Hort Innovation

Final Report

Identifying factors that influence spur productivity in almonds

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Delivery partner:

Department of Jobs, Precincts and Regions (formerly Department of Economic Development, Jobs, Transport and Resources

Project code:

AL14005

Project:

Identifying factors that influence spur productivity in almonds AL14005

Disclaimer:

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Content

Summary

Concerns with crop size variability from season to season prompted investigation of the basis of potential and realized crop size and the impacts of environment and management on the reproductive behaviour of spurs, the major fruit bearing structure on almond trees.

A large field experiment was established on a commercial orchard at Lindsay Point in north west Victoria to enable irrigation and nitrogen fertilizer management treatments to be imposed on Nonpareil and Carmel trees on a biometrically meaningful scale, and the effects on spur dynamics and kernel yield to be investigated over four seasons.

Reducing the volume of irrigation water applied from the industry standard of approximately 14 to 10 ML/ha/season and the standard nitrogen additions from 300 to 180 kg/ha/season did not result in significant yield reductions over the course of the experiment. The apparent effects of irrigation volume and nitrogen supply on yield in a season were a combination of the environmental and management effects the previous season and the season that the kernels were borne.

In this study the number of vegetative, floral and fruitful spurs per tree were estimated from the proportion of tagged spurs that bore flowers, set fruit and survived from season to season as well as the total weight of kernels yielded and average kernel sizes. As spurs died, new spurs were recruited into the study without prior knowledge of their age or reproductive history. The "tagged spur" approach was used because tree-scale spur population counts are difficult due to the large number of spurs on an almond tree.

Nonpareil spurs were more fertile than Carmel spurs; around 15% more Nonpareil spurs bore flowers and fruit. Nonpareil spur mortality rates were also higher compared to Carmel; Nonpareil spurs that bore a fruit had a high likelihood of dying off whereas the fruiting behaviour of Carmel spurs did not seem to affect spur survival.

Spur productivity was strongly influenced by spur location. Spurs high in the canopy were more likely to be fruitful, and to bear more fruit than spurs lower in the canopy. These trends were strongly related to the amount of light reaching those parts of the canopy; the strength of that relationship was stronger for Nonpareil trees than Carmel trees. The latter cultivar is far less prone to lower limb die back. Interestingly, the rate of spur mortality was only lower in the upper portions of Carmel trees relative to spurs located in lower positions.

Increasing the light in the lower regions of the canopy will not only increase the capability of spurs to ripen fruit and increase fruit retention but enable the survival of these spurs to the following season and stimulate bud emergence.

Reproductive spur mortality rates varied between the two cultivars, but given the generally high levels of productivity measured on the Lindsay Point trees, *ipso facto*, new spurs had to constantly emerge to compensate. Practically nothing is known about spur emergence. This is an area worthy of investigation because high levels of productivity are clearly predicated on new spurs arising, and knowing how to encourage that emergence would be advantageous in current and future production systems.

Keywords

Nonpareil; Carmel; spur dynamics; nitrogen; irrigation; light interception

Introduction

Australia is the second largest producer of almonds worldwide and almonds make up 62% of Australian tree nut production. Nonpareil and Carmel are the two major cultivars cultivated in Australia, contributing 50% and 34%, respectively, to total production in 2017. Almond production has more than

doubled since 2010 and is the fastest growing horticultural industry. Around 56% of the total planted area of 40 000 ha is located in north west Victoria, and 68% of the total Australian crop is produced in this region.

Seasonal yield fluctuations necessitated an understanding of the environmental and management factors contributing to inter-seasonal differences in yield. Yield is determined by the number of kernels produced by a tree and the tree's ability to fill these kernels. The number of kernels borne per tree is driven by the number of spurs on a tree, their fertility and whether they set a fruit.

Spurs are short proleptic shoots, meaning they arise from a quiescent bud. Spurs are the main fruit bearing structure on almond trees, but have a high turnover rate with fruiting spurs unlikely to survive beyond the season in which they bore fruit. Spur population dynamics have been well described from trials predominantly conducted in California on Nonpareil (Heerema *et al.* 2008, Lampinen *et al.* 2011, Valdebenito *et al.* 2017), but an understanding of the environmental and physiological factors affecting spur behaviour is limited.

A research project was conducted on a commercial almond orchard over five growing seasons to develop a better understanding of the factors that determine fruit number between seasons. The focus was on the management of two significant resource inputs, namely water and nitrogen, and how that affected spur turnover and yield formation.

The positive relationships between those two inputs on the one hand and kernel yield on the other is well supported by local and overseas research. A non-debilitating 30% reduction in water supply to almond trees at Lake Powell decreased yield (Sommer and Monks, 2014). Similarly, a non-debilitating 46% reduction in nitrogen inputs from around 309 kg/ha/season would be associated with significantly less yield (Muhammad *et al.* 2015). The scale of water and nitrogen supply reductions used in the project described herein were based on those two studies.

The project was designed and conducted to provide insights into spur dynamics under Australian growing conditions and provide a more objective basis to improve resource use efficiency. The knowledge generated would also be useful in the design of future orchard systems.

Methodology

Project reach

The project was conducted in north-west Victoria, but the outputs are applicable to the whole Australian almond industry.

Target audience

Almond producers, industry consultants, breeders, service providers and other researchers.

Description of methods (and justification)

An understanding of the factors that influence spur viability, fertility and longevity is required to manage seasonal yield fluctuations and to develop appropriate management practices that deliver consistently higher productivity. This research project focused on defining the effect of key environmental and management factors on spur productivity.

In 2014 a field trial site was established on a mature commercial orchard located at Lindsay Point, north-west Victoria, to address two objectives (see below). A 2×2 factorial design was used and included six replicates of each of the four treatments. During the winter of 2015, irrigation and fertigation infrastructure was installed to enable the manipulation of both water and nitrogen supply in a structured manner.

Observations were made on Nonpareil and Carmel. Nonpareil spur behaviour has been studied in California (Lampinen *et al.* 2011, Tombesi *et al.* 2011, Valdebenito *et al.* 2017), but there is very little information on Carmel spur behaviour despite it making up approximately 25% of current Australian plantings and will continue to be the second most planted cultivar behind Nonpareil for some time.

Detailed methodology can be found in Appendix A.

Objective 1. Quantify the longer-term behaviour of fruiting spurs of Nonpareil and Carmel almond cultivars under standard management practices.

A population of spurs were tagged and followed for five years. Assessments included their reproductive behaviour and vegetative traits, as well as their mortality rate. A similar and successful approach was used to study the effect of water and nitrogen inputs on Nonpareil by Lampinen *et al.* (2011).

Objective 2. Investigate the effects of key environment and management factors (tree architecture, light interception, irrigation and nutrition) on spur productivity.

The irrigation and nitrogen treatments began in August 2015. The control treatment amounted to the default management practices applied to the rest of the orchard. Water and nitrogen inputs were determined by the property's agronomist using soil moisture monitoring, vigour assessments and soil and leaf analyses, as well consideration of removals the previous season. The reduced irrigation treatment was applied as a sustained deficit amounting to 70% of normal orchard irrigation levels; that level of reduction was based on the Lake Powell deficit irrigation trial (Sommer 2012). The low nitrogen treatment involved restricting supply to around 180 kg N/ha/season throughout the irrigation season, that being 54% of the recommended rate. The reductions in irrigation and fertigation levels were chosen to achieve an observable difference without reducing yield beyond which would amount to a significant impost on the co-operating enterprise, or debilitating the trees (Sommer and Monks 2014).

Ceptometers and light-sensitive tape were used to describe light extinction by canopies and light receipts at spur level. Ceptometers are widely used across horticultural crops, including almond, to quantify photosynthetically active radiation (PAR). Light tape is a novel way to assess light receipts at spur level and supplied a means to assess the light environment of multiple spurs over time.

The responses to irrigation and fertigation were investigated by measuring midday stem water potential (SWP), leaf conductance and stomatal density. SWP and leaf conductance are reliable indicators of tree water status and their use in almonds well documented (Fulton *et al.* 2014). Tree nutrient status was assessed annually through standard leaf tissue analysis.

Objective 3. Communicate project findings and outcomes to the almond Industry.

Research updates and findings have been delivered regularly through a number of platforms. Annual presentations to the ABA Production Sub-committee have enabled industry oversight and input into the project. Presentations were made at biennial ABA Australian Almond Conferences and at the industry's Research and Development Fora held in alternate years. Both were well attended by almond producers, industry consultants and other researchers. Presentations were also made at industry field days. A technical report describing seasonal growth and development of Nonpareil and Carmel spurs has been compiled. Project information was further made available through the Horticulture Industry Network's webpage and Research Mildura Facebook page. Project staff presented project outcomes to fellow research through presentations at Agriculture Victoria Research seminars.

A presentation was made at the International Society for Horticultural Science's *VII International Symposium on Almonds and Pistachios* held in Adelaide in 2017. Useful discussions were held with almond researchers during an international irrigation conference in Spain in the early stages of the project.

Outputs

The following outputs were delivered during the life of the project.

Objective 1. Quantify the longer-term behaviour of fruiting spurs of Nonpareil and Carmel almond cultivars under standard management practices.

a) Summary report of annual spur growth dataset for seasons 1-4.

Objective 1 is discussed in detail in Appendix A. Annual spur population dynamics and reproductive behaviour were also reported on in milestone reports (see Objective 3 (h) for details) and summarized across seasons in the technical report drafted in 2018 (Objective 1 (b) and 2 (b)).

b) Technical report quantifying seasonal spur growth and development for Nonpareil and Carmel by 30 November 2018.

A combined technical report which addressed Objective 1 (b) and 2 (b) was submitted to Hort Innovation on 14 December 2018 and has been accepted.

Coetzee, Z. and Treeby, M., 2018. *Quantifying seasonal spur growth and development of Nonpareil and Carmel – the effect of key management factors on spur population dynamics in almond*. Agriculture Victoria Research technical report.

c) Draft journal paper submitted for peer review by 31 May 2019.

This date was postponed to coincide with the new submission date of the final report (30 November 2019) to accommodate inclusion of the additional observations and additional physiological data. Manuscripts on the outcomes of Objective 1 (c) and 2 (c) will be compiled from the outcomes reported on in the final report and submitted to a suitable peer-reviewed journal.

Objective 2. Investigate the effects of key environment and management factors (tree architecture, light interception, irrigation and nutrition) on spur productivity.

a) Annual light interception, irrigation and nutrient dataset reported for seasons 2-4.

Objective 2 is discussed in detail in Appendix A. Annual light interception, irrigation and nutrient datasets were reported on in the milestone reports (see Objective 3, (h)) and related data included in the technical report (Objective 1 (b) and 2 (b)).

b) Technical report quantifying seasonal spur growth and development for Nonpareil and Carmel by 30 November 2018.

Please see details under Objective 1(b).

c) Draft journal paper submitted for peer review by 31 May 2019.

As detailed under Objective 1(c) manuscripts on the outcomes of Objective 1 (c) and 2 (c) will be drafted from the outcomes reported on in the final report and submitted to a suitable peer-reviewed journal.

Objective 3. Communicate project findings and outcomes to the almond Industry.

a) Annual project progress briefing to the ABA production sub-committee, June 2016, 2017, 2018 and 2019.

On-going informal briefings were delivered to Mr Ross Skinner, CEO Almond Board Australia, over the course of the project.

Progress information was also provided to the ABA Production Sub-committee meetings held on in February, May and August of 2017, 2018 and 2019.

b) *Annual article introducing and reporting progress against objectives submitted to an industry journal (Nut Grower or In a Nutshell). The first article will introduce the new work in this project as building on the study at Lake Powell.*

An introductory article was published in Spring 2014 and available for viewing in Appendix C.12.

Brown, B., Monks, D., Sommer, K., 2014. 2014 Crop review. *In a Nutshell* **14** (3), 18-19.

An article ("Management inputs and spur behaviour", Coetzee, Z., Taylor, C. and Treeby, M.) setting out some of the research outputs has been submitted for inclusion in *In a Nutshell.*

Project outcomes were further mainly conveyed to fellow researchers, growers and the general public at several events during the lifetime of the project, reaching a broad audience.

The following posters and presentations were presented at these events and posters are available for viewing in Appendix C.

EVENT	OUTPUT
2015 Mildura Horticulture Field Days	Poster: *Growing spurs not trees* (Appendix C.1)
2016 Mildura Horticulture Field Days	Poster: *Spurs: Driving Productivity* (Appendix C.2) Poster: *Water: Almond productivity during deficit* (Appendix C.3)
2018 Mildura Horticulture Field Days	Poster: *The effect of water and nitrogen on yield of almond trees* (Appendix C.4) Almond tastings: 342 members of the public in attendance engaged in randomised triangular discriminative taste difference testing using 2018 Nonpareil kernels from the four treatment combinations.
2019 Mildura Horticulture Field Days	Poster: *The effect of water and nitrogen on almond production* (Appendix C.5) Almond tastings: as per 2018, but with 378 members of the public using 2019 Nonpareil kernels. The Victorian Minister for Agriculture Jaclyn Symes was also in attendance and participated in the exercise.
ABA Sunraysia/Riverland pre-harvest field walk, 14 August 2019	Update to growers: trial progress Re-presented 2019 Mildura Horticulture Field Days poster; viz. *The effect of water and nitrogen management on yield of Nonpareil*
World Bank delegation from India	Presentation: *Identifying factors that affect spur productivity in almond*
Agriculture Victoria Research AgriBio seminar series	Presentation: *Management Strategies to Maintain High Productivity in* Prunus dulcis *Mill. (Almonds). Water & Nitrogen Supply Affecting Dynamics of Fruit Bearing Structures* (schedule available in Appendix C.6)
Agriculture Victoria Research Regional Science conference	Presentation: *Orchard management -spur production* (abstract available in Appendix C.7)

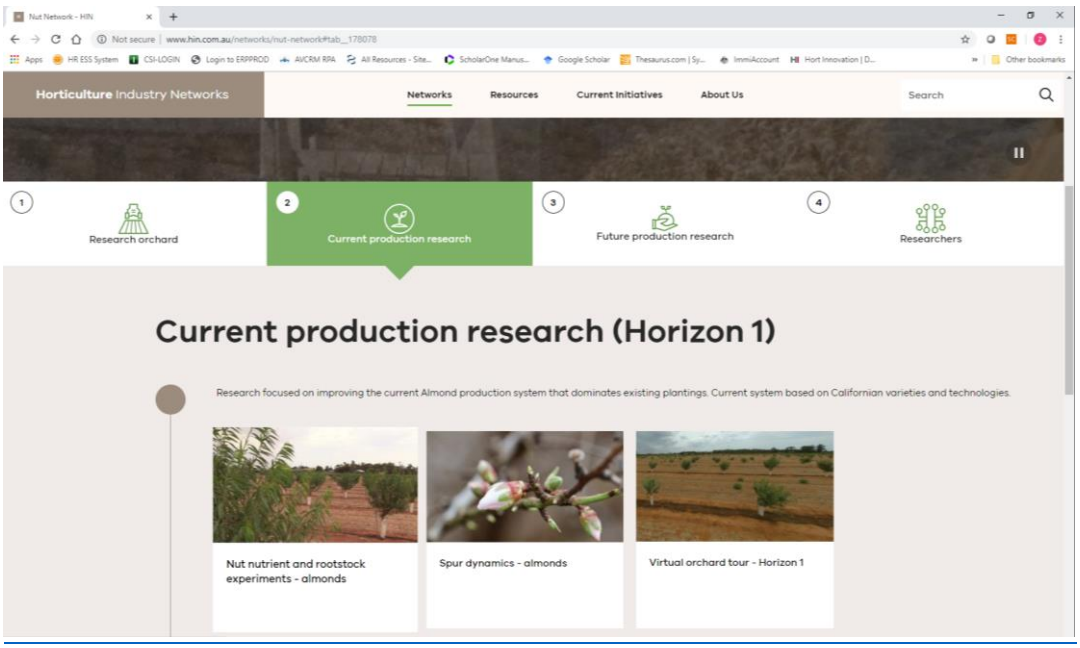
Almond tastings were conducted at the 2018 and 2019 Mildura field day events, during which 342 and 378 members of the public were engaged, respectively. In 2019 Jaclyn Symes, the Victorian Minister for Agriculture, visited the Agriculture Victoria tent and participated in the tastings.

The Victorian Minister for Agriculture, Jaclyn Symes (center) visited the Agriculture Victoria site at the 2019 Mildura Field days and participated in the almond tasting. The photo was recorded by Melanie Curtis and the property of Agriculture Victoria and used with permission.

c) *Project introduction and progress updates will be made available for distribution through the HIN website and on Mildura's Facebook page in June 2015, 2016, 2017, 2018 and 2019.*

The team has a strong presence on the HIN website as part of the Nut Network (screenshot below of the interface) and videos discussing the project are available on the website.

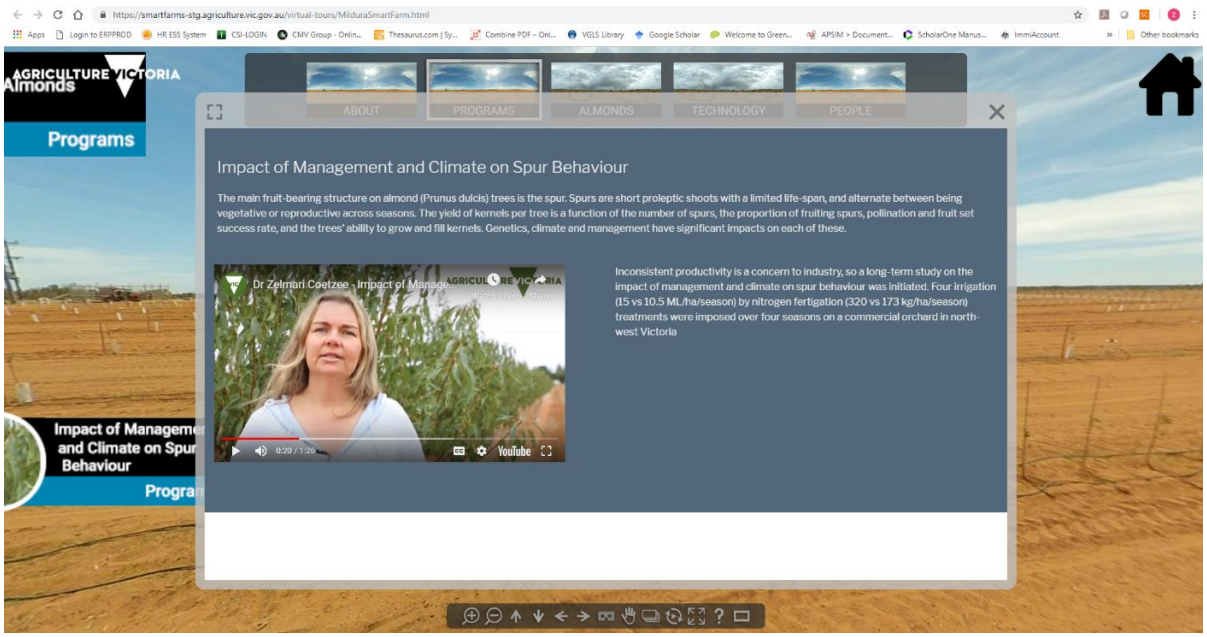
http://www.hin.com.au/networks/nut-network#tab__178078



Several informal communications were done on the Research in Mildura Facebook page and can be viewed online.

https://www.facebook.com/Research-at-Mildura

In addition to an online presence on the HIN website, project videos are available online as part of the Agriculture Victoria Virtual Smart Farm. A screenshot of the project introduction and progress video on the internal AVR Virtual Smart Farm webpage is shown below. A video link is temporarily available for public access (https://youtu.be/gfjNIhp5Vgo).



d) Annual presentation of results at the Australian almond conference (October 2015, 2016, 2017, 2018 and 2019).

The following presentations were made and posters presented at the Australian almond conferences, ABA R&D fora and other almond-related events over the course of the project.

Conference	Date	Presentation title	Presenter
16th Australian Almond Conference (340 attendees)	30 October 2014	*Orchard productivity: a population of spurs*	Dave Monks (oral)
Activated Almond Forum (100 attendees)	28 October 2015	*Spurs: driving productivity*	Dave Monks (oral)
17th Australian Almond Conference (409 attendees)	8-10 November 2016	*Spur survival: Difference between cultivars*	Cathy Taylor (poster)
17th Australian Almond Conference	8-10 November 2016	*Spurs: Driving productivity*	Cathy Taylor (poster)
2017 Australian Almond R&D Forum (221 attendees)	24 October 2017	*Identifying factors that influence spur productivity in almond*	Michael Treeby (oral)
7th International Symposium on Almonds and Pistachios (144 attendees)	9 November 2017	*Leaf mass per unit leaf area increases as light interception increases within almond (*Prunus dulcis *[Mill.] D. A. Webb) canopies*	Michael Treeby (oral)
2018 Australian Almond Conference (484 attendees)	30 October - 1 November 2018	*AgVic's Field Laboratory: A Platform for Current & Future Production Systems* (AL14005's spur dynamics data used)	Michael Treeby (oral)
5th Australian Almond R&D Forum (220 attendees)	30 October 2019	*Identifying factors that influence spur productivity in almonds*	Zelmari Coetzee (oral)

e) Study tour report for the key Italian and Spanish research and production areas, documenting new collaborations, new research findings and production issues raised during the tour.

Dave Monks attended the Australian almond industry's study tour of Spain from 28 May to 5 June 2015. The travel was combined with attendance at the 8th ISHS Irrigation Symposium in Lleida, Spain, during which he presented the research outcomes of *AL12010 - Impact of strategic deficit irrigation for almonds on tree phenology, bloom, nut set and hull rot through deficit irrigation strategies*. The conference abstract is available in Appendix C.8 and the following publication was published as part of the conference proceedings, available in Appendix C.12.

> Monks, D.P., Taylor, C., Sommer, K. and Treeby, M.T. (2017). Deficit irrigation of almond trees did not decrease yield. *Acta Horticulturae* 1150, 251-260.

f) Conference report from biennial attendance at the Almond Board of California's annual conference documenting new collaborations, new research findings and issues raised.

Michael Treeby attended the Almond Board of California's 2016 and 2017 annual technical conferences held in Sacramento, California. The travel reports are available in Appendix C.10 and C.11.

g) Journal paper contributions to PFR tree architecture and CSIRO pollination research as required.

Circumstances dictated that the PFR tree architecture research (*AL14007*) was conducted on another research site to *AL14005*.

The findings from the CSIRO pollination research (*AL14004*) were published as a final report (https://www.horticulture.com.au/globalassets/laserfiche/assets/project-reports/al14004/al14004-final-report.pdf-542.pdf). The pollination trial layout was superimposed over *AL14005* treatments. Spur trait data (spur reproductive and vegetative characteristics) collected for *AL14005* were used to characterise the Nonpareil spur population for the site. Canopy light interception data was further used to determine the association between the light environment and the number of flowers.

Outside of the research agreement, a new collaboration was formed with *AL16005 – An integrated disease management program for the Australian Almond Industry*. Following completion of AL14005, the AL16005 project team took over the site and infrastructure. Data from *AL14005* were used to determine possible physiological characteristics impacting on disease incidence and the effect of altered management practices on the severity and frequency of hull rot as part of Outcome 1 of Hort Innovation's Almond Strategic Investment Plan (SIP) 2017-2021. The *AL16005* team will continue relevant measurements and build on data that was collected for *AL14005*.

h) Annual Hort Innovation progress reports

The following milestones were submitted in accordance with the reporting schedule.

Reporting output	Due date	Status
Milestone 102	30 April 2016	Submitted, accepted
Milestone 103	1 August 2016	Submitted, accepted
Milestone 104	30 April 2017	Submitted, accepted
Milestone 105	1 August 2017	Submitted, accepted
Milestone 106	30 April 2018	Submitted, accepted
Milestone 107	31 August 2018	Submitted, accepted
Technical report	14 December 2018	Submitted, accepted
(190) Final report	30 November 2019	Submitted

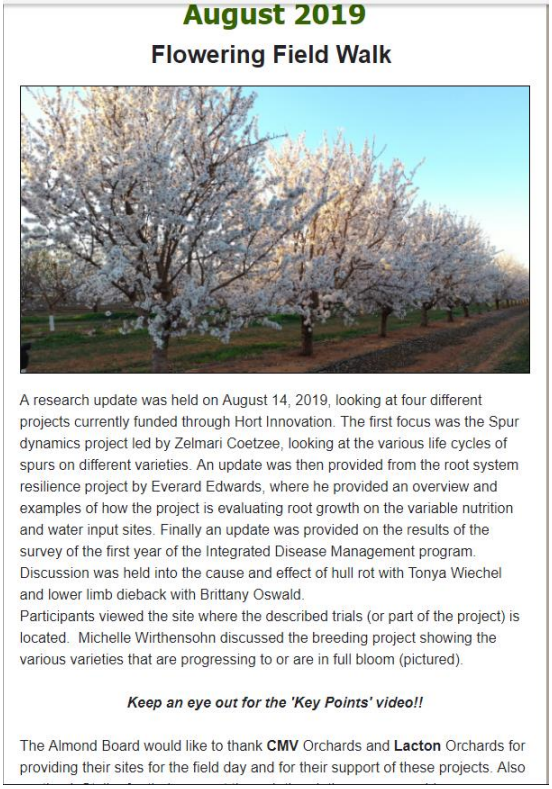
i) Field day for growers at Lindsay Point (experiment location) by 28 February 2019.

The field day was held in conjunction with the ABA flower walk on 14 August 2019 during which an update was given to growers on the research findings of the experiment at Lindsay Point. Forty-one growers attended the project update presentations of four Hort Innovation projects at the Paringa Hotel, which was followed by a visit to the experimental site at Lindsay Point.

The reasoning to change the original date of the field day was twofold. It was firstly decided to have the field day at the end of winter not only to avoid accessing the farm during preparations for harvest and during the harvest period, but also to ensure more almond producers were able to attend. It was further decided to combine the field day with one of ABA's field days or flower walks in that region to increase the number of attendees.

The August 14 field day was held in combination with the ABA flower walk during which Dr Michelle Wirthensohn (right image, centre) updated industry on the performance of the new almond cultivars. Photos by Zelmari Coetzee.

An informal discussion with Mr Tim Preusker, the farm manager, and other almond producers in attendance, corroborated the results of the trial. The event was rated highly by the industry attendees (Josh Fielke, personal communication). The field day was summarised in the August 2019 edition of Almond Bytes (https://industry.australianalmonds.com.au/), the ABA's monthly e-newsletter and a screenshot included below.



August 2019

Flowering Field Walk

A research update was held on August 14, 2019, looking at four different projects currently funded through Hort Innovation. The first focus was the Spur dynamics project led by Zelmari Coetzee, looking at the various life cycles of spurs on different varieties. An update was then provided from the root system resilience project by Everard Edwards, where he provided an overview and examples of how the project is evaluating root growth on the variable nutrition and water input sites. Finally an update was provided on the results of the survey of the first year of the Integrated Disease Management program. Discussion was held into the cause and effect of hull rot with Tonya Wiechel and lower limb dieback with Brittany Oswald.
Participants viewed the site where the described trials (or part of the project) is located. Michelle Wirthensohn discussed the breeding project showing the various varieties that are progressing to or are in full bloom (pictured).

Keep an eye out for the 'Key Points' video!!

The Almond Board would like to thank **CMV** Orchards and **Lacton** Orchards for providing their sites for the field day and for their support of these projects. Also

j) Hort Innovation final project report by 31 May 2019.

The final submission date was extended to 30 November 2019.

Outcomes

1. *Establish the response of spur productivity (including the number and area of leaves, the number of flowers and fruit and the weight and number of kernels) to light.*

Spur productivity was highly modulated by the spur position within the canopy. Measurements of spur level light receipts in the final season indicated a rapid vertical decrease in light receipts, indicating that spur positions in the canopy can be representative of light interception.

Spur position clearly dictated the reproductive behaviour of spurs, and to some extent the number of fruit borne spurs due to the role light is believed to play in the initiation of floral buds. To that end these outcomes were determined by the fruit set success rate and the number of fruit that were retained. It is likely that the main driver in the spur productivity response is not linkage between light and bud fertility, but a physiological response to the low light environment in the lower parts of the canopy. Spurs located in these positions may be unable to fully contribute to the spurs' carbon economy due to reduced photosynthetic activity of , thus inducing a large percentage of flowers and fruit to drop.

Spurs only live for a few seasons, so their mortality and turn-over rate are important factors contributing to tree productivity. Carmel spurs were more likely to survive compared to Nonpareil spurs.

Nonpareil spur mortality was related more to cropping and spur leaf area, and less to spur position; the majority of Nonpareil spurs produce fruit and die shortly thereafter.

Carmel mortality was related to spur position, increasing from the upper to lower parts of the canopy. Less leaf area per spur and less chlorophyll per unit leaf area, combined with the low light environment would have diminished the carbon contribution of these spurs. Carmel, however, does not exhibit the lower limb dieback symptoms seen on Nonpareil trees. It is possible that Carmel spurs and supporting wood have a lower carbohydrate requirement for maintenance and a lower light requirement for bud initiation compared to Nonpareil. This will enable a higher spur turn-over rate in Carmel in relation to spur mortality.

Increasing the light in the lower regions of the canopy will not only increase the capability of these spurs to ripen fruit and improve fruit retention, but the survival of these spurs to the following season and stimulate bud emergence.

It should be borne in mind that the response of spur productivity to the amount of light reaching different parts of the canopy is made up of several relationships between the components of spur productivity and light. One of these is the relationship between light and floral initiation, which is still unknown. Observations across multiple seasons to determine light thresholds for floral bud initiation and spur genesis will allow the overall relationship between light and spur productivity to be more robust. Incorporating a stochastic element into the light/spur productivity relationship may prove useful.

2. *Determine the effect of water and nitrogen deficits on the light interception and spur productivity response functions.*

Water and nitrogen supply were linked to the extinction of light from the top of the canopy to the bottom. Reduced water supply generally improved the amount of light reaching the lower parts of the canopy. An effect of reduced nitrogen inputs was not readily apparent overall, but in some seasons reduced nitrogen supply was associated with more light reaching the lower parts of the canopy, but the effect was inconsistent. Spurs in the lower parts of the canopy were generally more likely to be vegetative and less likely to retain a fruit through to maturity. These spurs were also more likely to only bear one fruit compared to spurs higher up bearing two or more fruit.

Spur-level responses to management practices however differed not only between seasons, but also

between cultivars which suggests that cultivars may need to be managed differently. Even though reduced water applications resulted in lower yields per ha in some seasons, the overall reduction was not great, and the improvements in water use efficiency were apparent from the first season treatments were applied. This suggests that on-farm water use can be reduced; an observation consistent with Outcome 3 of the Almond SIP 2017-2021.

3. *Test and validate the yield prediction from the L-Systems model developed in California for Australian conditions.*

The project team was unable to secure access to the L-Systems model. To overcome this circumstance, the knowledge generated modelling light extinction in trellised stone and pome fruit canopies is being used as the basis to develop a model of light extinction and spur dynamics/productivity in H1 canopies and to use that model to develop the design specifications for the next generation of almond tree training system.

4. *Developed and delivered a package of information for growers on the effects of management and environment on the fate of spurs.*

Research findings and the availability of the final report on the Hort Innovation website will be communicated to growers through publications in the ABA's "In A Nutshell" journal and other industry journals. A paper will also be produced for publication in a peer-reviewed journal.

Multiple presentations have been made at various industry fora informing almond producers of the impacts of irrigation and nitrogen fertilizer management on spur dynamics, the yield potential and realizing that yield. Interest was shown at these events in the outcomes of *AL14005* and the advances that were made in the spur dynamics space through this project. An interim technical report was also produced.

Links to all presentations, articles and the final report will be made available on the HIN network and AVR Virtual Smart Farm webpages. Presentations delivered at ABA Research and Development forums are available online (https://industry.australianalmonds.com.au/research-topics/archived-event-presentations/).

5. *Use the results of this project to provide basis for next generation tree pruning and training systems.*

The project has provided insights into light extinction through Nonpareil and Carmel canopies in relation to spur turnover, fertility and productivity, and the modulating impact of irrigation and nitrogen fertilizer management. The light/fertility relationships can be used as design parameters for the next generation of tree pruning and training systems, and the spur fertility and final fruit retention data provide some key performance indicators for those systems (Almond SIP 2017-2021 Outcome 3).

The project enabled the identification of a major deficiency in the understanding of the basis of yield potential determination; namely, spur genesis. Clearly, the rate of appearance must more-or-less match the rate spurs die for potential yield to be more or less constant over time. To improve productivity in H1 orchards, spur fertility and fruit retention need to be improved over the entire canopy and allowing better light penetration will be the key. To make the next generation of tree pruning and training systems (*i.e*. H3 production systems) at least as productive as H1 plantings may require encouraging more spurs to emerge and/or reducing their mortality. Spur genesis is poorly understood. The means to quantify spur populations on a meaningful scale would be beneficial.

Monitoring and evaluation

The project delivered against Outcome 3 of the Almond SIP 2017-2021 by identifying more efficient resource and identifying canopy design and performance indicators for the next generation of pruning and tree training systems. The project has also served to identify spur genesis as a knowledge gap potentially having important implications for future production systems as well as current H1 orchards.

The project's research platform was the field experiment set up in a commercial almond orchard located approximately 160 km from the AVR's Irymple site. The support provided by the on-site team was outstanding, both in terms of monitoring the site and imposing the irrigation and nitrogen supply treatments, and especially providing technical support during whole tree fruit harvesting.

The commercial planting consisted of Nonpareil, alternated with Carmel and Monterey. Essentially, two experiments were conducted in parallel; one on Nonpareil and one on Carmel. Thus, it was not possible to assess whether cultivar was a significant source of variation in any response to the water and nitrogen management treatment. There was a significant number of observations that led to the project team suspecting that the two cultivars did not behave the same. Being able to assess objectively whether that was indeed the case could have provided industry with new knowledge and been the basis for more appropriate irrigation system design, for example. A larger experiment with cultivar included as a treatment would have been helpful.

From a WHS viewpoint, the return trip from AVR's site at Irymple amounted to about 4 hours, most of it on a major highway with the attendant risks associated with native and feral animals and heavy traffic. This travel time was non-productive and amounted to a significant cost. These considerations add further weight to the argument that a dedicated experimental site within easy reach of AVR's Irymple site would be advantageous.

A mid-project review was conducted by Dr Byron de Kock (R&D Manager - Hort Innovation). A report on progress and preliminary analysis of the data collected up to that point was provided, and a more general discussion held regarding the complexities of operating on a remote site. Feedback provided at the time indicated satisfaction with the progress and the report prepared which included an acknowledgement that such field experiments were not a trivial matter.

Recommendations

Spurs need to be exposed to sufficient light to directly or indirectly influence the likelihood of flower bud initiation and development and fruit retention. This will further enable sufficient photosynthesis to contribute to spur carbon balance and reduce spur mortality. Spur genesis has hitherto been implicitly assumed to be a constant, but there is no evidence to support this.

Reducing seasonal water inputs, and to a lesser degree the nitrogen supply, allow for more light to pass through the canopy and increase the quantity of light reaching the lower parts of the canopy. This will improve the conditions for floral bud initiation by improving both the spur carbon balance and light environment and in turn increase the number of fruit per tree.

A relatively substantial reduction in nitrogen supply as imposed here did not result in a loss in productivity overall. The generalization is based on four successive seasons of measurements, and one of those seasons' observations were compromised by hardware-related treatment imposition issues the previous season. There is likely to be ample scope to reduce nitrogen inputs without compromising orchard productivity, but a caveat might include the proviso that leaf nitrogen needs to be monitored. The input cost savings across the industry would likely be significant.

