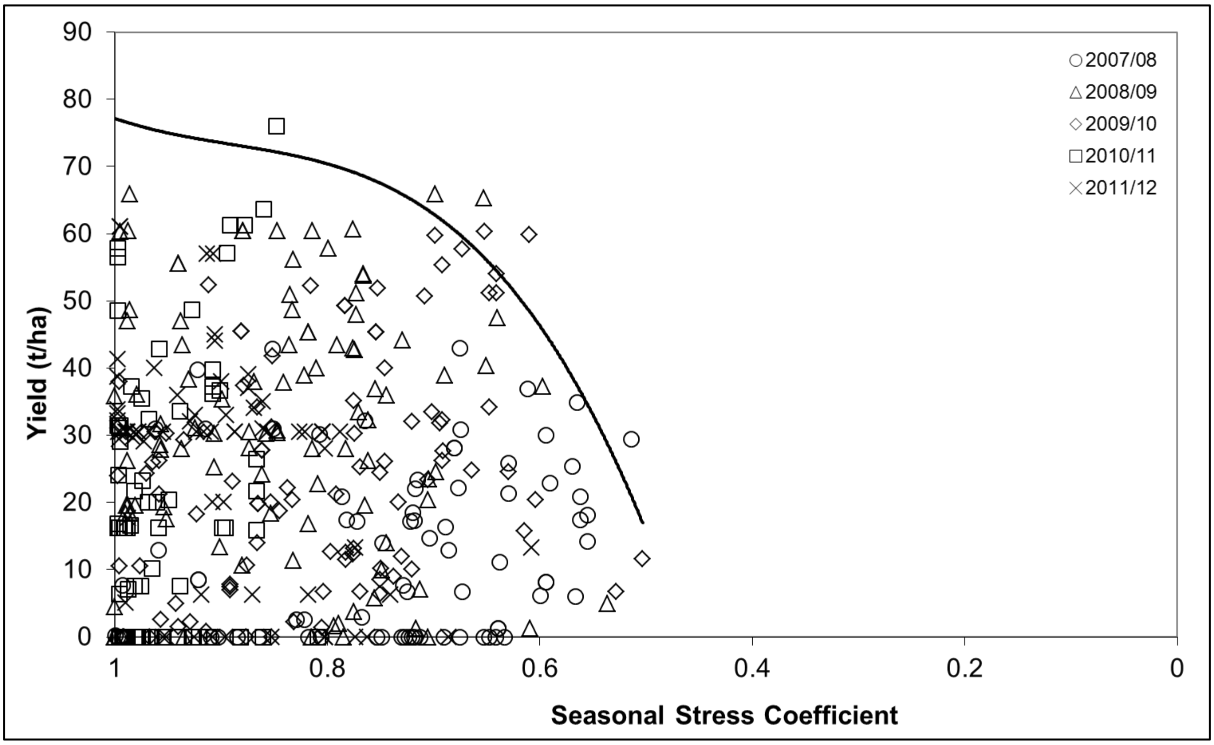


Figure 22: Yield by seasonal water stress coefficient for Navel Oranges

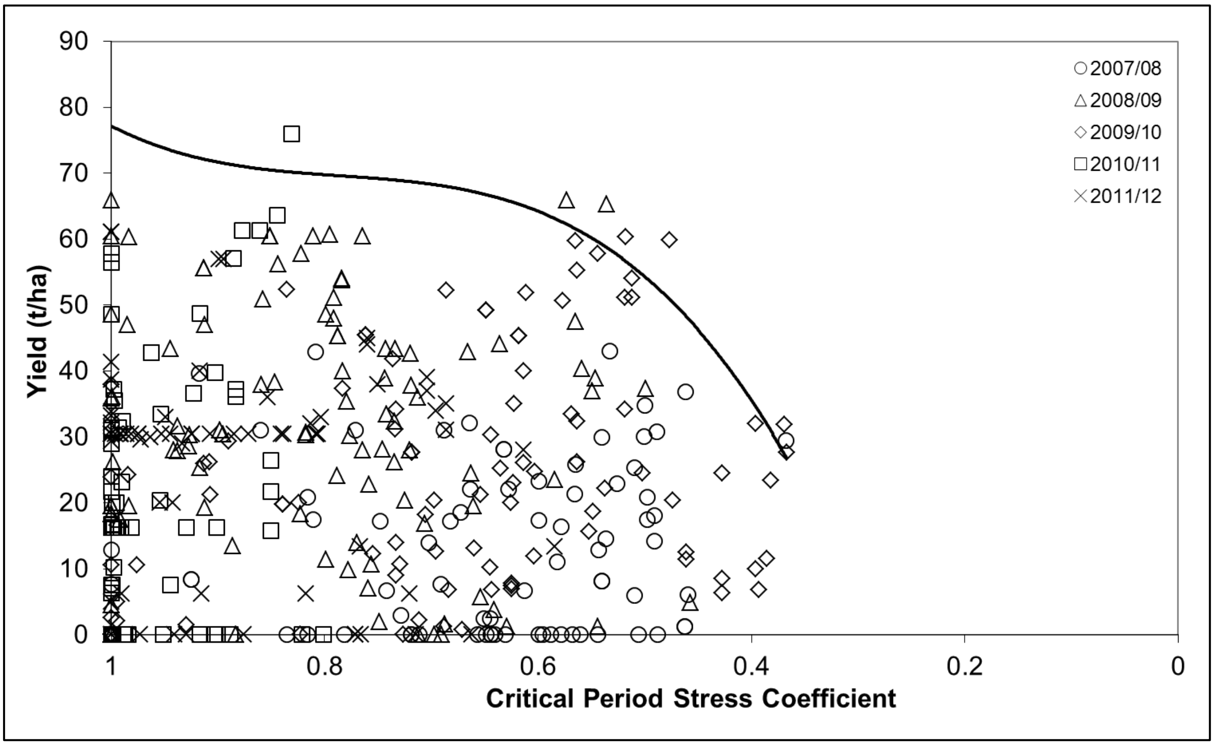


Figure 23: Yield by critical period water stress coefficient for Navel Oranges

Results of regression analysis of a range of parameters against citrus yield are shown in Table 15. The estimates listed are the partial regression coefficients of square root of filtered yield (t/ha) on the various parameters. Analyses are displayed for each season of data collection, as well as for 5 year average yield. Significance levels may occasionally be optimistic in view of the unbalanced nature of the particular data set.

Discussion

Citrus Drought Research Trial

Plant Physiology

The results presented above indicate that the imposition of deficit irrigation produced significant changes in tree physiology, and further that a greater deficit induced greater changes. Although not consistent across the season, differences were measured in canopy temperature, leaf water potential (Ballester et al., 2013a; Gonzalez-Altozano & Castel, 2000a), and leaf area index (Hilgeman & Sharp, 1970).

In a study comparing late Navel oranges and Persimmons, Ballester et al. (2013b) concluded that canopy temperature is less suitable for evaluating stress in citrus due to their relatively greater sensitivity to variation in vapour pressure deficit (*VPD*) than crops such as Persimmon.

Despite the differences identified between irrigation treatments, there is little evidence that the cultural treatments had any impact on tree stress as measured by *Tc*, *Ψp*, *Ψlm* or *LAI*.

