Final Report

Advanced production systems for temperate nut crops

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Delivery partner:

Department of Jobs, Precincts and Regions

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ST16001

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Content

Summary

Australia's temperate nut industries acknowledge the need for advanced production systems. The almond industry views their current production based on large widely spaced trees as inconsistent with its strategic aim of moving to next generation shake-and-catch harvesting, and that a production system based on closely spaced smaller trees is needed. Effective resource use, including water and nutrients is a critical component of these desired new generation production systems, as well as for existing orchards.

To meet this need and opportunity, the 'Advanced production systems for temperature nut' project established the temperate nut orchard and commenced a program of research at the Mildura SmartFarm in north-west Victoria on 21.5 ha of land gazetted for horticultural research purposes.

The key output of the investment is a significant experimental and demonstration orchard platform that will enable the demonstration of and research into the design and management of next generation orchards that are strongly desired by industry and aligned to strategy. The SmartFarm orchard plantings now provide a unique, fit-for-purpose and at suitable scale research and innovation asset that will serve the industry through new knowledge and management practice development, generating returns on the initial investment for at least the next two decades.

In total six trial plantings were established. Two major plantings (5 and 6.5 ha, respectively) were established to deliver against the scheduled project research outputs, and both plantings had purpose-designed drip irrigation systems installed to impose treatments, reduce plot-to-plot variability and facilitate management. Three of the other plantings were established as longer term resources to address specific questions that arose as a deeper appreciation developed of the implications of moving from the current 3D fruiting space to a 2D fruiting space. The final planting was established to serve as a demonstration site of alternate nut crops.

Extensive assessments of the trial site have been completed ensuring essential baseline knowledge to underpin the experimental design and provide fundamental data for research purposes. The site's soils were surveyed and tested to support irrigation design and to provide a yardstick against which the impact of almond production on the soil asset could be assessed in the future.

Research outcomes and the implications for industry include:

- The possible oversupply of nitrogen fertiliser to young trees was linked to the strong inertia of tree nitrogen status and the reliance on an inappropriate yardstick.
- Mineral nutrient supply and rootstock modulation of a cultivars' natural tree architecture was identified.
- AgTech sensors playing fundamental roles in managing site-specific issues (*e.g*. soil variability) and foundational roles in identifying new ways to manage inputs in real-time were assessed for their implementation in industry.
- LiDAR renderings of tree architecture and simulation of hedging effects signpost canopy densification and poor light penetration related to scion growth habit and use of high vigour rootstocks in higher density plantings.
- Soil variability highlighted the need for smaller irrigation units and systems to sense tree and soil water status to drive irrigation autonomously.
- Rootstock-related scion water status management is potentially an exploitable trait to improve scion water use efficiency.

Research results were presented at industry events and to fellow researchers; 7 oral and 12 poster presentations were made. Results were also published in three technical articles and a literature review on nut composition was prepared for publication in a peer-reviewed journal. The project had a strong online presence, featuring on the Horticulture Industry Network and in several online articles. A factsheet and brochure have been produced for distribution at events. The main event hosted at the Mildura SmartFarm was the launch of the site by the Victorian Minister for Agriculture, at which representatives from the region's major horticultural organisations and Agriculture Victoria executives were in attendance.

Recommendations for future research and innovation stemming from the project include:

- Continue productivity measurements as trees mature to provide industry with more robust performance data upon which informed investment decisions can be made.
- Maintain nitrogen fertigation treatments to drive tree N status divergence and provide a better basis for evaluating leaf reflectance spectra as a real-time decision support and to develop a more responsive indicator of tree nitrogen status.

- Develop a framework to maintain N at optimum concentration whilst supplying sufficient water.
- Investigate rootstock-scion water stress responses to identify traits and genotypes better suited to short-term water shortage to provide industry means to make better use of water.
- Investigate rootstock and mineral nutrient supply influences on scion branching patterns with a view to develop better means for producers to influence scion architecture/tree shape and the number of potential fruiting sites.
- Use purpose-established platforms to derive orchard design parameters (*e.g*. row width and orientation) based on light versus spur fertility relationship and 2D fruiting space productivity limits.

Keywords

Almond; temperate nuts; research platform; higher density planting; cultivar; rootstock; resource use; sustainability; fertiliser; water

Introduction

Production systems and practices are central themes in the Australian almond industry's long-term strategy to thrive and grow. Moving away from the current production system to one that allows shake and catch harvesting and making better use of resource inputs are key parts of the strategy. It was recognised that a departure from the current large expansive 3-dimensional fruiting space to a more intensive 2-dimensional fruiting space was required. Other temperate nut industries have similarly recognised the need for next generation, more intensive production systems to maintain market access and improve profitability. The knowledge gaps to be addressed were complex, multi-seasonal, did not lend themselves to quick answers and needed to be addressed from the ground up; in other words, planting material, orchard design and tree management (size, architecture and training). Suitable research platforms did not exist.

This project was one of four in a multi-agency industry program established to develop advanced production systems for the nut industries using two tree nut crops, almonds and walnuts, as model crops, and to address some aspects of resource use and sustainability.

The temperate nut orchard at the Mildura SmartFarm was established by Agriculture Victoria as a platform to:

- Research ways to improve tree establishment, early cropping and — as a corollary — resource use.
- Address key questions underpinning the design of more intensive almond production systems.
- Assess new technologies to assist in orchard management.
- Ameliorate abiotic stress effects.
- Communicate and demonstrate research outputs.

The program's co-investment partner was the Australian Government through DAWE's Rural Research and Development for Profit Program and the program was overseen by Horticulture Innovation Australia.

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 researchers.

Description of methods (and justification)

Below is a summary of the project methodology. Detailed methodology can be found in Appendix A: Research outputs.

Experimental platform development

The temperate nut orchard at the Mildura SmartFarm was established in the north west of Victoria on 21.5 ha of land gazetted for horticultural research purposes as a long-term demonstration site and research platform. The experimental plantings will provide guidelines towards the use of resource inputs (fertiliser and water) as well as serve to demonstrate improved irrigation practices through closed-loop irrigation. To assist the industry in moving towards integrated shake-and-catch harvesting systems, the performance of new Australian-bred self-fertile cultivars were assessed in higher density planting systems.

The site's soils were extensively surveyed and tested to support irrigation design and to provide a yardstick against which the impact of almond production on the soil asset could be assessed in the future. Six trial plantings were established. The two major plantings (5 and 6.5 ha, respectively) were established to deliver against the scheduled project research outputs, both these plantings had purpose-designed drip irrigation systems installed to impose treatments, reduce plot-to-plot variability and generally facilitate management. Three of the other plantings were established as longer term resources to address specific questions that arose as the implications of moving from the current 3D fruiting space to a 2D fruiting space developed. The last planting was established to serve as a demonstration site.

The 5-ha planting was designed to deliver on the Australian almond industry's desire to better use fertiliser inputs in the current production system. Nonpareil, Carmel and Monterey trees on three different rootstocks were established in 2018 and an irrigation-fertigation system installed capable of delivering three fertigation regimes. The design allowed the investigation of the impact of the concentration of nitrogen in the readily available water on the establishment and performance of nine rootstock × scion cultivar combinations. The nitrogen fertigation treatments were based on controlled glasshouse experiments that identified a concentration of nitrogen beyond which no further advantage was conferred. The trees were also used to assess the suitability of new-generation portable spectroradiometers to determine tree nutrient status.

The 6.5-ha planting was established to develop knowledge to enable industry to transition over coming decades to more intensive production systems based on closer plantings and new cultivars. It is not known what tree architecture would be suitable for a more intensive production system. Twelve cultivar × rootstock combinations were planted at densities ranging from 500 to 2000 trees/ha in 216 individually valved plots. The cultivars differ in their growth habit and the rootstocks differ in the vigour conferred to scion cultivars. The site covers a range of soils and soil depths with a concomitant range of readily available water holding capacities. To avoid under- and over-watering, and avoid abiotic stress in general, a network of 72 soil moisture sensors was installed in a third of the plots. Their outputs are communicated wirelessly to drive irrigation decisions for each plot across the site. Tree architecture was investigated using ground-based LiDAR to derive a virtual 3D projections of tree architecture to allow *in silico* simulation of pruning and/or hedging severity on branching. Tree branching and spur distributions were also assessed.

Three smaller plantings (each less than 1.5 ha) have been established as resources for the future. In one planting radical tree training techniques were applied to a range of new almond cultivars (that differ in their growth habits) on a range of vigour-imparting rootstocks planted at standard through to ultra-high (500 to 4000 trees/ha) densities. The aim being to estimate the productivity limit of the 2D fruiting space concept implicit in the move to a more intensive production system. Another planting was established to enable the quantification of the quantum of light spurs need during the critical floral bud initiation period. The final planting was established to explore the natural tree architecture of a range of almond cultivars.

A 1.6-ha planting of hazelnut, walnut, pecan, chestnut, macadamia and pistachio was established primarily to assess and demonstrate the suitability of different cultivars and — where possible — different rootstocks for higher density plantings but also to be a platform to communicate the region's suitability for a number of other temperate tree nut crops. Uniquely, the planting will serve to allow producers and potential investors to assess each crop and cultivar under the same climatic, soil and management conditions.

Tree performance

Tree growth is not only an indication of the rate at which trees will fill the tree line, but also indicates the suitability of scion cultivar and rootstock combination in higher density plantings where a specific tree size has to be maintained throughout the season to accommodate an overhead harvester. Tree architecture indicates the growth habits of trees and the propensity to produce axillary growth, both of which have implications for canopy light interception. LiDAR technology, which produces 3-dimensional representation of trees, was used because it allows for the investigation of tree architecture from multiple angles compared to 2-dimensional images. Furthermore, canopy management actions can be simulated on the 3D point cloud images and, in combination with theoretical data collected on tree growth habits, changes in tree architecture over multiple seasons can be modelled.

Tree growth

Tree growth and biomass were assessed through the increases in canopy size and trunk diameters. Tree dimensions were manually measured at the end of each growing season prior to hedging. Trunk diameters were measured with Bluetooth calipers at the end of each growing season after active growth had ended. To increase the efficiency in tree dimension data collection, a method was developed and validated to determine tree height from images collected using a UAV-platform.

Tree architecture

High resolution light detection and ranging (LiDAR) 3-dimensional images of each treatment in the higher density plantings were collected in winter 2020 and 2021 with a 3D laser scanner. Hedging was simulated from the rendered images by virtually removing that part of the canopy that would have been removed by the hedging action.

Shoot architecture assessments were conducted in winter 2021 to describe natural shoot architecture and the degree and location of axillary growth on shoots after apical dominance was removed during the hedging action. Hedged and unhedged shoots (n = 288 per type) were assessed for each treatment and the number of blind, vegetative and reproductive buds as well as the number, nature and length of axillary shoots determined.

Light interception

Photosynthetically active radiation (PAR) intercepted by the canopy was measured at multiple time points during the growing season in both the H1 and H3 plantings. Measurements in the H1 were conducted in the 2018-19 and 2020-21 growing seasons and in the 2019-20 and 2020-21 seasons in the H3. Intercepted PAR was measured within the planting square for each treatment in both plantings with a ceptometer and light interception was expressed as the effective area of shade.

Tree physiology

Phenology

Phenological assessments were undertaken in the higher density plantings to assess any impact rootstock and spacing may have on flowering behaviour. Because these cultivars are self-fertile, the need for overlapping flowering periods are not as critical as the need for overlapping flowering periods for non-self-fertile cultivars. Flowering behaviour does however have implications for scion cultivar and rootstock selection in areas that may, for example, be prone to frost in early spring. Furthermore, large disparities in flowering time are generally accompanied by differing phenology milestone timings which will have implications for spray programs.

Phenological assessments were initiated at the start of the second leaf season (2020-21) and repeated at the start of the third leaf (2021-22). Detailed flowering, leaf-out and nut development assessments were conducted weekly on the scion cultivar and rootstock combinations in the 2-m spacing according to the methodology used by industry[1]. In 2021-22 observations were also made of the percentage of flowering for the remainder of the plant spacings.

Tree water use

Water potential (Ψ) is an accurate and well accepted indicator of plant water status. Whereas pre-dawn Ψ (Ψ_{PD}) indicates how much water in the soil is available to the tree, stem Ψ (Ψ_{SWP}) is an indicator of the efficiency with which the tree is using the water when photosynthetic activity and transpiration will be at the highest rate. To assess tree water use efficiency an experiment was conducted to measure the changes – as a function of cultivar, rootstock and spacing – in tree water status (Ψ_{PD} and Ψ_{SWP}) as soil water was depleted. This experiment also served as an indication of the resilience of trees when water availability is low, either due to water being unavailable or other circumstances.