Similarly, some modest reduction in water inputs seems possible without compromising orchard productivity. Again, that generalization is based on all the seasons' data, and seasonal productivity was

more sensitive to water supply than it was to nitrogen supply, but the reduction imposed here was around 30%; a less drastic reduction would still deliver a significant water savings across the industry. Reducing water inputs further significantly increased the water use efficiency of the trees.

Clear differences in the effect of water and nitrogen management on Nonpareil and Carmel production and physiology further necessitates that consideration be given to managing these two cultivars separately.

Refereed scientific publications

Referred publications are available in Appendix C.13 and C.14.

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Intellectual property, commercialisation and confidentiality

No project IP, project outputs, commercialisation or confidentiality issues to report.

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Ian Goodwin's (AVR) editorial input and suggestions for improvement are also gratefully acknowledged.

Appendix A Results and discussion

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Materials and methods

Experimental site

The project commenced in 2014 and was conducted on a commercial almond orchard at Lindsay Point in the north-west of Victoria (34°4'39.65" S, 141°0'21.06" E) over five seasons. The orchard was established in 2005 with a NE-SW row direction and a 7.2 m between and 4.0 m within-row tree spacing. Rows of Nonpareil trees alternated with rows of Carmel and Monterey as pollinators.

Twenty-four plots, each comprised of four rows of eight trees, were distributed across the 2.2 ha research area (Figure 1) in a factorial design with six replicates per treatment. The treatments were applied to whole plots. The four central trees of each of the two middle rows of each plot — adjacent rows of Nonpareil and Carmel — were used. The two outer rows and the two trees at either end of the two central rows served as buffers.

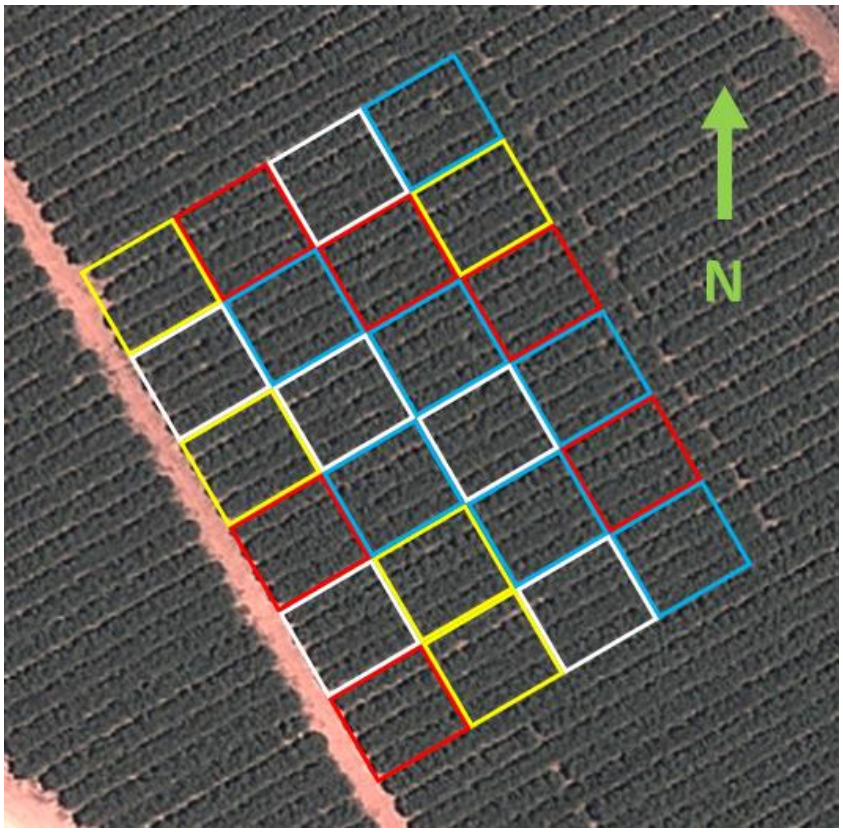


Figure 1 Layout of replicated plots across the trial area.

White = 100% water and 100% N ("+W+N"); blue = 100% water and 56% N ("+W-N"); yellow = 70% water and 100% N ("-W+N"); red = 70% water and 56% N ("-W-N").

Treatments

The site's existing irrigation infrastructure was modified during the 2015 winter to deliver irrigation volume ("W") and nitrogen supply ("N") treatments, which commenced in August of that year (S1). The nominal amounts of water and nitrogen applied in each treatment and in each of the four seasons (S1 to S4) are detailed in Table 1. The actual volumes of water and amount of nitrogen supplied are detailed in Table 5.

The control irrigation treatment was irrigated and fertigated according to the management practices applied on the rest of the orchard. Water and fertigation inputs were determined by the property's agronomist. Water applications were regulated through soil water monitoring, and seasonal nitrogen inputs were determined and adapted to soil and leaf analyses, crop removal and visual monitoring during the season. Regular water applications were reduced by 30%, and seasonal nitrogen application by 44% by reducing the amount of urea applied. Nitrogen was also supplied as potassium nitrate (KNO_3) and mono-ammonium phosphate (MAP); the amounts of these nitrogen sources were the same for both the +N and -N treatments. Other nutrients were supplied at normal industry rates, and all nutrients were applied by fertigation.

Table 1 Nominal irrigation and nitrogen fertiliser supply treatment combinations and codes.

	ML water/ha	
kg N/ha	15	10.5
320	+W+N	-W+N
179	+W-N	-W-N

Spur selection

In the first season (S0), 48 spurs were tagged across the four central trees of each cultivar in each control plot. Each tree was nominally divided into quarters along and across the tree row and each quarter into three vertical strata (1.1 – 2.0, 2.0 – 2.9 and 2.9 – 3.8 m above the orchard floor) to create 12 light 'zones' (Figure 2). A quarter on either side of each tree was selected, and two spurs were tagged within each of the light zones. Across the four observation trees, each quarter was selected twice. Spurs were selected and tagged at bud swell (late July – early August 2014).

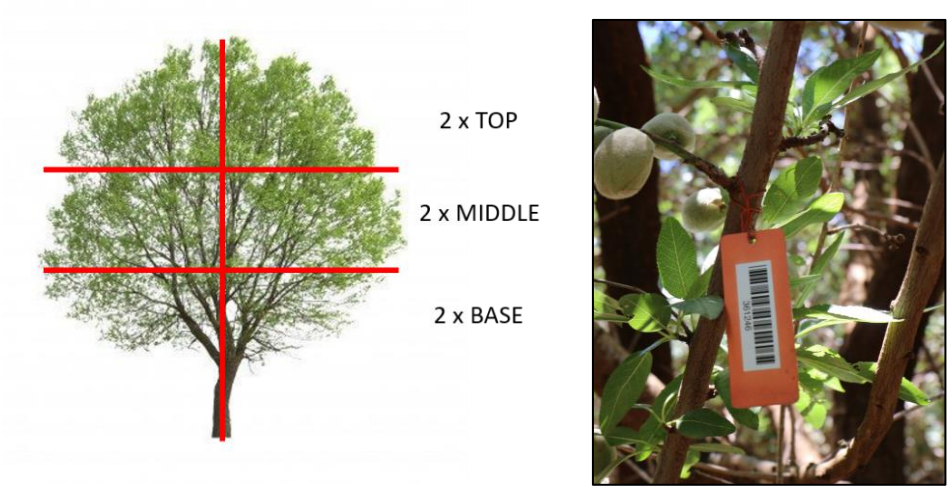


Figure 2 Tree canopy division to assess the relationship between spur position (and by implication, light exposure) and spur reproductive and vegetative behaviour.

Left-hand image, vertical division of tree into three layers, and right-hand image a tagged spur showing the identifying barcode (row, tree, quarter and position). Photo by Zelmari Coetzee.

In the second year (S1), a central Nonpareil and Carmel tree in each plot was selected for spur and tree assessments. Two representative spurs were selected in each of the trees' 12 light zones and tagged to give a total of 24 tagged spurs per tree. In total, 576 spurs were tagged per cultivar, amounting to 144 per treatment. Marked spurs were checked during dormancy each year, and any that had died were replaced with spurs in a similar light exposure circumstance within the same zone.

Environmental assessments

Macroclimate

The South Australian Research and Development Institute (SARDI) provided weather information collected during the co-located Hort Innovation supported project *AL14006 - Managing almond production in a variable and changing climate* and the South Australian River Murray Sustainability Program industry-led research sub-program project *IRSP-006 Identifying and managing weather and climate risks to almond production.* Daily and hourly temperature data were calculated from hourly air temperature measurements by Tinytag Plus 2 TPG 4500 dual channel temperature sensors placed in a Stevenson Screen. The sensors were located in an unplanted part of the property approximately 2.5 km from the trial site.

Rainfall data were collected from the Lindsay Point automatic weather station which is available on the Bureau of Meteorology's website (http://www.bom.gov.au/climate/data/stations/).

Canopy light interception

Photosynthetically active radiation (PAR, expressed as µmol/m^2/s^1) intercepted by the canopy was measured at ground level over the planting square using a ceptometer (AccuPAR LP-80, Meter Group Inc, Pullman, USA). Measures were taken within an hour either side of solar noon. Forty-nine measures comprising seven rows of seven readings were taken within each planting square. PAR was measured every four to six weeks during the growing season (September to February).

Spur light exposure

The quantum of light at each tagged spur was measured using Optoleaf solar radiation film (Y-1W - Taisei Fine Chemical Co. Ltd., Japan). The film is light sensitive and changes colour in proportion to the amount of light impacting on it. The colour (D) was read using a D-meter RYO-470 (Taisei Fine Chemical Co. Ltd., Japan). Strips of film were attached to locations adjacent to each spur and oriented horizontally using glue dots (Glue Dots International, Germantown, Wisconsin, USA).

Film was placed in Nonpareil trees on 18 January 2019 and Carmel on 1 February 2019, during the likely period of floral bud initiation and around the time of hull split. A set of calibration strips were also placed outside the orchard in an unshaded position. Before their absorbance reached the point of saturation (0.6), all strips were collected and measured. The percentage of light absorbed by the film was calculated as:

$$\frac{D}{D_0} \times 100$$

where D = the absorbance of the tape located near the spur, and D_0 = the absorbance of tape located at the top of the canopy.

Soil moisture

In July 2018 loggable gypsum blocks (GBug Lite - Measurement Engineering Australia, Magill, Australia) were installed in each plot of both cultivars to provide a continuous record of soil moisture. Blocks were installed 10 cm from the dripper line at a depth of 20 cm and equidistant between two trees. The Nonpareil data were downloaded manually using an MEA retriever. The Carmel data were downloaded automatically into a MEA Plexus datalogger (Figure 3) and were available in real-time through the Greenbrain network.

Figure 3 An MEA Plexus datalogger installed in August 2018 for continuous soil moisture logging in Carmel in S4. Photo by Zelmari Coetzee.

Productivity and physiological assessments

Tree water status

Tree water status was quantified as midday SWP measured at approximately six-week intervals throughout the season according to Fulton *et al.* (2014). Half an hour before testing, foil laminate bags (PMS Instrument Company, Albury, USA) were placed over a leaf from the inner canopy of the two central trees of each cultivar in each plot. The leaves were then removed from the tree and SWP measured using a Scholander pressure bomb (Plant Water Status Console 3005 series, Soil Moisture Equipment Corp., Santa Barbara, USA).

Leaf nutrients

Leaf nutrient status was measured in January of each season during the trial period. Sixty well exposed non-fruiting spurs were collected from the central trees of each plot. The leaves were washed in lightly acidified water with a few drops of phosphate-free detergent, rinsed several times in de-ionised water and dried at 60^{o}C. Nutrient analyses were conducted by a NATA-accredited analytical laboratory (CSPB Soil and Plant Analysis Laboratory, Bibra Lake, WA, Australia). Nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, sodium, boron, copper, iron, manganese, molybdenum (2019 only) and zinc determination were conducted as per McQuaker *et al.* (1979). The concentrations of mineral elements in dry leaf material were assessed against the accepted interpretative standards for almonds (Robinson *et al.* 1997).

Trunk circumference

The circumference of the trunks of the central four trees of each plot were measured at 40 cm above the ground. Beginning in 2016 measures were taken during the dormant period each year and the circumference increment between seasons calculated.

Spur vegetative and reproductive traits

Spur summer assessments were carried out 12 weeks after flowering subsequent to the third fruit fall and at the end of the active vegetative growth period. The number of fruit and leaves per spur and the length of the longest leaf were recorded. Spur leaf area (SLA) was estimated from the length of the longest leaf and the number of leaves per spur as described in Heerema *et al.* (2008). The algorithm was re-parametrised for the experimental site over two seasons (2016-17 and 2018-19).

At the end of winter all spurs were again assessed for their vitality, the dead spurs recorded and replaced with a nearby spur with a putatively similar light environment. At the same time, the number of flower buds per spur were noted for the new season's set of monitored spurs.

Seasonal spur behaviour and mortality rates were classified according to the spurs' fruiting behaviour (*i.e*. vegetative or fruit bearing) and SLA categorised as small (0 – 20 cm^2), medium (20 – 50 cm^2) or high (> 50 cm^2).

Prior to the commercial whole-tree harvest, fruit from each tagged spur were collected and the dry weight of the fruit and kernel determined.

Spur leaf area algorithm

In late December to mid-January, 12 spurs were collected from one tree of each plot; six from each of the NW and SE sides of the tree. Spurs were randomly selected from each of the three vertical strata, ensuring two of the spurs were fruiting. The number of fruit, leaves and length of the longest leaf were noted. All leaf blades from a spur were then scanned along with a calibration scale using an A4 scanner (Canon, Pixma MG2160) and the length of the longest leaf noted. Leaf area per spur was determined using "Fiji", an open-source platform for scientific image analysis.

Leaf conductance

Leaf conductance (mmol/m^2/s) was measured using a SC-1 Leaf Porometer (Meter Group Inc, Pullman, USA). Measures were taken within an hour either side of solar noon during the 2018-2019 growing season simultaneous to SWP measurements. Three fully exposed leaves from non-fruiting spurs on the NW side of the tree were measured on each tagged tree.

Stomatal density

To determine the effect of the water and nitrogen treatments on stomatal density, three exposed and three shaded leaves were collected from each of the measurement trees in January 2019. Stomatal slides were made of the underside of each leaf using a nail polish blotting method (Zhu *et al.* 2018). A Leica DFC295 camera (Lecia, Wetzlar, Germany) attached to an optical microscope (Olympus BX51 Microscope, Tokyo, Japan) was used to capture digital images at 100x magnification. The number of stomates per observed area was noted.

Chlorophyll

Four leaves, at two positions on the northern side of the canopy (shaded and exposed), were sampled in January 2019 from each plot. Six disks (each 0.28 cm^2), three from each side of each leaf's central vein, were removed using a single-hole punch. The resultant twenty-four disks were combined and split into two groups, placed in pre-weighed micro-centrifuge tubes, capped and fresh mass determined. For dry mass determination, one of each pair of tubes was placed in a drying oven at 65°C for 48 h, re-weighed

and the ratio of fresh to dry mass calculated.

The remaining tubes were used to determine the amount of chlorophyll in the leaf disks according to the method of Hiscox and Israelstam (1979) optimised for almond leaves. Briefly, the disks were frozen, transferred to 10 mL tubes and ground under liquid nitrogen using a micro pestle. Ten mL of dimethyl sulfoxide (DMSO) was added, the mixture vortexed and extracted in a shaking water bath at 65°C for 6 h. The tubes were centrifuged, the supernatant removed and retained, and the remaining pellet re-extracted in 2 mL of DMSO at 65°C for an hour. After centrifugation, the supernatants were combined and the absorbance at 645 and 663 nm determined using a SpectraMax Plus 384 benchtop spectrophotometer (Molecular Devices Corporation, Sunnyvale, USA). The concentrations of chlorophyll *a*, *b* and the total chlorophyll concentration of the supernatants were estimated as follows:

$$Chl_a(g/l) = 0.0127\,A_{663} - 0.00269\,A_{645}$$

$$Chl_b(g/l) = 0.0229\,A_{645} - 0.00468\,A_{663}$$

$$Chl_{a+b}(g/l) = 0.0202\,A_{645} - 0.00802\,A_{663}$$

Yield per hectare

At harvest the four central trees of each plot were shaken, and the fruit collected and weighed with a pallet scale (Accuweigh, Willetton, Australia). Subsamples (approximately 6 kg) were collected from each plot and used to determine the mean crack-out percentage and kernel mass per replicate; these data were used to estimate the kernel yield per hectare and the number of kernels produced per tree. Kernel yield per hectare was estimated as the product of kernels/tree by trees/ha (347 trees at the orchard's row and tree spacing).

Kernel tasting

Kernels from the 2018 and 2019 harvests were subjected to discriminatory taste testing at the Mildura Horticultural Field Days held in May of each year. Volunteers were asked to indicate which of three kernels offered was different to the other two during triangular taste tests. Tests were designed to cover all treatment comparisons possible (*i.e.* +W+N vs +W-N, ….. -W+N vs -W-N). Three sets of randomised tests were designed and kernels were assigned a code consisting of three random numbers (Figure 4). Thurstonian theory was used to estimate the effect size (d') as well as the variance of d' using tables provided in Ennis *et al*. (2011). Test power was calculated using an ExcelSTATS® program and was based of a formula with α=0.05 and β=0.20. Means and significance levels for degree of difference between samples were calculated in Microsoft Office Excel® using Student's t-test.

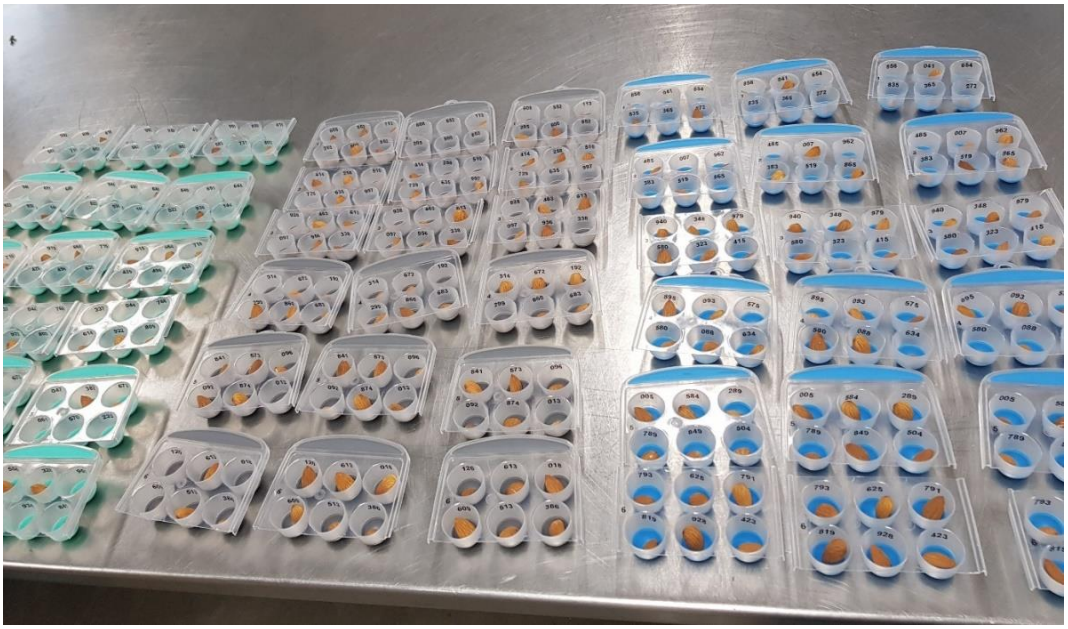


Figure 4 Three sets of randomised tests, demarcated by three different colours of tasting trays, prepared for taste testing at the Mildura Horticultural Field Days.

Photo by Zelmari Coetzee.

Data management and analysis

All data were entered into computer-based spreadsheets. The data for replicates within treatments were subjected to outlier detection using the Grubbs test as described by Rohlf and Sokal (1981).

Genstat (18th Edition) was used for all biometric analyses. Percentage data were arcsine transformed to ensure compliance with the assumptions of analysis of variance. Other data were checked for normality and variance homogeneity, and appropriate transformations applied to also ensure compliance with the requirements for analysis of variance. Significant sources of variation were identified on the basis of a variance ratio with a Fisher's probability of 0.05 or less, and the least significant difference used to identify significantly different means.

OBJECTIVE 1 Long-term behaviour of Nonpareil and Carmel fruiting spurs under standard management practices.

The behaviour of trees under standard management practices (*i.e.* the "control" treatment) for the five seasons S0 (2014/2015) to S4 (2018/2019) are presented herein as Objective 1. Irrigation volume and nitrogen supply treatments were imposed from S1 onwards; measurements collected on those trees are presented and discussed as Objective 2.

Irrigation and fertigation

Treatment applications

The control trees received the same irrigation and fertiliser inputs as the rest of the orchard. Irrigation was regulated through soil water monitoring. Seasonal nitrogen applications were determined from soil and leaf analyses and the potential nitrogen removal by the crop; those assessment being conducted by an agronomist. Nitrogen applications were further moderated during the season according to shoot growth and general tree vigour.

Table 2 Standard irrigation water volumes and N applications per season for the experimental period. Values are the totals per season. Averages are for the five seasons, but excludes S1 for nitrogen.

	NONPAREIL		CARMEL	
Season	**ML water/ha**	**kg N/ha**	**ML water/ha**	**kg N/ha**
S0	15	274	15	274
S1	15.5	177*	15.9	177*
S2	12	314	12.7	314
S3	14	270	15.4	270
S4	16.3	322	17.8	322
Average	14.6	295	15.4	295

* The low nitrogen applications attributed to teething problems with the new equipment and the trial site's irrigation system.

On average, Nonpareil and Carmel received 14.6 and 15.4 ML of water per ha per season (Table 2), respectively; volumes close to the industry standard of 14 ML/ha/season (Almond Board of Australia 2018). The higher volume applied to Carmel was due to the longer irrigation period related to the later timing of hull split compared to Nonpareil.

Seasonal irrigation volumes were adapted to the climatic conditions and were adjusted to allow for significant rainfall during the growing season and the frequency and severity of heat waves. For example, irrigation volumes were reduced in S2 and S3 because 267 and 148 mm, respectively, of rain fell during those growing seasons. Irrigation volumes were further reduced in S2 due to the milder temperatures experienced in that season (Table 4).

The lower than planned nitrogen applications in S1 were due to teething problems with the newly installed dosing system. Those issues were addressed by S2 and the planned nitrogen supply treatments reliably imposed from that point onwards. The amounts of nitrogen applied to the control trees from S2 through to S4 were approximately 300 kg/ha/season, which is very close to the 309 kg/ha/season identified by Muhammad *et al.* (2015) as optimal for yield of kernels on Nonpareil trees in California. Nitrogen applications in S3 reflected the orchard manager's assessment that tree vigour was slightly excessive during that growing season. Increased vegetative growth was evident from the large spur leaf

areas (SLA) for both cultivars (Table 3) and proportion of incident light intercepted by the canopy early on in the season (Figure 7). Nitrogen inputs were restored to higher levels in S4 (Table 2).

Seasonal climate trends are discussed in more detail in Objective 2.

Tree water status

Stem water potential measurements confirmed that the trees were well watered during the trial period (Figure 5) and the majority of measurements indicated that trees experienced either no or low stress (*i.e.* above -10 bar; Fulton *et al.* (2014)). The few outliers in the mild stress class (Figure 5) were from measurements conducted in the canopy fill period when rapid vegetative growth would have increased water requirements to sustain new growth.

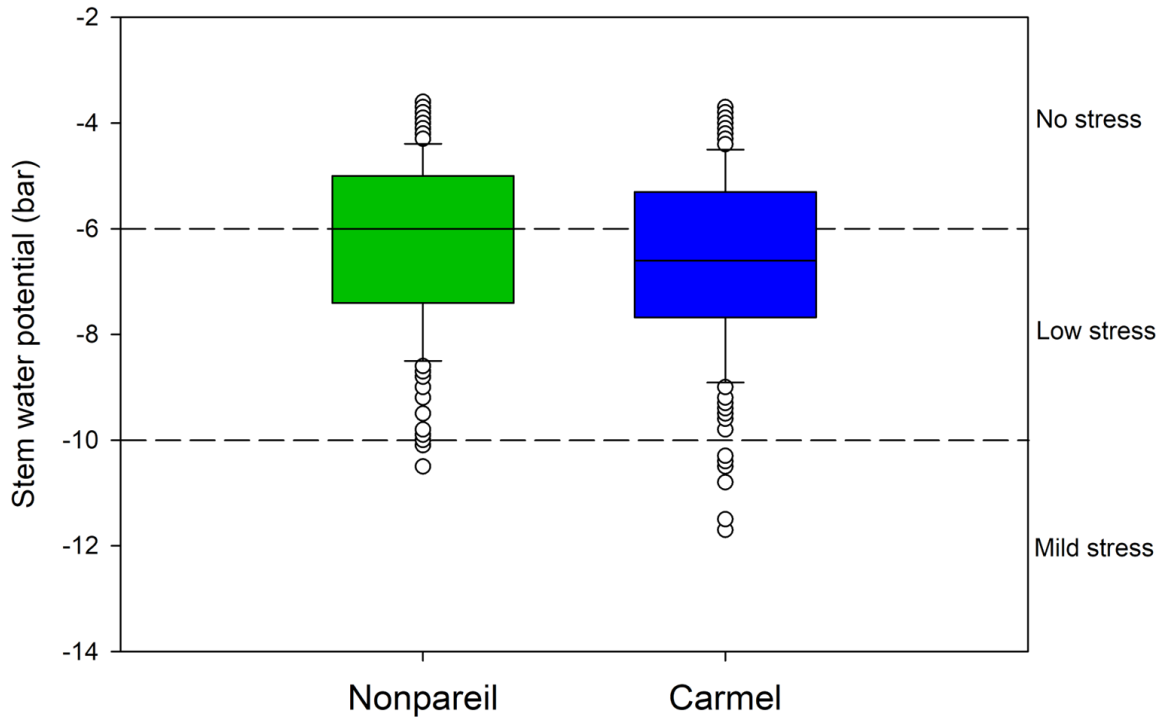


Figure 5 Box plots for all SWP measurements on control trees over the course of the trial period for each cultivar.

Horizontal dashed lines represent boundaries between water status interpretative classes (Fulton et al. 2014). The open circles beyond the boxes' tails are considered outliers and not part of the true population of measurements. The coloured boxes encompass the middle 50% of measurements and the tails on either end the upper and lower 25% of measurements, respectively. The solid black line across each box represent each

Leaf nitrogen content

Leaf nitrogen concentrations between 2.0 and 2.5% are considered adequate for mature almond trees under Australian growing conditions (Robinson *et al.* 1997). Maximum yields are obtained at 2.5% leaf nitrogen (Muhammad *et al.* 2015) and yield does not improve further as tree nitrogen status, as reflected by leaf nitrogen levels in mid- to late summer, increases.

Leaf nitrogen concentrations were adequate for the majority of the seasons (Figure 6), except in S2 when the leaf nitrogen concentration was below 2.0% in both cultivars. These low leaf nitrogen levels are most likely the result of the nitrogen mis-dosing in S1 (Table 2) referred to earlier. Carmel has a larger canopy surface than Nonpareil (discussed in detail in Objective 2) and would require higher levels of nitrogen to support the greater biomass.

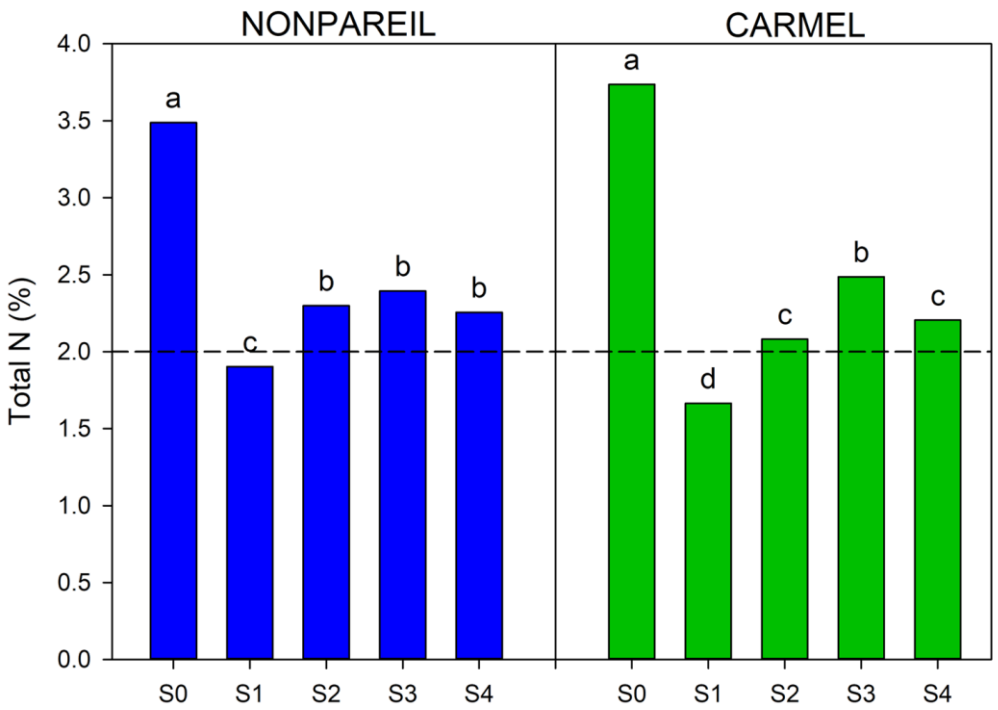


Figure 6 January Nonpareil and Carmel leaf total nitrogen concentrations.

Values presented are means (n=6), and different letters above columns indicate significant (P=0.05) differences between seasons for each cultivar. The horizontal line indicates the threshold between adequate and deficient leaf nitrogen concentrations.

Seasonal effect on light interception under standard management practices

Seasonal light interception patterns were similar; interception maxima were generally reached in December at the end of active vegetative growth. The continued increase in light interception in S2 indicates that vegetative growth continued beyond this point. Carbon allocations were likely allocated to vegetative growth in response to the low number of fruit that the trees were ripening in that season (Figure 10 (c)). The wetter than usual conditions during the growing season would have further stimulated vegetative growth. Light interception fell toward the end of the season in some seasons indicating that canopy density was reduced through leaf fall events. These events were clear in S1 and S4 and more prominent in Nonpareil than in Carmel, and would have been in response to, amongst other factors, high temperatures. Seventy and 86 h above 40°C were recorded in S1 and S4, respectively. The sudden decrease in nitrogen supply in S1 could also have contributed to the loss of leaves towards the end of the season. Leaf loss was especially drastic in Nonpareil as evidenced by approximately 10% more light passing through the canopy at the end of the growing season than in December. This was not evident in Carmel and might indicate that nitrogen reserves, among other factors, were relocated to sustain the canopy.

Leaf loss in S4 was attributed to extreme weather conditions; extended periods of very hot and dry conditions prevailed in January of that season. Tree canopies of both cultivars were noticeably denser in S4 compared to other seasons (Figure 7 and confirmed by visual observations). Trees were continuously watered (Table 2) to overcome the dry and hot conditions, but both Nonpareil and Carmel dropped large numbers of leaves, on more than one occasion (visual observations). Defoliation was more drastic in Nonpareil as trees became heavily infested with mites towards the end of the season.

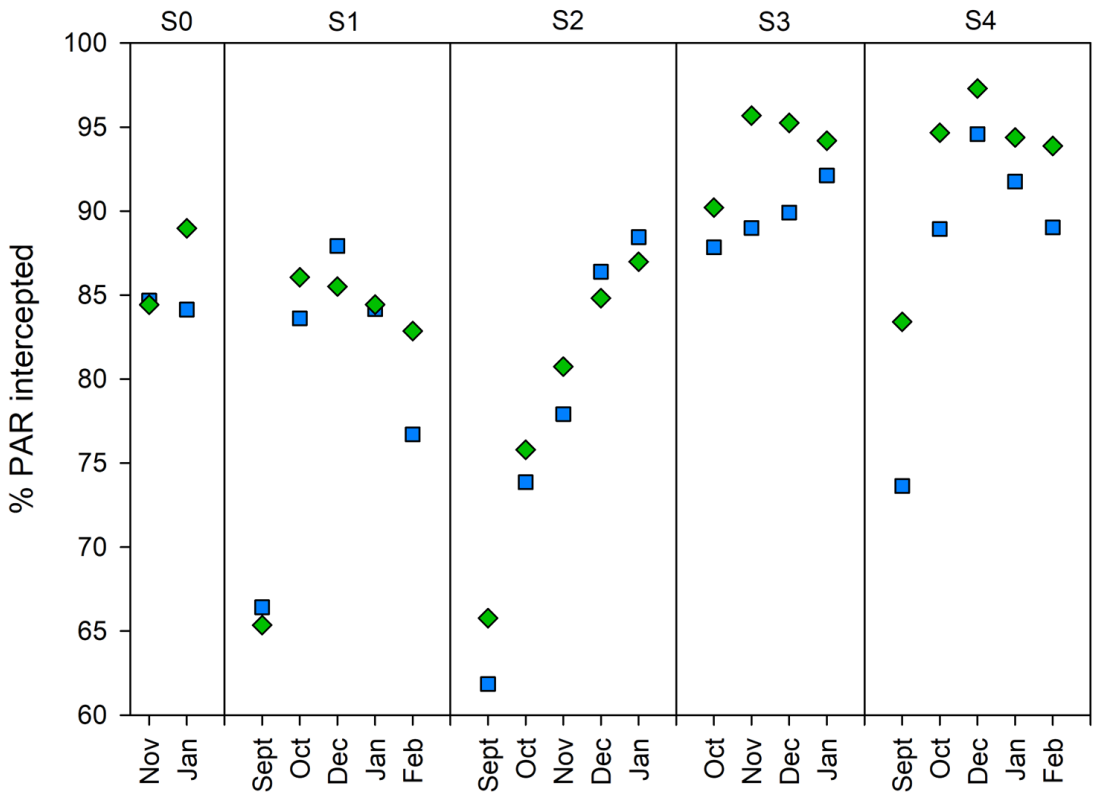


Figure 7 The percentage PAR intercepted by Nonpareil and Carmel canopies within seasons across the trial period in the control treatments.

Values presented are means (n=6).

Seasonal spur behaviour under regular management

Spur reproductive behaviour

Spurs are short proleptic shoots, and within a given season spurs can either be vegetative or bear one or more fruit. Spur fertility is determined, at around hull split the summer of the previous growing season, when floral bud initiation occurs. The number of spurs on a tree, the number of fertile spurs and the number of flower buds per fertile spur, set the upper limit on the number of kernels per tree. The final number of kernels per tree is determined the following spring and depends on fruit set and the severity of three fruit drop events. Final yield — expressed as kg kernel/ha/season — is a function of the number of kernels that reach maturity and their final mass. Various biotic and abiotic factors affect each of these steps directly or indirectly, and to varying degrees from season to season. The combination of all these steps and influences is what ultimately determines season-to-season variability in productivity. Factors that affect spur reproductive behaviour are discussed in detail in Objective 2.

Yield potential determination is further complicated by the stochastic nature of inter-seasonal spur reproductive behaviour. Not all vegetative spurs will bear fruit in the following season and revert to being vegetative in the season after that. Many reproductive spurs will die by the end of the season in which they bear fruit. For these reasons, spurs are thought to be inherently alternate bearing. That belief cannot be extrapolated to tree- and orchard-scales because new spurs arise on the tree every season. The physiology underpinning appearance of replacement spurs is poorly understood.