This result suggests that, although the irrigation treatments applied were effective in inducing stress in the trees, as was the intention, none of the cultural treatments were effective in significantly mitigating that stress, or if they did mitigate the stress, the indicators used were not sufficiently sensitive or reliable to identify the difference.

In this context, it is interesting to note that Levy (1983) showed that citrus leaves acclimatise to water stress. While the difference in stress levels between irrigation treatments in the current study was apparently sufficient to show up in physiological measurements, it is likely that any differences between cultural treatments would have been smaller, and more easily masked by acclimatisation.

Crop Response

In line with the tree physiological responses measured, significant crop responses were found at the level of irrigation treatments, in the form of reduced fruit growth (Goldhamer & Arpaia, 1998; Gonzalez-Altozano & Castel, 2000a; Hilgeman & Sharp, 1970; Kanber et al., 1999), reduced yield (Ballester et al., 2013a; Gonzalez-Altozano & Castel, 2000a; Hilgeman, 1977; Hilgeman & Sharp, 1970; Kanber et al., 1999) and smaller final fruit size (Ballester et al., 2013a; Gonzalez-Altozano & Castel, 2000a; Hilgeman, 1977; Hilgeman & Sharp, 1970; Kirda et al., 2007) in deficit irrigation treatments.

Fruit growth, and therefore final fruit size, is particularly affected by water deficit, reducing the marketability of fruits, and in turn reducing returns to the grower (Kirda et al., 2007). However, trade-offs between crop load and fruit growth rate lead to complexity in the crop response to reduced water availability (Ballester et al., 2013a; Gonzalez-Altozano & Castel, 2000a; Kirda et al., 2007).