Ψ measurements were conducted in the 2020-21 season in the higher density plantings with a pressure chamber according the method described in Scholander *et al.* (1964). Prior to the start of measurements the soil profile was filled as close as possible to field capacity after which irrigation was withheld for a period of eight days. During this period Ψ_{PD} measurements were conducted prior to sunrise on the first and last day of the water withholding period. Every second day Ψ_{SWP} measurements were conducted around solar noon according to the method of Fulton and Buchner (2014).

At the end of the drying out period the trees were re-watered and a final Ψ_{SWP} measurement performed a day after re-watering to assess the tree recovery response.

[1] Thomas, D. and J. Connell. 2018. Assessing Phenology of Almonds. Government of South Australia. p. 7.

Leaf nutrient status

Leaf nutrient analysis is the industry standard method to determine the nutrient status of trees. Leaf nutrient status was used as a tool in two of the project outcomes aimed at increasing the efficiency of resource inputs, specifically nitrogen. The analyses were firstly used to determine the changes in nitrogen status of trees in the H1 planting in relation to scion cultivar and rootstock and in response to halving and doubling the optimal nitrogen level determined in glasshouse trials. In the H3 planting these analyses were used to explain difference in the nitrogen status of trees between scion cultivar, rootstock and spacing with the aim to adjust fertiliser inputs according to the differing needs of trees brought on by the treatments. The data also provided insight into the drivers of differences seen in the leaf nutrient status.

An alternative method to determine tree nutrient status non-destructively and in real-time was also investigated to determine the potential of this method as a tool for producers to adjust fertigation regimes throughout the growing season.

Leaf samples were collected from the H1 planting in January of 2019 and 2021 and from the H3 planting in early March 2020. Leaf samples were collected from measurement trees according to the method described in Robinson *et al.* (1997). Leaf samples were washed, dried and sent to a NATA-accredited analytical services for analyses of the full suite of plant mineral nutrients.

Proximal spectral analyses of leaves were conducted with a spectroradiometer using a pre-optic accessory specifically designed for leaf reflectance measurements. An integrated light source eliminated potential environmental noise. Subsamples of leaves collected for nutrient analyses were scanned and partial least square regression analyses performed to determine the prediction accuracy of the model for the total leaf nitrogen concentration from the spectral data. Water content in the leaves were determined by weighing the samples before and after drying and used to determine the prediction accuracy of the model for leaf water content.

Productivity

Yield indications in higher density plantings are important to determine if scion cultivar, rootstock and spacings are economically viable in future planting systems. Flower numbers, in combination with a credible pollination and nut retention rate, is a good indication of the potential yield. Currently, empirical observations are conducted to determine floral numbers in commercial orchards, but with advances in technology the potential exists to conduct these assessments with the use of artificial intelligence. Flower count models for pears have been developed by Green Atlas at the Agriculture Victoria SmartFarm, but a model for almonds wasn't available.

Flower numbers for each treatment in the higher density plantings were determined at the start of the 2021-22 season from images collected with a Green Atlas Cartographer with a flower count model developed by Green Atlas. The model was calibrated with manual flower counts conducted at the time of scanning. Projected yield was determined by extrapolating the flower numbers to the number of flowers per ha, using global value of 35% to estimate the potential number of fruit that the tree will retain until harvest, and calculating the kernel yield per hectare from the number of fruit and the mean kernel masses observed in AL12015 for the three cultivars.

Project communication

Research updates and findings have been delivered regularly through a number of platforms. Presentations were delivered at the 18th Australian Almond Conference in 2018 and two Australian Almond Research & Development Forum & Field Days (2017 and 2019) which were attended by almond producers, industry consultants and fellow researchers. Project outcomes were also presented to fellow AVR researchers through four presentations at the Agriculture Victoria Research (AVR) Regional Science Conference and AVR Science webinars.

Results were presented in three industry articles that were published in two main Australian nut industry journals. Project outcomes were further delivered to the general public through nine posters that were presented at four Mildura Horticultural Field days. A factsheet and brochure on the Mildura SmartFarm have also been compiled for distribution at events.

Up to 2020, before COVID-related restrictions put limitations on visitations to the Mildura SmartFarm, ten groups visited the site. Three groups have been hosted at the Mildura SmartFarm since then during periods of relaxed restrictions and included ABA staff, SARDI co-operators and Mallee Region Innovation Centre staff. The Mildura SmartFarm launch was attended by representatives of the region's major horticultural industries' organisations (Almond Board of Australia, Australian Table Grape Association and Dried Fruits Australia) and ancillary bodies

(SuniTAFE, Mallee Regional Innovation Centre and Mildura Rural City Council) along with Agriculture Victoria leadership. Research outcomes were presented through posters and technology implemented at the Mildura SmartFarm was showcased to attendees through visualisation of the technology outputs.

Online presence remain strong through project information that is available through the Horticulture Industry Network's webpage and AVR's "Project-on-a-Page" webpage, and internaly on the AVR Virtual SmartFarm platform. The Mildura SmartFarm further featured in four online articles following the launch.

Outputs

The Mildura SmartFarm as a nut industry research platform

The Mildura SmartFarm temperate nut orchard is now an established industry research platform and long-term demonstration site for the nut industry. The site's location, soils and the plantings' scale reflect real-world relevance to industry.

The fit-for-purpose almond and other nut plantings are suitable for ongoing physiology, morphology and agronomy research. The platform consists of six experimental plantings, each with a unique experimental objective delivering against the planned outcomes in the almond industry's strategic investment plan.

An array of sensors has been installed that enable the investigation and optimisation of resource use efficiency. Several advanced technologies were utilised to assess tree growth, development and yield performance. The sensors will continue to help manage the plantings to industry best practice standards.

In future projects, these platforms will contribute to the development of guidelines for use of resource inputs (fertiliser and water) as well as serve to demonstrate improved irrigation practices through closed-loop irrigation. Capturing long-term outcomes of the suitability of new Australian-bred self-fertile cultivars for higher density planting systems will serve to assist the industry move towards integrated shake-and-catch harvesting systems.

Figure 1 Aerial view of the Mildura SmartFarm in March 2021
The image was recorded on 15 March 2021 when the new office/laboratory/equipment storage facility was under construction (left of image).

In addition to the establishment of a long-term research and demonstration research platform, the Agriculture Victoria research team has gained greater understanding of almond production practices as well as an enhanced understanding of almond physiology, morphology and agronomy. The team has acquired capabilities in the use of novel research technologies which, coupled with the capabilities and resources the team already have in analytical chemistry, plant physiology and disease and pest management, has expanded the scope of skills that can be brought to bear on realising industry's strategic objectives.

With an eye to the availability of future researchers, the establishment of the light and spur fertility research platform to enable the investigation of the relationship between light and floral bud initiation and development (see page 47) presented an excellent training opportunity for an early career researcher. To this end, an Agriculture Victoria sponsored PhD scholarship was advertised and a suitable applicant identified; approval has been delayed by COVID-related restrictions.

Communication outputs

The Mildura SmartFarm launch

The research orchards and activities being undertaken received major exposure during the launch of the Mildura SmartFarm by the Victorian Minister of Agriculture, The Hon. Mary-Anne Thomas, on 31 March 2021.

Figure 2 AV researcher Michael Treeby explains to the Hon. Mary-Anne Thomas, Minister for Agriculture (Victoria) the relevance of tree architecture in advanced production systems (left) before the minister addressed attendees (right)

Images used with approval.

The event was managed according to the Department of Jobs, Precincts and Regions' COVIDSafe plan. The launch was staged during a period of relaxed restrictions with attendee numbers limited to 30. Representatives of the region's major horticultural industries' organisations (Almond Board of Australia, Australian Table Grape Association and Dried Fruits Australia) and ancillary bodies (SuniTAFE, Mallee Regional Innovation Centre and Mildura Rural City Council) were in attendance, along with Agriculture Victoria executives.

Agriculture Victoria research staff showcased and discussed some of the research technology implemented at the Mildura SmartFarm with the Minister and attendees. Application of the Aquaflex soil moisture sensor network, the handheld spectroradiometer and LiDAR were demonstrated through visualisations of the outputs of the technology and posters provided additional information (Table 1). Following the event Michael Treeby was interviewed by three radio networks (ABC, ACE Radio Network and MMM) and by *Australian Nut Grower* for a feature in the near future. Several on-line articles also resulted from the event and are listed under *Online presence*.

In preparation for the ministerial launch, a professional photographer[2] recorded images and video footage of the Mildura SmartFarm focussing on the AgTech being used in the plantings for research and management. The images and footage are available for use in future promotional material and in presentations. A promotional brochure and factsheet on the Mildura SmartFarm were also prepared and can be viewed in *Appendix B: Communication* in Figure B 1 and Figure B 2.

Presentations at events

Presentations and posters were presented at ABA R&D forums, Australian almond conferences and other almond related fora over the course of the project. Project outcomes were also conveyed to fellow researchers, growers and the general public at several events during the lifetime of the project, reaching a broad audience.

Posters and other presentations are listed in Table 1 and posters can be viewed in *Appendix B: Communication.*

[2] https://www.michaelwoods.com/

Table 1 Events where the Mildura SmartFarm was featured

Event	Date and location	Presentation title	Presenter
2017 Mildura Horticulture Field Days	May 17-18, 2017, Mildura	*Rootstock/fertiliser management systems for almonds* (Figure B 3)	Peta Faulkner (poster)
2017 Australian Almond Research & Development Forum & Field Day	October 24-25, 2017, Loxton (221 attendees)	*Mid Area experimental orchard*	Michael Treeby (oral)
2018 Mildura Horticulture Field Days	May 18-19, 2018, Mildura	*Soil pH – how much does it matter for almond rootstocks?* (Figure B 4)	Belinda Kerridge & Michael Treeby (poster)
18th Australian Almond Conference	October 30 – November 01, 2018, Melbourne (484 attendees)	*Mid Area experimental orchard*	Michael Treeby (oral)
AVR Regional Science Conference	April 3-4, 2019, Tatura (76 attendees)	*Industry overview current to future*	Michael Treeby (oral)
"	"	*The Mid Area Temperate Nut Field Laboratory: A research platform for current and future production systems*	Belinda Kerridge (oral)
2019 Mildura Horticulture Field Days	May 17-18, 2019, Mildura	*Nitrogen/rootstock interactions – fertiliser management for almonds* (Figure B 5)	Belinda Kerridge, Glenn Henderson & Michael Treeby (poster)
"	"	*Advanced almond production systems* (Figure B 6)	Belinda Kerridge, Glenn Henderson & Michael Treeby (poster)
2019 Australian Almond Research & Development Forum & Field Day	October 30-31, 2019, Loxton (220 attendees)	*Mid Area temperate nut experimental orchard*	Michael Treeby (oral)
Mildura SmartFarm Ministerial launch & 2021 Mildura Horticulture Field Days	March 31, 2021 (30 attendees) & May 21-22, 2021, Mildura	*Predicting nitrogen in almond trees through proximal and remote spectral imaging* (Figure B 7)	Zelmari Coetzee, Peta Faulkner & Michael Treeby (poster)
"	"	*Autonomous irrigation management: one solution for two problems* (Figure B 8)	Zelmari Coetzee & Michael Treeby (poster)
"	"	*Defining tree architecture for advanced almond orchard systems* (Figure B 9)	Zelmari Coetzee & Michael Treeby (poster)
"	"	*Ag Technologies at the Mildura SmartFarm* (Figure B 10)	Zelmari Coetzee & Michael Treeby (poster)
AVR Science webinars	May 14, 2021, online (62 attendees)	*The Mildura SmartFarm – a research platform for the temperate nut industry*	Michael Treeby (oral)
AVR Science webinars	August 13, 2021, online (76 attendees)	*Mildura SmartFarm: Technologies to assist in orchard management*	Zelmari Coetzee & Peta Faulkner (oral)

In particular Agriculture Victoria has had a long association with the annual Mildura Horticultural Field Days. Barring 2020 when the event was cancelled due to COVID-related restrictions, the Irymple team has been present at each field day since the start of the project. The event has been a good platform to introduce the general public to the Mildura SmartFarm, to communicate aims of the research in general terms and to highlight the AgTech being used.

Figure 3 The Mildura SmartFarm being promoted at the 2021 Mildura Field Days.

Pictured are AV researchers Zelmari Coetzee and Audrey Delahunty manning the Irymple group's display/communication stand.

The event ran over two days (21 to 22 May 2021).