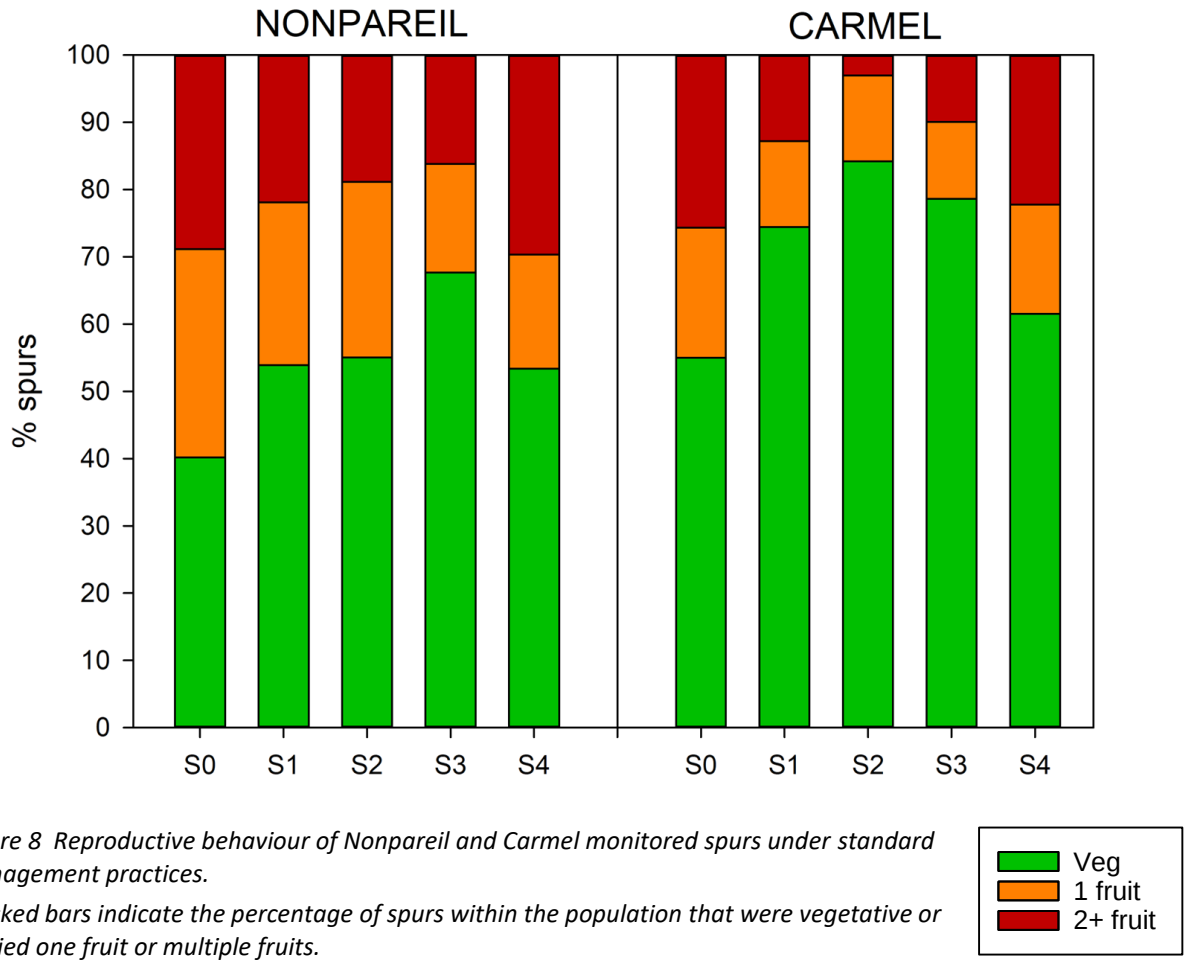


Figure 8 Reproductive behaviour of Nonpareil and Carmel monitored spurs under standard management practices.

Stacked bars indicate the percentage of spurs within the population that were vegetative or carried one fruit or multiple fruits.

On average, approximately 55% of Nonpareil spurs were productive whereas only 30% of Carmel spurs produced fruit. The ratio of vegetative to reproductive spurs for each cultivar varied across seasons (Figure 8), but the cultivar-to-cultivar relativity of spur fertility did not. This observation points to a significant genetic component influencing spur fertility and possibly the commonality of the environmental and management factors that modulate the expression of that genetic potential from season-to-season.

Carmel reacted strongly to the reduced nitrogen availability in S1 with only 16% of spurs carrying fruit in S2 compared to 45% of Nonpareil spurs. This was, however, not due to a decrease in the potential of the spurs to produce a crop. A high percentage of spurs not only bore flowers, but also had a normal number of floral buds per spur. This was likely due to an increase in the light incidence in the canopy the summer before in response to the reduced nitrogen availability. The small number of spurs that ended up carrying a fruit was the result of the low set success rate, possibly in combination with high fruit drop rates as spurs carried few fruit (Table 3). Even though spurs had a high number of floral buds at the start of the season, a large number of flower buds may have been non-viable for unknown reasons.

Half of the fruiting spurs on Nonpareil tended to bear multiple fruit, but there were clear seasonal effects on the ratio between spurs that bore one or multiple fruit in Carmel. The low percentage of Carmel spurs that bore multiple fruit in S2 was likely due to intense fruit drop as discussed above.

Spur mortality rate under standard management practices

Empirical observations of Nonpareil spurs identified spur leaf area, and the number of fruit borne by a spur in a given season as major factors determining the probability of a spur dying off at the end of that season.

Cumulatively, half of Nonpareil spurs did not survive to the next season, but only a third of Carmel spurs died off. In both Nonpareil and Carmel, a third of the vegetative spurs died at the end of the season. Carmel reproductive spurs were, however, more likely to survive than Nonpareil reproductive spurs; approximately a third of Carmel spurs that produced fruit died at the end of the season compared to the Nonpareil fruit-bearing spur mortality rate of 80%.

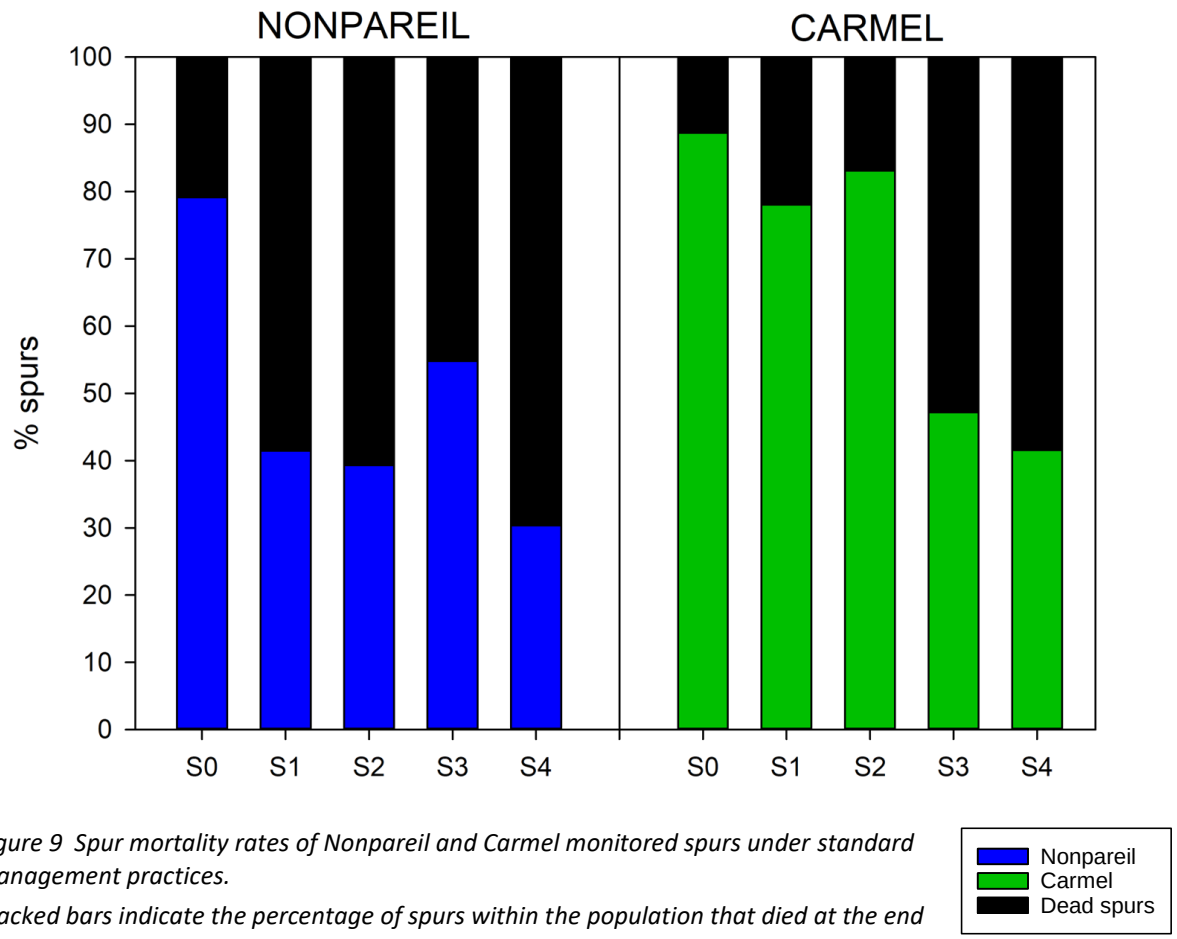


Figure 9 Spur mortality rates of Nonpareil and Carmel monitored spurs under standard management practices.

Stacked bars indicate the percentage of spurs within the population that died at the end of the growing season.

As observed with spur productivity, spur mortality rates differed between seasons. Carmel and Nonpareil spurs did not appear to behave the same; three times more Nonpareil spurs did not survive at the end of S1 than in S0, whereas the percentage of Carmel spurs that died only doubled between these years. This observation is discussed in detail in the section “Seasonal effects on spur productivity and yield”.

At the end of every season, new spurs were tagged to replace spurs that had died off. Low numbers of new Carmel spurs needed to be recruited into the study between seasons due to Carmel spurs’ inherently low mortality rate. The increase in the death rate toward the end of the trial could be partially attributed to a large percentage of the marked spur population reaching the natural end of their life cycle. The age of any spur recruited into the study was unknown at the time it was tagged.

The high turnover rate of Nonpareil reproductive spurs highlights the importance of spur genesis. Pushing Nonpareil trees to produce high yields will result in most fruit-bearing spurs not surviving. If new spurs don't emerge at the same rate to replace those that die, productivity can be expected to decline and is discussed further in Objective 2. The logistical difficulty of determining with any certainty the number of spurs on a tree means that quantifying the appearance of new spurs is problematic, making the development of an understanding of the physiology of their aetiology similarly difficult. Inferring spur numbers from total kernel yields per tree, mean kernel weight, % reproductive spurs *etc*. is useful, but, at best an approximation.

Seasonal effects on spur productivity and yield

Seasonal yields for each cultivar are presented in Figure 10. The dramatic drop in yields from S1 to S2 in both cultivars were attributed to the nitrogen mis-dosing in S1. Different sets of circumstances can, however, be attributed to the decrease in productivity for the two cultivars.

Table 3 Seasonal effects on reproductive and vegetative traits of Nonpareil and Carmel spurs under standard management practices.

	Season	% floral buds	floral buds/spur[a]	% fruit retained[a]	% fruiting spurs	fruit/spur[a]	g/kernel[a]	SLA (cm^2)[a]
NONPAREIL	**S0**	77	3.1 c	64 b	60	1.7 b	1.08 b	33.7 b
	S1	71	3.3 b	35 c	46	1.9 ab	1.12 b	32.1 b
	S2	72	3.4 b	33 c	45	1.7 b	0.89 c	40.3 b
	S3	50	2.7 c	49 a	32	2.0 ab	1.20 a	61.0 a
	S4	76	4.3 a	29 c	47	2.2 a	1.12 b	48.0 b
CARMEL	**S0**	66	3.5 a	60 a	45	1.9 a	0.98 b	28.0 b
	S1	53	3.3 ab	25 ab	26	1.8 ab	1.01 bc	31.6 b
	S2	60	3.8 a	15 b	16	1.3 b	1.02 ab	29.6 b
	S3	34	2.3 b	43 a	21	1.6 ab	1.15 a	53.0 a
	S4	68	3.8 a	26 ab	38	1.9 a	0.84 c	41.7 a

[a] *Values presented are means (n=144) per season and different letters within traits and cultivars indicate significant (P=0.05) differences between seasonal means.*

Nonpareil yield in S1 (Figure 10 (a)) was not affected by the nitrogen mis-dosing mentioned previously. Trees produced less kernels compared to S0 (Figure 10 (c)) because fewer fruit were retained even though spurs had a higher chance of producing more fruit (Table 3). The larger kernel size in S1 (Figure 10(b)) brought the kernel yield per hectare that season to almost match S0 which means that Nonpareil could maintain assimilate production to grow and fill kernels under conditions of inadequate nitrogen supply. Assimilation rates were likely sustained by the relocation of reserves from the permanent tree structures. This suggests that Nonpareil might be genetically programmed to favour seed maturation to ensure reproduction.

Carmel kernel yields, on the other hand, dropped 30% in S1 from S0 (Figure 10 (a)) as trees likely dropped a large percentage of the crop while sustaining kernel size (Figure 10(b)). This is evident from the same decrease in the number of kernels per tree (Figure 10 (c)) and is reflected in the low set and fruit retention rate (Table 3).

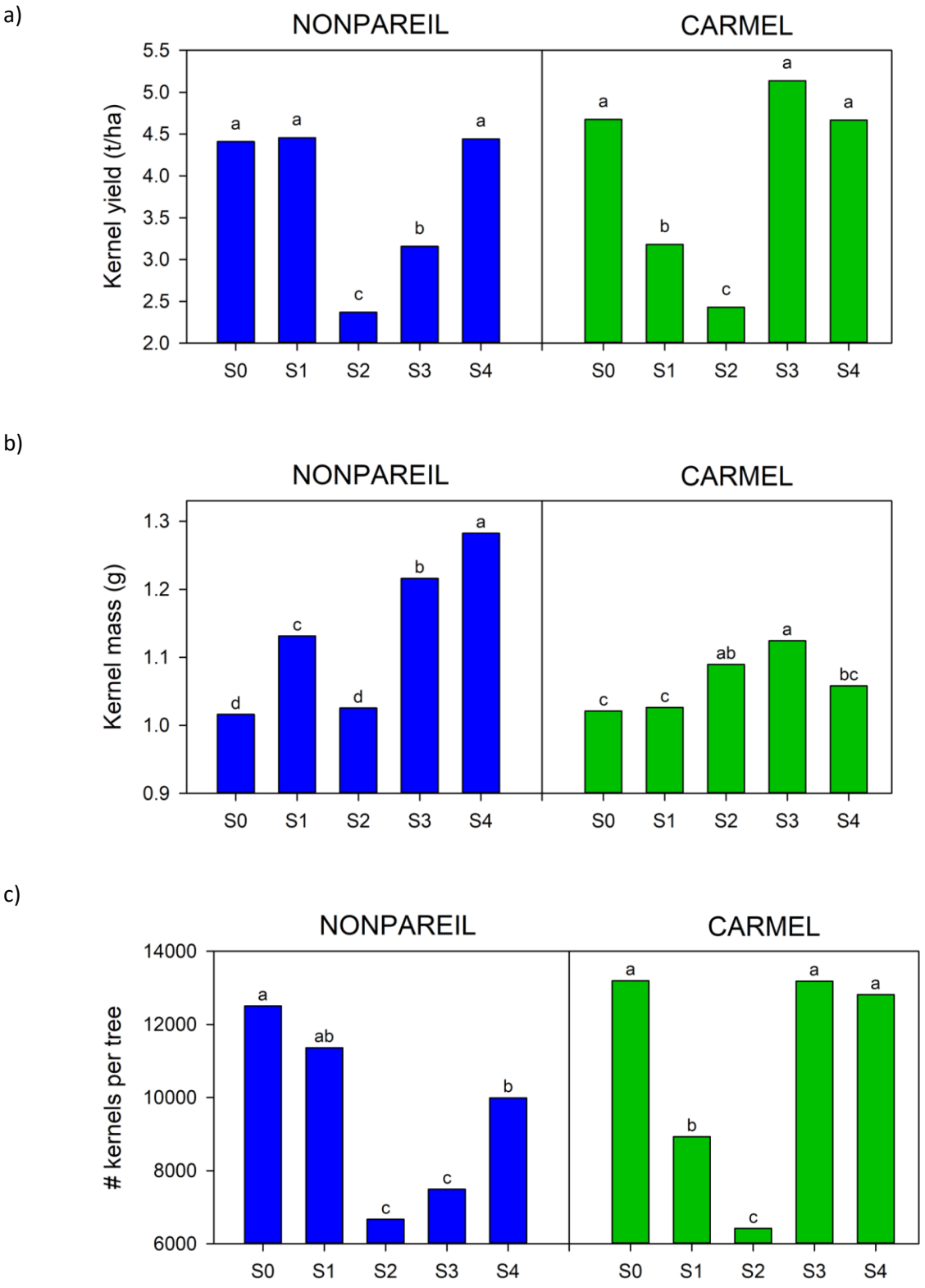


Figure 10 Seasonal effects on (a) estimated yield, (b) kernel mass and (c) number of kernels per tree per hectare for Nonpareil and Carmel under standard management practices.

Values presented are seasonal means (n=6) and different letters above columns within each cultivar indicate significant differences between seasons (P= 0.05).

Nonpareil's low yield in S2 (2.37 t kernels per hectare) was due to the fact that 60% of the spurs didn't survive from S1 to S2 (Figure 9). As approximately half of Nonpareil spurs bear fruit (Figure 8), this would have diminished the reproductive spur population and the number of kernels per tree (Figure 10 (c)). Assessments of marked spurs, of which a large percentage would have been recently recruited, showed that spurs that did survive in S1 had the same yield potential as spurs in other years (Table 2). The reduced application of nitrogen in S1 may have inhibited new spur emergence, and the improved nitrogen supply in S2 stimulated spur emergence sufficiently to replace spurs lost in S1. New spurs are vegetative and would only start producing fruit in the second year or third year, which potentially accounts for the gradual yield recovery in Nonpareil (Figure 10 (a)). Assimilates would have been relocated to support the new growth and could account for the smaller kernels in S2 (Figure 10 (b)).

Carmel trees did not suffer such a marked drop in spur numbers as Nonpareil (Figure 9) and a smaller proportion of Carmel spurs actually carry fruit (Figure 8). The low yield by Carmel trees in S2 (2.43 t kernels per hectare) can largely be attributed to a combination of poor pollination and fruit retention coupled with the small proportion of spurs that were reproductive in any case (Table 3 and Figure 8). These observations indicate that Carmel again dropped large numbers of fruit, but the reason was likely different in S2 than in S1. As mentioned before, poor mineral nutrient supply will result in poor floral bud initiation and development (Socias i Company *et al.* 2017), and non-viable flowers will be dropped which will drastically reduce the number of kernels per tree (Figure 10). As for Nonpareil, assimilates would potentially have been allocated to the formation of new spurs.

Yields on Carmel trees returned to normal in S3 and S4 (Figure 10 (a)) and Nonpareil trees in S4. Even though Nonpareil did not produce a similar number of kernels as it did in S0, the kernel yield per hectare was increased to similar levels because kernels were 20% larger in S4 compared to S0. Nonpareil seems to compensate for lower number of kernels per tree by increasing the kernel mass when there is little or no competition for nutrients or water.

OBJECTIVE 2 The effect of key environment and management factors (tree architecture, light interception, irrigation and nutrition) on spur productivity.

Climate overview

The driest seasons during the experimental period were S1 and S4, and the wettest season S2 with 268 mm recorded from August to March (Table 4). About half (*viz*. 124 mm) of the rainfall in S2 fell in September.

Temperatures during S2 were moderate compared to temperatures in the other seasons. The highest number of growing degree days were accumulated during S1. The highest number of hours above 35°C was also recorded during this season. However, 86 hours of temperatures above 40°C were registered in S4 of which 59 hours were recorded in January. This was also a dry month with only one rainfall event of 3.2 mm. The remainder of S4 was also dry with 1.2 and 3.4 mm recorded for February and March, respectively, also in one event per month.

Table 4 Seasonal overview of rainfall and temperature from August to March.

		S1	S2	S3	S4
Total rainfall (mm)		101	267	148	130
Growing degree days		2767	2390	2567	2526
# hours	**> 35°C**	423	252	267	335
	> 40°C	70	43	58	86
Mean temperature (°C)	**January**	25.5	25.8	26.8	27.9
	February	25.0	23.9	25.6	24.0
	March	24.1	24.2	22.1	23.9

Treatment applications

The regularly watered plots received an average of 14.5 ML/ha/season across the four experimental seasons, close to the industry average of 14 ML/ha/season applied to mature orchards in Australia (Almond Board of Australia 2018). Across all four seasons, 30% less irrigation water was applied to the reduced water plots (Table 5); those plots receiving the equivalent of 10.4 ML/ha/season. Irrigation volumes were reduced in S2 due to significant rainfall during the season (Table 4). Increased irrigation volumes in S4 season can be attributed to hot and dry summer conditions in January (Table 4). Carmel trees received on average 1 ML/ha more water than Nonpareil (15. 5 and 14. 5 ML/ha/season, respectively). Compared to Nonpareil, Carmel has an extended irrigation period because hull split and harvest occur later. Irrigation frequency and volumes are detailed in Supplementary Table 1 in Appendix B.

Nitrogen (as urea) supply to the reduced nitrogen plots was decreased by 46% (Table 5). The average nitrogen input in the regular N treatments from S2 to S4 was 300 kg/ha/season. Muhammad *et al.* (2015) showed that maximum kernel yield is reached at approximately 310 kg/ha/season above which yield plateaus.

The lower than intended nitrogen applications in S1 were due to teething problems with the new dosing equipment at the onset of the treatment applications.

Table 5 Irrigation volumes and nitrogen applications for Nonpareil and Carmel trees at Lindsay Point.

		NONPAREIL		CARMEL	
		ML/ha/season	*kg N/ha/season*	*ML/ha/season*	*kg N/ha/season*
S1	+	15.5	177	15.9	177
	-	11.3	95	10.9	95
S2	+	12.0	314	12.7	314
	-	8.7	170	9.0	170
S3	+	14.0	270	15.4	270
	-	10.0	146	10.5	146
S4	+	16.3	322	17.8	322
	-	11.4	174	12.5	174
Avg	+	14.5	271	15.5	271
	-	10.4	146	10.7	146

Stem water potential

Across all seasons and measurement points, the two single factors affecting SWP of each cultivar were season and water (Table 6).

Table 6 SWP variation accounted for by season, water supply and nitrogen supply, and interactions thereof, for Carmel and Nonpareil trees at Lindsay Point.

Source of variation	Cultivar	
	Carmel	Nonpareil
	% variation accounted for	
Rep/measurement time	6	5
Season	19	22
Water	24	20
Nitrogen	0	0
Season × water	2	1
Season × nitrogen	2	1
Water × nitrogen	0	0
Season × water × nitrogen	0	0
Residual	48	51

Consideration of all the SWP measurements (n=288 for each cultivar), irrespective of treatment and made over the course of the trial (Figure 11) suggests that more than 50% of the measurements of both cultivars were in the low stress range and that most measurements were in the mild to low stress ranges (Table 8).

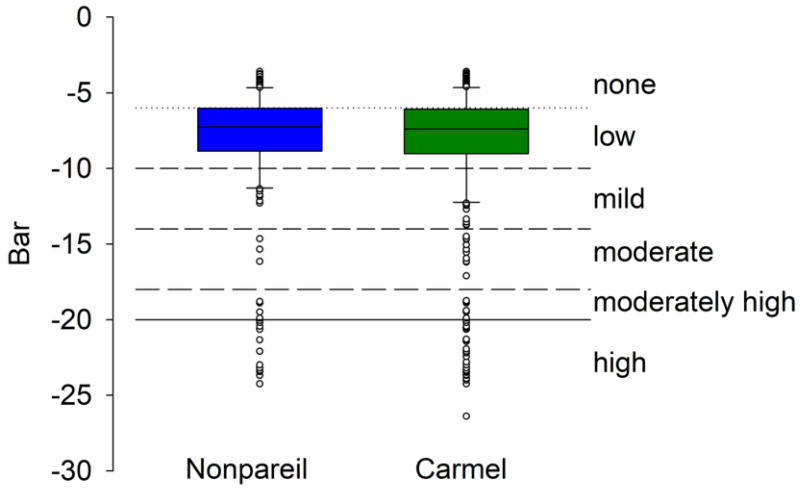


Figure 11 Box plots for all SWP measurements over the course of the trial for each cultivar.

Horizontal lines represent boundaries between interpretative classes (described in detail in Table 8). Black horizontal bars across each box represent the median for each population excluding the outliers beyond the tails indicating the extent of the 1st and 4th quartiles.

Some measurements identified as outliers suggested that some trees were undergoing water stress (Figure 11), and these were traced to single measurement times in S2 and S3 (Supplementary Figure 2 and Supplementary Figure 3). During the S2 canopy fill period (November to December 2016), SWP of trees in the reduced water treatments indicated high water stress (Supplementary Figure 2 and Supplementary Figure 3). A similar observation was made in S3 in Nonpareil during the same phenological period, but only for the reduced nitrogen treatments (Supplementary Figure 2). The basis of these observations is unclear. Canopy light interception measurements during these periods (Figure 16 and Figure 17) indicated that the apparent water stress had not affected canopy fill. Stress during this period may, however, offer some benefit by reducing canopy density which should lead to more light reaching the lower parts of the canopy. Given that SWP measurement times were dictated by cloud cover and not the calendar, it is possible that on both occasions the conduct of measurements coincided with the drawing down of soil water just prior to refill. But overall, the treatment means suggest that -W trees predominantly experienced mild water stress and +W trees experienced low or very little water stress.

In general, reducing irrigation volumes by 30% did not result in notable water stress in either cultivar (Table 8) but SWP was lower in trees that received less water compared to trees that received the regular amount of irrigation (Table 7).

Table 7 Water (W) by nitrogen (N) supply main effects on Carmel and Nonpareil trees' SWP (bars). Values presented are means (n=144 or 72 for water and nitrogen main effects and interactions, respectively). Note that in each cultivar the -W SWP was significantly different to the +W SWP (P=0.001).

Carmel	**+N**	**-N**	**W main effects**
+W	-6.8	-6.8	-6.8
-W	-10.5	-10.6	-10.6***
N main effects	-8.6	-8.7	
Nonpareil	**+N**	**-N**	**W main effects**
+W	-6.4	-6.6	-6.5
-W	-9.3	-10.2	-9.7***
N main effects	-7.8	-8.4	

Nitrogen supply as a main effect did not significantly influence SWP, and any interaction term involving nitrogen similarly accounted for very small proportions of the variation. This is illustrated in Table 7 that sets out the water and nitrogen main effects and interactions. Water supply was clearly the stronger influence on SWP for each cultivar over the four seasons.

Table 8 Midday stem water potential interpretation guidelines for almonds based on Fulton et al. *(2014).*

SWP range (bars)	Interpretation	Symptoms/crop behaviour
0 to -6	none	Not commonly observed.
-6 to -10	low	Stimulates shoot growth, especially in developing orchards. Higher yield potential may be possible if these levels are sustained (all other influencing factors not limiting).
-10 to -14	mild	Still able to produce competitively. Recommended crop stress level after harvest.
-14 to -18	moderate	Stops shoot growth in young orchards. Mature almonds can tolerate this level during hull split and still yield competitively. May expedite hull split and lead to more uniform nut maturity.
-18 to -20	moderate to high	Should be avoided for extended periods. Likely to reduce yield potential and contribute to lower limb dieback.
-20 to -30	high	Wilting observed. Some defoliation. Impacts yield potential.

Water supply tended to have a larger effect on Carmel SWP than Nonpareil (Table 6 and Table 7). This is suggestive of differences between cultivars in water use and the need to differentially manage irrigation between cultivars.

Soil matric potential

The soil remained wet in the regular water treatments in both cultivars (Figure 12), indicating that more than enough water was available in the soil to meet demand. The soil of the reduced water treatments was slightly drier compared to when regular volumes of water were applied (Figure 12).

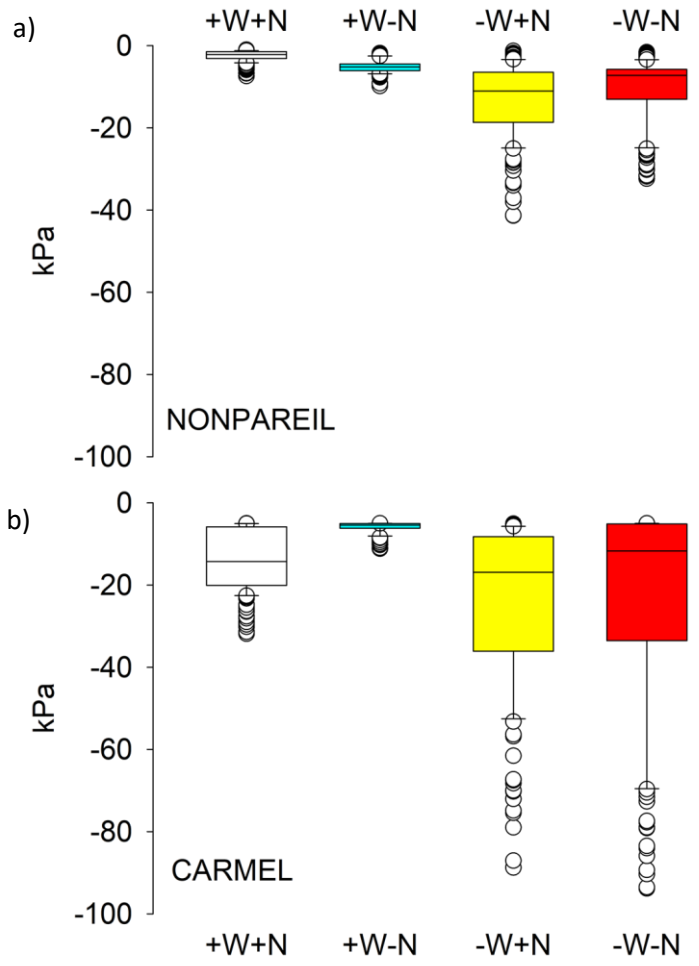


Figure 12 Soil matric potential (kPa) readings for Nonpareil (a) and Carmel (b) during S4 from September to January.

The black horizontal bars across each box represent the median for each population excluding the outliers beyond the tails indicating the extent of the 1st and 4th quartiles.

The seasonal soil matric potential for Nonpareil was lower than in Carmel (Figure 12). As both cultivars received similar volumes of irrigation (Table 5), it can be inferred that Nonpareil used less water than Carmel during the season. This should indicate reduced transpiration rates in Nonpareil. Carmel has a larger canopy surface area than Nonpareil which should be associated with greater transpiration. This reconfirms that cultivars need to be irrigated separately according to their water requirements. Over-irrigation is considered detrimental because nitrogen can be lost beyond the rootzone when nitrate is leached downward, and waterlogging may result in root death and enfeeblement of the scion as well as increase disease susceptibility.

Because SWP did not differ between the two cultivars and remained at low stress levels (Figure 11) it can be inferred that water demands were met for all treatments. But it is evident from the soil moisture data (Figure 12) that trees in the reduced water treatments extracted more water from the soil to meet that demand; this suggests that almond trees are able to adapt to lower irrigation volumes. It may be that root systems increased their effective area in response to the water treatments over the course of the trial. The collaborative work with CSIRO (*AL13009 Better tree performance and water use efficiency through root system resilience*) will provide further insight.

Not obvious in Figure 12 is the variability in the soil matric potential during specific phenological periods which were noticeable in both cultivars and more pronounced under Carmel trees. The daily soil moisture tension readings for Nonpareil and Carmel are shown in Supplementary Figure 4 and Supplementary Figure 5, respectively. During the period of rapid canopy fill and closure, available soil moisture dropped rapidly as trees required more water to sustain new vegetative growth. Soil under Carmel trees in the reduced water treatments dried out during this time (Supplementary Figure 5, outliers in Figure 12) due to the extent of the developing canopy surface. This indicates that the reduced irrigation volumes were not sufficient to provide for Carmel trees' water needs during this phenological stage. The potential to apply deficit irrigation according to the phenological stage remains an option to be investigated and could be used by industry in conjunction with real-time tree water status monitoring. The technology to monitor tree water status has become more readily available and affordable, but data management and interpretation lag.

The reduced canopy density in Nonpareil could have further impacted the soil evaporation rate through an increase in solar radiation reaching the soil surface when compared to Carmel. This has implications in new tree establishment systems. Although soil temperature or soil evaporation weren't measured, the implications of different canopy densities for soil water evaporation and temperature needs to be considered when determining the water use of different cultivars and in new production systems.

Tree growth

Diurnal trunk circumference expansion and contraction are considered a good indicator of tree water status (Goldhamer and Fereres 2004). Equally, trunk circumference increments over the longer term reflect irrigation management (*AL12010 - Impact of strategic deficit irrigation for almonds on tree phenology, bloom, nut set and hull rot)*.

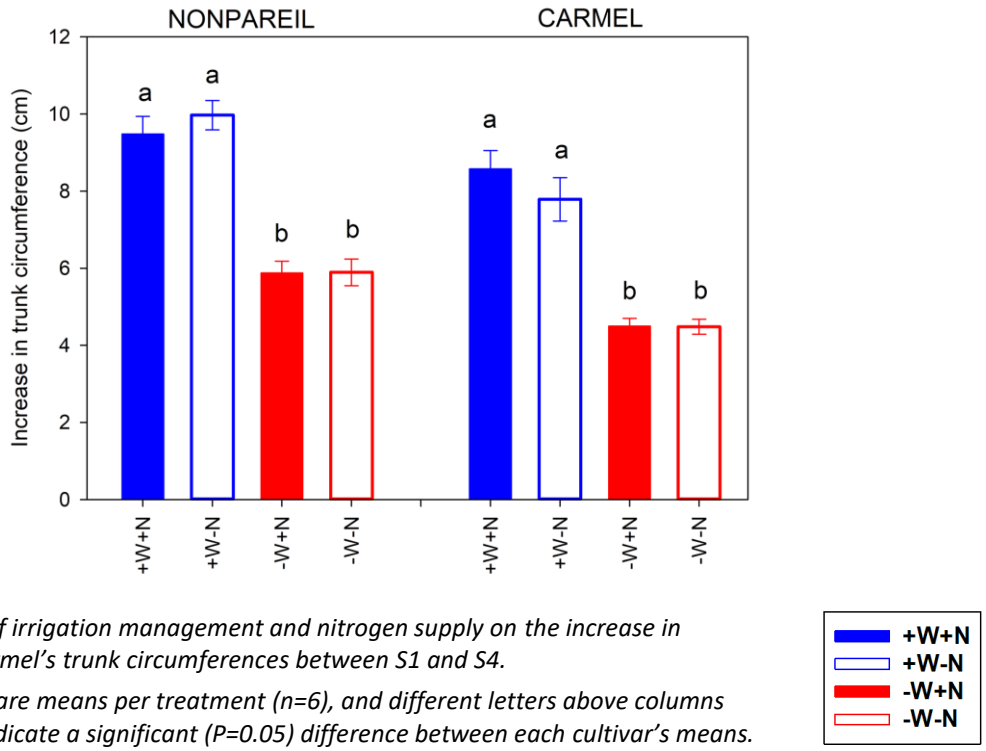


Figure 13 Effect of irrigation management and nitrogen supply on the increase in Nonpareil and Carmel's trunk circumferences between S1 and S4.

Values presented are means per treatment (n=6), and different letters above columns within cultivars indicate a significant (P=0.05) difference between each cultivar's means.

Average increases in trunk circumference from S1 to S4 indicated that reducing irrigation volumes applied to Nonpareil and Carmel trees by approximately 30% resulted in the trunk circumference increase over that period being reduced by approximately the same proportion (Figure 13).

Leaf nutrient content

As mentioned previously, leaf total nitrogen concentrations (% N) between 2.0 and 2.5% are considered adequate under Australian growing conditions (Robinson *et al.* 1997). The effect of the fertigation mis-dosing during S1 was clearly evident in the leaf nutrient analysis (Figure 14). Total leaf nitrogen concentrations were below the adequate threshold for all treatments in S1, with Carmel leaf total nitrogen low enough to be classified as deficient (Figure 14).