In this context, Regulated Deficit Irrigation (RDI) can avoid much of the impact of water deficit on crop load by applying deficit after summer fruit drop, but can still lead to reduced fruit size in Navel oranges if sufficient care is not taken in managing irrigation through the fruit growth period (Ballester et al., 2013a). The recovery of fruit size in the MDI 2Y treatment after June 2010 (Figure 10b, Table 9) is suggestive of this response, whereby the lost fruit growth experienced prior to the July resumption of full irrigation was regained once full irrigation was resumed.

It is interesting to observe the recovery of fruit size in the MDI treatment in 2009/10 (Figure 10b and Table 9). Up until to July 2010, fruit size on MDI 2Y was significantly lower than on FI and MDI 1Y. However, after full irrigation was restored in July 2010, MDI 2Y fruit caught up to the other treatments, showing no significant difference by November 2010 (Table 9).

Another result of note in the current trial, linked to this complexity of response to water deficit, was the generation of a biennial bearing pattern in the MDI 2Y treatment that was out of phase with the remaining treatments. This was potentially the result of low to moderate stress in 2009/10, leading to a reduced crop load in 2010/11, which combined with a return to full irrigation, allowed these trees to rebuild reserves at a time when the other treatments carried heavy crops.

Kanber et al. (1999) found no yield difference between 2 different irrigation amount treatments, but analysis of the paper indicates that their “k2” irrigation treatment provided more water than the crop required, with the result that the deficit irrigation treatment “k1” did not result in a large water deficit, similar to the 2009/10 season in this present study.

The irrigation level treatments in the present study were sufficient in year 1 (2008/09) to produce significant differences in yield and yield components, but no significant responses were found between cultural treatments at either of the 2 irrigation deficit levels. This mirrors the plant physiological results, and further underlines the ineffectiveness of cultural treatments in overcoming water stress in any meaningful way.

Maintaining Yield under Moderate Deficit

A key aim of this trial was to test whether yield of citrus trees could be maintained under a moderate reduction in the availability of irrigation water. The trial design tested a number of cultural treatments which are claimed to provide some level of relief from stress (particle film), or to conserve water (polymer and mulch).

As discussed above, none of these cultural treatments produced significant changes in plant physiology, yield or its components when compared to an untreated control. However, there was also little difference between the MDI and FI irrigation treatments in some indicators. In particular, total yield over 4 seasons (Figure 12) showed no significant difference amongst these treatments, and there was a significant difference in only one out of 4 individual seasons (Figure 11).

This result indicates that citrus trees are quite resilient, and will recover from short term water deficit almost immediately, as seen in the MDI 1Y treatments, which showed no significant difference in yield over the whole trial. A second season of deficit had a greater effect, although the level of deficit in this season was minimal, and recovery was still very rapid once full irrigation was restored.

Whilst this result provides confidence for irrigators to cut water back significantly in a single season when allocations are reduced, the effects of such cutbacks are likely to increase dramatically over consecutive seasons of significant deficit. Also, the impact on fruit size distribution must be borne in mind, and the flow-on impact on profitability in turn. In addition, any deficit tends to exacerbate biennial bearing post deficit, with its attendant issue of fruit size variation from season to season.

Maintaining Plantings under Severe Deficit

An additional question asked in this work concerned minimising the impact of dramatic reductions in irrigation on the ability of trees to recover once water availability was restored. Crop load reduction techniques were the focus of this study, and included Gibberellic Acid, Ethrel and hedging.

Results from this portion of the trial identified clear impacts, especially on yield and its components, from such a severe reduction in water, but again there were no significant differences between cultural treatments. The reason for this is revealed in Figure 9, where the reduction in fruit number was the same for all EDI treatments, irrespective of cultural treatment. It seems that these treatments experienced a level of fruit drop that overwhelmed the fruit drop generated by any of the cultural treatments, purely as a result of the stress caused by the high level of water deficit.

Although this dramatic crop reduction led inevitably to lower total yields over the 4 seasons of this trial (Figure 12), it is pertinent to note that yield did recover rapidly in seasons 3 & 4 (Figure 11). This indicates that such a dramatic reduction in irrigation may be an effective tool for managing short term (1 or 2 seasons) drought, if the orchard business has sufficient cash reserves to ride out a season or 2 of little or no return, bearing in mind that costs associated with pumping water and applying nutrients will also be reduced to some degree.

On-Farm Drought Monitoring Program

Loss of Monitoring Sites

The reasons for the reduction in the number of sites over the course of the monitoring program (Table 11) varied. In some cases the drought was very directly responsible, as the continued lack of water and the cost of leasing water caused a reassessment of growers' plans, and the removal of patches previously selected for retention.