Publications

Industry articles

Faulkner, P., Coetzee, Z. & Treeby, M. 2019. It's nuts not to future-proof nitrogen. *Australian Tree Crop*, Oct/Nov, 30-31.

Coetzee, Z. & Treeby, M. 2020. Growth habits of new Australian almond cultivars in advanced production systems. *In a nutshell*, 20 (4), 16-17.

Coetzee, Z., Grossman, B., Treeby, M. & Faulkner, P. 2020. Agriculture Victoria is changing the face of almond research. *In a nutshell*, 20 (3), 23-25.

Articles can be viewed in Appendix B: Communication outputs.

Refereed publications

A literature review of the factors influencing almond nut composition has been compiled by Marica Mazza and will be submitted as a review paper to a suitable peer-reviewed journal.

Data collected during the 2020-21 season will be compiled and submitted to peer reviewed papers. The following papers have been identified for publication:

- A collaborative paper with SARDI on almond leaf spectral characteristics and leaf mineral status. The method development and results on SARDI's salt tolerance trial and AVR's nitrogen trial will be included.
- Shoot architecture and apical dominance in almond cultivars and the effect of management practices on tree architecture.
- A collaborative paper between the AVR Irymple and Tatura researchers and Green Atlas on the flower prediction model.

The PhD student will publish papers on the physiology underpinning the linkage between light and floral bud initiation and present at scientific conferences over the course of their candidature.

Reports and fact sheets

ST16001 MS101. Milestone report to Hort Innovation - January, 2017

ST16001 MS102. Milestone report to Hort Innovation - May, 2017

DEDJTR research supporting the Australian almond industry transitioning to more intensive production systems - HIA project ST16001: Advanced production systems for temperate nut crops. Summary report prepared for the Australian Almond Board - September, 2017

ST16001 MS103. Milestone report to Hort Innovation - October, 2017

ST16001 MS104. Milestone report to Hort Innovation - May, 2018

ST16001 MS105. Milestone report to Hort Innovation - October, 2018

ST16001 MS106. Milestone report to Hort Innovation - October, 2019

ST16001 MS107. Milestone report to Hort Innovation - May, 2020

ST16001 MS108. Milestone report to Hort Innovation - October, 2020

ST16001 MS109. Milestone report to Hort Innovation - May, 2021

SmartFarm Mildura. Factsheet – September, 2021

Online presence

The temperate nut experimental orchard at the Mildura SmartFarm is featured on the Virtual SmartFarm (VSF) platform which is under development for the visualisation of the agtech outputs installed at the Mildura and other AVR SmartFarms (https://smartfarms.agriculture.vic.gov.au/mildura). Visuals of the Mildura SmartFarm will be updated when COVID travel restrictions allow travel from Melbourne to regional areas.

The project also features on Agriculture Victoria's "Project-on-a-Page" website which can be viewed at https://avrwebcontent.z26.web.core.windows.net/poap/poap_temperate_nuts.html

An HD high-definition IP camera[3] was acquired in 2021 with funding provided by Agriculture Victoria's On-Farm Internet-of-Things Trial which will livestream the Mildura SmartFarm plantings through the HIN and/or VSF platforms. Delivery and installation of the equipment has been impacted by COVID restrictions but online access will be available in early 2022.

The project's strongest presence is within the Nut Network on Agriculture Victoria's Horticulture Industry Networks (HIN) website and images and interviews with research staff can be accessed at http://www.hin.com.au/networks/nut-network#tab__178082. HIN pages will be updated as soon as travel restrictions are lifted.

Discussions with the webpage developer[4] also confirmed that outputs on the platform can be increased and will be updated to facilitate interactive farm visits. Visitors will be able to access information on the plantings and research outcomes on the Nut Network pages by scanning QR codes in the planting or treatment plots of interest.

The temperate nut experimental orchard at the Mildura SmartFarm has also featured in several online articles:

- *Unlocking opportunities for the Almond Industry* – 31/03/2021 (https://www.rdv.vic.gov.au/news/unlocking-opportunities-for-the-almond-industry)
- *Growing Victoria's thriving agrifood sector* – 01/04/2021 (https://www.invest.vic.gov.au/news-and-events/news/2021/april/growing-victorias-thriving-agrifood-sector)
- *Unlocking opportunities for the almond industry* – 07/04/2021 (https://victorianfarmer.com.au/unlocking-opportunities-for-the-almond-industry/)
- *New technologies are applied to more efficient nut production* – 05/04/2021 (https://www.stockandland.com.au/story/7192896/smarter-ways-of-farming-nuts/)

A photo-journalist representing *Good Fruit and Vegetables* was in attendance at the ABA's biennial R&D Forum in 2018 and highlights of the forum were published on the website (www.goodfruitandvegetables.com.au/).

The temperate nut experimental orchard and research staff were featured in *Agriculture Victoria Research News* which provides montly updates on state-wide research activities to Agriculture Victoria staff. The following articles were published in the newsletter:

- *Sensing technologies and 3D trees – transforming almond harvesting* (May 2021)
- *Orchards of the future – customised nitrogen and water management* (July 2021)
- *A nutty vision bears fruit – improving crops and designing orchards* (July 2021)

[3] http://agcloud.com.au/aggc1/

[4] Mark Hincksman, Agriculture Victoria

Seeing is believing

In 2018 two visiting groups, sponsored by Australian Government's Department of Agriculture Water and the Environment (DAWE) and AusTrade, respectively, were briefed about the overall tri-state temperate nut program in general terms and the Mildura SmartFarm in detail. Between 2019 and the introduction of COVID-related restrictions on visitors a further seven groups have visited the Mildura SmartFarm. Four of those groups were sponsored by DAWE and the others were part of an Agriculture Victoria project ("Horticulture Industry Network") activity.

The Department of Jobs, Precincts and Regions' Secretary Simon Phemister, Deputy Secretary Emily Philips and Deputy Secretary Beth Jones visited the Irymple site and Mildura SmartFarm as part of the DJPR Conversation on 22 November 2019.

Since early 2020, COVID-19-related restrictions on movement (particularly across state borders), social distancing requirements and the number of people that can meet precluded any meeting with industry or the staging of any industry knowledge transfer event, thus preventing field walks and any other on-site extension activities in the past 18 months. This also meant that the AV group could not participate in any industry knowledge transfer event. Additional restrictions on travel for Victorian Public Service employees, as well as limitations on vistors to governement sites, further restricted these activities.

The AV project team was able to host SARDI collaborators on 11 February 2021 while state borders were open to view mechanical "shake-and-catch" harvesting of almonds on the SuniTAFE farm at Koorlong. This rare opportunity was capitalized on to inspect and discuss the establishment and operation of the temperate nut plantings in relation to the research strategies articulated at pre-COVID meetings. COVID-19 social distancing was observed at all times. The SARDI team had experienced similar issues related to weather conditions and soil-borne disease.

The AV team briefed Mallee Region Innovation Centre staff on 7 May 2021 on the project and the various sensors being used in the trials to monitor soil moisture, tree growth and quantitatively describe tree architecture. Following a visit by the organisers, the Mildura SmartFarm was selected as the "field visit" site for delegates at a planned conference showcasing AgTech to be hosted by the Mallee Regional Innovation Centre in May 2022. The conference was originally planned for November 2021, but postponed in the light of potential lockdowns.

The recent completion of the new facilities at the Mildura SmartFarm provides an opportunity to host larger groups when COVID restrictions relax. Farm-wide connectivity also broadened the possibilities for interactive farm walks for visitors.

Future events will mainly focus on events to showcase the plantings and outputs to almond producers, but will also include educational workshops to attract school students to science careers in general and agricultural science in particular. The group is also active on the Woman in STEM platform and aim to show female students the possibilities of being a female researcher in agriculture.

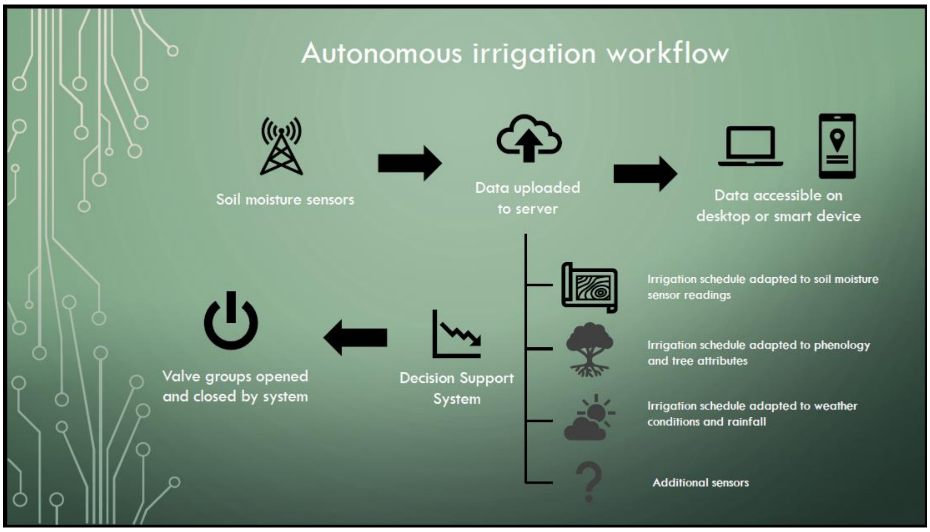

Figure 4 The interactive display prepared for visitors to the Mildura SmartFarm to explain the autonomous irrigation workflow.

Selecting an icon (except for greyed out icons that are for future use) takes the user to a separate page with more information on the individual workflow steps. This enables the user to have direct access to additional information on aspects of the workflow they have interest in.

An interactive touch screen system that was funded by Agriculture Victoria's SmartFarm initiative has been acquired to facilitate future farm visits. Figure 4 shows the interactive display that has been prepared in anticipation of visits that will provide producers/visitors/stakeholders with more information on the closed-loop autonomous irrigation workflow.

In addition, a 50-inch smart television has been procured through funding also provided by Agriculture Victoria's SmartFarm initiative and installed in the office space at the new farm shed at the Mildura SmartFarm. This enables the team to host smaller groups onsite for presentations and meetings and to participate in on-line meetings with researchers at Tatura and interstate collaborators (*e.g*. SARDI and CSIRO).

Outcomes

A program logic framework was developed at the outset of the project and is presented in *Appendix C: Project related documentation.* Briefly, against the four key headline end-of-project outcomes, the project has:

- Established robust platforms to enable the rigorous evaluation of scion x rootstock suitability for higher density plantings.
- Identified traits and genotypes that may help water use efficiency.
- Identified fertiliser management practices for young trees that may be inefficient.
- Established baseline soil chemistry/fertility against which long term impacts of high input almond production practices may be assessed.
- Used leading edge technologies to help identify growth habits and vigours more likely to be useful in high density plantings.
- The Agriculture Victoria research team has acquired new skills, technologies and crop-specific understanding to service industries' R&D needs, and a platform has been established to train an early career scientist to PhD level.
- Knowledge, skills and equipment have been shared across the three R&D agencies and a strong co-operative and consultative ethos been developed as part of the overall program.
- The potential for international collaboration is now stronger because plantings are fit-for-purpose with biometrically robust experimental designs on a credible scale. Collectively the plantings are a unique resource on a world-scale.

Agriculture Victoria has established the temperate nut orchard at the Mildura SmartFarm as a platform to research ways to improve resource use in current production systems, to provide answers to key questions underpinning the design of more intensive almond production systems and to research ways to improve fertilise use in almond orchards. The plantings are part of a larger program of work developed in conjunction with the Almond Board of Australia (ABA), the South Australian Research and Development Institute (SARDI) and NSW Department of Primary Industries (NSW DPI) with the overall aim of delivering robust knowledge that almond producers and temperate nut producers more broadly need to confidently embrace or consider more intensive production systems. The issues being tackled in the temperate nut orchard at the Mildura SmartFarm and the approaches being taken are complementary to the issues being addressed and approaches adopted by SARDI on the ABA's Loxton site. The temperate nut orchard at the Mildura SmartFarm is a unique resource.

Optimal rootzone mineral nutrient concentrations have been quantified in controlled glasshouse experiments and whilst rootstock was the single biggest and most consistent source of variation across the experiments, it was observed that the production of laterals was discouraged by low K supply, and high P supply and N supply only encouraged biomass production. As the mechanism of reduction in growth by dwarfing rootstocks is unknown, a potential connection was made with the role that rootstocks may play in modulating scion architecture as well as size, raising the possibility of growing trees better suited to higher density planting.