Leaf % N recovered in the following season to above the adequate threshold. Interestingly, the recovery of leaves on Carmel trees receiving the reduced nitrogen treatments was better in comparison to the regular nitrogen treatments even though the leaf % N was deficient in Carmel and classified as marginal in Nonpareil (Figure 14).

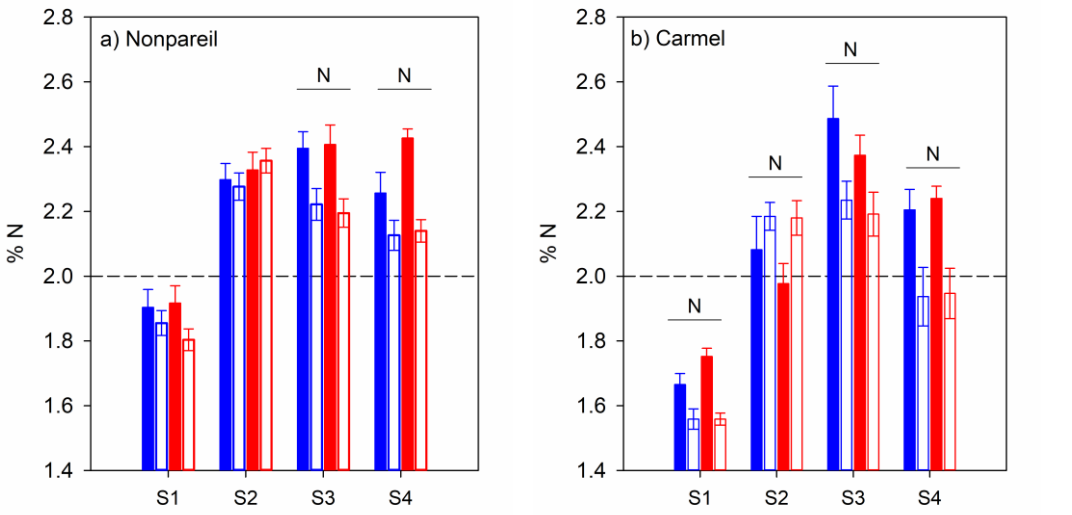


Figure 14 Effect of irrigation and nitrogen fertiliser supply on Nonpareil (a) and Carmel (b) January leaf % N in each season.

Values presented are means (n=6). An "N" over a horizontal line covering a season's means indicates that nitrogen supply was the major source of variation (P=0.05) between means for that season. The horizontal line represents the boundary line for an adequate leaf nitrogen concentration.

Leaf nitrogen levels in both cultivars were generally adequate for all treatments from S2 onwards (Figure 14). Despite the reduced nitrogen treatment involving a reduction of nitrogen supply by almost 50%, significantly lower leaf % N were only observed in the last two seasons in comparison to the regular nitrogen supply. These levels did not drop below the marginal/adequate threshold of 2% (Figure 14). The exception was Carmel in S4 when leaf total nitrogen fell below the marginal/adequate threshold in the reduced nitrogen treatment (Figure 14 (b)). The decline in leaf nitrogen on trees receiving the reduced nitrogen treatments probably represents a gradual drawdown of tree nitrogen reserves. The more rapid decline in Carmel leaf nitrogen suggests that this cultivar has a higher nitrogen requirement or exports more nitrogen than Nonpareil. The lack of lower limb dieback and the greater leaf cover on Carmel versus Nonpareil (Figure 15) suggests that the former explanation is more likely. The sensitivity of Carmel to the initial mis-dosing and the decline in leaf nitrogen in the reduced nitrogen treatment supports the idea that the nitrogen management of Carmel needs to be different to the nitrogen management of Nonpareil.

Figure 15 Lower limb dieback in Nonpareil (right) in comparison to Carmel (left).
Photo by Zelmari Coetzee.

Levels of the remaining mineral nutrients were generally in the sufficient ranges. Leaf chloride levels in both cultivars were slightly above the upper margin for all treatments across all seasons.

Canopy density

Below canopy light measurements

The amount of photosynthetically active radiation (PAR) reaching the soil surface below a canopy is an indirect indication of a tree's canopy density. Irrigation management was the main driver (P=0.05) of light interception for both cultivars in every season (Figure 16 and Figure 17) across the trial period. Nitrogen supply should have been a significant influence on intercepted PAR because under well-watered conditions 300 kg N/ha/season would be expected to result in greater vegetative growth relative to those trees supplied a reduced amount of nitrogen. However, there was very little consistent evidence that this was the case. Nitrogen fertigation is typically terminated in November to avoid further leaf expansion and meristematic growth.

Treatment effects were also not discernible at the start of the season, but generally became more apparent around December (Figure 16 and Figure 17), when canopy closure occurs and active spur elongation ceases (Socias i Company *et al.* 2017). The changes in light interception between September and December (Figure 16 and Figure 17) indicate that the rate of canopy growth was faster in the well-watered treatments than in the trees that received less water.

The stress observed in the reduced water treatments in both cultivars during the canopy fill period in S2 could likely have contributed to the clear differentiation in light interception between the water treatments at this time (Figure 16 and Figure 17).

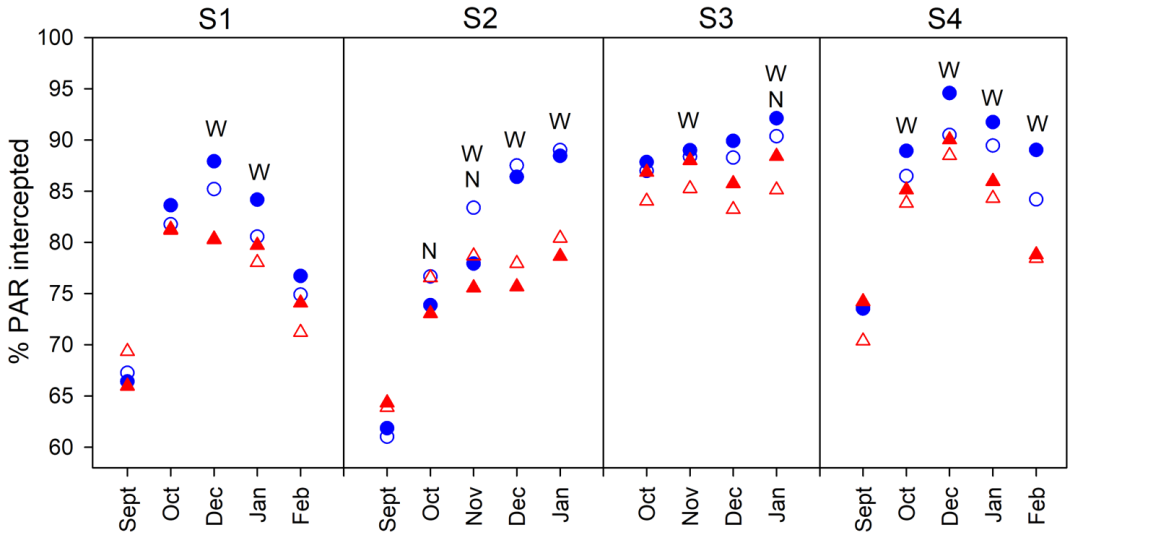


Figure 16 The effect of irrigation management and nitrogen supply on the percentage PAR intercepted by Nonpareil canopies across the four seasons.

Values presented are means (n=6), and a "W" and/or an "N" above a group of means for a specific measurement date indicate that irrigation management and/or nitrogen supply were significant sources (P=0.05) of variation between that group of means.

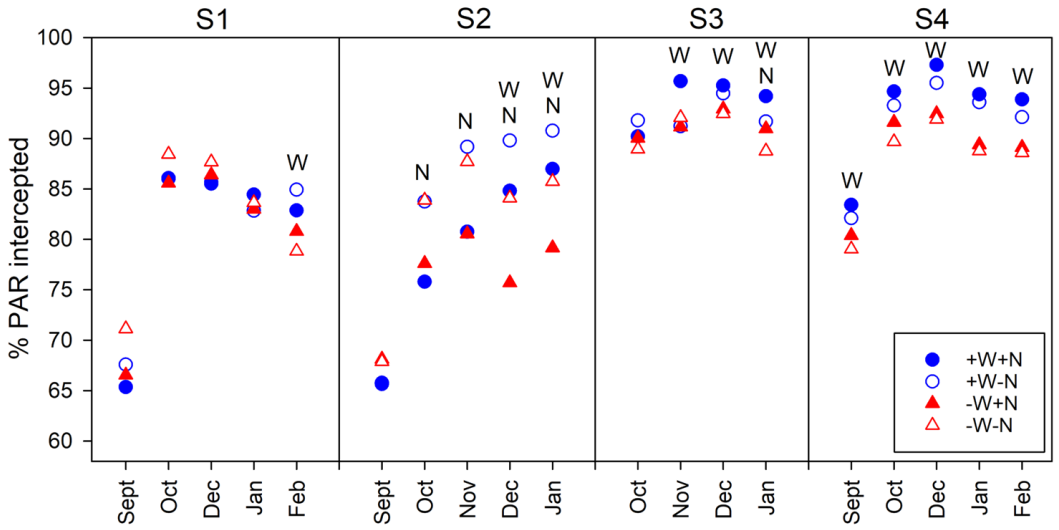


Figure 17 Effect of irrigation management and nitrogen supply on the percentage PAR intercepted by Carmel canopies across the four seasons.

Values presented are means (n=6), and a "W" and/or an "N" above a group of means for a specific measurement date indicate that irrigation management and/or nitrogen supply were significant sources (P=0.05) of variation between that group of means.

The decrease in light interception in the later part of S4 — more prominent in Nonpareil than in Carmel (Figure 16 and Figure 17) — can be attributed to defoliation events in that season (Figure 18), likely brought on by the hot and dry weather conditions (Table 4). Carmel has a larger canopy and hence a larger transpiration surface; from this it can be deduced that Nonpareil may not have been as adept at handling these conditions as well as Carmel.

Figure 18 Evidence of a strong leaf fall event under Nonpareil trees during S4 at Lindsay Point. Photo by Zelmari Coetzee.

Light tape

Measuring the incident light at the spur level is quite difficult using conventional instrumentation. "Light tape" is a light-sensitive material that changes colour depending on the amount of light that strikes the material. The colour change of the material over time is related to the amount of light that has struck the material during that period. Positioning the tape securely and oriented such that the light incidence is broadly reflective of light incidence on the closest spur was problematic. Nonetheless, by fixing the tape to the branches upon which the tagged spurs were borne, approximations were made of the amount of light incidence in the general vicinity of each spur for the period that the tape was attached. By comparing the amount of light received by the piece of tape attached to the branch to the amount of light received by an unshaded piece of tape exterior to the tree canopy, some indication was gained of the amount of incident light reaching each spur and by inference the amount of light being extinguished by the canopy above, and the effect of the treatments on both. This made it possible for the team to relate certain physiological responses (*e.g.* spur fertility and vitality, spur population dynamics) to the light environment of the spurs at each position.

The data are a snapshot of the light incidence of a spur for a week in the growing season, as close to floral bud initiation as possible as could be determined from the literature available on this topic. A further complexity in determining the long-term spur light exposure is that within canopy light interception patterns will change as the solar azimuth and zenith change during the season. The changing weight of the fruit further alters the orientation of the branches.

The tape was deployed at different times for each cultivar, reflecting the logistics of the exercise, and at different times in relation to phenological development (*i.e.* hull split and maturity). So, aside from the non-randomisation of Carmel and Nonpareil limiting direct statistical comparisons, the spur-level light incidence estimates are strictly only of comparative use within each cultivar because variations in weather conditions during the measurement periods – *e.g*. cloud cover – would have affected the measurements.

Variation in spur-level incident light from the top of the canopy (*i.e*. Spur 1) to the bottom of the canopy (*i.e*. Spur 6) was influenced by irrigation management (Figure 19 and Figure 20) while nitrogen supply had no discernible effect. More light reached the lower spurs when the volume of water applied was reduced (Figure 19 and Figure 20).

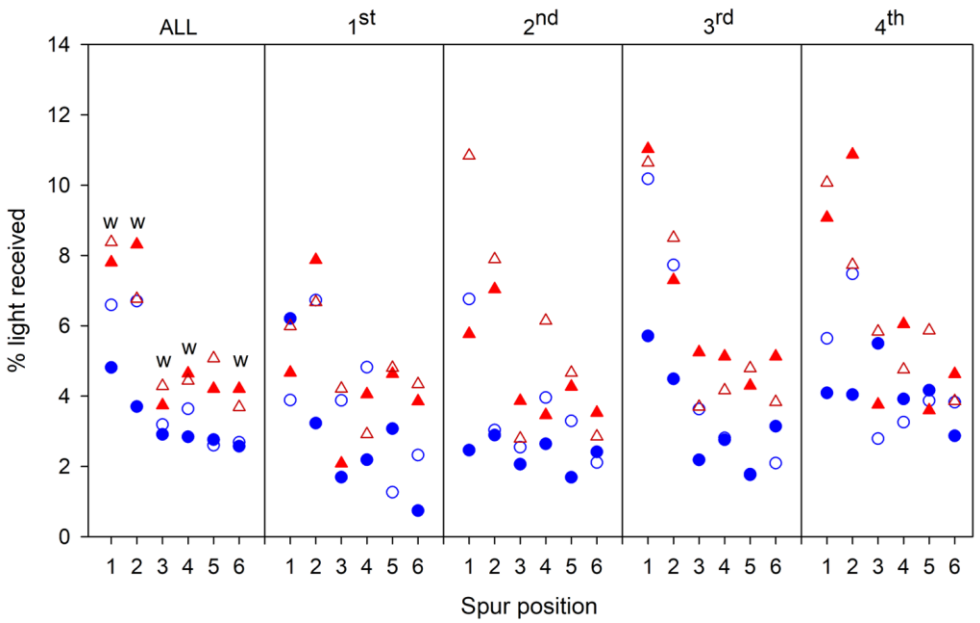


Figure 19 Irrigation and nitrogen supply effects during S4 on light receipts according to spur position and in the four quarters of the tree in Nonpareil.

Values presented are means of each treatment's replicates per spur position (n=4 for each quarter and 24 for all quarters). "W" above a group of means for a specific spur location indicate that irrigation supply was a significant source (p=0.05) of variation between that group of means.

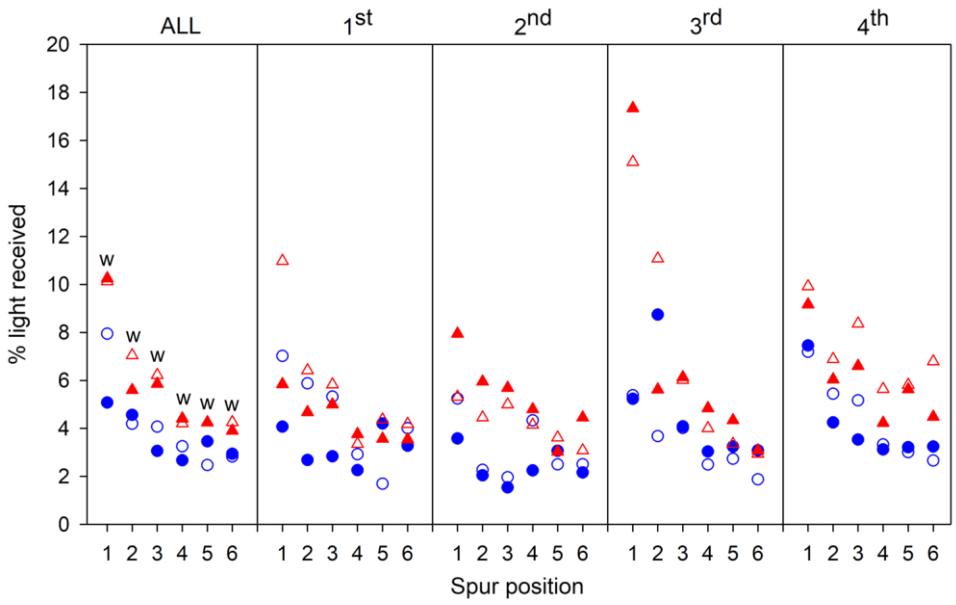


Figure 20 Irrigation and nitrogen supply effects during S4 on light receipts according to spur position and in the four quarters of the tree in Carmel.

Values presented are means of each treatment's replicates per spur position (n=4 for each quarter and 24 for all quarters). "W" above a group of means for a specific spur location indicate that irrigation supply was a significant source (p=0.05) of variation between that group of means.

Correlating light interception to the fertility of the buds in the following year was inconclusive. Providing they don't die, spurs randomly alternate between vegetative and reproductive states between seasons (Figure 25 and Figure 26), and predicting a spur's reproductive nature in the following season could not be determined from these measurements.

Quarters represent the four orientations of the canopy in relation to the movement of the sun, and clockwise from the 1st to 4th face south to west. The increase in light exposure in the 3rd quarter in Carmel (Figure 20) could be attributed to hedging on this side of the canopy in winter. Although hedging is used as a canopy management practice to increase light interception in the lower parts of the canopy by opening up the interrow space, excessive irrigation and nitrogen fertigation may counteract this action. During S4, hedging stimulated vegetative growth in the upper parts of the canopy, specifically in the control treatments, that essentially closed the interrow space (Figure 21). This not only reduced light incidence in the lower parts of the canopy, but photoassimilates would have been allocated to the new growth during the late stages of the growing season.

Figure 21 Lateral growth in the control treatments shading the interrow space.

The image was recorded by Peta Faulkner in spring of the following season, but even though the canopy is not filled shading is already noticeable on the ground.

Spur dynamics

Spur fertility and fruiting behaviour

Almond fruit production from floral bud initiation through to final maturity spans two growing seasons. This adds complexity to understanding the effect of management practices on spur reproductive traits. The lifespan of spurs — the predominant fruit bearing structure — spans multiple seasons. Their longevity is a function of their reproductive history; genetics too plays a role.

A fertile spur is understood to be a spur that carries one or more floral buds. The observed spur fertility in a given season is determined by circumstances and events during the previous season, particularly in the critical floral bud initiation period (Socias i Company *et al.* 2017). These factors, as they are understood, are summarised in Table 9.

Table 9 Factors affecting Nonpareil spur fertility.

Factor	Possible mechanism	Possible effect	Reference
Light environment	shading CHO supply	poor initiation floral primordia abortion	Socias i Company *et al.* (2017)
Current reproductive status	competition for CHO endogenous phytohormones	poor initiation floral primordia abortion	Polito *et al.* (2002), Lampinen *et al.* (2011), Valdebenito *et al.* (2017), Lampinen *et al.* (2018)
Spur leaf area	CHO supply ∝ photosynthetic capacity maintenance sink strength >> floral primordia sink strength	poor CHO supply poor initiation floral primordia abortion	Lampinen *et al.* (2011)

The precise period of floral bud initiation is difficult to ascertain because the timing is affected by, among other factors, varietal differences and within-tree variability of individual buds' development (Lamp *et al.* 2001). In addition, all fertile spurs may not set fruit, and these spurs will be vegetative for the remainder of the season (Table 14 and Table 15).

Whether a fertile spur actually flowers, and whether each flower is pollinated, sets a fruit and retains that fruit through to maturity is governed by another set of biotic and abiotic factors summarised in Table 10. Three fruit drop events occur in almond and are related to the environment and to management practices (Kester *et al.* 1996).

Table 10 Factors affecting pollination and fruit set success and fruit retention in Nonpareil.

Factor	Possible mechanism	Possible effect	Reference
Pollen viability	pollen germination and germ tube growth	pollination failure	Socias i Company *et al.* (2017)
Bee visitations	flower visitation rate	poor pollen delivery	Tombesi *et al.* (2017)
Spur leaf area	local CHO supply	fruit drop	Tombesi *et al.* (2015)
Irrigation	reduced tree stress	increase fruit set	Goldhamer and Smith (1995), Esparza *et al.* (2001)

The biometric analyses of the percentages of reproductive and vegetative spurs indicated that the proportion of the variability accounted for by the trial's fixed effects (*i.e.* season, irrigation and fertigation management, and interactions thereof) only amounted to 33%. Of the fixed effects, season and spur position were the strongest influences, with some indication that the position effect was modulated by seasonal influences on Nonpareil spurs, but not Carmel spurs.

Position effects on spur reproductive behaviour are presented graphically in Figure 22 and Figure 23 for Nonpareil and Carmel, respectively. Across all seasons and treatments, approximately 70% of tagged

Nonpareil spurs were fertile. The comparable statistic for Carmel spurs was 57%. Reduced irrigation had a positive effect on the proportion of flower-bearing to vegetative spurs, increasing the number of spurs that flowered by around 5% in both cultivars (Figure 22 (a) and Figure 23 (a)). The effect of nitrogen supply on the number of floral-bearing spurs was not as strong as that seen for the effect of irrigation management. Most of flower-bearing Carmel spurs were located in the higher positions in the canopy, but this was not as apparent in Nonpareil. Spurs are generally more likely to be reproductive when located in the upper parts of the canopy due to the increase in light exposure in this zone (Figure 19 and Figure 20).

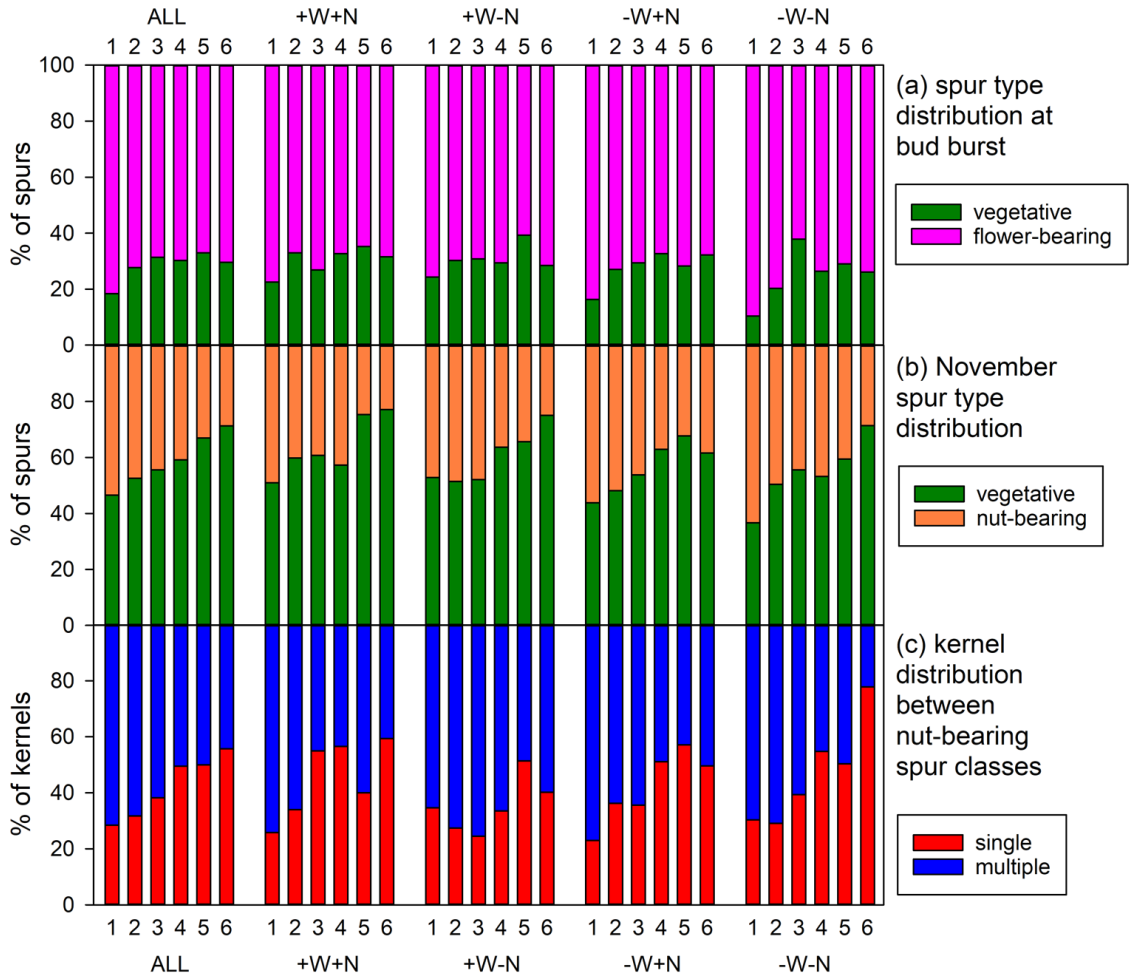


Figure 22 Effect of position (1, top of canopy,…, and 6, bottom of canopy) on Nonpareil spur reproductive behaviour over the four seasons across all treatments and for each treatment combination.

Percentages presented are means (n=24).

Nonpareil spurs in the lower parts of the canopy (positions 5 and 6) were more fertile compared to Carmel (Figure 22 (a) and Figure 23 (a)). Less light was intercepted by Nonpareil canopies than Carmel (Figure 16 and Figure 17) canopies, which would effectively increase the light exposure of spurs located in the lower parts of the tree. Assuming that light was the only limiting factor in floral bud initiation, this effect would have increased the number of floral buds on spurs on the lower limbs in Nonpareil. The high fertility of spurs in the upper parts of Nonpareil canopies could also have been driven by increased nitrogen in these parts of the tree because most of the transpirational stream would have been consumed in the upper canopy due to the diminished amount of light in the lower canopy.

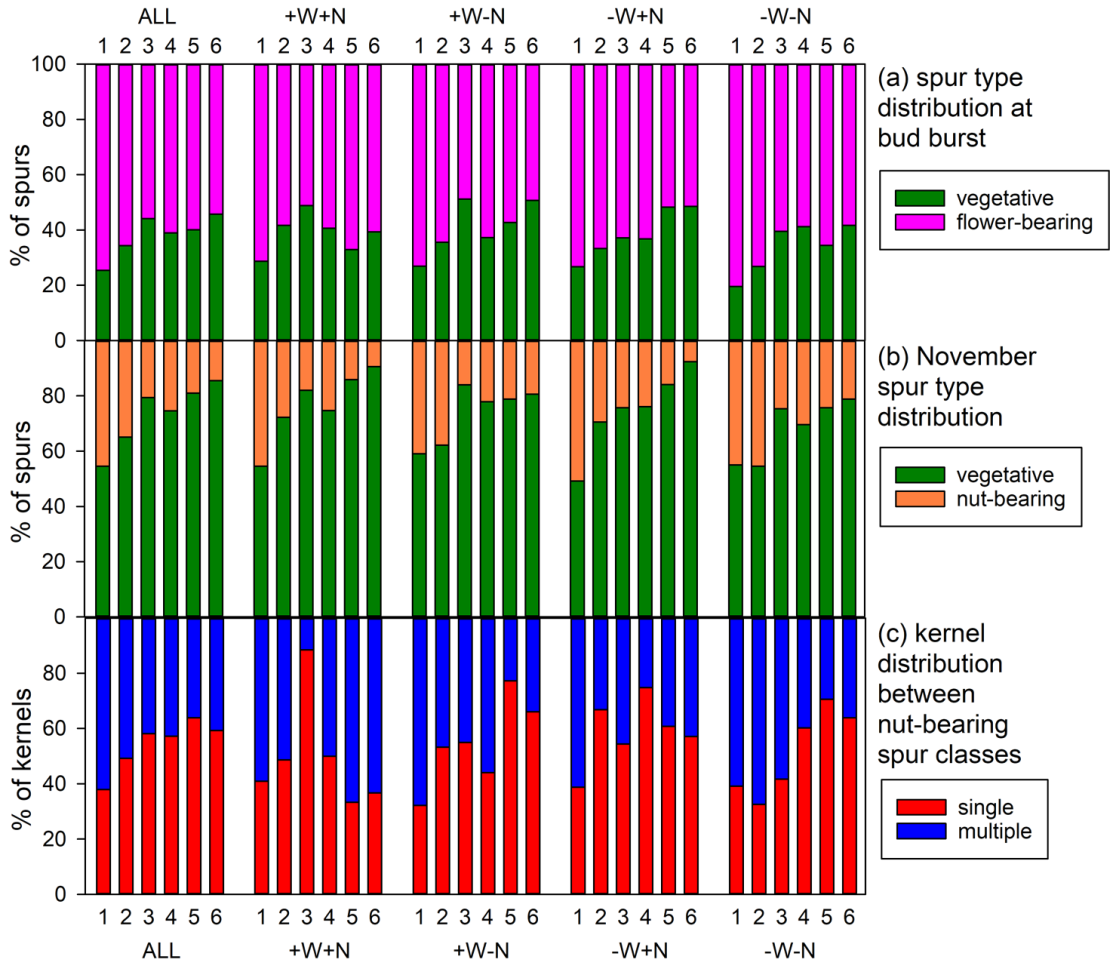


Figure 23 Effect of position (1, top of canopy,…, and 6, bottom of canopy) on Carmel spur reproductive behaviour over the four seasons across all treatments and for each treatment combination.

Percentages presented are means (n=24).

Ultimately, after fruit set and three fruit drop events, half of Nonpareil spurs had fruit, but only about a third of Carmel spurs. On average, 40% of Nonpareil flowers were successfully pollinated (Table 13) and the fruit retained, but this number was much lower in Carmel (27%; Table 14). Lower water supply increased the total percentage of spurs that carried fruit by 7% on Nonpareil trees and 5% on Carmel trees. Applying less nitrogen increased the percentage of Carmel spurs that bore fruit by 5%, but nitrogen only had a minor effect on fruiting spur numbers in Nonpareil.

Effective fruit set decreased from the top of the canopy to the lower parts of the canopy. This resulted in the distinct differences in the number of spurs that bore fruit in the top and lower parts of the canopy (Figure 22 (b) and Figure 23 (b)). Regular rates of nitrogen application decreased the number of fruiting spurs in the lower parts of the canopy in Carmel, specifically the spurs close to the orchard floor (position 6, Figure 23 (b)).

Spurs located in the upper parts of the canopy tended to bear multiple fruit on a single spur while spurs on the lower limbs mainly bore single fruit (Figure 22 (c) and Figure 23 (c)). This was due to the culmination of events that started during the previous season. As mentioned above, the propensity of spurs to be reproductive decreased vertically downward in a canopy, so spurs on the lower limbs produced less fruit. In addition, the chances were much higher for these spurs to carry a single fruit, if it did succeed in carrying a fruit at all.

Spur mortality

As for spur fertility and fruit retention, several factors have been found to affect Nonpareil spur mortality rates (Table 11).

Table 11 Factors affecting spur mortality rate in Nonpareil.

Factor	Possible effect	Possible mechanism	Reference
Leaf area	spur CHO	photosynthetic capacity ∝ CHO supply	Lampinen *et al.* (2011), Lampinen *et al.* (2018), Heerema *et al.* (2008)
Fruit load	CHO drain	fruit sink strength>>spur storage sink strength	Esparza *et al.* (2001), Reidel *et al.* (2004), Valdebenito *et al.* (2017), Tombesi *et al.* (2011), Heerema *et al.* (2008), (Fernandez *et al.* 2018)
(Genetic pre-disposition)	(Nonpareil vs Carmel)	(spur wood CHO requirements?) (epigenetics?)	–

Overall, annual spur mortality was approximately 60% for Nonpareil and 30% for Carmel spurs. Neither the water nor nitrogen treatments affected spur mortality in either cultivar. A significant, though modest, seasonal effect was noted.

No obvious spur location-related trend in Nonpareil mortality (Figure 24) was evident even though high spur mortality rates were expected due to higher spur productivity in the upper part of the canopy (spur positions 1 and 2, Figure 22 (b)). The presence of any fruit on Nonpareil spurs would have increased the likelihood of spurs dying in these positions by the end of the season even with a relatively large SLA (Table 11). Although a smaller population of reproductive spurs were located in the lower layers of the canopy, approximately half of these spurs bore multiple fruit.

Carmel spurs located on lower positions did die at a faster rate than spurs located at the top of the canopy and half of the spurs in these positions were lost in the final two seasons (Figure 24). It would be expected that the large percentage of spur mortality in the lower canopy layers in Carmel would induce lower limb dieback symptoms as seen in Nonpareil, but this was not the case (Figure 15). A possible explanation is that a larger number of spurs emerge in Carmel in the lower parts of the canopy than are lost to spur death even though this part of the canopy is more shaded than comparable parts of Nonpareil canopies (Figure 17).

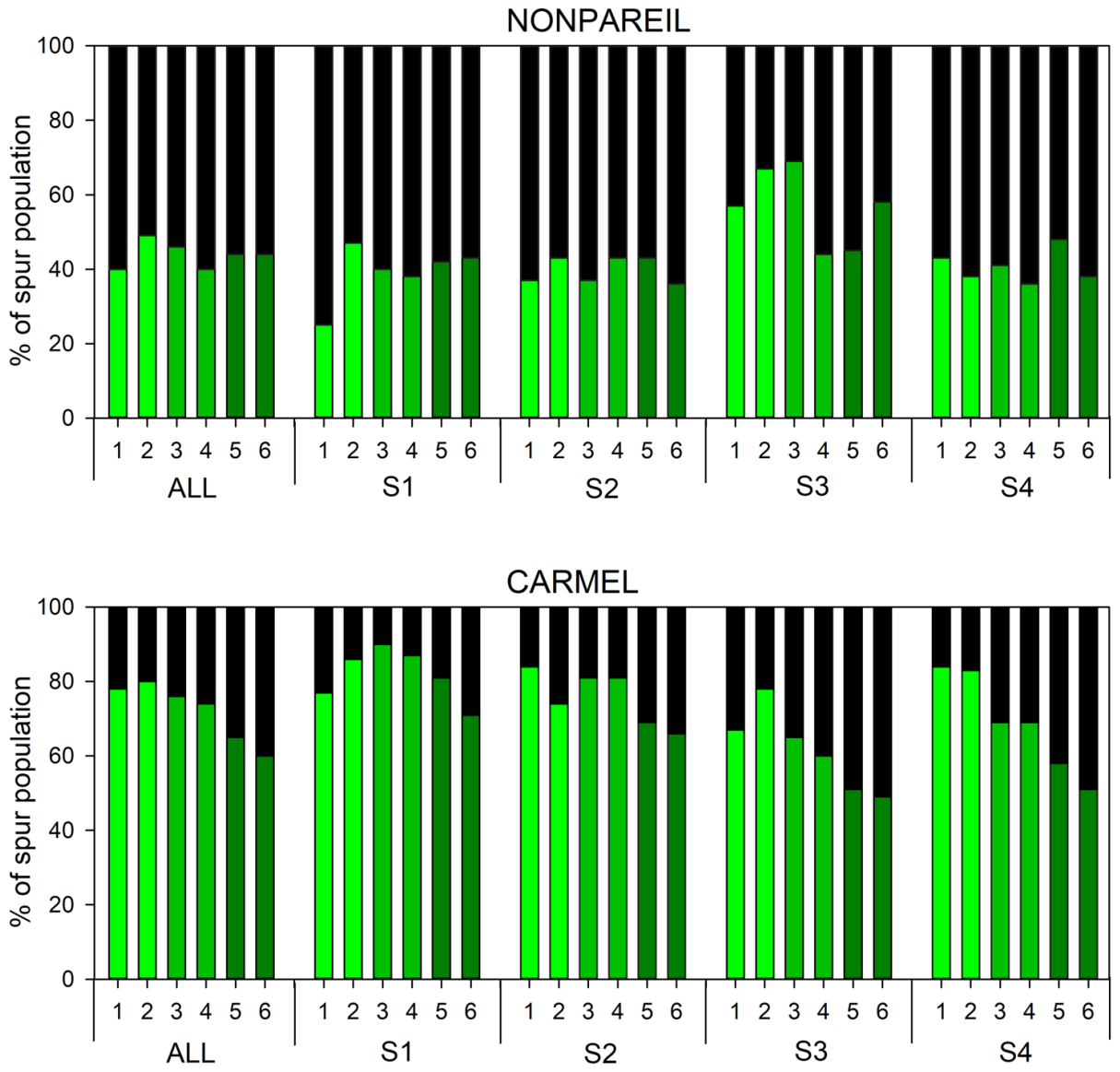


Figure 24 Nonpareil and Carmel spur mortality rates (black) for each season at each spur location.