In other cases industry conditions contributed to the removal of plantings, initially in the winegrape industry, where returns for fruit were very low during the drought. On properties with a mix of crop types, it became common for the grapes to be removed, with water being consolidated onto other, more economically viable crops.

Removal of almond patches as a response to the drought was much less common than in grapes, as this industry was far more robust. The economic situation for citrus growers began to decline toward the end of the drought, and saw the number of sites decline late in the project.

In addition to the factors identified above, there were a number of properties where personal circumstances intervened, with personal or family sickness or tragedy intervening in the case of 3 properties, all of which were solely citrus growers, resulting in the loss of a total of 16 sites.

Drought Management Strategies

As described in the Results section, there was a far greater range of drought management strategies undertaken in citrus orchards than in almond orchards. There are a number of reasons for this.

One key reason is the difference between deciduous and evergreen trees. Being deciduous, almonds have a response mechanism, whereby the canopy does not grow as rapidly or as large if water is restricted from the beginning of the season. Citrus trees being evergreen, on the other hand, require more direct action to reduce canopy size, and therefore crop water demand, and Table 13 confirms that this was a strategy embraced by a number of citrus growers.

There was another important difference between drought management of citrus and almonds, however. This was as a result of the economic conditions within each of the industries, as alluded to in the section above.

During the time of the drought, almond nuts were in high demand, and returns to growers were high by comparison to other crops, on a per hectare basis. Most almond growers experimented with reducing irrigation during the initial season of reduced allocations, and suffered a yield drop as a result. The economic value of the yield decrease experienced in that season was higher than the cost of leasing sufficient water to cover the reduction in allocation. As a result, the most common drought management strategy amongst almond growers after this initial season was water leasing.

The demand for citrus fruit was generally lower than almonds during the drought, due to external market conditions. Differences in value between varieties and markets led to preferential sacrificing of some plantings to provide water to other plantings, and this was accompanied by the other cultural management strategies listed in Table 13.

Yield Response Data

The graphs of yield response to water applied, evapotranspiration and stress are similar between crops, including those not shown (including other citrus varieties, almond pollinator varieties, wine-grapes and avocadoes). Common features of these graphs are the reduction in potential yield (represented by the boundary line) as water applied or used (evapotranspiration) declined, and as stress increased. The actual yield levels, as well as the amount of water or stress producing zero and maximum yield, naturally varied between crops, and varieties within crops.

These comparisons clearly supported the conclusion that there is an optimum water supply level for any horticultural planting (which may vary according to crop type and variety, canopy size, crop load and a range of other factors), and supplying less than that amount will reduce the potential yield from the planting.

However, the wide scatter of data points below the boundary line in all graphs indicates that there were a number of other factors involved in determining final yield, such that many sites which received the appropriate amount of water did not produce anywhere near the potential yield. Potential factors at play here include poor nutrition, salinity, pests and diseases.

Statistical analysis of almond yield data (Table 14) indicated that all of the management practices analysed except Anti-transpirant exerted a significant influence on average yield across the 5 seasons, and all of them influenced yield in at least one individual season, though the influence of Seasonal K_S was not at all consistent. In addition to the influence of irrigation management (i.e. applied water, K_S and ET_C indicators), the major influences on yield in almonds were related to irrigation system type and configuration.

The influence of irrigation system configuration on yield is complicated, as both wetted area % and Readily Available Water (RAW) were significant in all years except 2007/08, but the sign of the estimate was positive for Wetted Area %, and negative for RAW, even though these two indicators were closely correlated. However, including both probably assisted in fine-tuning responses to other parameters. Conversion to drip was also a significant positive influence in 2 seasons and over the average. The indication from exploring graphical presentations (not shown) seems to be that wetted area and RAW are not linearly related to yield, but the relationship is more complex, and may include a minimum wetted area and/or RAW figure below which yield is compromised. Moreover, the yield compromise may be a delayed response to water deficit, as suggested by the lack of a response in 2007/08. This relationship invites further investigation.

Anti-transpirant spray, applied in the 2007/08 season, showed significance only in 2008/09, and significance at only $p < 0.1$ over the average of all five seasons, suggesting there is some benefit in applying such a spray under drought conditions, to reduce the evapotranspiration demand of the crop, and therefore reduce stress levels experienced by the trees. It is interesting that the treatment applied in 2007/08 produced a significant result in the following season, indicating that the tree response was translated into greater flowering/fruit set in the second season relative to trees which were not treated. This does suggest a real impact on tree stress in the 2007/08 season.