The N supply regime imposed on the trees in the H1 planting were based on the outcome of the glasshouse experiments. Leaves collected in H1 trees' first and third leaf indicated that despite a four-fold range in the amount of N supplied, it is very difficult to move % N in any agronomically significant manner although there were obvious signs that aspects of tree growth responded to increasing N supply. Data collected in the glasshouse trials indicated that there is little advantage in allowing the concentration of N around the roots to exceed 2 mM, a concentration which when scaled up using current water usage is in line to current N fertiliser inputs based on Californian research (Muhammad *et al.* 2015). Given the Australian almond industry strategic aim of making better use of inputs, utilising the differential rate of water versus N uptake to reduce N inputs without sacrificing productivity may be a possibility.

The literature review indicated that an understanding of the genetic, environmental and management factors that affect kernel protein qualitatively or quantitatively is largely superficial; though kernel N is known to be responsive to N supply, albeit slowly. As mentioned, the continued imposition of N supply treatment is expected to result in a population of trees with a larger differentiation in N status as trees mature, indications of which were observed with last leaf sampling.

Another inference made is that % N may not be the best indicator for assessing tree N status. The relationship between leaf N and leaf reflectance properties was not strong within the narrow range of leaf % N measured, but the data analyses conducted pointed toward other phytochemicals that potentially may be a more reliable indicator of N status of trees. Advances in the robustness and utility of spectrophotometric equipment raised the possibility that approaches could be developed that serve to provide orchard managers with better means of assessing tree N status in more or less "real time".

Observations over seasons may well be more important in the longer term because trees produce nuts as "mature" trees a lot longer than they are thought of as "establishing" trees. The availability of a planting like the Mildura SmartFarm's H1 presents an opportunity to generate a population of trees with a history of consistent nitrogen supply, and equally an opportunity to observe these trees' growth and N status, and changes in kernel N, as modulated by N supply, rootstock and scion cultivar. Further, as the trees grow larger the capacity to store nitrogen during winter and to re-mobilise it in spring becomes greater. The size of reserves has proven important in another perennial crop system in supporting spring growth before uptake becomes significant (Treeby and Wheatley 2006).

The H3 site typifies what almond producers contend with in terms of topography and the range of soil types and readily available water holding capacities. Large areas with varying topography and soil types valved singularly result in under- and over-watering of some trees; the ensuing variability in tree establishment, growth and performance is lost in averaging. In a research context, that source of variability has to be eliminated or least minimised in order to allow true treatment signals to be detected. The H3 site represents an attempt to do just that on a meaningful scale, and so a significant outcome of the project is that almond producers can be confident that project outputs are objective and robust and relevant to their orchard development and/or re-development decisions.

The outcomes of the soil survey, the H3 planting's design, the investment in irrigation infrastructure including individually valved plots, and the investment in a soil moisture sensor network has resulted in greater confidence that the responses observed and measured are a true reflection of how well-watered trees behave under the experimental conditions imposed. It also provided the opportunity to draw preliminary inferences regarding the demand for water by scion cultivar × rootstock combinations as affected by tree spacing (i.e., planting density). Tree water use efficiency was shown to be mainly driven by the rootstock and soil moisture content changes confirmed these findings. The effect of trees spacing became apparent when irrigation was withheld (wider spaced trees were less stressed). However, demand of the wider spaced trees will increase as the space fills out. Demand should more-or-less plateau over time as tree canopies are managed to not exceed a certain extent.

Data collected in the higher density plantings confirmed differences in tree architecture and irrigation indicators like the area of shade (*i.e.* canopy light interception) are modulated by the genotype and plant spacing. Observations in the higher density plantings form a unique record of multiple factors that contribute to water use by the tree and evaporation from the soil surface, as per real world conditions, and can be used to infer the amount of water demanded by each of the 72 reference plots, and by inference any plot linked to that plot. The H3 planting's irrigation system's autonomous capability means sets of plots can be watered when those plots' reference plot's soil moisture sensor detects the refill point and stops irrigating when field capacity is sensed.

Tree responses to intensive canopy management in preparation for shake-and-catch harvesting indicated clear changes in tree architecture and growth which affect the suitability of certain scion cultivar × rootstock combinations for higher density plantings. However, it is imperative to assess the long-term effects of tree hedging on the canopy as it will have implications for light interception and the degree of canopy management to maintain canopy dimensions over time. These will in turn have an effect on productivity.

Differences observed in the phenological cycle of genotypes have implications for orchard management (*e.g.*, the timing of foliar sprays to enhance aspects of reproductive biology) and the suitability of cultivars in certain locations (*e.g.*, frost-prone areas).

Although outcomes of the first two growing seasons elucidated trends, certain observations raised questions about responses that need clarification. For instance, trees on RP40 indicated tree water efficiency expected from a growth reducing rootstock, but the tree growth was similar to that of trees on the industry standard rootstock Nemaguard. The response of trees on RP40 points towards an abiotic stress avoidance strategy.

The development of science capability — both human and technical — has been another positive outcome of the establishment of the temperate nut orchard at the Mildura SmartFarm. The growth in understanding of almond production and almond physiology, the acquisition and use of new technologies, the collection of measurements and observations over three seasons and the processing and analyses of those measurements and observations has grown the skills base available to address industry's R&D priorities. Another positive stemming from the overall RRDP program has been the extensive consultation between the Agriculture Victoria and the SARDI researchers to ensure trials established on the Mildura SmartFarm and Loxton site are complementary and that common yardsticks were planted to ensure comparisons can be validly made.

Monitoring and evaluation

The project delivered against Outcome 3 of the Almond SIP 2017-2021 by providing recommendations to improve efficiencies in current production systems (Horizon 1) and through the development of the Horizon 3 planting. The project delivered these outcomes by evaluating new cultivars from the industry-supported almond breeding program in higher density planting systems established and managed to accommodate shake and catch harvesting technology. The project further delivered outputs toward the improvement of on-farm water use efficiency through the establishment of an extensive soil-moisture sensing network that demonstrate the use of soil moisture, and in the longer-term additional plant sensing technologies, to optimise irrigation management. Irrigation efficiency and irrigation management efficiency will further be improved through the demonstration of autonomous closed-loop irrigation. Input use was evaluated and nutrient thresholds determined in controlled glasshouse experiments which is now implemented in the plantings.

The demonstration and research platform at the Mildura SmartFarm was established across 21.5-ha, and consists of six plantings, each with a unique research aim and communication angle that contribute to the 2017-2021 and the refreshed almond SIP. The hands-on involvement of the research team in the establishment of the platforms vastly improved their knowledge of almond physiology and agronomy and resulted in a group of researchers with the capabilities to manage these plantings and produce research outputs with the use of advanced technology.

Several of the new Australian cultivars are used in the plantings in combination with industry standard rootstocks (Nemaguard and Garnem) as well as growth reducing rootstocks (RP20 and RP40) to assess their performance in a standard and in higher densities planting. During the course of the project the plantings have been monitored for performance, especially the H3 planting to determine the suitability of different genotypes (three scions on four rootstocks) at three different tree planting spaces. Several novel technologies were assessed and used to deliver research outcomes and an array of advanced AgTech to assist and improve orchard management practices have been installed in the plantings and utilised in management of the plantings.

Extension activities have been difficult to stage since the COVID pandemic began 18 months ago. The project team was unable to host producers and stakeholder face-to-face at the experimental orchards. However, the group was able to still communicate outcomes and promote the temperate nut orchard at the Mildura SmartFarm on virtual platforms and at other agricultural events held during periods of relaxed restrictions. Preparation have been made in anticipation for future visitors.

Potential delays in obtaining planting material, as experienced in this project and by the other delivery partners, need to be taken into consideration when timelines are established for outputs in future projects that involve establishment of perennial research platforms. The effects of adverse weather and other abiotic as well as biotic stressors need to be borne in mind.

Prior to COVID-19, the SARDI and Agriculture Victoria project teams met regularly to discuss and debate approaches, avoid duplication by ensuring complementarity of research foci and to share observations and experiences. The "conversation" has continued during COVID using online meeting platforms. The ongoing contact has been instrumental in sharing equipment and expertise, empirical observation and experience. Importantly, multi-agency collaboration is now foremost in researchers' considerations when putting together proposals; it is not an afterthought.

A mid-project review was conducted by Dr Byron de Kock in Leeton on 4 April 2018; all delivery partners were in attendance. Feedback provided at the time indicated satisfaction with the progress and reporting, and an acknowledgement that establishing field experiments was not a trivial matter and the negative impact that planting material availability, adverse weather and other factors had had.

A steering committee meeting on 9 November 2020 *via* video conferencing, and again the feedback from Hort Innovation's Dr Adrian Hunt and Ms Kathryn Young was positive.

Recommendations

Resource management

Resource input use efficiency continues to be a strategic priority for the Australian almond industry. Mineral N build up during the period of N applications suggests oversupply and inefficient use of N at the operational level. The identification of a concentration of mineral nitrogen — in the soil water surrounding the roots — above which conferred no advantage was an output of the more detailed work underpinning the design nitrogen fertigation treatments imposed on the H1 trees. However, herein may lay an opportunity to develop better means of avoiding under- and over-fertilising trees. Water and mineral nitrogen are not taken up by roots at the same rate as evidenced by mineral N build up. Modelling water and nitrogen removal from the rootzone may provide a framework to maintain N around the rootzone at approximately the "optimum" concentration whilst keeping the amount of readily available water topped up. The solutions may involve variable N and water supply. The technologies exist to manage each more or less independently but using water as the means to get nitrogen to the rootzone as well as to dilute N in the rootzone needs to be managed as part of an integrated system. The algorithms needed to drive such a system are lacking.

The difficulties encountered trying to establish a chemometric model linking leaf N status and the associated reflectance spectra highlighted two issues: the crudeness of %N as an index of tree N status and the inertia of tree N status as indicted by leaf %N. The two are not unrelated. Leaf reflectance properties was pursued in order to assess the efficacy of the technology to estimate leaf %N — the yardstick industry uses to assess tree N status. Spectrophotometry technology potentially offers a means of assessing tree N status in real time in order to modify fertigation programs during the season. It is recommended that the H1 treatments continue to be imposed to generate leaf %N values over a wider range than has been hitherto seen, and that a wider net be cast in terms of leaf N pools to identify a better yardstick. Spectrophotometry still offers the most deployable means of assessing leaf spectra properties, but the measurement mode should include absorbance (*i.e*. how much of each wavelength gets through a leaf) as well as reflectance (*i.e*. how much of each wavelength is reflected off the leaf surface).

Orchard management

Large differences in water requirements of different cultivars × rootstock × tree spacing, even early in orchard establishment, was observed. These differences in tree water needs are largely predicted by canopy size and density. This was evident in the preliminary water potential measurements and from soil water extraction rates. We have established in previous trials that cultivars need to be managed differently in irrigation, but rootstock completely masked this observation in this trial and this may become more apparent over coming seasons.

The project has also established that multiple levels of monitoring, *e.g*. soil water in combination with plant response measurements, are needed to improve irrigation efficiency. The H3 site thus presents further opportunities to identify amounts of water demanded by particular scion cultivar × rootstock × tree spacing combinations through establishment and into full production. The potential use of RP40 as a more efficient user of resources also needs further investigation.

Furthermore, the way the different rootstock × scion cultivar combinations behaved, particularly those on RP40, in response to soil water depletion differed, and this may represent an exploitable trait/behaviour to improve water use efficiency and to avoid or diminish the likelihood of abiotic stress. As trees have only reached their third leaf at the end of the project, current recommendations are preliminary and have to be confirmed as trees mature and after multiple seasons of canopy manipulation. Some of these findings can however be simulated and predictions made through the use of technology implemented at the Mildura SmartFarm.

Trends attributable to cultivar × rootstock × tree spacing emerged during the tree establishment phase and in response to initial canopy manipulations. Excessive growth in certain combinations indicate that additional management actions will be needed to prepare plantings for harvest where modified grape harvester are used. Initial observation of the growth rate of trees on the rootstocks that are currently used in industry indicates that these rootstocks will likely not be suitable for future planting systems. The densification of the canopies on these rootstocks also anticipates that productivity will gradually be reduced as less light reach the internal parts of the canopy over time.

Initial observations on the performance of the closely spaced trees seems promising but can change as canopies are filled out more and competition for nutrients and water become higher. Should these trees bear large crops, water and nutrient inputs will have to adjusted accordingly, and may even be similar to the needs of trees at a wider spacing.