Examining Table 12 shows that the Nonpareil mortality rates documented as part of this project were in agreement with the trends identified in Californian studies. Nonpareil spurs that bore fruit were more likely to die at the end of the season, especially when the spur had a small SLA. Similar trends were seen between seasons and the water and nitrogen treatments did not have an obvious effect on the trends except in the severity of spur death within seasons. Saa *et al.* (2017) also observed that increased soil and foliar nitrogen applications did not affect the spur mortality rate.

Fruit load and SLA did not noticeably affect the mortality rate in Carmel as observed in Nonpareil. Seasonal differences were more prominent in Carmel (Table 12), but are likely more attributable to the age of spurs than to spur vegetative and reproductive traits. Spurs are generally viable for 3-5 years (Lampinen *et al.* 2011). The high spur mortality rate observed in Carmel in S3 and S4 may be partially explained by the low mortality rates of spurs recruited into the trial at the outset and reaching end of their life in S3 and S4.

Table 12 Treatment effects on Nonpareil and Carmel spur mortality for each season.
Values presented are means (n varies between classes). Data presented are percentages of tagged spurs in fruitfulness (rows) and spur leaf area (columns) classes that did not survive through to the following season. Heatmaps show spur mortality severity from none (green) to all (red).

			S1			S2			S3			S4		
			0-20	20-50	>50	0-20	20-50	>50	0-20	20-50	>50	0-20	20-50	>50
NONPAREIL	+W+N	Veg	35	31	26	63	35	25	33	19	30	75	42	53
		1 fruit	87	64	0	88	86	50	100	58	50	89	50	100
		2+ fruit	89	100	100	100	60	-	100	100	60	93	85	75
	+W-N	Veg	54	31	0	62	48	25	0	33	27	70	29	28
		1 fruit	87	63	-	100	94	83	60	71	80	88	60	33
		2+ fruit	91	88	100	94	100	0	100	100	80	84	88	40
	-W+N	Veg	65	20	33	46	29	41	50	43	24	80	48	15
		1 fruit	95	75	100	79	54	80	100	78	75	75	60	75
		2+ fruit	97	86	100	100	75	100	90	57	50	92	82	75
	-W-N	Veg	45	22	33	69	37	16	43	23	13	30	39	14
		1 fruit	94	73	0	100	50	33	71	28	38	85	75	36
		2+ fruit	82	86	100	96	86	-	91	73	25	100	88	50
			0-20	20-50	>50	0-20	20-50	>50	0-20	20-50	>50	0-20	20-50	>50
CARMEL	+W+N	Veg	21	12	7	25	8	0	50	52	40	80	55	44
		1 fruit	33	20	0	14	0	0	100	33	17	100	33	33
		2+ fruit	44	25	0	100	0	0	100	67	0	67	31	25
	+W-N	Veg	18	5	0	38	20	7	27	33	18	48	15	4
		1 fruit	38	0	0	80	0	67	67	33	0	33	31	29
		2+ fruit	20	20	0	78	50	-	91	57	25	33	0	0
	-W+N	Veg	26	9	0	31	0	6	47	21	19	36	30	8
		1 fruit	20	29	0	33	13	0	100	20	20	67	23	0
		2+ fruit	25	0	0	40	0	0	100	33	43	100	33	0
	-W-N	Veg	12	6	0	53	17	10	42	15	33	41	16	7
		1 fruit	67	25	0	70	33	0	75	50	0	67	35	0
		2+ fruit	62	43	0	71	38	100	80	67	25	67	50	18

It should be noted that the age and the reproductive history of new spurs selected to replace dead spurs were largely unknown. Spur mortality data are therefore indicative of the spur mortality rate for a given season, particularly for Nonpareil where large numbers of spurs died every season and large numbers of new spurs needed to be recruited into the study.

Spur dynamics across seasons

Inter-seasonal spur dynamics are not shown per treatment due to the limited number of spurs that survived between seasons, particularly in Nonpareil (Figure 24). Mortality rate differed between cultivars and according to the fruiting behaviour of the spurs (Table 12) which is evident in the population numbers (Figure 25 and Figure 26). Data should therefore be interpreted as the proportion of spurs relative to the spur fruiting behaviour on a season-to-season basis.

Spurs that did survive were prone to be vegetative in the following season, irrespective of their fruiting behaviour in the current season (Figure 25 and Figure 26). Paradoxically, the few Nonpareil spurs that had a high fruit (two or more) load and survived, bore fruit in the following season (Figure 25). These spurs should not have survived because generally Nonpareil fruiting spurs have a high spur mortality rate (Table 11).

In addition to the fact that only a small percentage of Carmel spurs bore fruit (Figure 23), the majority of spurs that bore multiple fruit in a given season reverted back to being vegetative in the following season (Figure 26). Spurs that carried a single fruit did have a higher probability to carry fruit in the following season compared to spurs that bore two or more fruit (Figure 26).

The increase in fruiting spurs from season 3 to season 4 in both cultivars (Figure 25 and Figure 26) cannot be explained from our observations. Several factors determine if a spur will firstly survive (Table 11), and secondly if it will be fertile (Table 9) and ultimately carry fruit through to harvest (Table 10). Multileveled phenotypical responses all play a role in the ultimate fruiting behaviour of a single spur in a given season.

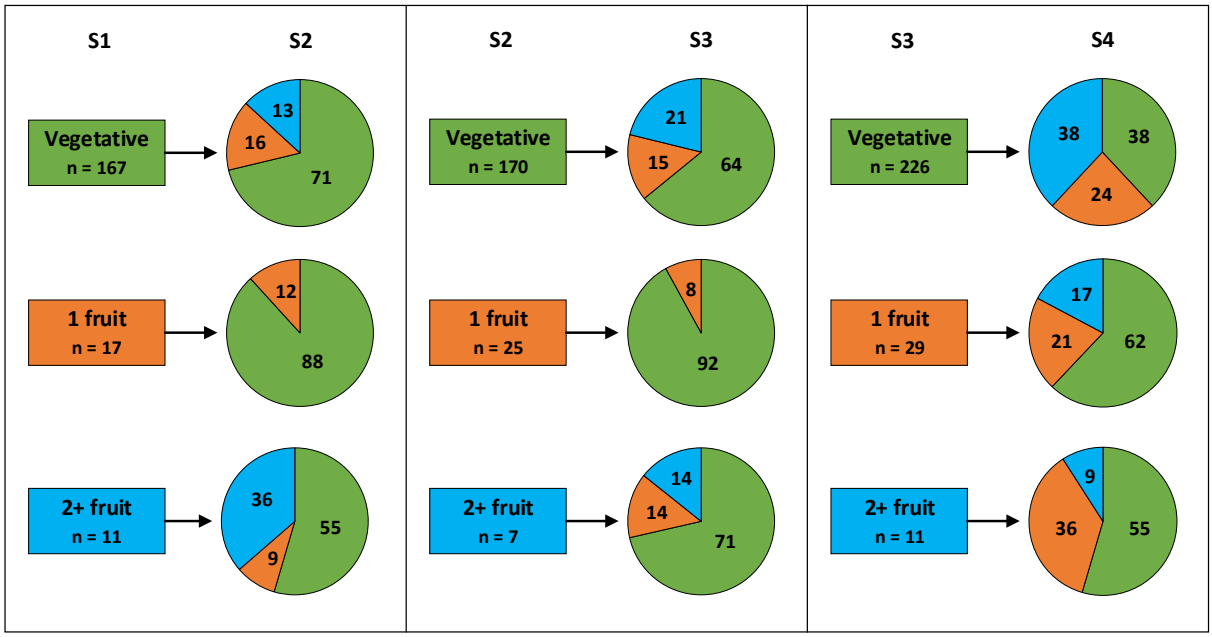


Figure 25 Inter-seasonal dynamics of Nonpareil spurs based on the fruiting behaviour of spurs in the first season
Pie charts represent the proportion of spurs in reproductive classes within the population of spurs that survived through from the previous season.

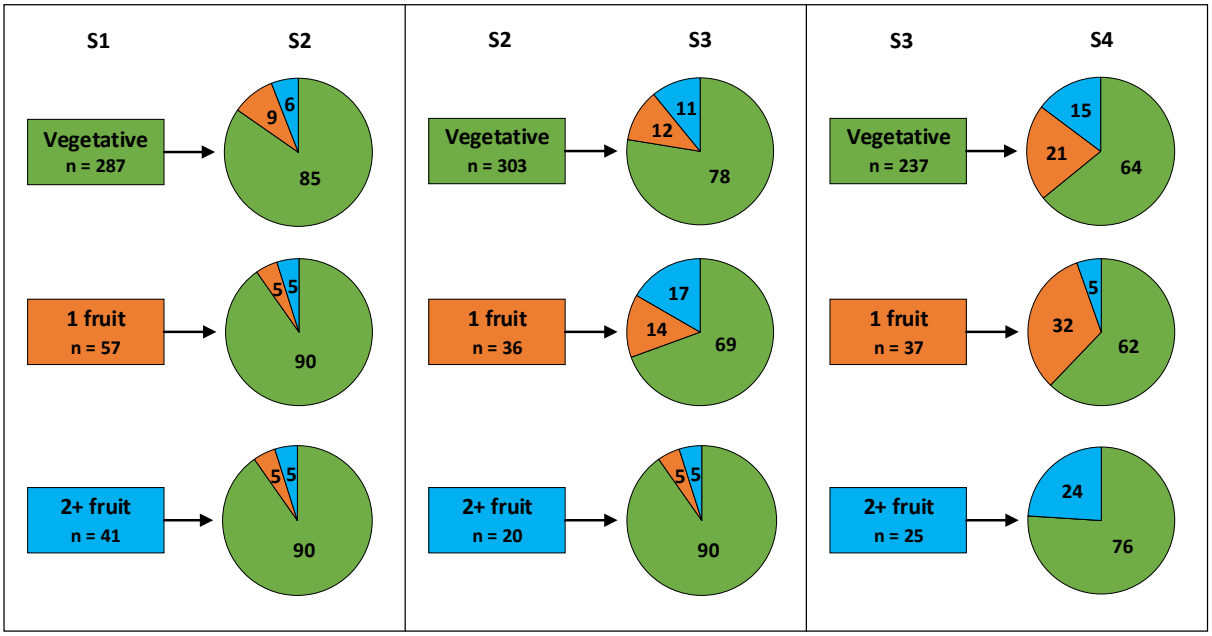


Figure 26 Inter-seasonal dynamics of Carmel spurs based on the fruiting behaviour of spurs in the first season
Pie charts represent the proportion of spurs in reproductive classes within the population of spurs that survived through from the previous season.

The likelihood of a spur bearing fruit in successive seasons is low; a pattern readily interpreted as an alternate bearing pattern. Alternate bearing is generally considered a whole-tree scale phenomenon in fruitfulness. Alternate bearing at a tree level was not determined from our observations across five seasons on the control trees, or the four seasons that observations were made on treatment trees. This suggests that almond spurs do not act in synchrony and are more-or-less independent of each other. The lack of synchrony may be related to the number of spurs on a tree and the observation that there is a degree of stochastic probability governing the spur-level vegetative-reproductive-death/vegetative pattern; there is no certainty, in other words. Thus, at a tree level there will be multiple cohorts of spurs at various points in that pattern. This means that overall yield on a tree scale is less a function of the inhibition of floral bud primordia initiation by the presence of one or more fruit on a spur, and more a function of the size of the spur population and the influence of environmental and management factors affecting the likelihood of floral bud initiation in vegetative spurs. An inadvertent example of the influence of management can be gleaned from lower than usual yield in S2 attributable to the nitrogen mis-dosing in S1 (Table 5). The inference of this circumstance though is that the number of spurs and the proportion of those spurs that have floral buds can be altered to a certain degree through the careful management of inputs.

Spur characteristics

Vegetative traits

The important role that light plays in many biological processes is well established. The decline in light incidence at the spur level from the upper to the lower portions of canopies (Figure 19 and Figure 20) warranted a focus on potentially associated changes in spur traits according to spur position.

Carmel spurs located in the lower parts of the canopy had less leaf area per spur whereas spur location did not have a major effect on Nonpareil spur leaf area (SLA) (Figure 27). Because light incidence decreased vertically (Figure 19 and Figure 20), a small SLA combined with a low chlorophyll concentration (Figure 28 (b)) would have limited the photosynthetic capacity of these spurs. This is

evident in the lower specific leaf weight (SLW) of shaded Carmel leaves (Figure 28 (a)). A scenario where a spur's leaves are unable to meet their own carbon needs or contribute to other spurs' carbon needs may account for the higher spur mortality of these spurs (Figure 24). Managing light intensity downward through a canopy through canopy management and irrigation and nitrogen supply could potentially increase the photosynthetic capacity of leaves on Carmel spurs in the lower parts of the canopy and may curb spur death to a degree.

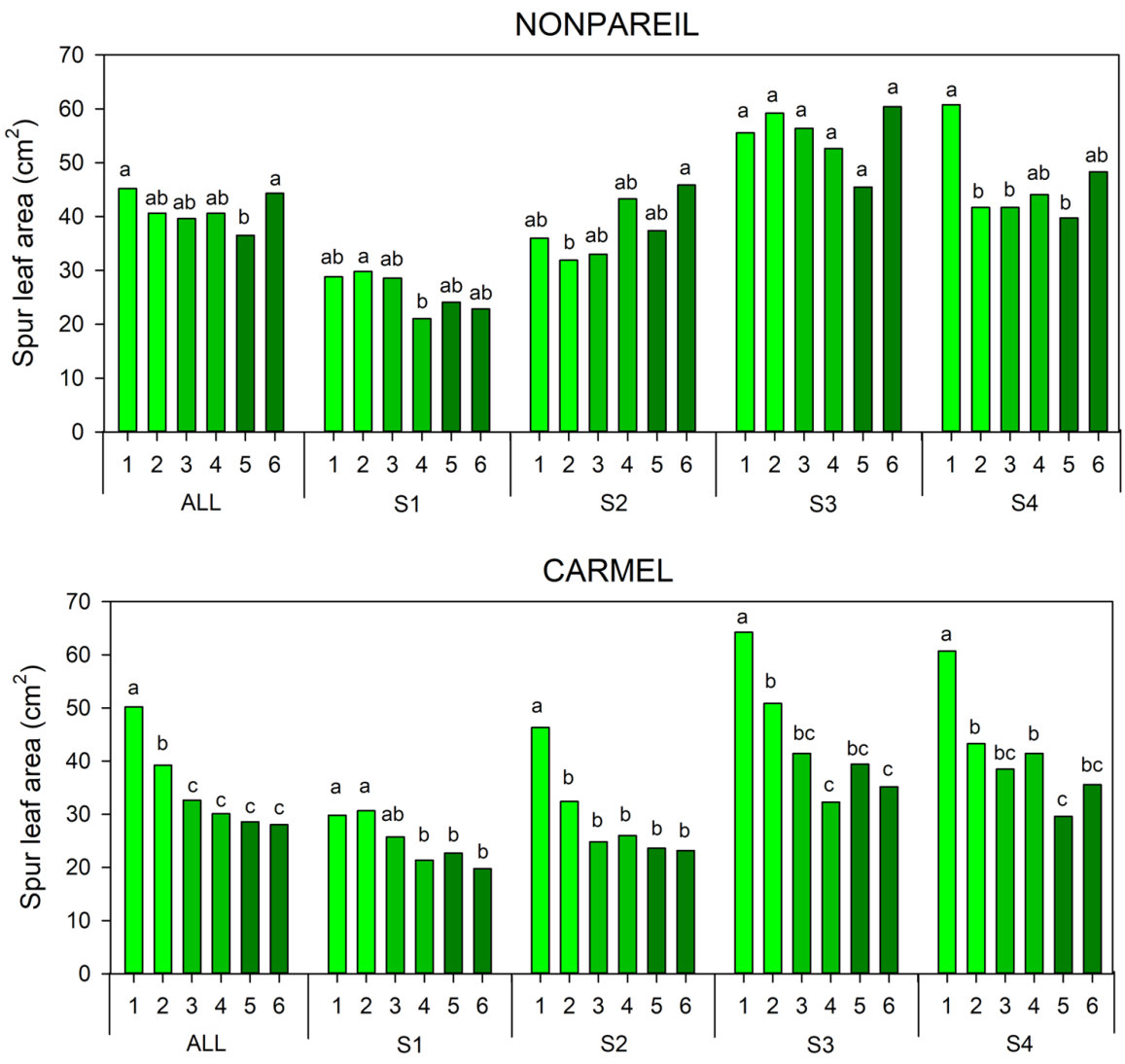


Figure 27 Leaf area on Nonpareil and Carmel spurs as a function of spur position (1 = uppermost, … , 6 = lowest) over seasons and for each season.

Values presented are means (n=24 per spur position and n=96 for all seasons), and different letters above columns within seasons indicate significant(P=0.05) differences between spur positions.

The occurrence of lower limb dieback in Nonpareil can be attributed to a lower spur replacement rate rather than low light-related spur death. Over time, the loss of spurs in this zone combined with the lack of new spurs as the trees get older and bigger would result in less assimilates being available to support the limbs' energy needs, and those limbs being less able to push out new spurs or shoots. Gradually those limbs would become enfeebled and die. Carmel spur genesis appears less affected by low light conditions, which explains the continued presence of spurs in the lower parts of the canopy (Figure 15).

Varietal light thresholds for spur emergence are unknown and need to be quantified to be able to adapt management practices to increase the number of spurs in tree canopies.

Table 13 Treatment effect on the number of leaves per spur and spur leaf area (SLA) of vegetative and reproductive spurs.

Values presented are means (n=6 and n=24 for all seasons).

		NONPAREIL			CARMEL		
		#	SLA (cm^2)		#	SLA (cm^2)	
		leaves/spur	vegetative	reproductive	leaves/spur	vegetative	reproductive
ALL	+W+N	7.9	56.5	26.8	7.1	39.5	37.1
	+W-N	8.1	54.2	23.5	6.4	31.3	32.6
	-W+N	7.7	47.1	22.8	6.6	37.8	29.3
	-W-N	7.1	43.9	25.7	6.3	36.2	29.0
	Driver[a]	*n.s.*	*water*	*n.s.*	*n.s.*	*nitrogen*	*n.s.*
S1	+W+N	6.9	36.2	20.8	6.5	29.2	23.4
	+W-N	6.3	36.7	14.2	5.3	20.1	15.6
	-W+N	5.5	32.2	14.0	5.7	23.5	27.3
	-W-N	5.4	26.4	15.4	5.0	22.1	23.0
	Driver[a]	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*nitrogen*	*n.s.*
S2	+W+N	7.9	49.9	24.5	6.5	35.5	25.3
	+W-N	8.6	52.4	25.0	6.7	33.4	23.9
	-W+N	7.6	37.5	23.3	6.2	28.1	20.9
	-W-N	7.3	49.6	17.4	5.6	29.2	21.4
	Driver[a]	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
S3	+W+N	9.4	69.3	43.8	8.8	52.7	54.5
	+W-N	8.3	64.4	26.7	6.4	35.3	38.4
	-W+N	10.3	62.1	31.1	7.7	54.4	33.4
	-W-N	8.2	53.6	37.7	7.9	50.6	37.8
	Driver[a]	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*nitrogen*	*n.s.*
S4	+W+N	7.4	67.8	21.5	6.8	41.9	42.7
	+W-N	9.2	61.3	27.1	7.4	36.3	54.0
	-W+N	7.4	56.1	23.8	6.9	44.8	34.0
	-W-N	7.3	44.8	33.5	7.2	43.1	32.7
	Driver[a]	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*water*

[a] *Indicates the significant source of variation (P=0.05) between means.*

Across seasons, irrigation volumes affected the SLA of vegetative Nonpareil spurs, whereas nitrogen affected Carmel vegetative spurs' SLA (Table 13). Within seasons, the irrigation and nitrogen treatments generally did not significantly affect the SLA for either cultivar's reproductive or vegetative spurs; the exceptions to that generalisation were lower nitrogen supply in two seasons reducing Carmel vegetative

spur SLA. This effect was first seen in S1 suggesting that the nitrogen needs of the new leaf growth could not be met from the trees' reserves following the imposition of reduced nitrogen supply. Carmel trees support larger canopies than Nonpareil trees which could account for this observation. The second event was during a season when Carmel spurs had a larger than usual SLA, which supports the idea that more than adequate nitrogen will induce an increase in vegetative growth and increase the density of the canopy as seen from the light interception data (Figure 17).

Research on Nonpareil in California suggests that high levels of nitrogen supply increases canopy density by stimulating vegetative growth (Muhammad *et al.* 2017). In contrast, the light interception measurements (Figure 17) suggested that in S2 — under the circumstances of the trial conducted at Lindsay Point — reducing nitrogen inputs increased canopy density. The mean SLA did not differ between the management treatments in that season (Table 13), but an increase in the percentage of vegetative spurs (Figure 22 and Figure 23) possibly combined with an increase in the overall number of spurs per tree could potentially explain the increase in canopy density.

Injudicious resource management has the potential to increase the total SLA as well as the number of spurs on a tree, *e.g.* through excessive nitrogen fertigation, and as a result increase the density of the canopy. This will have a negative impact on the spur fertility in the following season as light incidence on the spurs will be reduced; particularly lower in the canopy. It will also have an impact on the photosynthetic capacity of spurs located in the more shaded parts of the canopy, inhibiting photosynthesis due to insufficient light reaching these areas. This will in turn affect the carbon balance of the spur, which will negatively affect flower bud initiation, and could increase the possibility of these spurs not surviving at the end of the season.

In both cultivars, only 10% of spurs without leaves produced fruit. It is well-established that fruit bearing Nonpareil spurs have a smaller SLA in relation to vegetative spurs (Tombesi *et al.* 2015) and this was evident in Nonpareil in all seasons (Table 13). It has been hypothesised that low spur carbon status in reproductive Nonpareil spurs may contribute to the high spur mortality rate of spurs that bear fruit (Heerema *et al.* 2008). Vegetative and reproductive Carmel spurs, on the other hand, had very similar leaf areas per spur. Carmel spur mortality is not as sensitive to fruit load as Nonpareil (Table 12) and possibly this could be attributed to the similarities in reproductive and vegetative assimilate production capacity, and a subsequent better spur carbon status. This trait may be a desirable feature in new cultivars.

Leaf structural and physiological traits

Leaves of predominantly shaded and exposed spurs were sampled separately in S4 and physical traits relevant to their photosynthetic function determined. To facilitate discussion, in some instances spur position 1 has been identified as the most exposed and spur position 6 as the most shaded (Figure 19 and Figure 20) positions in the canopy. Overall the leaf area of Nonpareil spurs at these two positions did not differ (Figure 27) and the number of leaves per spur were similar. However, Carmel spurs at position 1 had a larger SLA (Figure 27) and more leaves per spur relative to position 6 indicating leaf differences between cultivars.

Not unexpectedly, specific leaf weight (SLW), chlorophyll concentration and stomatal density were significantly lower in the more shaded parts of the canopy (Figure 28 (a), (b) and (d)) where less light reached (Figure 19 and Figure 20). Chlorophyll concentrations on a dry mass basis (Figure 28 (c)) were in general higher in the shaded leaf positions than in exposed leaves. Less biomass was, however, present in shaded leaves (Figure 28 (a)) due to their diminished ability to photosynthesise in the low light environment. This, combined with shaded leaves containing more water than exposed leaves (data not shown) explains the dissimilarity in the chlorophyll concentration between shaded and exposed leaves (Figure 28 (b)).

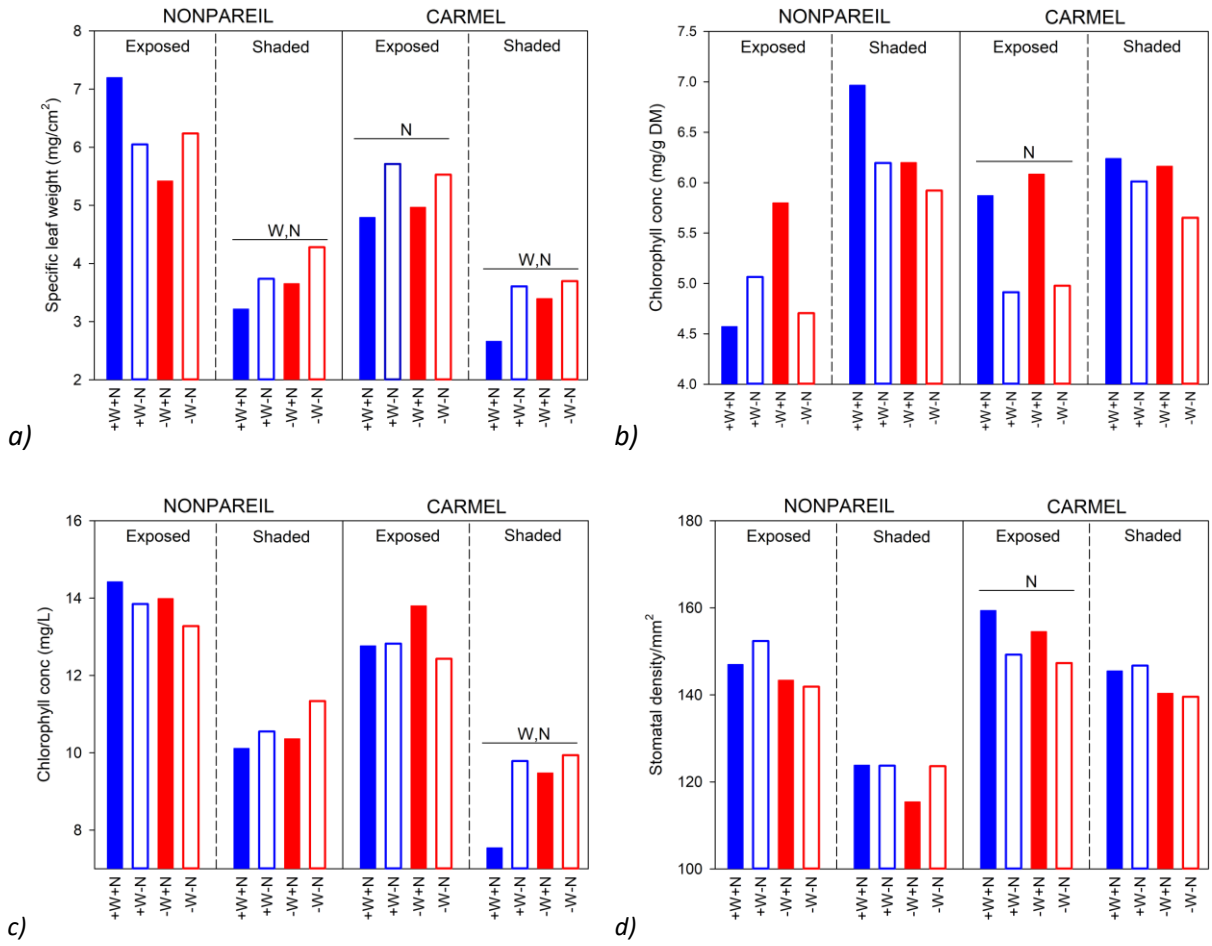


Figure 28 Treatment effects on the specific weight, chlorophyll content and stomatal density of leaves collected at hull split in S4 for Nonpareil and Carmel.

Data is shown per treatment and if the leaves were in a shaded or exposed position within the canopy. Values are the mean of treatment replicates per position in the canopy (n=6). Overhead bars indicate the major source of variation (water or nitrogen) between treatments (P=0.05).

Despite January being the warmest period in S4 (Table 4), Nonpareil leaf conductance remained relatively low during this time compared to Carmel (Figure 29). The implication is that Nonpareil is better able to regulate transpiration without compromising photosynthesis which is also evident in the SLW measurements (Figure 28 (a)). This concept is encapsulated in the term intrinsic water use efficiency (WUE) which describes the amount of carbon fixed by the leaves relative to a standard amount of water lost through the stomates to let that amount of carbon into the stomatal cavity as CO_2.

The larger number of stomates on both shaded and exposed leaves in Carmel (Figure 28 (d)) combined with a larger canopy surface area, will contribute to the loss of more water through transpiration than seen in Nonpareil and the extraction of more soil available water (Figure 12). Intrinsic water use efficiency can further be crudely approximated as kg kernel produced per kL of water supplied (WUE_Y) and is shown in Table 16.

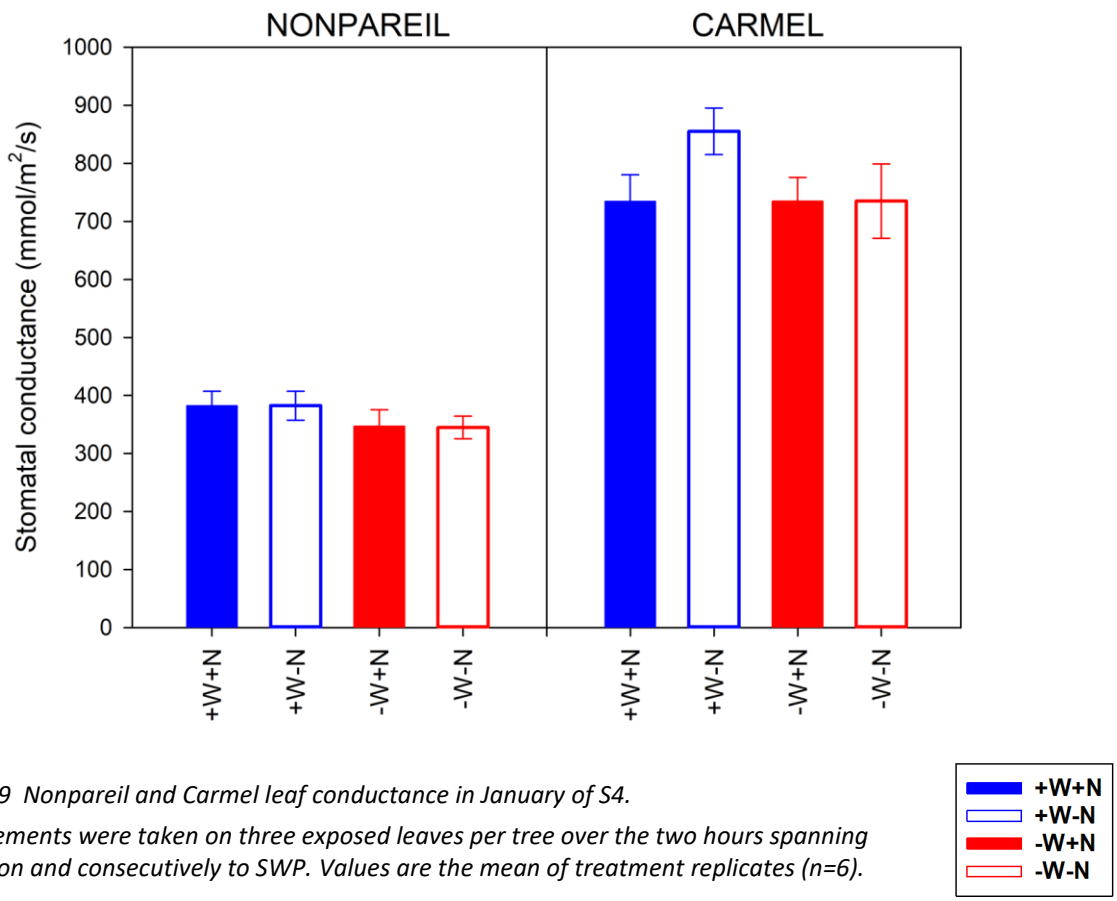


Figure 29 Nonpareil and Carmel leaf conductance in January of S4.

Measurements were taken on three exposed leaves per tree over the two hours spanning solar noon and consecutively to SWP. Values are the mean of treatment replicates (n=6).

Ultimately, reducing water or nitrogen inputs did not negatively affect the photosynthetic abilities of either cultivar's leaves. These data do, however, highlight the physiological differences between cultivars, especially the putative differences in WUE and ability to optimise photosynthesis during periods of extreme weather events.

Spur productivity

Yield is determined by the number of kernels produced by a tree and the average kernel mass. The latter is dependent on cultivar, irrigation management and crop size (Lampinen *et al.* 2011), but varies much less than the former. Fruit number is determined by a combination of the number of floral buds, the fruit set success rate (Tombesi *et al.* 2017) and the number of fruit retained to harvest. Fruit number is usually the factor that explains most of the variability in kernel yield per hectare (Tombesi *et al.* 2017).

Productivity of individual spurs

Approximately 70% of Nonpareil spurs and 56% of Carmel spurs had the potential to produce fruit because they bore floral buds at the start of the season. Only about 80% of these spurs ended up carrying fruit through to maturity. This difference is the end result of factors including the presence of nonviable flowers, poor set due to unfavourable conditions during flowering or lack of bees, and the severity of fruit drop events (Socias i Company *et al.* 2017).

Table 14 Flower and fruit traits of individual Nonpareil spurs.
Values presented are means (n=6 per season and n=24 for all seasons).

		% flowering spurs	flowers/ spur	% fruit set & retained	% spurs with fruit	fruit/spur	g/kernel
ALL	+W+N	67	3.47	34.9	47	1.87	1.17
	+W-N	69	3.46	37.4	48	1.92	1.17
	-W+N	71	3.56	42.2	52	2.03	1.05
	-W-N	73	3.28	39.5	54	1.83	1.03
	Driver[a]	*n.s.*	*n.s.*	*water*	*n.s.*	*n.s.*	*water*
S1	+W+N	71	3.27	33.6	49	1.87	1.20
	+W-N	73	3.62	39.2	51	2.11	1.12
	-W+N	76	3.46	48.5	59	2.16	1.05
	-W-N	78	3.41	42.9	59	1.88	0.97
	Driver[a]	*n.s.*	*n.s.*	*water*	*n.s.*	*n.s.*	*water, N*
S2	+W+N	72	3.43	32.9	46	1.73	0.95
	+W-N	65	3.09	40.4	50	1.55	1.17
	-W+N	75	2.92	38.1	46	1.66	0.82
	-W-N	76	2.78	35.5	49	1.76	0.96
	Driver[a]	*n.s.*	*water*	*n.s.*	*n.s.*	*n.s.*	*water, N*
S3	+W+N	50	2.65	48.6	39	2.00	1.29
	+W-N	65	3.66	37.8	42	2.02	1.28
	-W+N	46	2.52	52.3	36	2.14	1.26
	-W-N	62	2.93	49.4	48	1.84	1.17
	Driver[a]	*n.s.*	*nitrogen*	*n.s.*	*n.s.*	*n.s.*	*water*
S4	+W+N	76	4.31	28.7	56	2.13	1.23
	+W-N	71	3.45	32.1	50	1.98	1.12
	-W+N	86	4.83	35.0	69	2.11	1.06
	-W-N	77	3.94	31.7	58	1.81	1.04
	Driver[a]	*n.s.*	*nitrogen*	*n.s.*	*n.s.*	*n.s.*	*water, N*

[a] *Indicates the significant source of variation (P=0.05) between means.*

Treatment impacts on the number of flowers per spur were only apparent from S2 onwards. Nonpareil spur fertility was more sensitive to treatments within seasons than Carmel, but reducing the water improved the overall fertility of Carmel spurs (Table 14 and Table 15). Because the treatments did not induce water stress (Figure 11) or any great degree of nitrogen deficiency (Figure 14) the differences in the number of floral buds per spur between treatments were likely an indirect result. As discussed previously, light penetration deeper down in the canopy was improved when the water or nitrogen applications were reduced (Figure 16 and Figure 17), especially in the lower parts of the canopy (Figure 19 and Figure 20); this could be expected to improve bud fertility indirectly by improving spur carbon balance.