Analysis of the citrus yield data (Table 15) indicated a much more restricted group of management practices which significantly influenced yield in this crop. Apart from water applied and crop type (2011/12 and Average), cultural practices had an influence on citrus yield, in the form of conversion to Partial Rootzone Drying (PRD) (2009/10 and average), and hedging and/or topping (2008/09, 10/11, 11/12 and average).

Hedging involves trimming the outer canopy from trees, such that the amount of canopy removed can vary widely. Topping specifically refers to reducing the height of trees, and is most often applied in conjunction with hedging, to reduce the overall size of trees, and thus the volume of the canopy. Sites where trees were reworked, involving reduction in canopy size and the budding of alternate varieties onto mature trees, were also included in this category, as the effect of canopy reduction for reworking is the same as the impact of hedging and/or topping. In all cases, the reduction in canopy size resulted in a reduction in water demand, which reduced the stress experienced by trees when water availability was reduced.

Growers consistently reported that hedging and/or topping had a positive impact on yield under drought, and the statistical analysis supports this practice as a drought management strategy. In all seasons apart from 2007/08, the sign of the estimate was positive, indicating an increase in yield at those sites where hedging and/or topping was carried out, although the increase was only significant at the 1% level in 2008/09 and over the average of five seasons, and at the 5% level in 2010/11 and 2011/12. The negative sign of the estimate in 2007/08, although non-significant, was a response to the removal of young fruit in that season by the hedging and/or topping operation, reducing potential yield.

The impact of partial rootzone drying (PRD) is similar to hedging and/or topping, in that it reduces water demand by the trees (Hutton & Loveys, 2011), thus reducing the stress experienced when water availability is reduced. In the caser of PRD the reduction in water demand is the result of a hormonal signal produced by roots in the drying half of the rootzone, which results in a stomatal response in the leaves, reducing evapotranspiration rate. Again, however, there was a significant response in only one season (2009/10), and over the average of five seasons. The lack of response in the earlier seasons may have been due to the installation of a new irrigation system in 2007/08 at the sites involved, and the need for the root systems of the trees to adjust to the changed water distribution resulting from the new system.

Matching to Initial Research Outcomes

The outcomes and outputs for this project as laid out in the initial proposal have been substantially met.

The major output proposed for this project was an information package on managing citrus under drought. Two factsheets have been developed and posted on the SARDI website (http://www.sardi.sa.gov.au/water/publications/drought_management_posters). One summarises citrus specific drought management options (“Citrus Drought Information Package”), and the other contains more general tree crop information (“Tree Crop Drought Information Package”).

In addition, this report summarises all of the data collected and conclusions drawn from this extensive research program, and therefore provides a more detailed package of information on drought management.

Outcomes from this project will only be delivered when drought once again strikes the Murray Darling Basin, or other irrigated tree crop production regions in Australia. At that time the information collected and collated through this project will deliver management options to maintain plantings and production levels under reduced water availability.

Technology Transfer

Technology transfer has been an ongoing feature of this project. A range of discrete technology transfer events are summarised in Table 17. The types of activities have included organised field walks at trial sites and on growers' properties, oral presentations and poster displays at scientific and industry conferences, poster displays and one-on-one discussions at the Riverland Field Days, and articles in grower journals.

Additionally, 2 feedback workshops have been held each year, one in Loxton and one in Mildura. These were aimed in part at the cooperating growers on whose properties the on-farm monitoring sites were located. However, they were also open events, with anyone welcome to participate. In particular, representatives from horticultural industries and other government research and extension officers attended these workshops in order to keep abreast of developments and knowledge in drought management.