Third-leaf flower count data show that there are trends in the number of flowers borne on trees across the cultivar × rootstock × tree spacing combinations. These data can serve as an indication of the potential productivity of trees, but projected yields were also strongly affected by the assumed average kernel masses used to estimate potential yields. The effect of treatments on the kernel mass, potentially growth reducing rootstock, and ultimate number of nuts over coming seasons is still under investigation. Changes in light interception as a result of the changes in tree architecture in relation to the genotypes and canopy manipulation will also modulate reproductivity in coming season. Potential densification of trees on certain rootstocks is a reality considering the natural growth habits and growth response of these rootstocks to the hedging actions.

The additional platforms developed to quantify design parameters for the orchards of the future have reached research-ready stage. Their designs and purposes are unique. It behoves the investment partners to make use of these resources to answer some of the key questions underpinning future orchard design. Data collected thus far can be used in longer-term economic modelling of costs associated with establishment and management of higher density plantings. Productivity, which will ultimately determine the profitability of these plantings, however, needs to be validated in coming seasons as trees mature and the effect on reproductivity and kernel size in relation to the treatments become apparent.

The initial cost for the establishment of higher density plantings will be higher compared to current commercial plantings due to the larger number of trees and the additional labour input required to stake trees *etc*. Extra capital expenditure may need to be made to acquire additional machinery to maintain the plantings, *e.g.* hedgers. The decrease in row width will also increase costs for irrigation infrastructure.

Initial establishment costs may be offset over the longer term by reduced need for multiple harvesting actions and reduced inputs, specifically water. It has been suggested that the smaller size of the trees will decrease irrigation inputs, and water requirements may be even further reduced for the reduced vigour rootstocks as observed in this study. The use of closed-loop irrigation — irrigating trees only when water is needed — potentially may reduce water usage to an absolute minimum and generate cost savings. A reduction in the quantities of nitrogen fertiliser used is also possible because of less unproductive vegetative growth.

Related future research opportunities

Apart from the continuation of monitoring and assessments of the plantings as noted within *Appendix A: Research outputs*, additional research questions have been identified that can be addressed using the temperate nuts orchard at the Mildura SmartFarm.

The major Australian tree fruit and nut industries are looking to move to more intensive production systems based on closer plantings and managed tree canopies. To that end, tree architecture is currently the focus in relation to the suitability of cultivars for such circumstances, and the tendency to throw more or less lateral shoots is a key determinant in this respect. Understanding of how rootstock affects tree vigour is relatively qualitative, and there is only a rudimentary appreciation of how rootstocks may alter tree architecture, but that interest is growing. A linkage between mineral nutrient supply and the impact of rootstock on scion branching has been noted in another woody perennial crop system (Cochetel *et al.* 2018). An effect of P and K supply on young grafted almond trees was observed as part of the glasshouse experiments. These observations come on the back of the discovery of a hitherto unknown class of phytohormones (Gomez-Roldan *et al.* 2008) — *viz*. strigolactones — has added another dimension to that understanding. The molecular bases of their synthesis by roots and their perception by shoots are being teased out on model dicotyledonous plants, but the knowledge being generated has clear implications for the architecture of grafted trees growing on genetically distinct rootstocks. Applying those findings to identify the mode of action of rootstocks on scion vigour and architecture may provide additional means to grow trees more suitable for closer plantings. Research in this space would likely have a broad generic application and provide benefits to industry in the medium to long term. As such, initial co-investment from sources supportive of basic research may be more appropriate.

Plant protein as a food segment is growing in importance as western populations lower red meat consumption per capita. Almond kernels contain 25% protein; an attribute used in marketing to particular demographics. As mentioned, the continued imposition of N supply treatment will result in a population of trees with differing N status, indications of which were evident with last leaf sampling. Fruit N status in many crops is affected by N supply as well as the size of the crop, and almonds are no exception (Muhammad *et al.* 2015). It is unlikely that protein is the only form of N in kernels but it does represent a very large proportion. The literature review showed that it is unknown how responsive almond kernel protein is to tree N status and hence N supply, and management and environment in general. Working toward an understanding of how to reliably manipulate kernel protein levels may present market segmentation opportunities and provide an alternative end use for damaged kernels.

An additional outcome of the establishment of the temperate nut orchard at the Mildura SmartFarm, coupled with the scope and scale of the AgTech sensors installed and the site's connectivity has been the recognition that the site is a unique platform to develop an aspect of traceability hitherto largely overlooked, namely the projection of an industry's or an enterprise's eco-credentials. A significant contributor to the success of "Brand Australia" as a food exporter is its' reputation as a "clean and green" producer. The various exporting industries that make up the horticultural sector have leveraged off this reputation to position themselves as suppliers of high-quality safe food produced in "clean and green" production systems. Many consumers would be unable to communicate what "clean and green" means exactly beyond broad notions of safe food being produced in bucolic rural landscapes. There is clearly a gap between consumers' understanding of "clean and green" and producers' and industries' efforts to be productive, meet community expectations, comply with government regulations and generate profits; be sustainable in other words. Bridging that gap may be important because Australia's competitors are improving their environmental credentials and a number of international markets require these credentials for importing. The traceability initiative coupled with the "Internet of Things" concept and a cultural expectation of ubiquitous data access provides a timely opportunity to demonstrate a means of bridging that gap.

Refereed scientific publications

Several initial papers have been identified and are currently being drafted for journal publication:

- A collaborative paper with SARDI on almond leaf spectral characteristics and leaf mineral status. The method development and results on SARDI's salt tolerance trial and Agriculture Victoria's nitrogen trial to be included.
- Shoot architecture and apical dominance in almond cultivars and the effect of management practices on tree architecture, light interception and bud initiation.
- A collaborative paper between the Agriculture Victoria Irymple and Tatura researchers and Green Atlas on the flower prediction model.
- A literature review of the factors influencing almond nut composition.

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Intellectual property, commercialisation and confidentiality

No IP, commercialisation or confidentiality issues to report.

Appendices

Appendix A: Research outputs

Appendix B: Communication outputs

Appendix C: Project related documentation

Appendix A: Research outputs

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Establishment of the Mildura SmartFarm research platform

The Australian temperate nut industries have acknowledged that new production systems need to be developed and adopted over the longer term to maintain market access and improve profitability. Possibly because it is more exposed to international market forces, the almond industry understood the drivers and was able to articulate the desired characteristics of future production systems. Nonetheless, the other temperate nut industries have — to varying degrees — also recognised that a move to more intensive production systems, based on smaller trees and closer plantings, is required. These circumstances led Agriculture Victoria, SARDI, NSW DPI and the almond industry's peak body, the Almond Board of Australia (ABA) to seek co-investment through DAWE's Rural Research and Development for Profit program to support a multi-agency co-ordinated program to develop key elements of an advanced production system using almond as an example.

As part of its component of the multi-agency program, Agriculture Victoria has developed an experimental orchard to serve as a research and communication platform for the Australian temperate nut industries. Almond is the major focus, but significant plantings of other temperate nut crops as well as macadamia were established that are consistent with the intensive production systems theme of the overall program. The Agriculture Victoria and SARDI teams consulted exhaustively to ensure that the almond plantings established on either team's sites were complementary. Part of that complementarity included using common rootstock/scion combinations as yardsticks. Agriculture Victoria's trials were also designed mindful that "seeing is believing" carries more cachet with industry than other technology transfer methods; realistically scaled trial plantings allow producers to objectively compare alternative orchard designs, rootstock/scion combinations and tree management options under the same edaphic, climatic and orchard management regimes.

The almond production system used in Australia is largely based on Californian practices. High producing almond orchards on the light textured free-draining poorly fertile soils along the Murray Valley and the Adelaide Plains use approximately 14 ML of water/ha/season (Stevens *et al.* 2012) and large amounts of fertiliser (Rosenzweig undated).

Agriculture Victoria's component also included establishing a baseline against which the long-term impact of almond production on the types of soils upon which most Australian almond orchards are established could be assessed, and to address the efficiency of some aspects of the current high input practices. Accordingly, to those ends, an extensive soil survey of the Agriculture Victoria site was undertaken using a range of conventional physical and chemical methodologies and the newer electromagnetic approach. Some of the data collected were instrumental in the design of the trials and in the design of the irrigation systems to service each trial. Input use efficiency was addressed by establishing a purpose designed trial to investigate the interaction between nitrogen supply on the one hand and rootstock/scion combinations on the other. The scion cultivars used are reflective of the almond industry's current planting mix. Nitrogen supply was the focus because of the large quantities industry uses and the known linkage with long-term soil acidification in other plant production systems. This particular trial also afforded an opportunity to test the efficacy of some proximal and remote spectrophotometric equipment with respect to more timely and frequent assessments of tree nutrient status.

Excess cation over anion removal in plant material from plant production systems is an important factor contributing to long term (*i.e.* multi-decadal) soil acidification (Bolan *et al.* 1991). From a stoichiometric viewpoint, plant roots typically take up more cations (*i.e.* NH_4^+, K^+, Ca^{2+}, Mg^{2+}, Na^+, Cu^{2+}, Zn^{2+} Fe^{2+} and Mn^{2+}) than anions (*i.e.* NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}, SiO_4^{2-}, Cl^- and MoO_4^{2-}). Typically, also, plant roots release enough H^+ to match the number of positive charges take up and release enough OH^- to balance the number of negative charges taken up. In the normal course of events there would be no net loss of nutrients and no net gain of H^+ from the system in the longer term because plants remain *in situ* and any parts shed or lost to herbivores remain more-or-less in close proximity to where it was produced. When plant material is removed from the system — as when harvested nuts are taken from an orchard — there is a net gain of H^+ in the soil, and the soil becomes more acidic as a result. Excess cation removal is the main contributing factor to soil acidification in low rainfall well irrigated situations, but there are other contributing factors: use of acidifying fertilisers such as ammonium sulphate [$(NH_4)_2.SO_4$] and mono- and di-ammonium phosphate [$NH_4.H_2PO_4$ and $(NH_4)_2.HPO_4$, respectively, and commonly referred to as MAP and DAP] and nitrate leaching being the principles.

Robust baseline data are needed to be in a position in the future to objectively assess whether modern high input almond production practices and high levels of productivity affects the soil base in any way. The Mildura SmartFarm site represented a good candidate for this exercise because access to the site is assured, and records of inputs and outputs well maintained.

Further, because bespoke drip irrigation systems would need to be designed and installed, a detailed site-wide soil texture analysis was needed. This afforded an opportunity to collect soil samples for detailed soil chemistry analysis.

An earlier soil survey of the site (Wetherby *et al.* 1994) did not include any soil chemistry measurements.

The Mildura SmartFarm

Agriculture Victoria's Mildura SmartFarm, previously known as the Mid Area, is comprised of 57 ha of land made up of three parcels around three corners of the intersection of Campbell Avenue and McCracken Street, Irymple South, in north west Victoria. The land was gazetted in the 1950s for horticultural research purposes.

The experimental orchard was established on 21.5-ha of cleared land on a 27-ha parcel on the eastern side of Campbell Avenue and south of McCracken Street; the remainder of this parcel is covered in native vegetation (Figure 5). The 21.5-ha had been used for research on tree crops and vegetables in the 1970s and 1980s, and was subsequently leased to the Victorian and Murray Valley Vine Improvement Association to produce *Vitis* rootstock cuttings and *V. vinifera* budwood for grafting. The site was irrigated with overhead sprays, and that system is still operational. Following the cessation of the lease agreement in 2005, all the *Vitis* material was removed and the land left fallow through to 2016 when the temperate nut project commenced.

Figure 5 Satellite image of the Mildura SmartFarm site

The 21.5-ha parcel (bounded by the yellow lines) is part of one of the three parcels of land comprising the Mid Area title. The remainder of the parcel is covered with native vegetation.

The remainder of the title is composed of a small (3-ha) parcel of land north of McCracken Street and on which an office/lab/machinery building was constructed in 2021. The other parcel is west of Campbell Avenue and south of McCracken Street and comprises 27-ha native vegetation and 7-ha of cleared irrigated land leased to a commercial nursery.

Image courtesy of GoogleEarth

At the outset of the project described herein the 21.5-ha of cleared land was fenced off to prevent ingress by feral and native animals.

Soil husbandry

As indicated at the outset of this report, the 21.5-ha parcel of land on which the temperate nut experimental orchard was to be established had previously been used to grow *Vitis* material for rootstocks and budwood. The *Vitis* material had been removed in 2006 and the soil left fallow since that time. Following the clearing of volunteer weeds a top dressing of 10 tonnes of gypsum per hectare was applied (Figure 6). The gypsum was incorporated deeper into the soil with a combination of discing and cultivation and rinsing with a 4-hour irrigation through the overhead sprays.