Table 15 Flower and fruit traits of individual Carmel spurs.
Values presented are means (n=6 per season and n=24 for all seasons).

		% spurs with flowers	flowers/ spur	% fruit set & retained	% spurs with fruit	fruit/spur	g/kernel
ALL	+W+N	53	3.41	24.6	31	1.80	1.01
	+W-N	55	3.44	26.1	32	1.71	1.03
	-W+N	57	3.76	25.5	32	1.72	0.99
	-W-N	62	3.60	30.3	44	1.71	0.92
	Driver[a]	*n.s.*	*water*	*n.s.*	*n.s.*	*n.s.*	*water*
S1	+W+N	52	3.34	23.9	30	1.76	1.01
	+W-N	67	3.76	21.9	33	1.80	1.03
	-W+N	68	3.98	22.8	36	1.65	1.02
	-W-N	68	3.57	30.7	44	1.65	1.00
	Driver[a]	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
S2	+W+N	59	3.76	14.5	18	1.29	1.02
	+W-N	37	3.43	28.7	28	1.70	1.00
	-W+N	48	3.58	21.1	24	1.58	0.94
	-W-N	54	3.33	26.7	38	1.58	0.87
	Driver[a]	*n.s.*	*n.s.*	*nitrogen*	*n.s.*	*n.s.*	*water*
S3	+W+N	34	2.27	42.6	28	1.64	1.15
	+W-N	58	3.20	33.6	38	1.79	1.12
	-W+N	44	4.02	35.6	35	2.11	1.08
	-W-N	51	2.82	36.4	40	1.74	0.93
	Driver[a]	*n.s.*	*water*	*n.s.*	*n.s.*	*n.s.*	*water, N*
S4	+W+N	69	3.74	25.6	49	1.89	0.96
	+W-N	57	3.29	22.1	28	1.49	1.00
	-W+N	67	3.52	25.0	34	1.52	0.92
	-W-N	73	4.39	28.2	53	1.68	0.89
	Driver[a]	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*water*

[a] *Indicates the significant source of variation (P=0.05) between means.*

Treatment effects alternated between seasons in the percentage of spurs that ended up carrying fruit in relation to the percentage of fertile spurs at the start of the season, but had no effect on the number of fruit carried by spurs (Table 14 and Table 15). Carmel had a lower overall fruit retention rate than Nonpareil (Table 14 and Table 15). Effective fruit set also diminished for the spurs located in the lower parts of the canopy (data not shown). Moisture stress and nutrient deficiencies are thought to contribute to fruit drop (Kester *et al.* 1996), but it is evident in the Lindsay Point data that more fruit were retained on spurs in the decreased water treatments, particularly on Nonpareil (Table 14). Carmel showed a similar trend, but that trend was not statistically significant. The inadvertent decrease in nitrogen fertigation in S1 did not affect the percentage of fruit that were set and retained in Nonpareil

on surviving spurs, and low nitrogen supply had positive effects on fruit retention in Carmel in S2 (Table 14 and Table 15).

Spur productivity per hectare

Yield data per hectare were extrapolated from individual tree data. The estimated yields will be higher than the actual yield because no allowance was made for missing trees or heterogeneous areas within the orchard. Generally, the data collected for individual spurs showed similar responses to the treatments as that observed at harvest (Table 14 and Table 15 and Figure 30), but treatment effects were more pronounced at tree level. Consequently, individual spur assessments can be used as an indication of general trends in the overall spur population in relation to treatments. It is important to remember that individual spur assessments do not make provision for changes in the number of spurs on a tree in response to treatments due to changes to the light environment as will be evident in data on a tree basis.

Reducing irrigation volumes brought the date of hull split forward by an average of 10 days compared to the regular water treatments, which resulted in earlier harvest dates for the reduced water treatments which will impact commercial harvest schedules.

Across all seasons, Carmel productivity averaged 3.7 t kernels/ha and Nonpareil 3.5 t kernels/ha. Even though less Carmel spurs carry fruit and have a smaller average kernel mass compared to Nonpareil (Table 14 and Table 15), Carmel trees produced a relatively similar tonnage to Nonpareil. The treatments did not have an effect on the productivity of either cultivar over the complete trial period and any apparent treatment effects within a season alternated between seasons and Carmel trees were less responsive to the treatments (Figure 30). Reducing the water and nitrogen applications negatively affected kernel size, but simultaneously increased the number of kernels per tree (Figure 30). This points towards an increase in the fertility of the spurs in these treatments which resulted in similar yields across the water and nitrogen treatments for the total experimental period.

Treatments were applied from the start of S1 onwards and the drop in yield in the reduced treatments in S1 can be attributed to smaller kernels (Figure 30). The treatments didn't alter the number of kernels per tree in S1, as expected, because that yield component had been set during the floral bud initiation period the previous season before the treatments were imposed (Figure 30). The higher number of kernels on Nonpareil +W-N trees compared to the control was due to a higher number of fruit that were retained in this treatment (Table 14). Treatment effects only took affect from S3 onwards in the number of kernels per tree.

Nitrogen deficiency during S1 (Figure 14) noticeably reduced the estimated yield in S2 to approximately 2.5 t kernels per hectare. Insufficient nitrogen supply (Table 5) will negatively affect floral bud initiation thereby reducing the potential yield of the following season (Socias i Company *et al.* 2017). There wasn't a noticeable decrease in the number of floral buds in the monitored spurs that survived from S1 to S2 in relation to the remainder of the seasons (Table 14 and Table 15), but nitrogen deficiency had a positive effect on the number of floral buds per Carmel spur whereas a reduced water supply negatively affected the number of floral buds on Nonpareil spurs. This was echoed in the increase in yield in the decreased nitrogen treatments because of an increase in the number of kernels per tree compared to the control (Figure 30). The increase in the number of kernels per tree in Carmel in S3 can partially be explained by the higher percentage of spurs that bore a single fruit in S2 and were reproductive in S3 (Figure 26), as well as the high fruit retainment rate (Table 15).

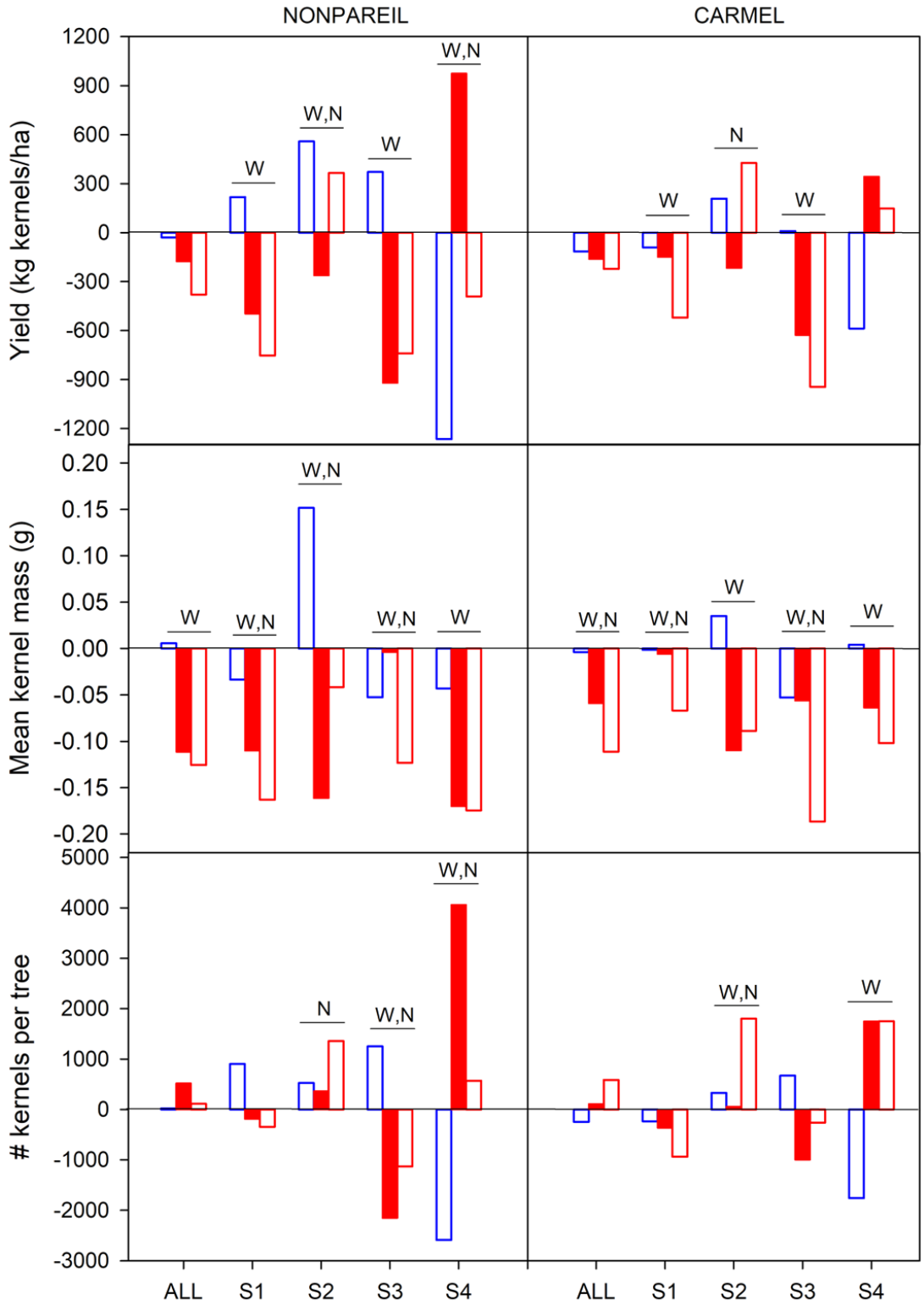


Figure 30 Treatment effects (relative to the control) per season on kernel yield per ha, mean kernel mass and kernels per Nonpareil and Carmel trees.

Values presented are means (n=6 per season and n=24 for all seasons), and horizontal lines covering a season's means indicate whether water and/or nitrogen was a significant (P=0.05) source of variation between means.

During S4, trees in both reduced water treatments produced more kernels than when trees received regular water applications, especially in combination with standard nitrogen applications in Nonpareil (Figure 30). This increase is noteworthy as the yield was increased in these treatments even though the kernels were smaller. It seems that conditions during S3 were conducive to floral bud initiation.

Decreasing the irrigation volume significantly decreased the mean kernel mass each season, but only by approximately 10% on average. The limited scale of the reduction could be attributed to the limited effect that reduced water supply had on tree water status during the cell division and kernel fill periods. Soil moisture measures around this time in S4 (Supplementary Figure 4 and Supplementary Figure 5) also showed that soil water was available during this period. This would be expected in every season as the trees were watered daily (Supplementary Table 1) and the canopy was still forming. Leaf conductance also did not separate according to treatment, which shows that water availability was not a limiting factor for leaf function to support fruit ripening or vegetative growth.

Reducing the irrigation reduced the size of kernels, with reduced nitrogen supply contributing to a lesser degree (Figure 30). Reduced nitrogen supply did, however, increase the number of kernels per tree (Figure 30). There is hence the potential to reduce water and nitrogen inputs whilst maintaining a large yield. A deficit of water and/or nitrogen starting during the canopy fill period may decrease the canopy density, allowing more light to enter the lower parts of the canopy, which would increase the fertility of buds in the internal parts of the canopy.

Table 16 Nonpareil and Carmel WUE_Y (kg kernels per kL of water) for all seasons.

Values presented are means (n=6 per season and n=24 for all seasons) and effects that resulted in significant (P=0.05) differences between treatments within a season shown.

		ALL	S1	S2	S3	S4
NONPAREIL	+W+N	0.26	0.29	0.20	0.23	0.27
	+W-N	0.25	0.30	0.24	0.25	0.19
	-W+N	0.32	0.35	0.24	0.22	0.48
	-W-N	0.31	0.33	0.31	0.24	0.36
	Driver [a]	*water*	*water*	*water, N*	*n.s.*	*water, N*
CARMEL	+W+N	0.26	0.20	0.19	0.33	0.26
	+W-N	0.24	0.19	0.21	0.33	0.23
	-W+N	0.34	0. 28	0.25	0.43	0.40
	-W-N	0.34	0.24	0.32	0.40	0.39
	Driver [a]	*water*	*water, N*	*water, N*	*water*	*water*

[a] *Indicates the significant source of variation (P=0.05) between means.*

In the majority of the seasons – with the only exception being S3 in Nonpareil – reduced water applications had a positive effect on the WUE_Y in both cultivars (Table 16). This indicates that higher yields can be achieved by reducing the water input in the orchard. Reducing nitrogen also had a positive effect on the WUE_y in some seasons, and in Carmel reducing the nitrogen inputs by almost half did not affect WUE_y in any way in the trial's final seasons. Reducing water inputs in the orchard is therefore a viable option to reduce input costs. Nitrogen inputs, however, needs to be evaluated on a seasonal basis.

Treatment effects on kernel taste

Anecdotal observations indicated that the treatments may induce differences in the taste and texture of kernels which could potentially be an opportunity for industry or a circumstance that producers would seek to avoid. In order to assess this we conducted discriminative tastings on kernels harvested in S3 and S4 at general industry events in 2018 and 2019. The results are presented in Table 17. To gather enough data to produce meaningful results only Nonpareil kernels were tasted.

Tasters represented a good cross-section of the population. Tasters were evenly distributed between male and female and generally all age groups were evenly represented. Most tasters consumed almonds regularly or on occasion and less than 10% stated that they never ate almonds.

Table 17 Tasting results of Nonpareil kernels harvested in S3 and S4.

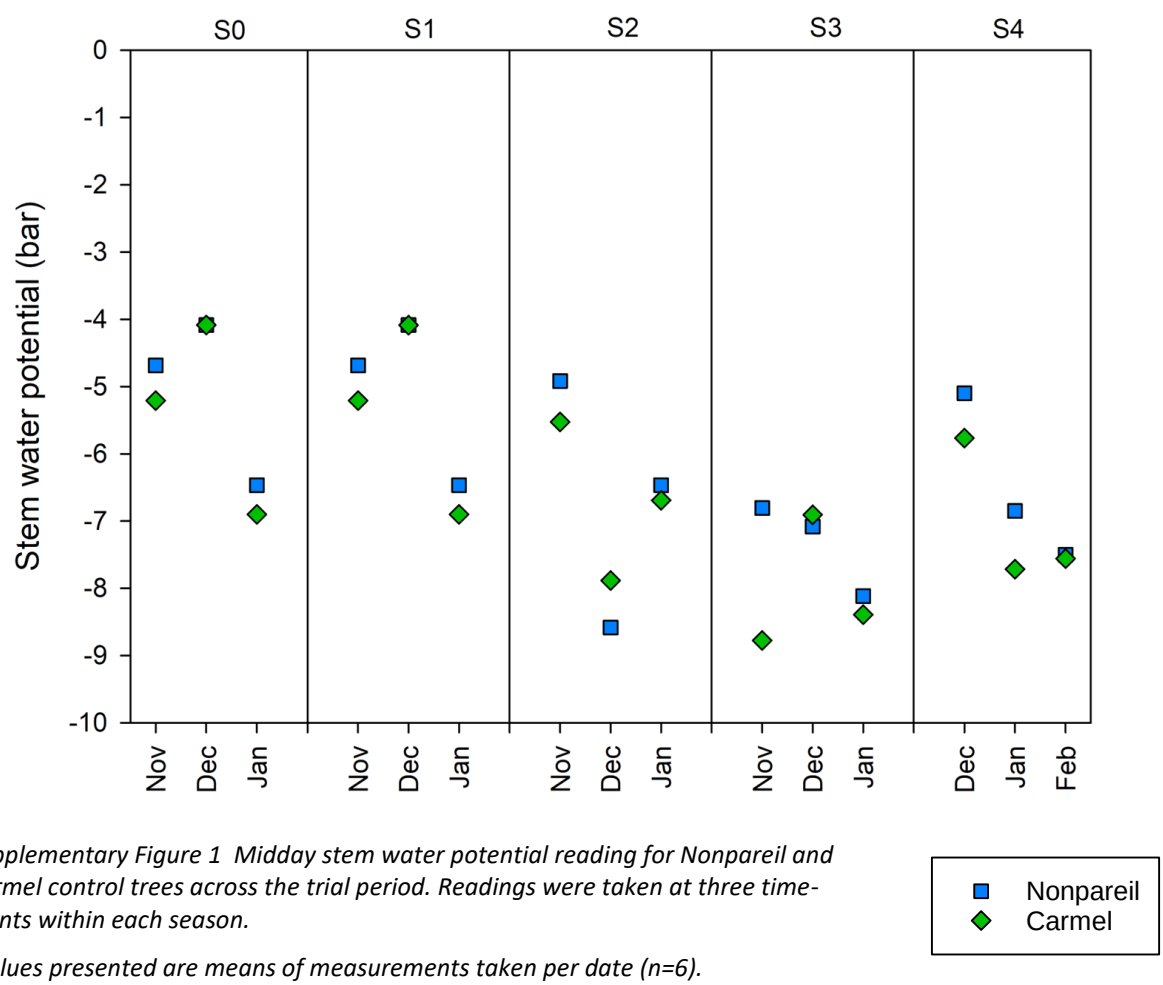
Values indicate the corrected proportion of tasters that could identify differences between the treatments within a combination. Values followed by a star indicated that the results were significant (P= 0.05).

		% correctly identified	
Tasting combination	**Variable**	**S3**	**S4**
+W+N *vs* **+W-N**	nitrogen	22	31
-W+N *vs* **-W-N**	nitrogen	36	48 *
+W+N *vs* **-W+N**	water	26	41 *
+W-N *vs* **-W-N**	water	31	32
+W-N *vs* **-W+N**	water & nitrogen	37	39
+W+N *vs* **-W-N**	water & nitrogen	33	41 *

Untrained tasters could not significantly detect differences between almond kernels that were harvested in S3. More than 40% of tasters could, however, correctly identify differences in kernels harvest in S4 in half of the treatment combinations. There were no trends in what drove the perceived differences, but almost half of the tasters could correctly identify kernels that differed in nitrogen application within the low water treatments. They could also identify kernels in which water and nitrogen was reduced, *i.e.* extreme treatments.

Several tasters verbally described why they perceived kernels as different and included attributes like sweetness, creaminess and crunchiness. The tasters were not formerly trained in descriptive analyses and their comments can only be used as subjective observations. It is, however, clear from their comments that formal descriptive tastings, combined with metabolomic analyses of kernel composition, is the logical next step to determine the true effect of nitrogen and water manipulation on almond kernels. Kinetic metabolomic analyses could also aid in scheduling deficit irrigation to optimise kernel composition.

Appendix B Supplementary data



Supplementary Figure 1 Midday stem water potential reading for Nonpareil and Carmel control trees across the trial period. Readings were taken at three time-points within each season.

Values presented are means of measurements taken per date (n=6).

Supplementary Table 1 Seasonal irrigation frequency and length in the standard (+W) and reduced (-W) treatments from 1 September to 31 January.

SEASON 1			SEASON 2			SEASON 3			SEASON 4		
Date	Hours		Date	Hours		Date	Hours		Date	Hours	
	+W	-W		+W	-W		+W	-W		+W	-W
1/09/2015	06:00	04:12	1/09/2016	05:00	03:30	1/09/2017	04:00	02:48	1/09/2018		
2/09/2015	03:00	02:06	2/09/2016			2/09/2017			2/09/2018		
3/09/2015			3/09/2016			3/09/2017			3/09/2018		
4/09/2015			4/09/2016			4/09/2017			4/09/2018	04:30	03:09
5/09/2015			5/09/2016			5/09/2017			5/09/2018		
6/09/2015			6/09/2016	05:00	03:30	6/09/2017			6/09/2018		
7/09/2015	06:00	04:12	7/09/2016			7/09/2017	04:30	03:09	7/09/2018	05:00	03:30
8/09/2015			8/09/2016			8/09/2017			8/09/2018		
9/09/2015			9/09/2016			9/09/2017			9/09/2018		
10/09/2015	05:00	03:30	10/09/2016	05:00	03:30	10/09/2017			10/09/2018	05:00	03:30
11/09/2015	06:00	04:12	11/09/2016			11/09/2017	05:00	03:30	11/09/2018		
12/09/2015	06:00	04:12	12/09/2016			12/09/2017			12/09/2018	05:00	03:30
13/09/2015	06:00	04:12	13/09/2016			13/09/2017			13/09/2018		
14/09/2015			14/09/2016			14/09/2017	06:00	04:12	14/09/2018	05:00	03:30
15/09/2015	06:00	04:12	15/09/2016			15/09/2017			15/09/2018		
16/09/2015			16/09/2016	04:00	02:48	16/09/2017			16/09/2018	05:00	03:30
17/09/2015			17/09/2016			17/09/2017			17/09/2018		
18/09/2015	05:00	03:30	18/09/2016			18/09/2017	06:00	04:12	18/09/2018	05:00	03:30
19/09/2015	06:00	04:12	19/09/2016	04:00	02:48	19/09/2017	06:00	04:12	19/09/2018	06:00	04:12
20/09/2015			20/09/2016			20/09/2017	06:30	04:33	20/09/2018	06:00	04:12
21/09/2015	06:00	04:12	21/09/2016			21/09/2017	03:00	02:06	21/09/2018	05:00	03:30
22/09/2015			22/09/2016			22/09/2017	06:30	04:33	22/09/2018	05:00	03:30
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5/11/2015	05:00	03:30	5/11/2016	05:00	03:30	5/11/2017	05:30	03:51	5/11/2018	06:30	04:33
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SEASON 1			SEASON 2			SEASON 3			SEASON 4		
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	+W	-W		+W	-W		+W	-W		+W	-W
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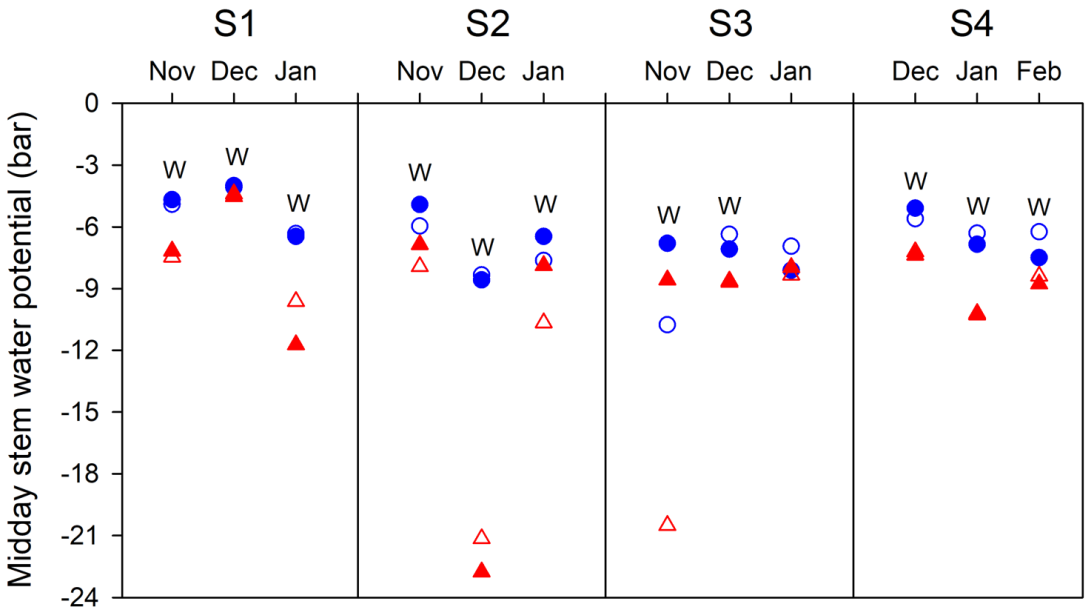
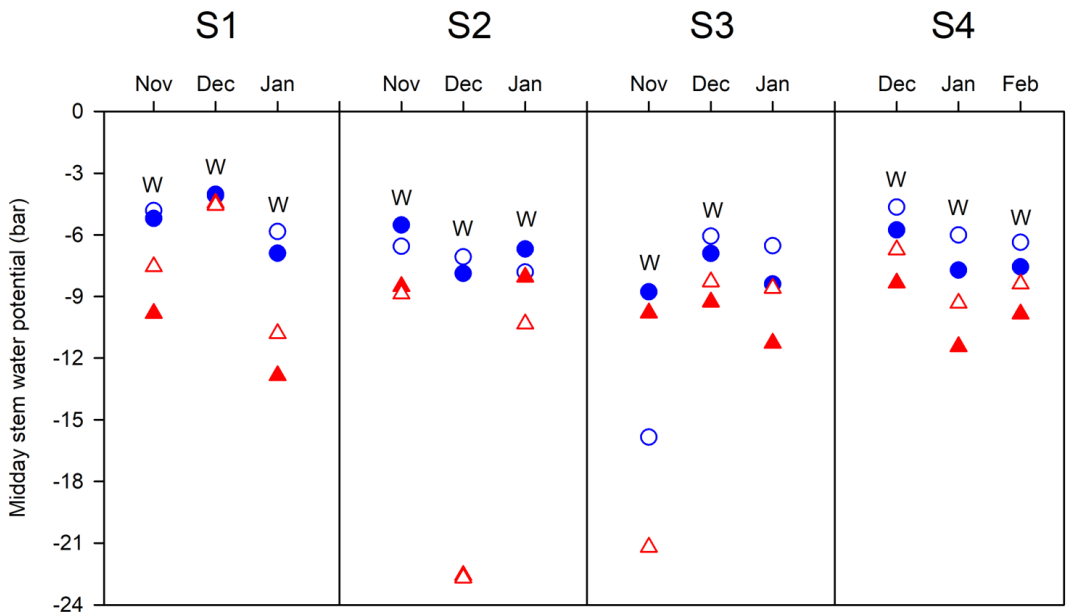


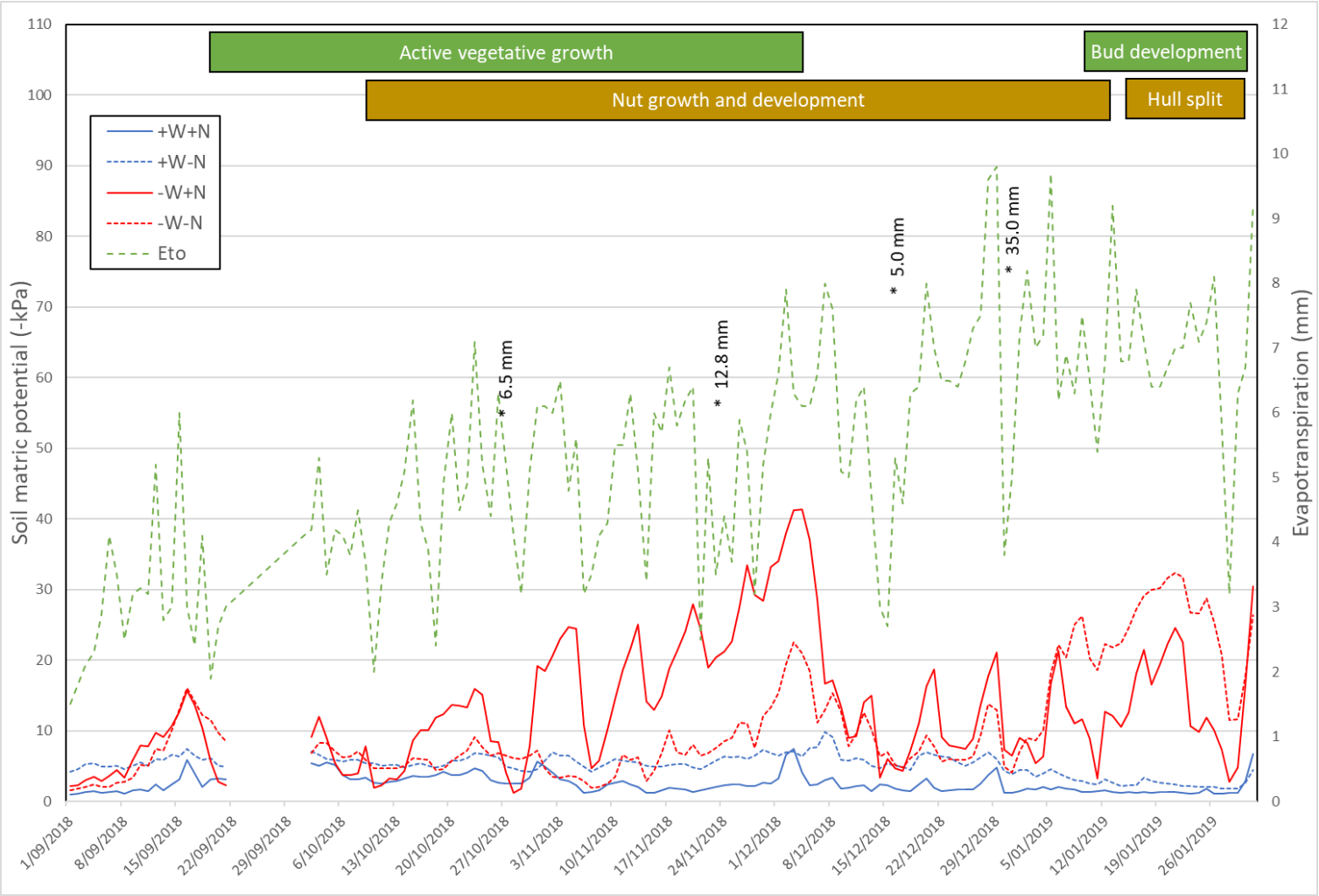
Supplementary Figure 2 Effects of irrigation management and nitrogen supply on the midday stem water potential (bar) in Nonpareil measured at three time points across the four seasons.

Values presented are means (n=18), and "W" above a group of means for a specific measurement date indicate that irrigation management was a significant source (P=0.05) of variation between that group of means.

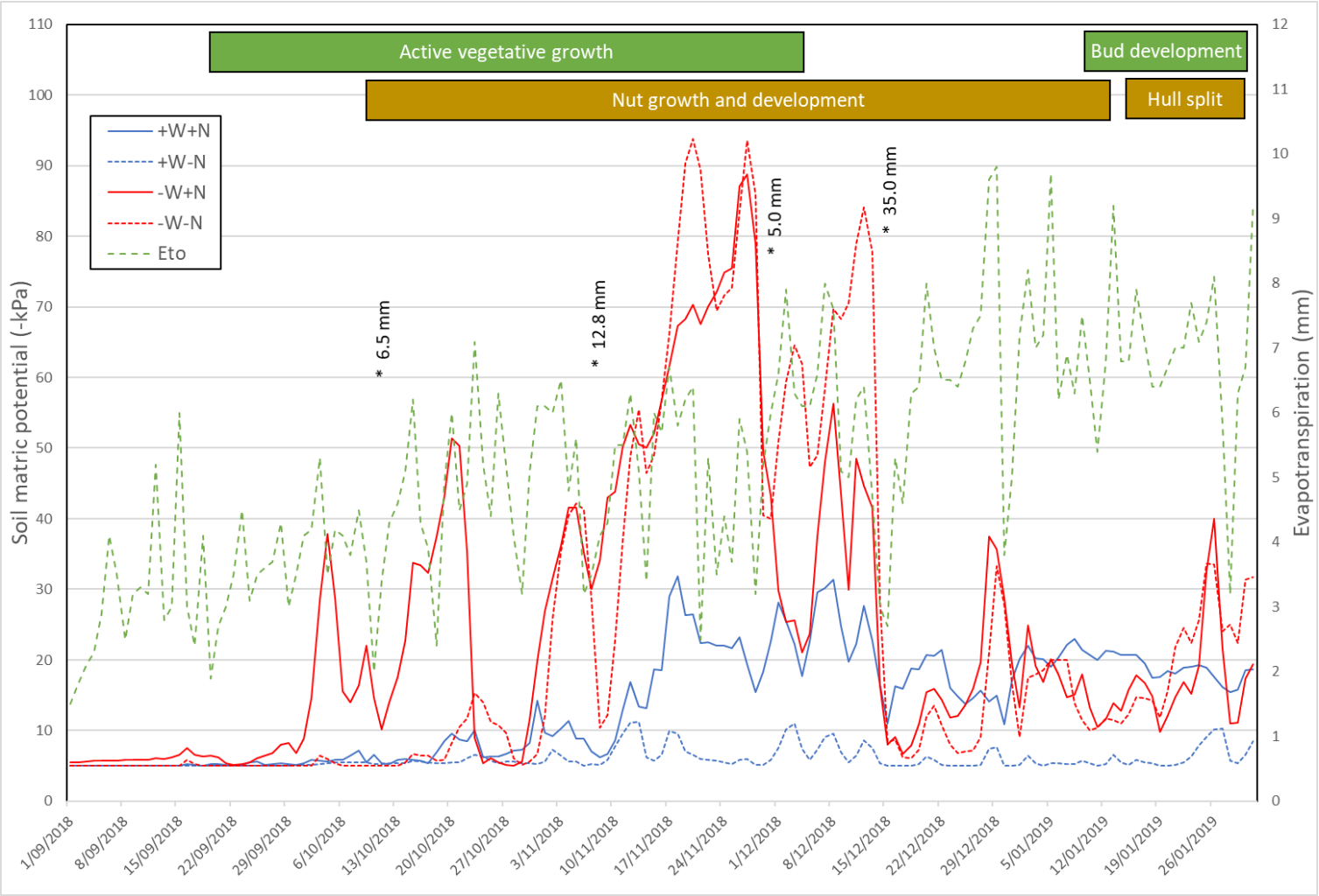


Supplementary Figure 3 Effects of irrigation management and nitrogen supply on the midday stem water potential (Bar) in Carmel measured at three time points across the four seasons.

Values presented are means (n=18), and "W" above a group of means for a specific measurement date indicate that irrigation management was a significant source (P=0.05) of variation between that group of means.



Supplementary Figure 4 Effect of irrigation and nitrogen management on daily soil matric potential (n = 6) in S4 from 1 September to 31 January in Nonpareil. Predicted vegetative and reproductive stages are indicated. Rainfall intensity over a 24-hour period is shown on the graph with the exclusion of very light rainfall (<5 mm). Daily ET_0, calculated from the LMW AWS located near the orchard, is also shown.



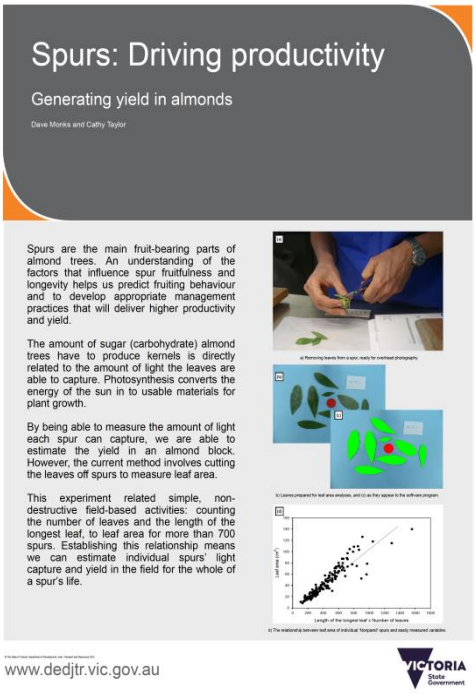
Supplementary Figure 5 Effect of irrigation and nitrogen management on daily soil matric potential (n = 6) in S4 from 1 September to 31 January in Carmel. Predicted vegetative and reproductive stages are indicated. Rainfall intensity over a 24-hour period is shown on the graph with the exclusion of very light rainfall (<5 mm). Daily ET_0, calculated from the LMW AWS located near the orchard, is also shown.

Appendix C Communication

Posters

1.

2.