Table 17: Technology transfer events during the project

Date	Event & Location	Type of Activity
17-18 Sep. 2008	Riverland Field Days, Barmera, SA	Manned Poster Display
22 Oct. 2008	CITTgroup Field Visits, Loxton & Waikerie, SA	Field Walk
4 Feb. 2009	Project Feedback Workshop, Loxton, SA	Interactive Workshop
21 Apr. 2009	CITTgroup Field Visit, Solora Estate, SA	Field Walk
March 2009	Article in "Australian Nutgrower"	Grower Journal Article
16-17 Sep. 2009	Riverland Field Days, Barmera, SA	Manned Poster Display
15 Oct. 2009	Project Feedback Workshop, Mildura, Vic	Interactive Workshop
16 Oct. 2009	Project Feedback Workshop, Loxton, SA	Interactive Workshop
20 Oct. 2009	IAL Conference, Swan Hill, Vic	Oral Paper Presentation
24 Nov. 2009	Murray Valley Citrus Board Mtg., Mildura, Vic	Update Presentation
15 Feb. 2010	Agri-Exchange Tech. Officers Meeting, Renmark, SA	Update Presentation
3 Mar. 2010	ABARE Outlook Conference, Canberra, ACT	Oral Paper Presentation
13 Sep. 2010	Agriculture Outlook Australia Conf., Canberra, ACT	Oral Paper Presentation
15-16 Sep. 2010	Riverland Field Days, Barmera, SA	Manned Poster Display
16 Dec. 2010	SA River Murray Advisory Com., Murray Bridge, SA	Update Presentation
15 Mar. 2011	Project Feedback Workshop, Loxton, SA	Interactive Workshop
16 Mar. 2011	Project Feedback Workshop, Mildura, Vic	Interactive Workshop
24 Aug. 2011	IAL Conference, Launceston, Tas	Oral Paper Presentation
14-15 Sep. 2011	Riverland Field Days, Barmera, SA	Manned Poster Display
23-26 Oct. 2011	CAL Conference, Nuriootpa, SA	Manned Poster Display
2 Nov. 2011	CITTgroup Meeting, Carabooda, WA	Interactive Workshop
20 Mar. 2012	Project Feedback Workshop, Mildura, Vic	Interactive Workshop
21 Mar. 2012	Project Feedback Workshop, Loxton, SA	Interactive Workshop
27 Jun. 2012	IAL Conference, Adelaide, SA	Oral Paper Presentation
19-20 Sep. 2012	Riverland Field Days, Barmera, SA	Manned Poster Display
18-19 Sep. 2013	Riverland Field Days, Barmera, SA	Manned Poster Display
16 Oct. 2013	Project Feedback Workshop, Mildura, Vic	Interactive Workshop
17 Oct. 2013	Project Feedback Workshop, Loxton, SA	Interactive Workshop
25 Oct. 2013	ABC Television News Story filmed at Loxton, SA	Television Interview

In summary, technology transfer activities associated with this project have included attendance at the Riverland Field Days for 6 consecutive years, as well as 2 Field Walks, 1 Grower Journal Article, 5 Oral Conference Paper Presentations, 3 other Update Presentations, 10 Interactive Workshops and a television story.

Other technology transfer materials have been developed as outcomes of the project. Two Factsheets summarising the outcomes of the project are attached to this report. These factsheets have been posted on the SARDI internet site (http://www.sardi.sa.gov.au/water/publications/drought_management_posters), and electronic copies have been distributed to relevant industry organisations (Citrus Australia Limited, Almond Board of Australia).

A conference paper summarising the statistical analysis of the drought monitoring component of the project has been submitted to the International Society for Horticultural Science congress to be held in Brisbane, Qld. in 2014.

Recommendations

The findings of the research trial and on-farm monitoring conducted as part of this project indicate that drought in irrigated tree crops can be managed in a number of ways.

Any reduction in water applied below the optimum results in a reduction in yield from citrus and almond orchards. The best means of avoiding the impacts of drought is to consolidate available water onto priority plantings, and/or purchase/lease water to cover reductions in allocation, in other words maintain full irrigation to as much of the orchard as possible. However, economic factors will determine whether purchasing water is a viable strategy, and which plantings should receive priority in water allocation.

Although not part of the work described in this report, trials conducted alongside this work under separate funding indicated that choice of rootstock can be a critical determinant of orchard drought tolerance, although this aspect of orchard management can only be manipulated at tree planting or replanting. For citrus orchards the commonly used replant rootstocks Swingle Citrumelo, and Troyer and Carrizo Citrange are suitably drought tolerant, and will give rapid recovery of yield once restrictions are relaxed. Cleopatra Mandarin is even more drought tolerant, but is NOT suitable for replant situations, and should only be considered if planting into virgin ground.

Matching water demand to water availability is critical to minimising the impact of drought on plantings. If water availability cannot be increased to meet demand of the existing orchard architecture, then orchard architecture may be modified to match available water, or at least minimise the difference.

Partial rootzone drying is a technique which reduces water demand, and therefore stress impacts on trees, when water availability is reduced. However, the required irrigation system modifications are expensive, and irrigation management becomes critical to the success of the technique.

Canopy reduction by mechanical hedging can reduce water demand whilst maintaining the ability to carry a crop. Care must be taken to avoid opening the canopy up too much, and exposing the major limbs to sunburn, or if this is unavoidable, whitewashing of the major limbs will be required. Reduction in water demand will be roughly proportional to the amount of leaf area removed. Regrowth may be limited while water is restricted.