A cereal (oats) cover crop was then sown with urea, single strength superphosphate and potassium sulphate at 80, 100 and 100 kg/ha. A light application of water to stimulate germination via the overhead sprays was applied. The crop was allowed to grow with an occasional irrigation before being slashed to about 150 mm (Figure 6) and left as is. The whole area has been cover-cropped every winter since.

Figure 6 Soil husbandry practices on the Mildura SmartFarm: (left) top-dressing with gypsum to improve aggregate stability and cover cropping (right) to improve soil organic matter and reduce wind erosion

Whole site soil survey

Electromagnetic survey

A Geonics EM38 Vertical Ground Conductivity Meter was used in the vertical (0.75 m) and horizontal (1.5 m) dipole modes to assess the major changes in soil texture across the site as indicated by apparent electrical conductivity.

The unit was towed behind a quadbike. The instrument's position (eastings, northings and elevation) was recorded every few seconds using differential GPS. The quadbike's path across the 21.5-ha site is shown in Figure 7.

A survey was conducted when the soil was dry and after being wetted up by rain and an irrigation that was applied using the overhead sprinkler system.

The data were spatially interpolated using VESPER, a shareware program developed by the University of Sydney[5]. Projections of EC across the site were prepared using ArcView.

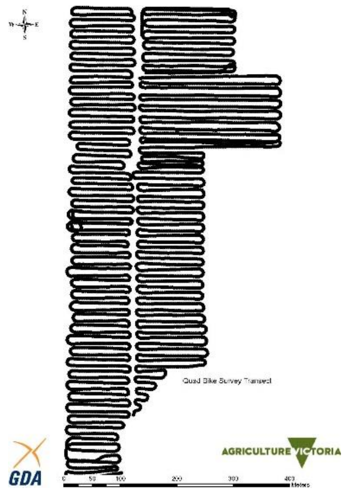

Figure 7 Quadbike path across the 21.5-ha site

Field survey of soil texture

The survey was undertaken in April 2016 by a commercial provider[6].

Forty-six pits on a 75 x 75 m grid (Figure 8) were mechanically excavated to a depth of approximately 1.5-1.8 m. Pit density was consistent with the 'Codes of Practice' and the Sunraysia Salinity Management Plan requirements for soil surveys for irrigation development. Texture analysis of each of the distinguishable soil layers evident in each pit were conducted as described by Wetherby (2011).

[5] https://precision-agriculture.sydney.edu.au/ resources/software/download-vesper/
[6] Dr. Ian Sluiter, Ogyris Pty. Ltd., PO Box 698, Merbein VIC 3498

The soil profile description at each pit consisted of:

- measurement of the depth and soil texture of each soil horizon or layer,
- assessment of the carbonate (lime) content of each layer as determined by reaction to dilute hydrochloric acid,
- carbonate layer classification (Wetherby and Oades 1975), including percentage, size and lithology of coarse fragments (if present),
- classification of the geology of each soil layer,
- determination of the wet soil colour from a Munsell Colour Chart,
- relative assessment of the moisture content of each layer,
- classification of pedality (structure) and
- measurement of the depth of topsoil and of the primary rootzone (PRZ).

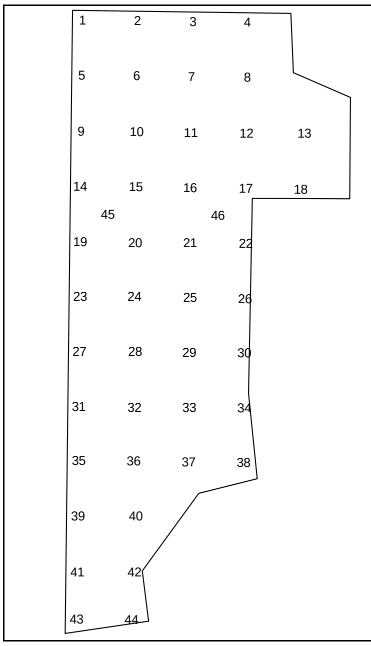

Figure 8 Projection of soil pit locations on the main 21.5-ha parcel making up the Mildura SmartFarm site

Soil chemistry/fertility indices

Approximately 1 kg of soil was collected from each layer identified in each of the 46 excavated pits. The samples (n = 183) were sent in sealed bags to a NATA-accredited commercial soil testing service[7]. The soil chemistry indices measured are listed in Table 2.

pH buffering

A pH buffering (pH_{BC}) assay described by Nelson and Su (2010) was conducted on all samples.

Briefly, the samples were air dried, sieved to 2 mm, and 7 × 2 g sub-samples were weighed into separate 25-mm screw-capped polyethylene tubes. Twenty mL of 0, 0.016, 0.032, 0.064, 0.8, 0.128 or 0.256 M HNO_3 was added to the samples amounting to 0, 160, 320, 640, 800, 1280 or 2560 mEq H^+ kg^{-1} soil. The tubes were capped, shaken at room temperature for 24 h, left for six days, shaken for a further two minutes and the pH measured with a glass electrode.

The determination of pH_{BC} relies on the fitting of a sigmoid decay function of the form:

$$pH = pH_{min} + \frac{a}{e^{\frac{-(A-A_{mid})}{b}}}$$

where A = the amount of acid added, and pH_{min}, A_{mid}, a and b are constants estimated by regression. Re-arranging that function to make A the dependent variable (*i.e.* in terms of pH) and differentiating yields dA/dpH, which is pH_{BC} in units of mEq/pH unit change:

$$pH_{BC} = \frac{a \times b}{(a - pH_{min} - pH)(pH - pH_{min})}$$

The pH value used to estimate pH_{BC} is calculated by using A_{mid} as the amount of acid added. The pH at A_{mid} is the sigmoid function's inflexion point.

Only 60% of the samples conformed with the assumed A versus pH sigmoid relationship described; the other 40% producing spurious results (*e.g.* negative A_{mid}) or the iteration process to derive the relationship's coefficients failed to converge. Further, the pH_{BC} estimates were orders of magnitude greater than published values [*e.g.* Nelson and Su (2010), Luo *et al.* (2015), Luo *et al.* (2015)]. An alternative and simple exponential decay function suggested by Luo *et al.* (2015) applied to all samples similarly resulted in spurious results or convergence failure.

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[7] https://www.nutrientadvantage.com.au/our-services/lab-services/soil-testing

Table 2 Summary of soil chemistry/fertility indices and extraction/assay methods used on soil samples collected from 46 soil pits on the 21-ha of cleared land on the Mildura SmartFarm site

Indice	Extractant/method	Unit
pH in water (pH_{H_2O})	water (1:5)	
pH in calcium chloride (pH_{CaCl_2})	calcium chloride (1:5)	
organic matter	sodium hydroxide	%
total carbon	(combustion)	″
carbonate (CO_3^{2-})	(rapid titration)	″
organic carbon (C)	CrO_4^{2-}/H_2SO_4	″
total nitrogen	(combustion)	″
nitrate-nitrogen (NO_3^--N)	potassium chloride	mg/kg
ammonium-nitrogen (NH_4^+-N)	″ ″	″
Colwell phosphorus ($P_{Colwell}$)	bicarbonate	mg/kg
BSES phosphorus (P_{BSES})	dilute sulphuric acid	″
available potassium (K_{avail})	ammonium acetate	″
sulphate-sulphur (SO_4^{2-}-S)	potassium chloride	″
″ ″ ″	mono-calcium phosphate	″
silicon – BSES (Si_{BSES})	dilute sulphuric acid	″
calcium (Ca_{exch})	ammonium acetate	cmol(+)/kg
potassium (K_{exch})	″ ″	″
magnesium (Mg_{exch})	″ ″	″
sodium (Na_{exch})	″ ″	″
aluminium (Al_{exch})	potassium chloride	″
cation exchange capacity - incl. Al (CEC)		″
exchangeable sodium percentage (ESP)		″
sodium as % of cations (incl. Al)		%
calcium:magnesium ratio		cmol(+)/cmol(+)
aluminium as % of cations		%
chloride (Cl)	sodium nitrate	mg/kg
boron (B)	calcium chloride	″
copper (DTPA-Cu)	DTPA	″
iron (DTPA-Fe)	″	″
manganese (DTPA-Mn)	″	″
zinc (DTPA-Zn)	″	″

Attempts to apply other exponential functions, including double sigmoid, were equally unsuccessful, and may have proven spurious in any case without the theoretical background described above to support any inferences drawn based on the regression coefficients estimated.

A simpler less quantitative approach was required. The sub-samples were classified based on the amount of acid required to drop the pH by at least 50% relative to the pH recorded for the sub-sample that had only 20 mL of water added. For example, if a 50% reduction in pH was observed between adding 320 mEq H^+ kg^{-1} soil and adding 640 mEq H^+ kg^{-1} soil that sample was given a rating of 3 (*i.e*. poor to moderate pH buffering capacity - Table 3). A rating of 7 (very strong buffering capacity) was given to samples where a 50% reduction was not observed.

Table 3 Soil pH_{BC} classification system based on the amount of acid added associated with a 50% pH reduction in devised for Mildura SmartFarm soils, and number and percent of samples that fell into each class

Assay conducted as per Nelson and Su (2010)

mEq H^+ added kg^{-1} soil for 50% pH reduction	class	pH_{BC} description	# samples	% of samples
0-160	1	very poor	17	9
160-320	2	poor	16	9
320-640	3	poor-moderate	16	9
640-800	4	moderate	5	3
800-1280	5	moderate-strong	19	10
1280-2560	6	strong	33	18
(50% reduction not observed)	7	very strong	77	42
		Totals	183	100

Whole site soil survey results

EM38 survey

Elevation across the site varied from about 61 to about 65 m above sea level. The site is typical of much of the Mallee; sandy ridges running more-or-less east-west with intervening lower swales.

The major textural changes across the site can be inferred from the projections of the kriged EM38 vertical and horizontal dipole measurements of soil electrical conductivity (Figure 9). The higher elevations (*i.e* the dunes) had the lowest EC and the lower elevations (*i.e*. the swales) had the highest. This co-incidence is consistent with the dunes being made up of lighter textured free draining soil types and the swales heavier textured poorer draining soil types.

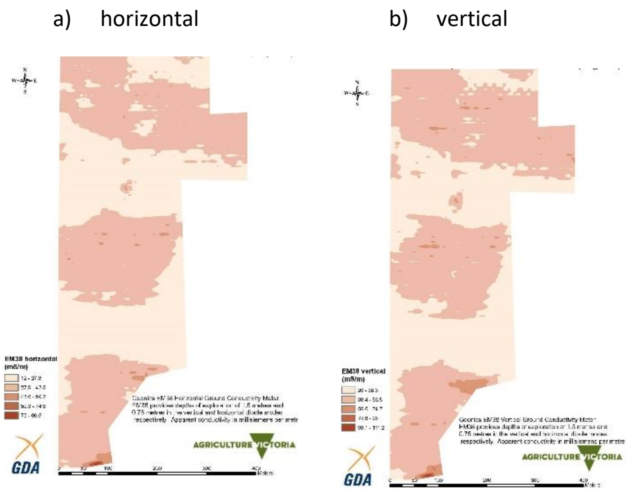


Figure 9 Projections of interpolated EM38 a) horizontal and b) vertical dipole estimates of soil conductivity ($mS.m^{-1}$) across the 21.5-ha main site

Soil chemistry/fertility indices

Some soil indices relevant to sustainability, irrigation management and almond reproductive biology for the first soil layer are presented in Figure 10. Levels of organic matter in the uppermost layer were not atypical of Mallee soils and are toward the lower end of soils in general. Building those levels with winter active cover crops and avoiding soil disturbance will contribute significantly to that aim.