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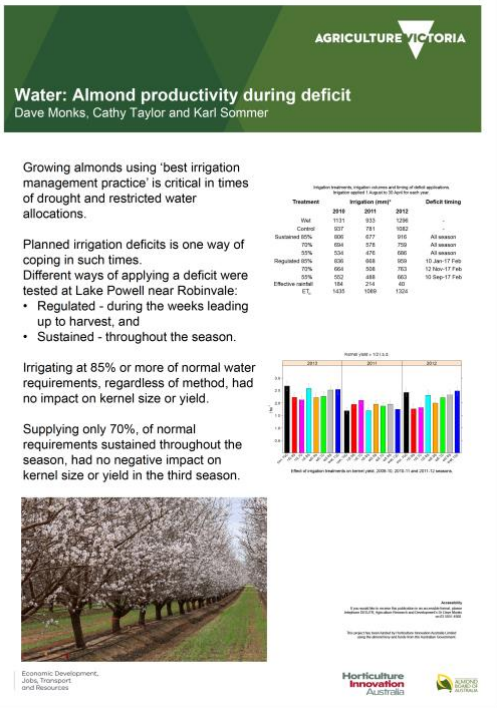
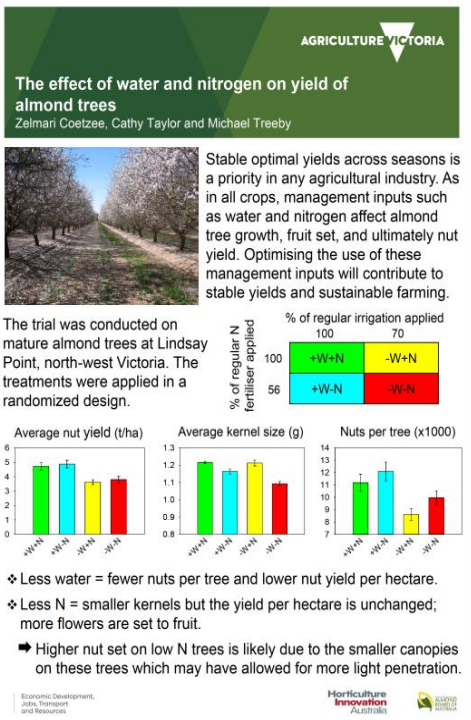
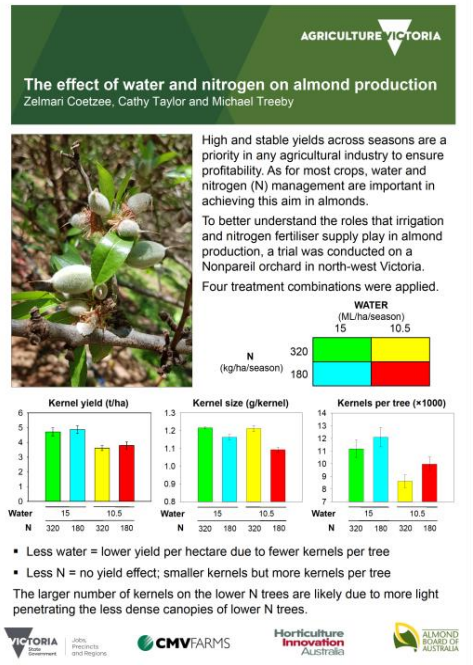


4.



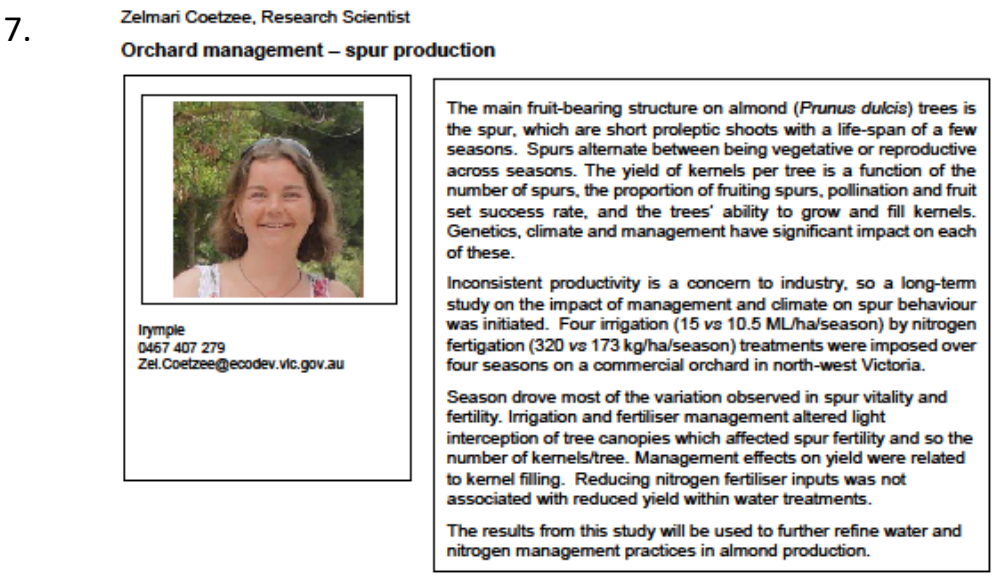
5.


AGRICULTURE VICTORIA
The effect of water and nitrogen on almond production
Zelmari Coetzee, Cathy Taylor and Michael Treeby
High and stable yields across seasons are a priority in any agricultural industry to ensure profitability. As for most crops, water and nitrogen (N) management are important in achieving this aim in almonds.
To better understand the roles that irrigation and nitrogen fertiliser supply play in almond production, a trial was conducted on a Nonpareil orchard in north-west Victoria.
Four treatment combinations were applied.
WATER (ML/ha/season)
15
10.5
N (kg/ha/season)
320
180
Kernel yield (t/ha)
Kernel size (g/kernel)
Kernels per tree (×1000)
Water
N
15
10.5
320
180
Less water = lower yield per hectare due to fewer kernels per tree
Less N = no yield effect; smaller kernels but more kernels per tree
The larger number of kernels on the lower N trees are likely due to more light penetrating the less dense canopies of lower N trees.
CMVFARMS
Horticulture Innovation Australia
ALMOND BOARD OF AUSTRALIA

6.


AgriBio Seminar Series
October – Early November 2018
Friday 12th October
12:00 - 1:00 pm
Dr Amanda Chamberlain, Agriculture Victoria Research
Identification of Regulatory Variants in Cattle using RNA Sequence Data
Host: Ben Cocks
Friday 19th October
12:00 - 1:00 pm
Jason Coposky, University of North Carolina, USA
Big Data in Research Management: The IoT (Internet of Things) Collaboration
Host: Kieran Murphy & Angela Avery
Friday 26th October
12:00 - 1:00 pm
Dr Peter Mee, Agriculture Victoria Research
Significant Livestock Vectors and their Microbiota –
Cryptic Culicoides (Biting Midges) and their Endosymbiotic Bacteria
Host: Brendan Rodoni
Friday 2nd November
12:00 - 1:00 pm
Zelmari Coetzee, Agriculture Victoria Research
Management Strategies to Maintain High Productivity in Prunus dulcis Mill. (Almonds) - Water & Nitrogen Supply Affecting Dynamics of Fruit Bearing Structures.
Host: Traci Griffin & Michael Treeby

7.


Zelmari Coetzee, Research Scientist
Orchard management – spur production
Irymple
0467 407 279
Zel.Coetzee@ecodev.vic.gov.au
The main fruit-bearing structure on almond (Prunus dulcis) trees is the spur, which are short proleptic shoots with a life-span of a few seasons. Spurs alternate between being vegetative or reproductive across seasons. The yield of kernels per tree is a function of the number of spurs, the proportion of fruiting spurs, pollination and fruit set success rate, and the trees' ability to grow and fill kernels. Genetics, climate and management have significant impact on each of these.
Inconsistent productivity is a concern to industry, so a long-term study on the impact of management and climate on spur behaviour was initiated. Four irrigation (15 vs 10.5 ML/ha/season) by nitrogen fertigation (320 vs 173 kg/ha/season) treatments were imposed over four seasons on a commercial orchard in north-west Victoria.
Season drove most of the variation observed in spur vitality and fertility. Irrigation and fertiliser management altered light interception of tree canopies which affected spur fertility and so the number of kernels/tree. Management effects on yield were related to kernel filling. Reducing nitrogen fertiliser inputs was not associated with reduced yield within water treatments.
The results from this study will be used to further refine water and nitrogen management practices in almond production.

8.

Deficit irrigation of almond trees did not decrease yield

Dave Monks, Cathy Taylor, Karl Sommer

Department of Economic Development, Jobs, Transport and Resources.

PO Box 905, Mildura, Victoria 3502, Australia. dave.monks@depi.vic.gov.au

Economic success of the Australian almond industry increasingly depends on the adoption of strategies that ensure the most effective and efficient use of irrigation water. An experiment was established in north-western Victoria, Australia. Five levels of irrigation were tested over three years: a fully irrigated control (100 %), three levels of deficit irrigation (55, 70 and 85 %) applied as regulated (RDI) or sustained (SDI) deficits and a high irrigation level (120 %). The 100 % control was defined as the level of irrigation that met plant water requirement. The results showed that irrigating at 85 % of full irrigation had no negative impact on kernel size and yield but irrigating at 70 % or less decreased kernel yield regardless of strategy. In the third year, trees with 70 % deficits applied throughout the irrigation cycle produced a higher kernel yield than the trees receiving the same deficit biased toward pre-harvest. Water deficits had no impact on the timing of flowering or fruit set but tended to accelerated hull split in line with the level of deficit. The study concluded that irrigating at 85 % of full irrigation, which represents a moderate deficit, has good potential to alleviate water shortages without loss of production despite midday stem water potential being significantly more negative two to six weeks before harvest. The results will be discussed in terms of irrigation management and potential water savings from adopting a moderate level of deficit irrigation.

9.

Department of Economic Development, Jobs, Transport & Resources

Internal briefing for Emily Phillips, Acting Lead Deputy Secretary Agriculture Energy and Resources

Subject	**Overseas Travel Report from Dr Dave Monks, Research Scientist, Horticulture Production Sciences, Agriculture Research**
Decision date	**N/A**

Core message

Dr Dave Monks travelled to Spain from 30 May 2015 to 14 June 2015. The objectives of the trip were to inspect high-density almond plantings, nurseries and support industries in north-western Spain and to present a paper on DEDJTR's Lake Powell (north west Victoria) almond irrigation research at the 8th International Symposium on Irrigation of Horticulture Crops held at Lleida, Spain.

Recommendation/s

That you:

a) Consider this overseas post-travel report for approval

[ ] Approved
[ ] Not Approved
[ ] Noted
[ ] Please Discuss

..... **Emily Phillips** Acting Lead Deputy Secretary Date: 28/9/15	**Comments:**

	Name	Signature	Date	Position	Phone no.
Approved	Michael Crawford		28/8/15	Research Director, Agriculture Production	(03) 5430 4301
Endorsed	Traci Griffin		24/9/15	Acting Executive Director, Agriculture Research and Development	(03) 8392 7186
Endorsed	Greg Harper		24/9/15	Acting Deputy Secretary Agriculture and Rural	(03) 8392 7185

<DivisionGroup>		
REQUESTED □	DEPARTMENT INITIATED □	DATE DUE IN MO: N/A
DEDJTR REF: <RegNo1>	FILE/TRIM REF: OG/09/0109	MINISTERIAL REF:

State Government Victoria

Key information

Trip details and key observations:

Dr Monks travelled to Spain to attend the world's leading irrigated horticultural crops symposium. He presented work on water use efficiency in Australian almonds. The trip also included meetings with leading science and commercial interests in the Spanish almond industry, discussing their experiences with higher density orchard plantings.

The key observations of the trip were that the Spanish almond sector is in the process of transforming itself from a low input, dryland, low output (200 kg kernels/ha) industry, to a high input, high density, irrigated, high output (1,700 kg kernels/ha) industry. There is a concomitant development of support industries (nurseries, equipment manufacturers, *etc.*) to satisfy the demand generated by the sector's transformation. There are obvious parallels with the state of the Victorian almond industry.

The key observation of the conference was the global imperative for robust, professional, long-term research to allow almond producers and policy-makers alike to make objective decisions regarding maximising returns on water used for kernel production.

Extent to which objectives were achieved:

Dr Monks' presentation was well received. It stimulated significant discussion and interaction with international scientists regarding the almond industry and almond research in Victoria. The tour of research and commercial facilities was valuable; discussing the lessons learned to date and how Victoria can adapt and build Australia's almond research.

Next steps/action plan:

Next steps were to brief the relevant internal staff regarding Spanish almond research and international irrigation research for integration into our current and future projects and to submit finalised paper to the symposium for peer review and publication. These steps have been completed.

Synopsis of key outcomes for DEDJTR Annual Report (limit 50 words):

Dr Monks presented data to, and discussed research outcomes with an international contingent of irrigation scientists at the 2015 ISHS Irrigation Symposium, Lleida, Spain. The trip also included meetings with the leading science and commercial interests in super-high density plantings – an exciting area of new research interest for Victoria.

Context

The conference ran over four days, including a day touring the irrigation infrastructure advancements in the district. Large, state-sponsored investment in irrigation has spearheaded a consolidation of land titles and management units – many years have been spent buying, selling and trading land titles to move landholders into, or out of, the irrigation districts; matching their risk profiles and desires has been an important part of the State's involvement. The new irrigation infrastructure adds to the existing area, traditionally drawn from the nearby river, with water dammed from the Pyrenees to the north.

Sessions at the conference focussed predominately on plant-based measures of water stress, and a number of advances having been made in remote sensing of plants. However, the development of satisfactory correlations with plant-based measures is ongoing. Discussions continued on the salinity interaction and management. International keynote presentations gave the global context for irrigation research, as California's drought continues to intensify, Israel battles with salt, managing quality with limited water supplies, and Australia comes out of a 10-year drought with

water buy-backs limiting the water available to the irrigation-community for the next, inevitable drought.

Many of the poster presentations looked at irrigation scheduling through the development of crop coefficients. A lively discussion was held on the value of crop coefficients outside a set of specific conditions – the discussion was driven by Profs. Richard Snyder and Larry Williams, both of UC Davis, USA and their contrasting views. Prof. Williams would prove to be a worthwhile candidate for our visiting scientist program.

The tour of research and commercial facilities was valuable; discussing the lessons learned to date and how Victoria can adapt and build Australia's almond research. For example, some orchards are being planted at >3000 trees/ha, compared with the Australian average of 320-350/ha. The trees are continually pruned to maintain a hedge that can be harvested using an over-the-row grape harvester, minimising labour costs and avoiding the need to have the almonds on the floor of the orchard. The Institut de Recerca i Tecnologia Agroalimentàries (IRTA) research work with almonds is trying to characterise the effect of different planting and management systems on a range of Spanish-bred varieties. They are investigating central leader systems using purpose-bred varieties, something our industry has looked at a number of times without success. Key contacts were made with those involved in this work and will be maintained into the future.

The transformation of the Spanish almond industry from low input, dryland, 200 kg/ha, to high input, high density 1700kg/ha almonds and the response of associated support industries continues apace. The conference showed the global imperative for science to identify best practice to maximise returns on water used, especially in light of the drought in California.

The Secretary approved this travel on 1 May 2015.

Attachments

No.	Attachment name
1	Budget and actual expenditure

Attachment 1 – Budget and actual expenditure

Final expenditure against original budget.

	Initial estimate of Costs paid by industry/ external source (from approved application)	**Initial estimate of Costs** paid by State Government (from approved application)	**Actual travel Costs** paid by industry/ external source	**Actual travel Costs** paid by State Government	Variance Reason
Air fares	2100		2610		Airfare had increased at time of booking relative to initial quote.
Surface travel	1000		216		Vehicle hire not required; all surface travel *via* combination of public transport and conveyance by hosts.
Accommodation	2100		1120		Lower cost options not advertised on the internet at the time budget was formulated were taken advantage of.
Personal expenses	1260		420		Lower cost options were taken where available.
Conference fees	1000		955		
Departure taxes					
Other expenses		150 (telephone roaming)		170	
Total :	$7460	$150	$5321	$170	
TOTAL COST OF TRIP:		**Estimate: $7610**	**Actual: $5491**	**$2119 under budget**	Surface travel, Accommodation and personal expenses were less than budgeted

	Name	Position	Phone no.
Prepared	Dr Dave Monks	Research Scientist, Horticulture	(03) 5051 4393
Reviewed	Dr Ian Goodwin	Research Manager, Horticulture Production Sciences	(03) 5833 5240

10.

Department of Economic Development, Jobs, Transport & Resources

Internal briefing for Lead Deputy Secretary Luke Wilson

Subject	**Overseas post travel trip report from Michael Treeby, who travelled to the USA from December 4, 2016, to December 12, 2016.**
Decision date	**N/A.**

Core message

Michael Treeby has prepared a post-travel trip report for his travel to Sacramento (California, USA). Treeby attended the Almond Board of California's annual technical conference in Sacramento to gain an in-depth understanding of the scope of the Californian almond research program, and identify potential areas of collaboration that may involve links with University of California researchers, other R&D providers and with the Almond Board of California.

Recommendation/s

That you:

Sign the attached letter.

[ ] Approved
[ ] Not Approved
[ ] Noted
[ ] Please Discuss

..... **Justin Hanney** Head, Employment, Investment and Trade Date:	**Comments:**

	Name	Signature	Date	Position	Phone no.
Approved	German Spangenberg			DEPUTY SECRETARY Agriculture Victoria Research	03 9032 7165
Endorsed	Emily Phillips			A/CHIEF EXECUTIVE, Employment Investment & Trade	03 8392 7185

Economic Development Employment and Innovation		
REQUESTED □	DEPARTMENT INITIATED □	DATE DUE IN MO: N/A if not relevant
DEDJTR REF: <RegNo1>	FILE/TRIM REF: DOC/16/XXXXXX	MINISTERIAL REF:

VICTORIA

Key information

This post travel trip report relates to approved international travel as documented and filed under BSEC17000XXX. A post travel trip report (for your signature) and travel diary have been prepared **(Attachments 1 & 2)**.

1. **Travel details and key observations or highlights**

   a) Attendance at the conference allowed a deeper appreciation of the extent of the collective Californian almond research program over the last decade. The presentations provided more insight into the historical basis and rationale of the production practices adopted by Australian almond producers.

   b) The trip included a meeting with University of California – Davis (UCD) researchers, Almond Board of California (ABC) staff and other visiting Australian researchers. Key potential UCD collaborators and commonalities in the issues being addressed were identified. Significant insight was gained into their respective research programs.

2. **Outcomes and benefits**

   The conference and researchers' meeting at Sacramento identified some commonality amongst the constraints the Californian and Australian almond industries contend with. This is a good basis to develop collaborative mutually beneficial linkages.

3. The travel complements the temperate nut and spurs projects being conducted by the Mildura group in Plant Production Sciences in Agriculture Victoria Research (AVR) and is part of the Minister's commitment to support the Victorian almond industry. Victoria is the largest almond producing state.

4. **Extent to which objectives were achieved**

   a) The objectives of the overseas travel were achieved.

   b) Key potential collaborators were identified and contacts made; these will be followed up by detailed discussion at subsequent international events in the future.

5. **Next steps**

   The almond research group at Mildura has recruited an additional pant physiologist and furthered developed its research program; the next contact will involve moving from "potential collaboration" status to concrete proposals for collaboration.

6. AVR is aware that a post-travel trip report for this travel was originally prepared, submitted and approved under ARD's system, but has also become aware that that approval process may have been inappropriate. AVR seeks to redress this by providing this report which complies with current DEDJTR requirements. All future Plant Production Sciences / AVR international travellers will conform with DEDJTR's international travel policy by providing a post-travel reports within a month of return.

Attachments

No.	Attachment name
1.	Post travel Trip Report [Michael Treeby]
2	Travel diary [Michael Treeby]

	Name	Position	Phone no.
Prepared	Michael Treeby	Group Leader	03 5051 4565
Reviewed	Ian Goodwin	Acting Research Manager	03 5833 5240

Appendix 1 Travel diary

Date	Country / City	Time		Appointment purpose (meeting, meal, invitation, event *etc.*)	Appointment participants
		Start	End		
4 Dec	Australia/Mildura → Melbourne	07:00	08:10	Travel	Michael Treeby
4 Dec	Australia/Melbourne → USA/Los Angeles	11:15	06:35	Travel, arrive LAX/USA	Michael Treeby
4 Dec	USA/Los Angeles → USA/Sacramento	11:00	12:23	Travel, arrive Sacramento, hotel check in	Michael Treeby
5 Dec	USA/Sacramento	08:30	17:30	Researchers' forum	Michael Treeby, & UCD, Plant & Food Research & Uni SA researchers, ABC staff
6 Dec	USA/Sacramento	09:30	12:00	Conference registration, presentations & welcoming event	Conference attendees & presenters
7 Dec	USA/Sacramento	08:30	17:30	Conference presentations	Conference attendees & presenters
8 Dec	USA/Sacramento	08:30	15:00	Conference presentations	Conference attendees & presenters
9 Dec	USA/Sacramento			DEDJTR project work in hotel room	Michael Treeby
10 Dec	USA/Los Angeles → USA/Sacramento	18:47	20:21	Hotel check out, travel	Michael Treeby
10-12 Dec	USA/Los Angeles → Australia/Melbourne	22:05	09:00	Travel, arrive in Melbourne	Michael Treeby
12 Dec	Australia/Melbourne → Australia/Mildura	15:55	17:05	Travel, arrive Mildura	Michael Treeby

11.

Department of Economic Development, Jobs, Transport & Resources

Internal briefing for Head, Employment, Investment and Trade

Subject	Overseas post travel report; Dr Michael Treeby, USA; 2 – 9 December 2017
Decision date	NA

Core message

Dr Michael Treeby has prepared a post travel trip report for his international travel to California (2 – 7 December 2017) where he attended the Almond Board of California's "2017 Almond Conference" and a) learned of the latest Californian almond research, b) represented DEDJTR at ancillary meetings with researchers from the University of California and c) developed collaborative linkages with other almond researchers.

Recommendations

That you:

a) Approve the attached post travel trip report

[ ] Approved
[ ] Not Approved
[ ] Noted
[ ] Please Discuss

..... Justin Hanney Head, Employment, Investment and Trade Date:	**Comments:**

	Name	Signature	Date	Position	Phone no.
Approved	German Spangenberg			Deputy Secretary, Agriculture Victoria Research	03 9032 7165
Endorsed	Emily Phillips			A/Chief Executive, Agriculture Victoria	03 8392 7185

Agriculture, Energy & Resources		
REQUESTED ☑	DEPARTMENT INITIATED □	DATE DUE IN MO: N/A
DEDJTR REF: N/A	FILE/TRIM REF: N/A	MINISTERIAL REF: N/A

State Government Victoria

Key information

This post travel trip report relates to approved international travel as documented and filed under MiBS BSEC17000713.

1. Trip details and key observations

Dr Michael Treeby travelled to the United States of America from 2 – 9 December. He attended the Almond Board of California's "2017 Almond Conference" in Sacramento, California. He held discussions with the UCD staff attending the conference to identify opportunities for collaborative research and to calibrate Irymple's almond research program against the research being conducted for the most part by the University of California at Davis (UCD) and co-funded by the Almond Board of California. He assessed the state of knowledge of environmental and management impacts on almond kernel composition, and learnt about trends in the processed plant-based food industries that may impact the Australian almond industry. He appraised the latest developments in almond rootstock/scion research and of the growing interest in higher density plantings. These areas closely align with Mid Area development plans which are geared toward the development of intensive production systems over the short to long term.

2. Outcomes of key meetings

a) Meetings with Professor Pat Brown and Dr Astrid Volder (both Department of Plant Sciences, UCD), – 6 & 7 December 2017.

Discussion with UCD researchers regarding potential collaborative work on refining soil water/solute movement in relation to almond root architecture and activity to improve resource use efficiency. Each industry has different drivers to improve resource use efficiency, but the research outcomes needed are the same. Bringing the complementary skill sets of the parties to the discussion to bear on the issue makes good sense.

Collaboration involving Californian and Australian researchers is often mentioned by industry as a means of fast tracking progress on issues of mutual concern. To date, there has been no proposal put to the either industry for consideration.

A proposal development road map was agreed upon, with Dr Treeby taking a lead role.

b) Discussions with Dr Gabriele Ludwig (Director of Sustainability & Environmental Affairs for the Almond Board of California) – 6 December 2017

Provided Dr Ludwig with a description of the Mid Area development and the relationship between that development and the ABA/SARDI Loxton orchard development. Also discussed with Dr Ludwig was the state of knowledge around kernel composition, and the unknown impact of environment and management on kernel composition. This is an area of research that DEDJTR would like to develop, and for which the trials being established on Mid Area will provide an excellent platform. An interest in kernel composition needs to be viewed in the context of a trend toward increasing consumption of plant-based foods, and in particular plant protein-based foods, in Western European and North American diets.

c) Discussion with Professor Pat Brown (UCD) – 6 & 7 December 2017

Improving the autonomy of irrigation systems and reducing within orchard/management units variability was discussed with Professor Brown. A previous UCD project provided the technical specifications for an irrigation system capable of irrigating single trees, but this idea had not progressed due, in part, to not having an inexpensive means to assess either the water status of each tree or the amount of readily available water in the root-zone of each tree, and an overarching framework to integrate that information into a volume of water each tree needs. These are clearly technical issues that need to be resolved to reduce within orchard/management unit variability, but also to improve the autonomy of irrigation systems.

d) Discussion with Associate Professor Ken Shackel (Department of Pomology, UCD) – 6 December 2017

Associate Professor Shackel's group is involved in research on the impact of tree water status on tree productivity; focussing not just on the growing season, but also on the dormant season. The

group has demonstrated that floral bud development can be affected negatively by low stem (branch) water potential during winter. This part of the phenological cycle is generally only viewed through a chilling requirement lens, but this observation suggests another factor in the diminution of potential yield is winter soil water management.

e) Discussion with Dr Bruce Lampinen (Department of Pomology, UCD) – 6 December 2017
Dr Lampinen leads a large program on almond and walnut orchard management, particularly the relationship between light extinction through a canopy and orchard productivity. The discussion centred on that nature of that relationship in the context of current orchard design and management which results in a 3-dimensional fruiting space. As trees are planted closer together within rows and rows are closer, tree shape will be dictated more by the need for farm machinery access; the fruiting space will become 2-dimensional. The upshot of this being that orchard design needs to be able to allow for more light to reach further down the narrow tree canopy to ensure productivity is evenly spread.

3. Extent to which objectives were achieved:

The objectives of the trip were achieved.

a) The discussions with the potential collaborators allowed identification of what each potential collaborator could contribute to the overall goal of improving the efficiency of on-farm resource use and reduce the off-site effects of their use. The articulation of a pathway to completion and the responsibilities of each potential collaborator to a document that each peak industry body could consider in the context of their stated desire to see the establishment of collaborative linkages between Californian and Australian researchers.

b) Much use was made of the formal poster session and the time between formal presentations to meet other UCD researchers and discuss areas of mutual interest, such that most was made of the time available. The outcome of the discussions with the other UCD researchers was assurance that the experiments being established on the Mid Area would contribute to improved management of almond orchards, and to the development of intensive production systems for the Australian almond industry, but that there were other issues that had not been considered but did need to be.

c) The discussions with the Almond Board of California provided assurance that development of a research program to investigate the linkage between orchard management and kernel composition would result in new knowledge that would be of use to the almond industry in the future as it moves to meet market niches. The discussions with the Almond Board of California were also helpful in removing some confusion on the Board's part regarding how the development of the two experimental orchards were linked.

4. Next steps:

a) Complete a preliminary draft of a the rationale for a collaborative project and circulate to potential collaborators for input reflecting their respective research interests, with a view to submitting the document to Almond Board of California and the Almond Board of Australia as a catalyst to developing more formal agreements with research groups, as appropriate.

b) Inform work colleagues of the discussions with Almond Board of California, re: kernel composition.

Attachments

No.	Attachment name
1.	Post Travel Trip Report; Michael; California; December, 2017
2.	Overseas Travel Diary; Michael Treeby; California; December, 2017

	Name	Position	Phone no.
Prepared	Ian Goodwin	Research Manager – Horticulture Production Sciences	0409 248 040
Reviewed	Traci Griffin	Research Director – Plant Production Sciences	0427 313 151

12.

2014 Crop Review

Ben Brown - Almond Board of Australia
Dave Monks and Karl Sommer - Department of Environment and Primary Industries, Victoria

The 2014 crop is currently estimated at 65000 tonnes, 17% lower than the initial opening season estimate (based on its plantings database and yield matrix) of 78,251 tonnes. This is the third of the last four crops that have been below expectations with total farm gate losses estimated to be in excess of $270 million (Table 1).

What's particularly disappointing with the 2014 crop was not just that it was down on estimates, but it was down 12% on the 2013 crop of 73361 tonnes with approximately 10488 ha still to reach full maturity (trees ≥ 8 years of age). There should have been an increase on the 2013 crop based on orchard maturity alone.

The degree of crop reduction was widespread but variable, some growers experiencing only a small reduction, whilst others experienced a severe reduction in crop.

An industry meeting was facilitated by the ABA in July to discuss the reasons behind the lower than expected 2014 crop. The meeting was well attended by 23 participants and the following key points were discussed and raised for consideration.

Almond is a perennial horticultural tree crop in which yield is developed over two seasons and the reasons for the low 2014 crop are likely to exist not just in the 2013/14 season but also the 2012/13 season. The development of yield involves three important stages (Kester et al, 1996) and is discussed in the context of the two seasons.

1. Establishing bearing potential

The entire first season (in this case the 2012/13 season) establishes the bearing potential of the second season (2013/14). This stage consists of active spur and shoot growth, vegetative bud development and floral bud development.

Establishing the bearing potential occurs by firstly having an adequately sized canopy to provide an upper bound; secondly by maintaining adequate return bloom from existing spurs; and thirdly by producing new floral positions from new spur and vegetative growth.

The upper bound of bearing potential is best measured using light interception where research (Lampinen, 2013) indicates the maximum potential production from traditional almond orchards is approximately 56kg/ha per 1% light interception, or 5600kg/ha. In reality, 100% light interception is not achievable nor recommended. Research indicates light interception should not exceed 80% (equivalent to a maximum potential production of 4500kg/ha) to optimise drying of harvested fruit and reduce food safety risks.

It appears not enough Australian orchards are near the recommended 80% light interception, either due to: immature canopies; trees missing following the wet 2010/11 season; excessive pruning, particularly of immature canopies; or the canopy size is too variable.

On a whole of industry basis, the grower meeting indicated trees that died following the wet 2010/11 season may not have been communicated to the ABA, and consequently not removed from the ABA industry yield estimates. The ABA will contact growers to confirm the acreage provided in the annual survey.

The likelihood of return bloom is important and positively associated with the preceding season's leaf area per hectare (Lampinen et al,

Table 1: Australian almond harvest estimates versus actuals, 2011-2014.

Harvest	Estimated (t)	Actual (t)*	Difference (t)	Financial Loss
2011	55,605	37,626	-17,979	-$80,905,500
2012	65,336	49,585	-15,751	-$78,755,000
2013	73,008	73,361	353	$2,365,100
2014	78,251	65,000	-13,251	-$115,283,700
		Total	**-46,628**	**-$272,579,100**

2011). The large 2013 crop may have been a result of a high number of fruit per spur and excessive carbon demand, thereby hindering the development of floral buds and return bloom for the 2013/14 season. Management options to alleviate this excessive demand is not well known but at the risk of generalising, it's likely to be associated with adequate light interception and spur nutritional status.

The excessive carbon demand may have also restricted the development of new vegetative spurs and floral buds, and this development may have been better served by demand driven water and fertiliser programs rather than calendar driven programs.

Concerns were also raised with several growers practising deficit irrigation leading into harvest, as this period coincides with floral initiation and next season's (2013/14) bearing potential. This was thought to be a risky practice as most orchards are planted on variable, low water holding capacity soils (sand) with drip irrigation. In many instances, particularly with a large 2013 crop, trees or even orchards may already have been stressed and this practice may have created further unwanted stresses, negatively affecting floral initiation. Furthermore, drying of the rootzone may have also made it difficult to re-establish soil water content in time for post-harvest fertiliser, leading to high electrical conductivity in the rootzone and unsuccessful plant nutrient uptake, again negatively affecting floral initiation. Deficit irrigation should be practised with caution and with the highest control. If deficit irrigation is to be practised, soil water monitoring, pressure bombs and confidence around accurate water applications are critical.

The opportunity to manage a canopy for maximum year on year production is the focus of five new almond R&D projects.

2. Establishing reproductive potential

The beginning of the second season (2013/14) establishes the quantity of nuts. This stage is driven by flowering, pollination and fertilisation.

Some of the issues encountered in the 2013/14 season that may have reduced yield were: hull boron concentrations often lower than the critical thresholds (Nyomora et al, 1997); variable beehive quality; and sub-optimum hive placement strategies.

Consequently, growers should focus their attention on: soil applications of boron supplemented with foliar sprays ground truthed by hull sampling; robust beehive auditing to ensure standards are being met; and beehives placed more evenly through the orchard to ensure optimum fruit set (Cunningham, 2014).

Adverse weather conditions and inadequate management may also have compromised maximum fruit (pericarp) growth potential and limited kernel size. Again, demand driven water and fertiliser programs are essential.

3. Establishing weight potential

Kernel weight is established during the second season (2013/14); beginning with kernel development, followed by dry weight accumulation. This stage is the final challenge in producing an adequate crop.

The demand for resources through this stage is particularly high and is the major sink for water and nutrition. Crucially, this stage of highest demand may have been negatively affected by high temperatures during December, January and February, leading to stomatal closure, and a decline in transpiration and carbohydrate production.

Some growers reported it was difficult to meet plant water use demand due to inadequate irrigation capacity or possibly inefficient and variable system performance. Nutrient applications during the early part of this stage may have also experienced the same fate.

Practising deficit irrigation at hull split to reduce hull rot was discussed and was again thought to be a risky practice as was the case with pre-harvest stress. As discussed earlier, deficit irrigation should be practised with caution and with the highest control.

In addition to the factors discussed above, several other key issues were discussed by the group:

- Nemaguard rootstock did not produce an adequate return crop following a heavy crop and clonal hybrid rootstocks performed better.
- Non-Infectious Bud Failure (NIBF) of Carmel was raised as a serious impact with reports the 2013/14 symptoms were the most severe experienced.
- Hull rot was also discussed with importance, with many growers indicating Nonpareil is continually being affected by spur decline in the lower part of the canopy where symptoms are greater.
- The combination of hull rot and poor shaking efficacy was of particular concern due to the fruit being grown but not harvested. Those who re-shook, particularly Nonpareil, reported figures of approximately 300kg/ha of kernel.
- Price yield was variable, not just between orchards but also within orchards.
- The inability to manage rain at harvest made it difficult to harvest all the crop and at a higher enough quality.

In summary, there were a myriad of topics discussed and it was difficult to isolate one or two issues that were responsible for the 2014 crop. In order for growers to determine the reasons for their low crop, they will need to examine both the 2012/13 and 2013/14 seasons in the context of the three critical stages of yield production. Nevertheless, it is reasonable to suggest many orchards have a reduced upper yield bound due to a lack of canopy size and light interception; water and nutrient programmes need to more demand based; and more of what's grown needs to be harvested.

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13.