Severe canopy reduction, or skeletonising, can assist in survival under severely reduced water availability, but this will generally be at the expense of yield, especially in the initial season. Whitewashing will be needed to protect the remaining limbs from sunburn, and recovery to full production will likely take between two and four years, depending on how far the trees are cut back, and how soon adequate watering can be resumed.

A variation on this strategy is reworking (or topworking), where the tree is cut back to facilitate budding over to a new scion. This process not only dramatically reduces the water demand by trees, it also introduces new varieties to the orchard much more quickly than can be achieved by planting new trees. This is an example of turning a negative (drought) into a positive (water savings and crop renewal).

If the canopy of citrus trees is not reduced during the period of water deficit, it is important that the trees receive attention at the time of return to full irrigation. Defoliation in response to water deficit will result in twig dieback, and possibly the death of whole branches if the deficit is severe. Not only is this dead wood unproductive, it also creates a source of fruit rind damage through scratching, which results in downgrading of fruit quality, and consequent reduction in fruit value. In addition to relieving this problem, hedging under conditions of adequate water availability also promotes growth of a new flush of foliage, assisting the recovery of production.

The findings of this project indicate that cultural treatments aimed at reducing the stress experienced by trees as the result of reduced water availability (for example kaolin clay films applied to the foliage) are of limited usefulness. Similarly, manipulating the movement of water in the soil (via soil applied polymers), or using mulching to reduce evaporation do not produce significant improvements in orchard performance under moderate reductions.

Statistical analysis indicated that irrigation system modifications to restrict the spread of sprinkler applied water to the shaded area under the canopy, in an effort to reduce evaporation, did not produce significantly better yields. Anecdotal evidence from workshops indicated that some growers saw benefits during drought periods, when irrigation volumes were reduced, but recovery was compromised if trees remained under partial cover irrigation once irrigation volumes returned to normal levels.

Citrus trees recover rapidly from moderate water restriction, particularly when the duration of the restriction is brief, for example only a single season, but severe water restriction (e.g. only 10% of normal water available) greatly increases the recovery time. However, biennial bearing is always a danger, and can be triggered by the sudden reinstitution of normal watering regimes following any period of water restriction. Crop load management may be required in the first few seasons following drought, to minimise the potential for biennial bearing.

Further Work

Interactions between irrigation system type and wetted area were identified as a significant factor in crop performance, under deficit irrigation and during recovery, in the on-farm monitoring program. However, the interaction is difficult to clarify, because the data come from a wide range of sites with various varieties, rootstocks, system configurations and management.

Further investigation of the impact of system type (drip or under-tree sprinkler) and wetted area on crop performance, especially under deficit irrigation, is recommended. The current work suggests that, while trees may cope with differences in water distribution under conditions of adequate water supply, reducing water supply may expose weaknesses in systems with inadequate coverage (e.g. <30% cover in drip, and partial cover under-tree sprinklers).

During the drought experienced here, almond prices were high, and the most common adaptation strategy undertaken by almond growers was to purchase water. This limited the scope of management strategies investigated in this work. It is recommended that further research be conducted into other adaptation strategies for almonds under deficit irrigation, such as crop removal and canopy management (through pruning or restricted spring irrigation), as well as the drought tolerance of commonly used almond rootstocks and varieties.

Finally, water stress is not always negative, and can be used as a tool for manipulating the balance between reproductive and vegetative growth, and fruit characteristics, for example. Plant based stress monitoring is a developing area of research, and irrigated tree crop industries would benefit greatly from applied research into the most appropriate plant based indicators for each crop, and critical values of indicators for specific outcomes.

Adoption Recommendations

Under current high storage and flow conditions in the Murray Darling Basin (December 2013) there is little appetite amongst the irrigation industries of the basin for information about managing drought. This is understandable, as irrigators have many other more immediate issues vying for their attention.

Some aspects of the research reported here need to be promoted in the absence of drought, as actions taken now can impact the resilience of plantings to future drought. These aspects include recommendations for rootstocks for new citrus plantings, the identification of issues around low wetted area under drip irrigation, and the establishment of Partial Root-zone Drying (PRD) capability. Addressing these issues can assist irrigators to manage future droughts.

It is acknowledged, however, that these issues are long term, and can be actioned only at certain stages of the production cycle, such as at replanting. As such, delivering outputs now may not result in the desired outcomes if replanting occurs at a future date when this information has been forgotten.

Other aspects of the research reported here will become relevant only when water shortages again threaten the survival and productivity of irrigated permanent tree crops. Reducing tree canopy to reduce water demand, for example, needs to be actioned during future drought events.