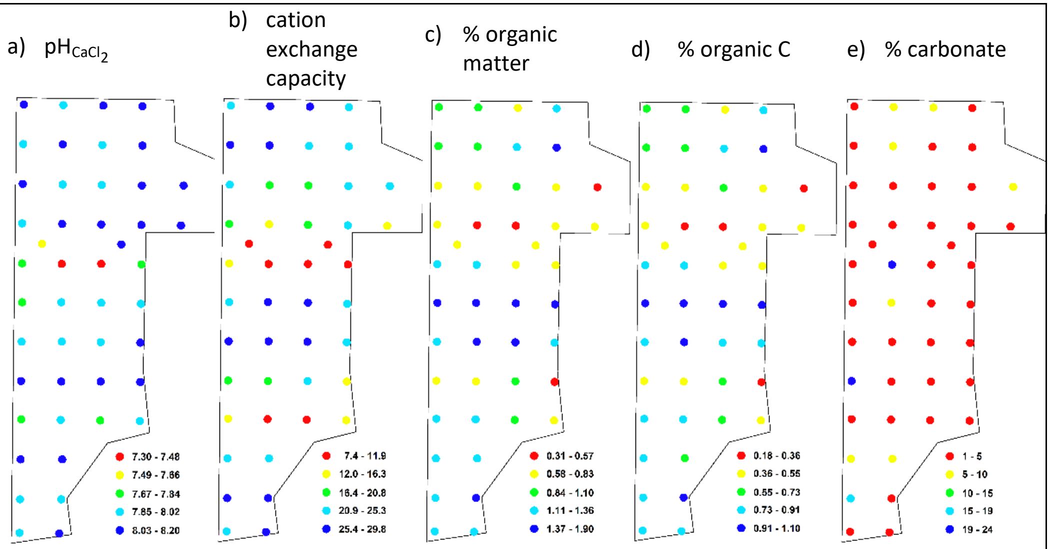


Figure 10 Selected soil indices for the upper layer for the 46 pits across the Mildura SmartFarm

Ranges at the bottom of each graphic are based on the range of analytical results across all layers

The CEC and Ca:Na ratios similarly are in the ranges likely to be measured on Mallee soils, and collectively supported the application of 10 tonnes of gypsum per hectare.

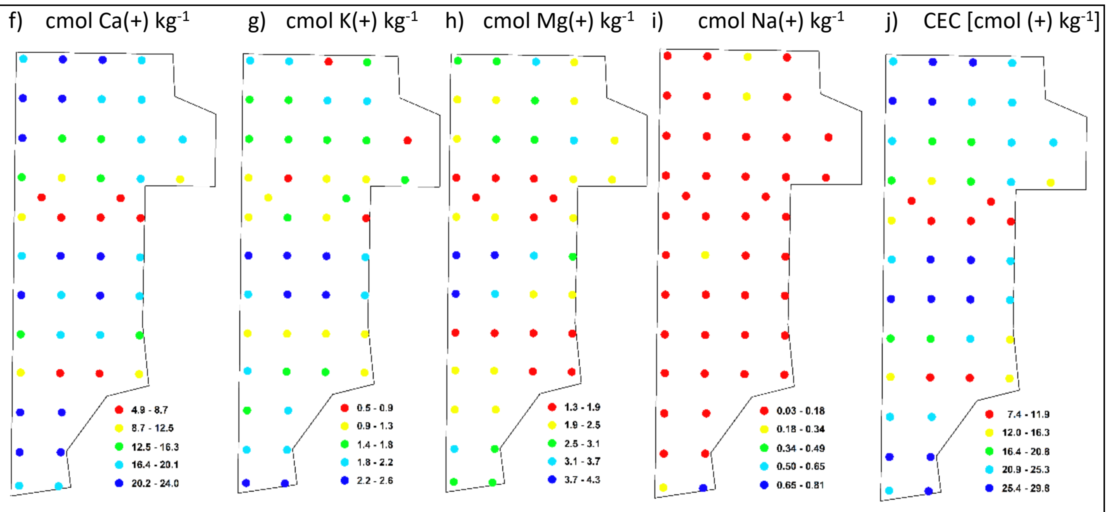


Figure 11 Soil cations for the upper layer for the 46 pits across the Mildura SmartFarm

Ranges at the bottom of each graphic are based on the range of analytical results across all layers

Using an ESP of 6 cmol(+) kg^{-1} as the sodicity threshold (Northcote and Skene 1972), all of the Mildura SmartFarm's top layer would be considered non-sodic (Figure 12), but sodicity becomes more obvious with each successive layer. The lower layers of the swale profiles were more likely to be sodic than the lower layers of the dune profiles.

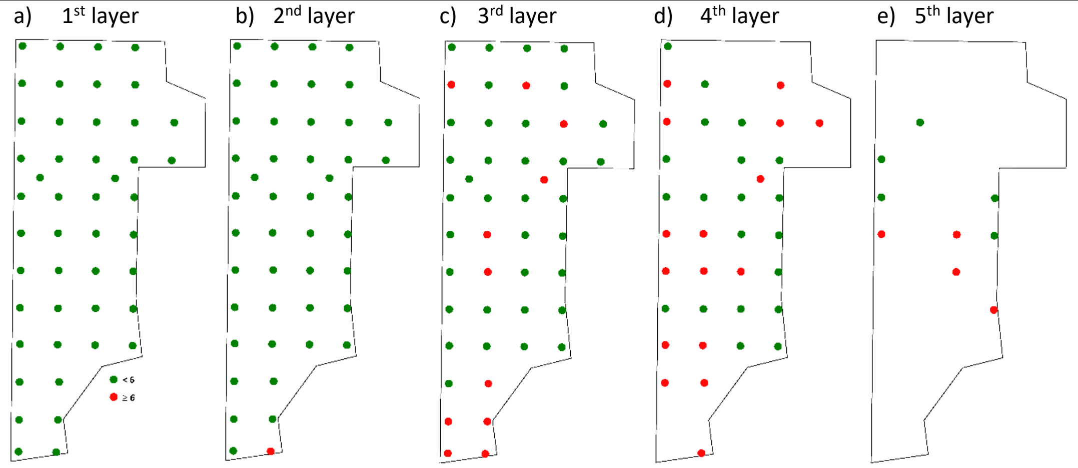


Figure 12 Soil pits with % ESP above or below 6 for each soil layer sampled

The indices of micronutrient availabilities (Figure 13) point to ongoing need to supplement soil B and Zn supply with foliar applications at appropriate times to ensure leaf function and enhance reproductive biology pollination. Manganese availability would appear to be less of a concern, but Cu and Fe potentially may be limiting.

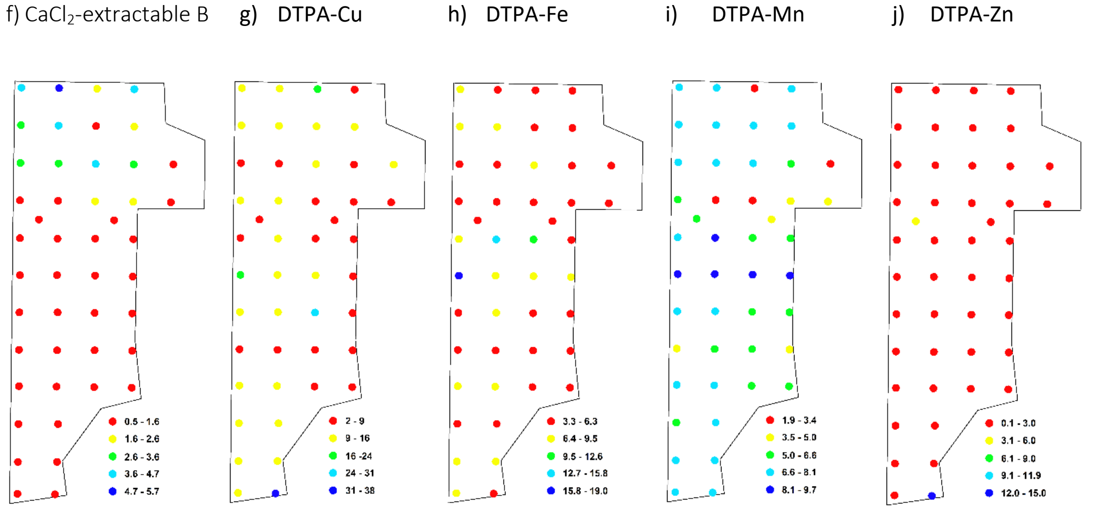


Figure 13 Micro-nutrient availabilities for the upper layer for the 46 pits across the Mildura SmartFarm

Ranges at the bottom of each graphic are based on the range of analytical results across all layers

Units are on a mg kg^{-1} basis

The amounts of readily available water (RAW) that can be held in the rootzone (Figure 14) varied by a factor of two or more across the site. The rootzones on the dunes can hold up to 69 mm of water, but the rootzones in the lower lying parts can only hold less than half that amount. These estimates of RAW were the basis of the delineation of irrigation zones across the site and informed the design of the trials established and the design of the irrigation systems installed to service the water needs of those trials.

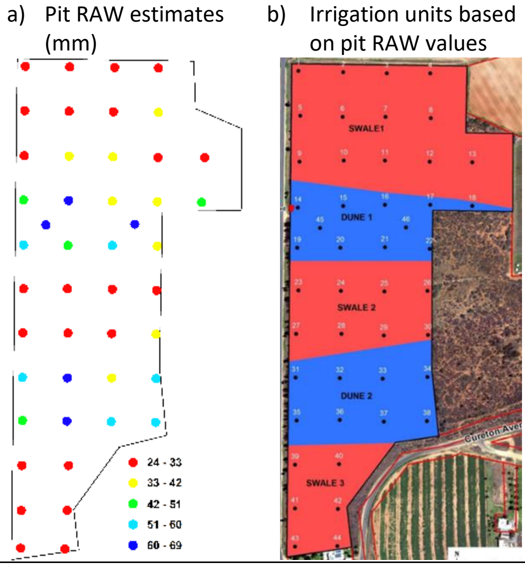


Figure 14 Millimetres of RAW that can be held in the rootzone of each soil pit and irrigation zones based on RAW values

Soil pH buffering capacity

Based on the acid added versus pH plots all samples could be broadly categorised as weakly buffered through to strongly buffered; About 40% of the samples were classified as having very strong buffering capacity. The generalisation is illustrated by the plots for six selected samples in Figure 15.

The application of the current understanding of soil pH buffering capacity failed to provide a means of differentiating the Mildura SmartFarm soil samples. The clear bi-phasic nature of the acid added versus pH relationship – evident in (c), (d) and (e) of Figure 15 – may be a strong factor in the failure of the current understanding in this field to shed any light on the pH buffering capacity across the site.

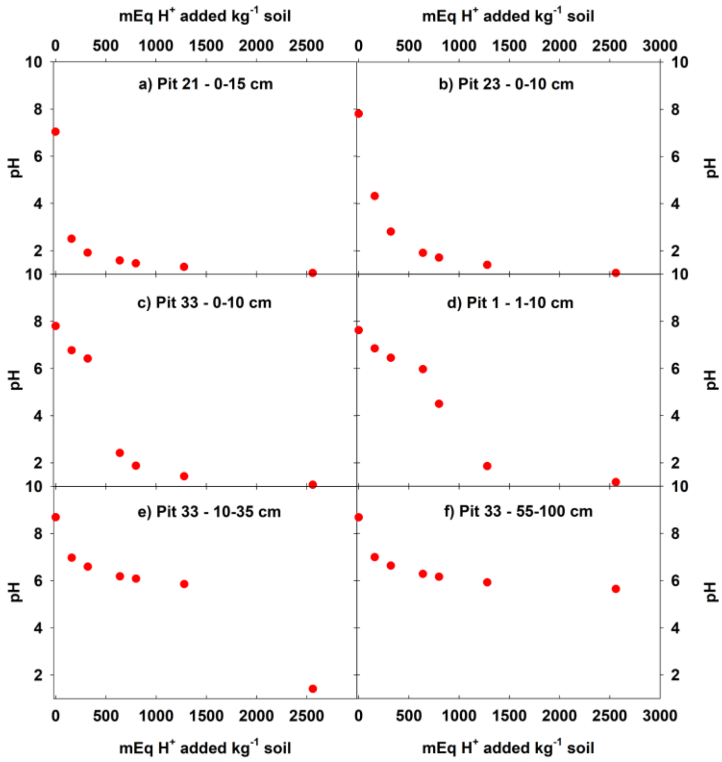
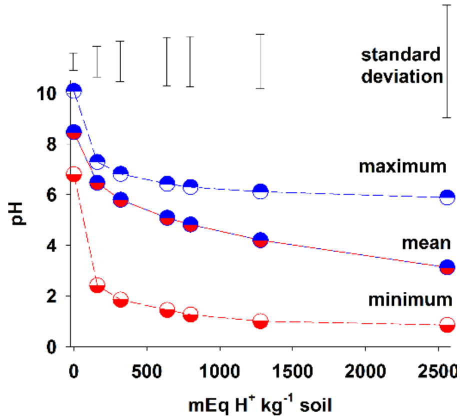


Figure 15 Effect of acid additions to the apparent pH of six selected soil samples from the Mildura SmartFarm

Population statistics (*i.e.* minimum, mean, maximum and standard deviation) for all the samples' pH measurements over the range of H^+ additions indicate that the samples quickly start segregating as more H^+ was added (Figure 16). The population standard deviation increases from 0.7 to 4.5 over the range of H^+ additions. The pH of all samples dropped with the smallest addition of acid, but the pH of 40% of the soil samples didn't decrease appreciably beyond that initial drop.