Deficit irrigation of almond trees did not decrease yield

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Abstract

The use of strategies that ensure the most effective and efficient use of irrigation water is a significant contributor to the economic success of the Australian almond industry. An experiment to test such strategies was established in north-western Victoria, Australia. Five levels of irrigation were tested over three seasons: a fully irrigated control (100%), three levels of deficit irrigation (55, 70 and 85% of the control) applied as regulated deficits (RDI) for specific periods during the growing season, or sustained deficits (SDI) throughout the growing season, and a high irrigation level (120%). The 100% control was defined as the level of irrigation that met the trees' water requirements and was not different from 120% in any variable measured. The results showed that irrigating at 85% of full irrigation had no impact on individual kernel weight and yield, but irrigating at 70% or less decreased kernel yield regardless of strategy, except for SDI 70% in Season 3. In Season 3, trees with SDI 70% deficits produced a higher kernel yield than the trees receiving the same deficit as RDI. Water deficits tended to accelerate hull split in line with the level of deficit. Midday stem water potential was significantly more negative two to six weeks before harvest in the deficit treatments.

Keywords: regulated, sustained

INTRODUCTION

Australia's 29,500 ha of commercial almond orchards are only possible with access to irrigation water from, primarily, surface waters in the Murray-Darling Basin. Competition for those resources from other users, including towns and environmental needs, puts pressure on almond producers' traditional practice of irrigating to satisfy their trees' full water use. During the 2000-2010 drought, for example, the cost of water quadrupled (Kaczan et al., 2011). Almond is considered a drought tolerant species (Fereres et al., 1981) because of their ability to regulate stomatal opening, osmotic potential, CO_2 assimilation and recover photosynthetic capacity when re-irrigated (Castel and Fereres, 1982; Girona et al., 1997; Romero et al., 2004; Shackel, 1996), but studies on the periods when water deficits least impact yield are limited. Many authors, including Goldhamer and Viveros (2000), Romero et al. (2004) and Girona et al. (2005), showed the application of a regulated deficit during the kernel filling phase impacted kernel yield the least, while Goldhamer and Viveros (2000) showed little difference between SDI and RDI strategies. The objective of this work was to compare the effect of sustained and regulated deficits on kernel dry matter and tree performance in an Australian environment.

MATERIALS AND METHODS

This experiment was conducted on a commercial almond (*Prunus dulcis* (Mill.) [Webb]) orchard planted in 2004 with 'Nonpareil' and 'Carmel' trees (7.25 m between rows × 4.65 m within rows) running north-south located at Lake Powell (-34.7111°S; 142.948°W), Victoria, Australia. The 'Nonpareil' trees were used in this experiment.

The 5.2 ha experimental site was divided into six blocks, each of which contained eight plots. Each plot was 8 trees long and 4 rows wide and consisted of alternating rows of

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pollinator ('Carmel') and non-pollinator ('Nonpareil') trees. The four centre trees (sample trees) of the second 'Nonpareil' row in each plot (counting from west to east) were used for regular monitoring of tree physiological- and production-related parameters. Double-line drip irrigation was used in this experiment. The 2.1 L h^{-1} emitters were spaced at 0.7 m, delivering 0.8 mm h^{-1}.

Three levels of deficit irrigation were applied in two patterns, either as sustained deficit irrigation (SDI), where the deficit was evenly applied throughout the irrigation season or as regulated deficit irrigation (RDI), where the deficits were biased toward specific periods in the pre-harvest period (Table 1). A "wet" treatment receiving 120% of the fully irrigated control was also applied. Thus, the experiment had a total of eight irrigation treatments.

Table 1. Seasonal irrigation, effective rain, irrigation plus effective rain and timing of deficit between August 1 and June 30 each season at Lake Powell, Australia (mm).

	Irrigation strategy and % ET_c applied	Irrigation	ET_c	Deficit timing
Season 1	Wet 120	1131	1362	-
Rain: 481	Control 100	937	1135	-
Effective rain: 184	SDI 85	806	965	All season
ET_o: 1435	SDI 70	694	794	All season
	SDI 55	534	624	All season
	RDI 85	836	1014	Jan 10-Feb 17
	RDI 70	664	831	Nov 12-Feb 17
	RDI 55	552	700	Sep 10-Feb 17
Season 2	Wet 120	933	1095	-
Rain: 618	Control 100	781	913	-
Effective rain: 214	SDI 85	677	776	All season
ET_o: 1089	SDI 70	578	639	All season
	SDI 55	476	502	All season
	RDI 85	668	824	Jan 10-Feb 17
	RDI 70	508	667	Nov 12-Feb 17
	RDI 55	488	561	Sep 10-Feb 17
Season 3	Wet 120	1296	1351	-
Rain: 236	Control 100	1082	1129	-
Effective rain: 40	SDI 85	916	960	All season
ET_o: 1324	SDI 70	759	790	All season
	SDI 55	686	620	All season
	RDI 85	959	1006	Jan 10-Feb 17
	RDI 70	763	811	Nov 12-Feb 17
	RDI 55	663	694	Sep 10-Feb 17

All RDI trees were irrigated to 100% of needs in the postharvest to leaf fall period. Deficit levels were 85, 70 and 55% of a fully irrigated control treatment; which amounted to approximately 12 ML ha^{-1} per season of irrigation and effective rainfall. Effective rainfall was defined as 50% of the precipitation equal to or above 12 mm within a 24 h period. Full irrigation was defined as the level of irrigation that meets crop water requirement (ET_c). The latter was estimated according to a standard protocol by multiplying empirically-derived crop factors (Cf) (Sommer, 2014) with readings from a standard Class A evaporation pan (E_{pan}) located near the experimental site.

$$ET_c = Cf \times E_{pan} \quad (1)$$

The current day's irrigation for each treatment was estimated from long term

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evaporation records or short term forecasts, after adjusting for the previous day's irrigation water balance (previous day's mm ET_c – previous day's mm irrigation application). The required irrigation was applied as hourly pulses; water being applied for one hour and turned off for the subsequent hour until the full requirement was met. Each irrigation treatment was equipped with a flow meter and the volumes applied were recorded daily.

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

Nutrients were supplied as dissolved salts in the irrigation water according to current industry practices; nitrogen (N), phosphorus (P) and potassium (K) were applied at kg ha^{-1} rates of approximately 320, 40 and 400, respectively, to all treatments. The dissolved nutrients were injected into the final irrigation pulse of the day.

Kernel development was monitored throughout each season. Four fruit $tree^{-1}$ were collected from the six middle trees of each plot every week in Season 1 and every two weeks in Seasons 2 and 3. Kernels were separated from the hull and shell, and oven dried at 65°C. Irrigation was ceased in all treatments for 48 h prior to harvest, to minimise shaker damage to the trunk. The four middle trees per plot were shaken commercially on February 17, 2010, March 2, 2011 and February 20, 2012. Nuts were left to dry on the ground until hull moisture reached 14%. Nuts were then swept into windrows and picked up into bulk bags. Bags were weighed and 3 kg sub-samples taken and dried to a constant weight. Kernel weight and percentage crackout were determined.

Midday stem water potential (Ψ_w) (Ritchie and Hinckley, 1975) was measured using a pressure bomb (Plant Water Status Console 3005 series, Soil Moisture Equipment Corp., Santa Barbara, CA). One or two hours before testing, foil laminate bags (PMS Instrument Company, Albury, OR) were placed over a leaf from the inner canopy of the two centre trees of each plot and measurements were taken as per Fulton et al. (2014). On each measurement date two leaves from each plot of the three western most blocks were tested. The main variables were analysed as a two-way randomised complete block design. A least significant difference test was used to compare treatment means ($P \leq 0.05$). Statistical analyses were conducted using Genstat 14.1 (VSN International Limited, Oxford, UK).

RESULTS

The volume of irrigation water applied varied by 300 mm between seasons (Table 1), driven by above average rainfall in Season 2 (2010/11) and below average rainfall in Season 3 (2011/12). In Season 2, the evaporative demand was reduced as a result of persistently humid and overcast weather with frequent, often heavy rainfall.

Based on the mean Ψ_w for the four periods delineated by the onset of an RDI treatment and the postharvest period, Ψ_w for the control (100%) and the wet (120%) treatments did not differ (Figure 1). For both RDI and SDI treatments in Seasons 1 and 3, Ψ_w became more negative as the season progressed, with the exception of the 55% treatment, where Ψ_w became less negative in the third period.

In Season 1, the minimum Ψ_w approached -3.0 and -3.2 MPa in the RDI 55% and SDI 55% treatments, respectively (data not shown). In Season 2, Ψ_w did not drop below -1.2 MPa and there was no difference in the mean Ψ_w for any period. In Season 3, Ψ_w was more consistent with observations made in the first season; approaching a minimum -2.5 and -2.0 MPa in the RDI 55% and SDI 55% treatments, respectively.

Yield reductions relative to fully irrigated control trees in most seasons were related to the severity of the applied irrigation deficits (Figure 2). Reducing irrigation to 70% or less of ET_c decreased kernel yield in Season 1, but little difference was observed between the 70 and 55% deficits. Biasing the deficit toward preharvest (RDI 70%), imposed from 12 November, resulted in lower yield relative to a sustained deficit (SDI 70%), imposed throughout the season. Reducing irrigation to 85%, regardless of the deficit strategy, did not reduce yield relative to control trees. Applying additional irrigation (120% ET_c) did not result in a yield gain relative to the control trees.

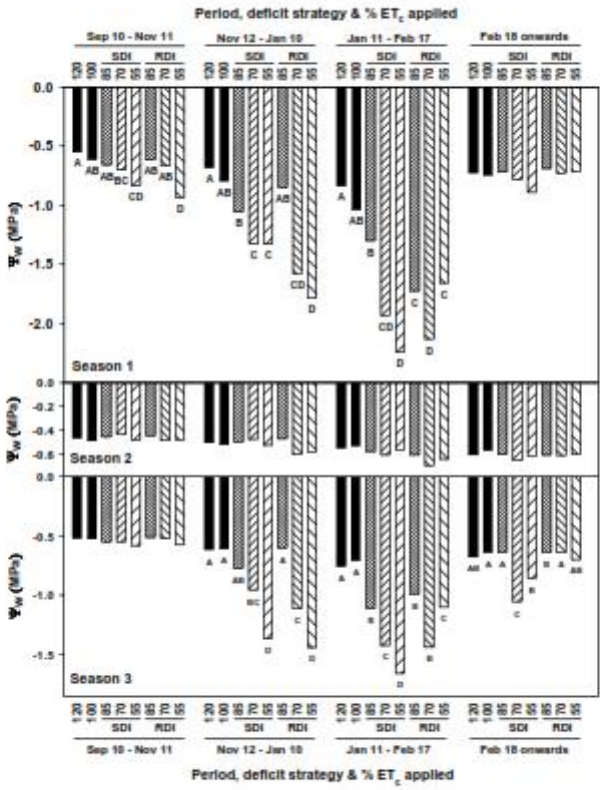

Figure 1. Mean midday stem water potential (Ψ_w) at Lake Powell, Australia. Values presented are means of multiple sampling measurements during the time periods indicated. Different letters below columns within periods indicate significant differences between means at P≤0.05.

In Season 2, average yield was 500 kg ha^{-1} less than in Seasons 1 and 3. Rainfall confounded the deficit treatments, leading to those trees under deficit irrigation out yielding those were not. No yield differences attributable to the irrigation strategy or rate treatments were discernible in Season 2.

In Season 3, treatment effects were similar to those seen in Season 1. Deficit irrigation with RDI 55 or 70% reduced kernel yield most strongly followed by SDI 55%. Neither SDI nor RDI at 85%, nor SDI 70%, reduced kernel yields relative to control trees.

Average kernel dry matters at physiological maturity were lower in the 55% irrigation treatments in Season 1 and Season 3 regardless of application strategy (Figure 3). No treatment response was apparent throughout Season 2.

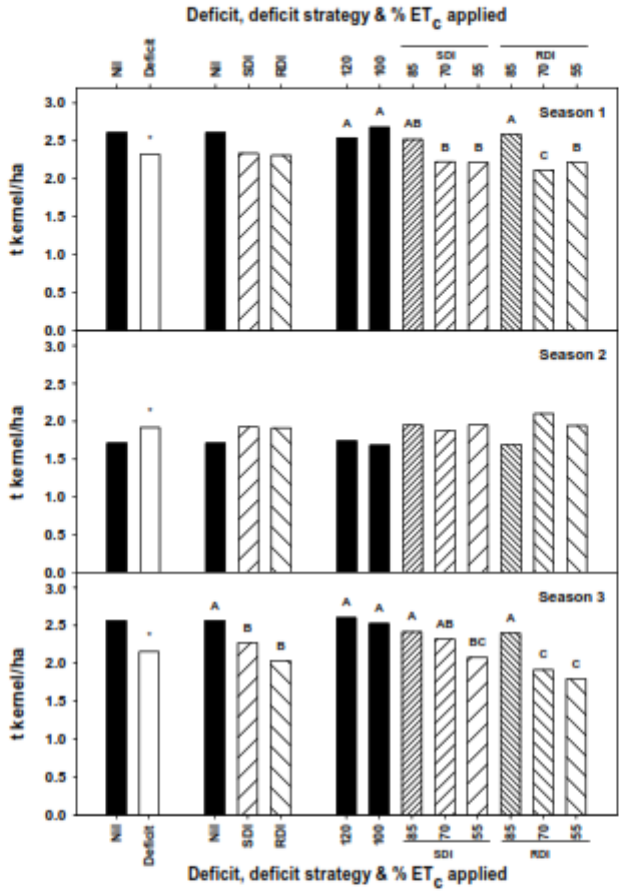

Figure 2. Kernel yield at Lake Powell, Australia. An asterisk above the main effect column indicates a significant water deficit effect, and different letters above columns in the deficit strategy and strategy volume groups indicate significant differences between means at P≤0.05.

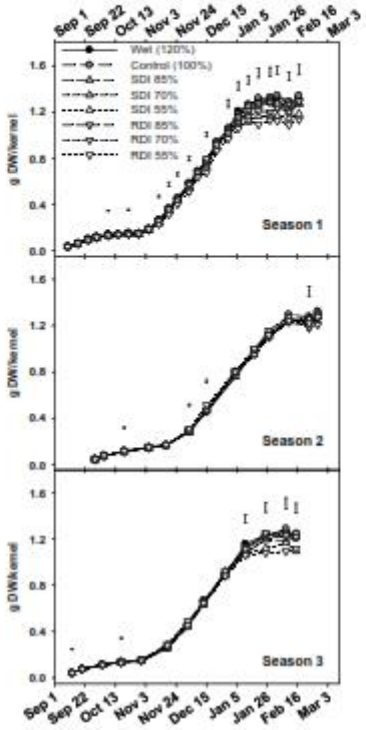

Figure 3. Kernel dry matter accumulation at Lake Powell, Australia. Values presented are means. Vertical bars indicate LSD for each sampling point at P=0.05.

In Season 1 and Season 3, deficit irrigation accelerated hull split and the degree of acceleration was correlated with the level of the imposed deficits. Full hull split in control and "wet" treatments in most seasons was approximately 2-3 weeks later, relative to the severest deficient treatments; namely, SDI and RDI at 55% of full ET_c. The progress of hull split in Season 2 showed no discernible treatment differences.

DISCUSSION

Minimum and maximum total applied water (irrigation + effective rainfall) during the experimental period ranged from 62% of ET_c (703 mm) to 118% ET_c (1336 mm), both during Season 3 (Table 1). Seasons 1 and 3 most accurately reflected the impact of strategic deficit irrigation on an average season in the almond growing region of south-east Australia, where annual rainfall was 481 and 236 mm for Season 1 and Season 3, respectively. The mean annual (1923-2008) rainfall for the nearest meteorological station (Bannerton, ~15 km west) is 314 mm.

Ψ_w was a sensitive indicator of the stress imposed by the irrigation deficits (Figure 1). Under SDI, as indicated by Ψ_w, the trial trees were generally less severely stressed than under the comparable RDI treatment. It is possible that this was observed because RDI trees went from being fully watered to a deficient state in a relatively short time period, compared with SDI trees, which possibly were able to gradually adjust to the imposed deficits. This is in contrast to the work of Goldhamer and Viveros (2000), who, using comparable irrigation

strategies, saw similar stress levels under SDI and RDI.

Their most water-stressed trees reached pre-dawn leaf water potentials (Ψ_{pd}) of -3.5 MPa. At similar water supply (% of ET_c), Ψ_{pd} is normally less negative than midday Ψ_w (Romero et al., 2004) (as used in the trial described herein) suggesting a greater level of stress in the Californian work than measured in the trees at Lake Powell. These extreme stress levels may explain why the trees under different irrigation strategies in the Californian experiments (Goldhamer and Viveros, 2000) responded more similarly than the trees under different irrigation strategies in our experiment. While 85% of ET_c applied using either strategy only resulted in a significant difference in mean Ψ_w during the third period in each of Seasons 1 and 3 (RDI 85% was imposed at the start of the third period), the measured values across most of the season (SDI) were consistently more negative than the controls. When comparing Ψ_w minima on specific days, means calculated over many days during periods, SDI and RDI 85% trees were greater than 0.9 MPa more negative than the controls in Season 1 (December 24 and January 30 for SDI and RDI, respectively) and more than 0.5 MPa more negative in Season 3 (January 2 and 30, respectively).

The results suggest that irrigation equal to or above 85% of ET_c applied as either SDI or RDI had no impact on production while irrigation equal to or below 70% is likely to depress kernel yield. These observations are very similar to the published literature. However, Goldhamer and Viveros (2000) concluded that a preharvest RDI strategy at 85% of full water requirements had a more negative impact on kernel yield than that reported here when a comparable deficit was applied throughout the season (i.e., SDI).

Ψ_w was more responsive to deficits imposed from November 12 (RDI 70%) and from January 11 (RDI 85%); their mean Ψ_w values for the period immediately following the imposition of the treatment was more than 200% as negative as the controls during the same periods. The extent of these responses are in contrast to Ψ_w of trees under RDI 55%, which, during the first period it was imposed (September 10 - November11) was only 150% of the non-deficit trees.

In Seasons 1 and 3, trees in the RDI 55% treatments had completely defoliated at least four weeks earlier than other treatments ($P \leq 0.05$) (data for canopy light interception not shown). It is reasonable to suggest that the failure of Ψ_w in these trees to continue to become more negative during the third period (January 11 - February 17) in Seasons 1 and 3 was because of the reduced transpiration demand from leaves.

Generally, a reduction in kernel dry weight accumulation correlated with the imposed stress levels (Figure 3). RDI tended to reduce kernel growth more than SDI, particularly for irrigation volumes below 70%. Many of the observed patterns were similar to those reported by Goldhamer and Viveros (2000), who described a similar, though more severe, impact on kernel growth of an equivalent preharvest RDI strategy compared to an SDI strategy and described a similar impact of the deficits on fruit and kernel dry matter accumulation. They also reported that RDI had a greater effect on kernel dry matter accumulation compared to hull and shell dry matter accumulation because hull and shell growth, unlike kernel growth, were mostly complete before the RDI irrigation deficits took full effect.

The onset and progress of hull split appears to be strongly influenced by tree water status such that its onset will be earlier and progress will be more rapid in line with a rising deficit. The work of Goldhamer and Viveros (2000) also suggests that there is a critical threshold beyond which the level of stress may inhibit rather than promote hull split. Using preharvest RDI and SDI deficit regimes of similar magnitude as presented here, they reported a comparable advance in hull split. An exception was their most water deficient preharvest RDI, which led to a reduction in hull split rather than an increase, and was attributed to severe drought stress. We did not see such a profound effect under RDI or SDI at 55% of full ET_c, probably because the trees used never reached such severe levels of water stress.

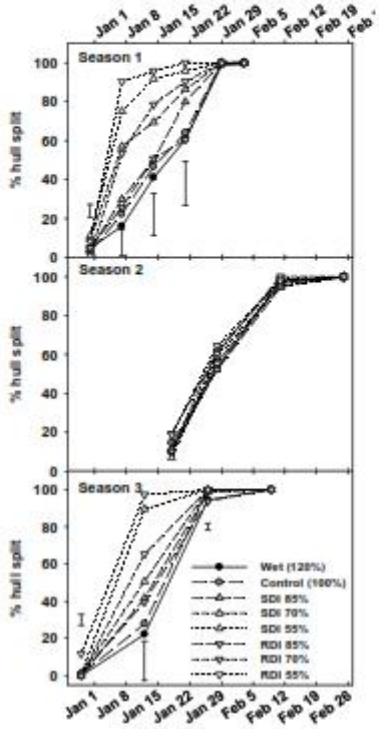

Figure 4. Percent hull split throughout fruit ripening at Lake Powell, Australia. Values presented are means. Vertical bars indicate LSD for each sampling point at P=0.05.

CONCLUSION

The study showed that irrigating at 85% of "full irrigation", which represents a moderate deficit, potentially could help almond producers maintain production during water shortages. The study also suggests that "full irrigation", as it currently stands, may be overly generous. Over all three seasons, applying 85% of ET_c resulted in 1.23 ML ha^{-1} saving without effecting yield compared with control.

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14.

Leaf mass per unit leaf area decreases as light is eliminated within almond trees (*Prunus dulcis*)

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Abstract

Almond spur leaf attributes and PAR attenuation in trees were measured. Spurs were collected from three horizontal zones above ground level within the canopies of commercial 'Nonpareil' and 'Carmel' almond trees, grown in north-west Victoria, Australia. Leaf mass per unit leaf area (M_A) was shown to be greater when PAR was greater. This relationship is discussed in relation to spur survival and the implications for spur population dynamics and future canopy architecture development.

Keywords: specific leaf mass, SLM, specific leaf weight, SLW, photosynthetically active radiation, PAR, spur

INTRODUCTION

Almond (*Prunus dulcis* [Mill.] D.A. Webb) is an important crop in Australia with approximately 31,000 ha currently under cultivation, and that area likely to grow by 50% over the next decade. Lower than expected yields and seasonal yield fluctuations have been of concern to the industry more recently. Understanding the environmental and management factors that contribute to yield, and the season-on-season variation in yield, is therefore important.

Spurs on an almond tree are short, proleptic shoots, and are the main fruiting unit in mature trees (Kester et al., 1996). Initially growing vegetatively in spring, the survival of spurs through winter and their continued contribution to yield is driven to a large extent by the amount of light they were able to capture the previous season (Heerema et al., 2008; Lampinen et al., 2011), as well as their reproductive status in a season. A spur's location within the canopy and its leaf area, dictate the amount of light it can potentially intercept and, therefore, how much carbohydrate it may generate and accumulate within a season.

It is well established in a number of woody perennial crops, including almond's close relative, peach (*Prunus persica* [L.] Batsch), that the amount of light that can potentially be intercepted by a spur is related positively to spur leaf attributes (Barden, 1974; Boardman, 1977; DeJong and Doyle, 1985; Patterson et al., 1978; Rosati et al., 2000). Various indices of those attributes, including leaf mass per unit leaf area (M_A), have been used to infer empirical models explaining almond kernel yield distribution on trees, particularly in the vertical dimension. On an operational level, having a reliable indicator of spur leaf potential productivity is useful due to the technical and logistical difficulties and costs associated with measuring light interception vertically through tree canopies, measuring carbon fixation by leaves directly and measuring the carbohydrate status of very small amounts of spur wood, and the numbers of samples needed to confidently infer anything about tree reproductive behaviour. In this paper the relationships between natural light attenuation within canopies and simple destructive measures of spur leaf attributes (i.e., mass, area and number of leaves) and calculated indices were investigated. A minimum threshold value is suggested for a spur leaf attribute index beyond which light interception may no longer be relevant. This is discussed in relation to spur survival and implications for future canopy architecture development. We also suggest that the nature of the relationships between spur leaf attribute indices and kernel yield may differ between cultivars.

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MATERIALS AND METHODS

The experiment was conducted in a 9-year-old highly productive commercial orchard, managed to best practice, at Lindsay Point, in the north-west of Victoria, Australia; -34.077° and 141.006°. The 'Nonpareil' and 'Carmel' trees used in this study yielded 5,349 (±163) kg kernel ha^{-1} in the 2014/2015 season; comparing favourably to an earlier industry yield benchmark of 3,200 kg kernel ha^{-1} (Pocock, 2007). All trees were grown on 'Nemaguard' rootstock.

The site's soils are typical wind-blown sands and sandy loams in a generally east-west running dune/swale landform ("Mallee"). The free draining soils are classified as highly calcareous earths, have low organic matter, and generally of poor to low fertility in their native state (Northcote et al., 1975).

Mean daily solar energy exposure in this region during October through to March is typically 20-26 MJ m^{-2} day^{-1} (Figure 1), and the annual daily average for the period 1990-2017 was 18.5 MJ m^{-2}.

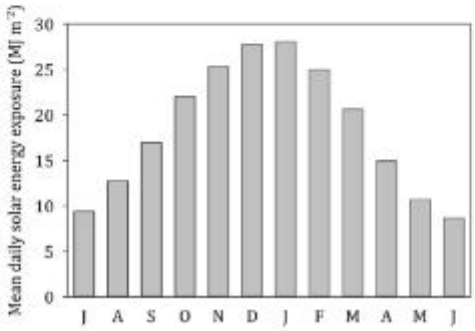

Figure 1. Monthly mean daily global solar energy exposure at Lindsay Point, north west Victoria, Australia. Values presented are means (1990-2017) of measurements collected approximately 3 km due south of the experimental site. http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=076133.

The trees used in the study were planted 4 m apart in rows 7.2 m apart; a total of 347 trees ha^{-1}. Every second row was 'Nonpareil' and alternating every other row were 'Carmel' and 'Monterey' as pollen source trees. Six replicate sets of four adjacent 'Nonpareil' and 'Carmel' trees were randomly selected from a 2.5 ha area inside the orchard. No two replicates were in the same rows.

To determine the interaction between light interception and spur leaf characteristics, six spurs were collected from each of six zones in a single measurement tree on 22 January 2015. The six zones were defined as being three horizontal strata within the tree (1.1-2.0, 2.0-2.9 and 2.9-3.8 m above ground level) on either the north facing or south facing aspects of each tree. The three horizontal strata are referred to subsequently by their lower bounds, i.e., 1.1, 2.0 and 2.9 m. The spurs were further segregated on the basis of whether they bore fruit or not, and the number of fruit per fruiting spur was also noted.

Prior to spur collection, 14 measurements of photosynthetically active radiation (PAR) at the base of each of the six zones around each tree were recorded within ±1 h of solar noon with an AccuPAR LP-80 ceptometer (Decagon Devices Inc., Pullman, Washington, USA).

Following PAR measurements, the spurs were collected, and transported back to the laboratory chilled, and the number of leaves and the length of the longest leaf were recorded. The leaf blades of each spur were then spread on a flat surface under glass, an electronic image was recorded, and the image was subject to image processing to estimate leaf area ("Easy Leaf Area", Heaslon). Each spur's leaves were then dried at 45°C to constant

weight and weighed. Two indices were calculated based on the direct spur leaf data, namely, specific leaf mass per unit leaf area ("M_A") as the ratio of leaf dry weight (in mg) to leaf area (in cm^2), and the product of the length of the longest leaf (in mm) and the number of leaves ("LN").

Tree dimensions including height, width, and height at maximum width were recorded post-harvest for three trees in each plot on 23 April 2015. The 'Nonpareil' trees used in this experiment were 6.1 m tall, compared with 'Carmel' of 6.0 m. Both cultivars had an average maximum width of 5.7 m, following a common pruning regime for machinery access.

The mean structured stratum/aspect/cultivar data were analysed by ANOVA as implemented in GenStat - Version 18.2.0 (VSN International Ltd.). Significant differences between three or more means were identified by least significant difference (LSD) where the variance ratio had a probability of 0.05 or less. Comparisons between two means were based on the variance ratio having a probability of 0.05 or less. Percentage data were arcsine transformed prior to analysis (Rohlf and Sokal, 1981).

RESULTS

Progressively more PAR was measured at the base of each stratum moving acropetally (Figure 2). Within the two lower strata, 50% of the PAR measurable at the base of the stratum above was extinguished. Overall, more PAR was intercepted by 'Carmel' canopies compared to 'Nonpareil' canopies, but the quanta of PAR intercepted on each side of the trees were similar.

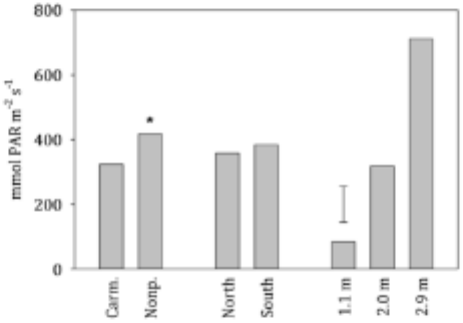

Figure 2. Cultivar ("Carm", 'Carmel'; "Nonp", 'Nonpareil', aspect and height main effects on PAR in almond trees at Lindsay Point. Values presented are means (n= 36, 36 and 24, for cultivar, aspect and stratum, respectively). Total incoming PAR was 2090 µmol m^{-2} s^{-1}. An "*" indicates a significant difference between a pair of means, and the vertical bar indicates LSD at P=0.05 for the stratum main effect.

The presence or absence of fruit on a spur accounted for very little of the variation in the direct measures of spur leaf attributes; leaves per spur, the length of the longest leaf in each spur, leaf area per spur and leaf dry weight per spur (results not shown). Similarly, the two indices of spur leaf productivity, M_A and LN, were also unaffected by the presence or absence of fruit.

Of the direct measures and indices of spur leaf attributes, the measures for 'Nonpareil' spurs were almost universally higher than the measures for 'Carmel' spurs (Table 1), but most measures were characterised by their inability to distinguish between the lower two strata. The exception was M_A; significant differences between M_A means were evident between the strata. The leaves of spurs collected from the highest stratum had the greatest M_A and leaves of spurs from the lowest stratum the least M_A. In other words, leaves from higher up the canopy were generally thicker than leaves from lower down the canopy.

Table 1. Cultivar, aspect and stratum main effects on direct measures and indices of almond spur leaf attributes. Values presented are means (n=36, 36 and 24 for cultivar, aspect and stratum, respectively). An asterisk following the second of two means indicates a significant (P=0.05) difference between those means. Means within groups of three with the same superscripted letters are not significant at P=0.05.

		Leaves spur^{-1}	cm^2 leaf spur^{-1}	Longest leaf length (mm)	g leaf DW spur^{-1}	M_A (mg cm^{-2})	LN
Cultivar	'Carmel'	6.5	35	58	0.22	6.1	389
	'Nonpareil'	7.3*	40*	57	0.27*	6.6*	432*
Aspect	North	7.0	37	56	0.25	6.4	411
	South	6.8	39	58	0.24	6.2	410
Stratum	1.1 m	6.1^A	36	57	0.17^A	4.7^A	363^A
	2.0 m	6.1^A	36	57	0.20^A	5.5^B	364^A
	2.9 m	8.5^B	41	57	0.37^B	8.7^C	505^B

Mean PAR at the base of each stratum was highly correlated with mean M_A for each stratum (Pearson's product moment correlation coefficient = 0.98). The linear regression line (adjusted R^2 of 0.94) suggested that mean specific leaf weight diminished by 1 mg cm^{-2} for approximately every 150 µmol PAR m^{-2} sec^{-1} eliminated down the canopy.

Exploring M_A in more detail, the individual spurs' data were partitioned into eight evenly spaced density classes. Across the 432 spurs sampled, the lowest M_A was 3.1 mg cm^{-2}, and the highest was 12.3 mg cm^{-2}; a range comparable to that reported for 'Nonpareil' in California (Heerema et al., 2008). Nearly half of all spurs sampled were in the lower two density classes, and three-quarters of all spurs sampled were in the lower four density classes. Analysis of the distribution showed that stratum was a significant source of variation in most M_A classes (Figure 3); the exception being the top class. Neither aspect nor cultivar were significant sources of variation in the distribution of spur leaf M_A across the eight classes. Proportionally more spurs were found in the lowest M_A class if the spurs had been sampled from lower strata. There were virtually no spurs in the top four M_A classes coming from the lower strata. The data suggest three more-or-less normally distributed M_A populations, with a strong separation between the two lower strata and the upper stratum.

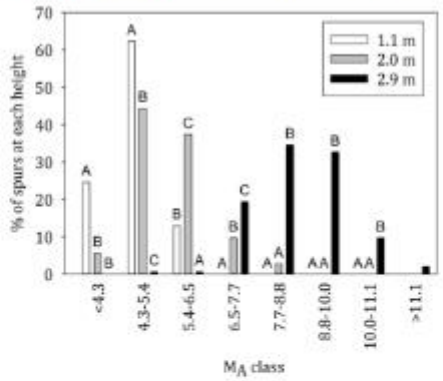

Figure 3. Effect of spur height on the distribution of spurs across 8 equally spaced leaf mass per unit leaf area (M_A) classes. Values presented are means (n=24). Different letters above columns within M_A classes indicate significant differences between means at P-0.05. The mean separations were on the bases of the analysis of the arcsine transformed data.

DISCUSSION

This work shows that when the amount of light available to spurs decreases, the leaf specific weight (i.e., M_A) also generally decreases. This relationship makes a certain amount of biological sense: devoting resources to capturing more of a diminishing resource may represent a poor return on investment.

Almond spurs may be considered semi-autonomous organs (Heerema et al., 2008), and carbohydrate sinks located on an individual branch are largely supplied by the sources located on that same branch (Tombesi et al., 2011). Without effective carbohydrate transport between spurs, the relationship between the total amount of PAR reaching each spur's leaves and the leaves' capacity to adsorb that energy becomes critical. Improving the likelihood of utilising PAR by increasing M_A would therefore be advantageous. It would also improve the likelihood of that strategy being successful by restricting the response to either the upper portions of the tree and/or to a threshold PAR level or greater. We suggest that M_A greater than 6.5 mg cm^{-2} is needed to take advantage of PAR levels greater than 400 µmol m^{-2} s^{-1}. Below these thresholds, there may be less likelihood that the additional investment in leaf development would result in more interception of what is a steadily diminishing resource basipetally.

Across the board, 'Carmel' canopies demonstrated greater PAR absorbance than 'Nonpareil' canopies, but there was no indication of any difference in the extent to which PAR was attenuated through the canopies of each cultivar. The greater PAR absorbance by 'Carmel' canopies compared to 'Nonpareil' canopies was not related to M_A; 'Nonpareil' leaves were thicker than 'Carmel' leaves. PAR attenuation was in the range of about 200-300 µmol PAR m^{-2} s^{-1} for each metre downward from a height of 3.0 m; the proportional attenuation being around 50% for each m down the canopy. The significance of that greater PAR absorbance by 'Carmel' canopies versus 'Nonpareil' canopies may lie in each cultivar's internal architecture and spur population dynamics. The limited data available suggests that 'Nonpareil' spurs have a higher rate of mortality than that of 'Carmel'. If the linkage between PAR availability and spur longevity is universal, one would expect a different distribution of spurs across each cultivar's canopies, related possibly to differences in the threshold for spur genesis, longevity and fertility. This is an active area of research.

Finally, estimating almond yield potential using understory light measurements (Lampinen et al., 2011) depends primarily on stable tree canopy architecture and more-or-less uniform PAR absorption across sampled trees and orchards that can be related – via spur population dynamics – to actual kernel yield (Rojo et al., 2013). It is likely however that this form of yield projection will need to be updated for each major architectural deviation from current industry standard practice because if more light is allowed to pass through the upper portions of a canopy, in an attempt to maintain productive spurs in the lower portions of the canopy, total tree productivity for each unit of overall intercepted PAR may change. Targeting new canopy architecture to maintain light above a minimum PAR interception threshold throughout the canopy could promote greater survival of existing spurs, perpetuating productivity in the lower parts of the canopy. However, pruning limbs to maintain a maximum canopy depth would likely also change the internal shading and light attenuation characteristics, and defining this relationship for commercial application may require a holistic research approach to include dwarfing rootstocks (to minimise pruning requirements) and different cultivars with lower light limits for spur survival and production. Modelling canopy architecture is an advancing field, and may be useful in the first instance to estimate internal canopy architecture and subsequent light attenuation, e.g., via 3D digitisers, functional structural models and light path ray tracing. Whilst the benefit of altered tree architecture remains to be realised, the physiological basis for the effect of tree architecture is becoming more clearly understood.

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