- It is recommended that the information in this report be disseminated widely across government, irrigated tree crop industry bodies, private consultants and irrigators, with the view to the information being accessible now, during future drought events, and during the intervening period. It will likely fall to government agencies to retrieve this information when required, and recirculate it in the time of need.

Recommendations to Government

Although the body of this report deals primarily with the response of irrigators to the drought, government and water managers also learnt valuable lessons during this event also. Below are some key recommendations on how best to manage water allocations during drought periods to assist irrigators to manage their plantings.

In the first season of drought (2006/07), allocations in South Australia were initially declared based on best estimates of minimal inflows into the Murray Darling river system. When the season proved to be a record dry season, with record low inflows, allocations were reduced mid-season (for example in SA allocations dropped from 80% to 70% in mid-October 2006, and dropped again to 60% in mid-November 2006. This caused major difficulties for irrigators, who had already applied significant proportions of their irrigation water on the basis of the initial allocations.

In subsequent seasons allocations were made only on water actually in storage, with allocations being revised upwards as inflows occurred. Although this presented its own challenges to irrigators, it was seen as the preferable way to manage allocations, as it provided transparency in the decision making process of water managers, and avoided surprises later in the season.

- It is recommended allocation of water in future drought events is based primarily on guaranteed supply, to avoid the prospect of reducing allocations in the event of unanticipated inflows.

- It is further recommended that water availability within the basin, and the principles upon which allocations are to be made, be discussed openly and transparently with the irrigator community, to assist them in managing the risk to their businesses posed by lack of water.

One of the most useful tools at irrigators' disposal during the drought was water trading across the Murray Darling Basin. Given the mix of crop types along the river system, some irrigators were in a position to postpone growing their normal crops (pastures for dairy, rice and cotton), and instead traded water to irrigators with permanent plantings who did not have the option to cease irrigating for a season or two, and then recommence irrigating.

- It is recommended that water trading continue to be as open and accessible as possible across the Murray Darling Basin.

Related to water trade, it was important that traded water could be transferred between licences as rapidly as possible, to allow irrigators to access traded water quickly. Mechanisms were put in place by the relevant state authorities to facilitate this process.

- It is recommended that best practice protocols for water transfer approvals be put in place in preparation for future drought events.

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Appendix

The following tables indicate the p-values of analyses presented in tables and figures in the "Results" section of this report.

Table 18: P values for canopy temperature analyses (see Table 7)

Date	P Value
18/12/2008	0.023
20/01/2009	<0.001
19/02/2009	<0.001
20/03/2009	<0.001
17/04/2009	<0.001
21/05/2009	0.021

Table 19: P values for leaf water potential analyses (see Figure 5 & Figure 6)

Date	P Value (Predawn)	P Value (Midday)
3/12/2008		0.063
18/12/2008	0.170	
21/01/2009	0.406	0.780
18/02/2009	0.018	0.055
20/03/2009	0.322	0.425
22/04/2009	0.507	0.019

Table 20: P values for leaf area index analyses (see Figure 7 & Figure 8)

Date	P Value (by Duration)	P Value (by Treatment)
February 2009	0.266	0.096
November 2009	<0.001	<0.001
July 20010	0.252	0.712

Table 21: P values for fruit count analyses (see Figure 9)

Date	P Value
03/12/2008	0.009*
20/03/2009	<0.001

*Significant p-value, but no differences found between treatments at 0.05% level.

Table 22: P values for fruit diameter analyses (see Table 8 & Table 9)

Date	P Value (by Treatment)	P Value (by Duration)
02/04/2009	<0.001	<0.001
29/07/2009	<0.001	<0.001
25/11/2009	<0.001	<0.001
01/04/2010	<0.001	<0.001
29/07/2010	0.196	<0.001
25/11/2010	0.885	0.137
07/04/2011	0.037	<0.001
28/07/2011	0.026	<0.001
24/11/2011	0.006*	<0.001
05/04/2012	0.002	<0.001
26/07/2012	<0.001	<0.001
22/11/2012	<0.001	<0.001

*Significant p-value, but no differences found between treatments at 0.05% level.

Table 23: P values for yield analyses (see Figure 11 & Figure 12)

Year	P Value
2008/09 (by Duration)	<0.001
2009/10 (by Duration)	<0.001
2010/11 (by Duration)	<0.001
2011/12 (by Duration)	<0.001
Sum Total (by Treatment)	<0.001
Sum Total (by Duration)	<0.001