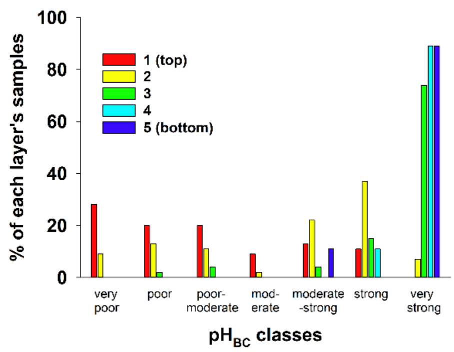
Figure 16 Basic population (n =183) statistics for soil pH as a function of H^+ added



The rating system set out in Table 3 is a simplification, but does allow some segregation of the samples. The majority of the very strongly buffered soils were found in the pits' lower layers whereas the majority of very poorly buffered soils were in the pits' top layers. In other words, rootzone soil is far more susceptible to acidification than the soil below the rootzone. It is within the rootzone that all the processes referred to previously (page 2830) take place.

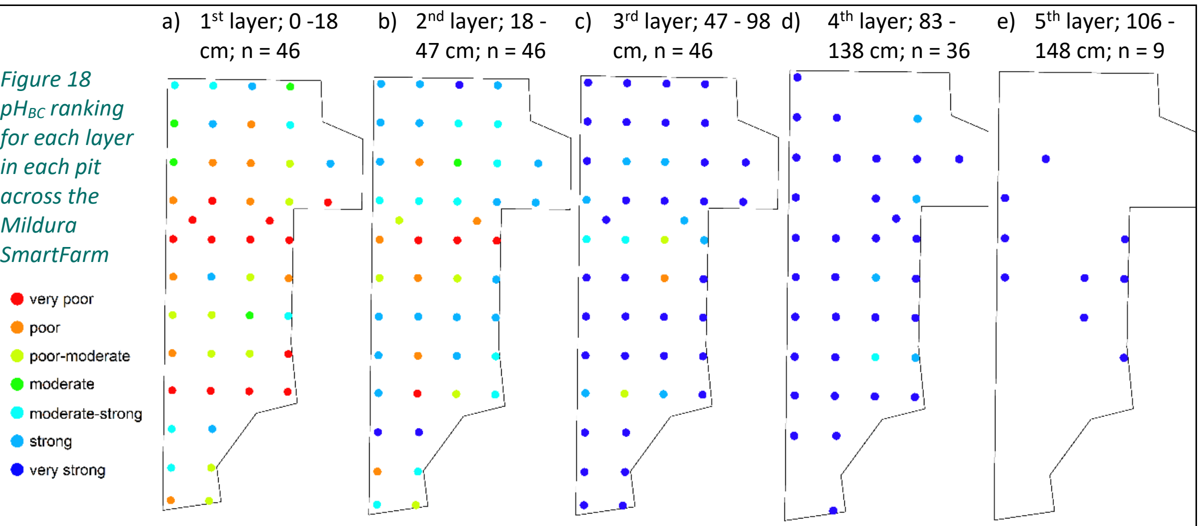
The spatial distribution of pH_{BC} rankings across the site and down the profile of each pit are presented in Figure 17and Figure 18.

Figure 17 Distribution of each layer's samples between pH_{BC} classes



Generally, the shallower soil layers were less buffered than the deeper soil layers, and the more poorly buffered soils tended to be lighter textured soils at the top of the dunes. The well buffered soils tended to be the heavier swale soils. Aside from the pits located on the dunes, most soils below 50 cm were well buffered. Building on the aforementioned more general case, longer term soil acidification is more likely down to about 50 cm on the lighter textured dune soil and less likely in the swales.

Figure 18 pH_{BC} ranking for each layer in each pit across the Mildura SmartFarm



Establishment of the research plantings

Horizon 1 platform

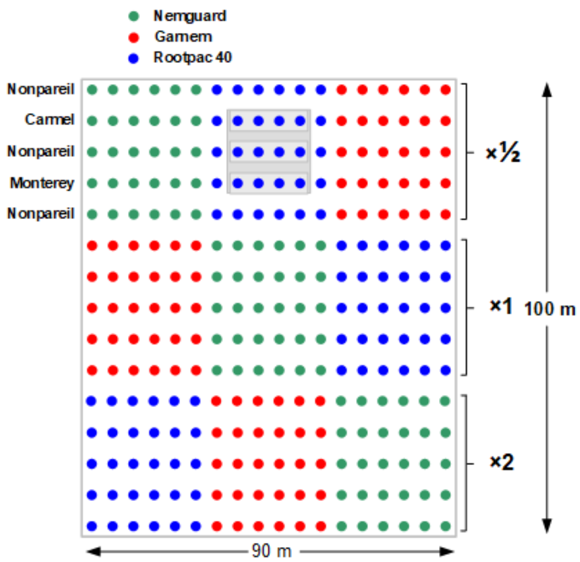
The H1 field trial planting is comprised of five blocks; the layout of a single block as an example is presented in Figure 19. Tree density is the current industry standard of 300 trees/ha; 5.0 m between trees within rows and 6.67 m between rows. Each of the five blocks cover approximately 0.9 ha, and the trial's footprint is approximately 4.5 ha (Figure 19). Including buffer trees, there are 1,350 trees within the H1 planting. Across the planting 540 trees were monitored, 108 in each block (replicate).

Figure 19 Layout of a single block for the scion/rootstock/fertigation trial established on the Mildura SmartFarm

Whole rows are planted to a single scion cultivar, with three rootstocks in each row.

A N concentration treatment was applied to five rows, which comprise a main plot.

The four middle trees of each cultivar within a main plot comprise a sub-sub-plot the middle six trees in each rootstock comprise a sub-sub-plot.



The trial is contained within the "Swale 1" portion of the northern end of the site (Figure 14).

The experimental design is a split-split plot design, where

block = block,

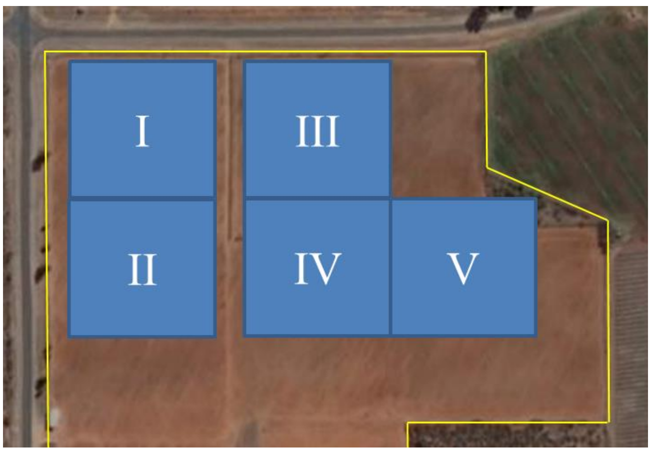
main plot = N concentration (*i.e.* ×½, ×1 or ×2 of the concentration of N identified in the glasshouse trials to be associated maximum shoot % N) applied in the irrigation water,

sub-plot = rootstock (*i.e.* Nemaguard, Garnem or RP40) and

sub-sub-plot = scion cultivar (*i.e.* Nonpareil, Carmel or Monterey).

Figure 20 Distribution of the five rootstock/fertigation blocks across the northern end of the Mildura SmartFarm

Note that this is the northern portion of the 21.5-ha shown in Figure 5



The first and last row in each main plot are buffer rows and the first and sixth trees in each sub-plot along the row likewise are buffer trees. The three centre rows of each main plot are a random arrangement of Nonpareil, Monterey and Carmel on each rootstock, but Nonpareil rows always have a Monterey and a Carmel row on either side as pollen sources as per current standard industry practice. The pollen source trees may be outer buffer trees. The design allows comparisons to be made across cultivars due to the non-random regular Monterey-Nonpareil-Carmel arrangement.

The high demand for planting material meant that only a sufficient number of trees on Garnem and Nemaguard were available to plant in early November, 2016, to fill out the three centre rows of the rootstock sub-plots. The nursery supplying the trees was affected by the storm cell that passed over the region in mid-November of that year, which pushed the availability of the remaining trees on Garnem and Nemaguard and all the trees on RP40 further into late 2017 or 2018. Supply recovered by late 2017 such that most of the trees needed to completely plant the trial were available from another source by autumn, 2018. The age difference between the trees already in the ground and the trees that were to be planted was judged to be likely to introduce a source of variability into the trial sufficient to reduce confidence in any observations or measurements made. The first trees were removed as a result, and the trial completely replanted in March, 2018. Not quite enough trees on RP40 were available due to the difficulty that the nursey had budding them over but sufficient trees had advanced to the point of being ready for planting by early winter at which time the trial was completely planted out. Growth on the trees planted in March 2018 was minimal, and it is a reasonable assumption that the 10-week difference in planting dates can be safely discounted in terms of assessing the effect of rootstock on tree establishment and time to first significant crop.

RP40 is described as moderately dwarfing, and persisting with it was a strategic decision justified by the high likelihood that it will play a significant role in future higher density almond plantings in Australia. The lack of experience more broadly in Australia with respect to the culture and grafting/budding of this rootstock will need to be addressed should the tree size and tree architecture characteristics be deemed suitable for future almond production systems.

The estimates of rootzone RAW-holding capacities for the planting varied between 24 and 42 mm (Figure 14); that range combined with the likely range in scion vigour associated with rootstock (*i.e*. Garnem > Nemaguard > RP40) on the one hand and N supply on the other, water demand by the trees was more likely to be driven by these two factors rather than cultivar. Accordingly, the system — designed, installed and commissioned in 2017 — has 45 valves to independently supply each of the nine rootstock × [N] combinations in each of the five blocks. This approach is consistent with irrigation management across the industry.

Four fertigation tanks and pulsing pumps were installed at the headworks; three units for injection of N treatment stock solutions and one unit for injection of other mineral nutrients and agrichemicals as appropriate. A Motorola irrigation control unit, capable of automatically operating up to 250 valves (*i.e.* irrigation management units), was controlled from a desktop PC through Netafim's Irritrol software package. Injections from the stock solutions were also under the control of the software.

The N supply treatments began in spring 2018. The treatments were based on the observation that 1 mM NH_4NO_3 in the nutrient solution supplied to seedling rootstocks growing in sand in a glasshouse was associated with the maximum above ground biomass production (page 64). Above this concentration of NH_4NO_3 in the nutrient solution shoot biomass did not increase significantly.

Assuming half, the same and twice that concentration of N (*i.e*. 1, 2 or 4 mM, respectively, equivalent to 14, 28 and 56 mg/L, respectively) in the fertigation mix to be supplied to the trees in the field, and assuming a reasonable range of water requirements based on the likely relative vigour of trees on each of the rootstocks modulated to some extent by N supply, allows estimates of the likely amounts of N that would be applied to trees over the course of a season (Table 4). The amounts of N likely to be supplied when the equivalent concentration of N was supplied that resulted in maximum shoot % N under controlled glasshouse conditions were more-or-less the current industry practice (*i.e*. approximately 300 kg N/ha/season). Similarly half and twice that concentration would half and double the concentration of current industry practice, respectively. The projections in Table 4 suggest that treatments being applied to trees in H1 cover the deficient through to the supra-optimal, and of sufficient range to describe response curves.

Aside from N, the H1 mineral nutrition program broadly followed industry best practice for establishing trees. Based on standard seasonal P and K input rates of 170 and 340 kg/ha, respectively, inputs in the trees second leaf were 40% of the base rate and 75% in the third leaf. The fertigation program begins in September and runs through to April, with injections at least once per week.

Table 4 Projected water demands and implied N supply for trees in the H1 planting receiving half, the same and twice the N concentration associated with maximum shoot % N in controlled glasshouse experiments

	[N] (mg/L)		
Rootstock	14	28	56
	estimated water demand (ML/ha/season)		
Garnem	10	12	14
Nemaguard	9	11	13
RP40	8	10	12
	implied N supply (kg N/ha/season)		
Garnem	140	336	785
Nemaguard	126	308	729
RP40	112	280	672

Irrigation was scheduled based on capacitance probes installed in one of the five blocks. Additional probes based on another technology were installed for diagnostic purposes. Soil moisture sensing technologies used across the Mildura SmartFarm are discussed in more detail elsewhere (page 59).

Porous ceramic soil water sampling tubes[8] were installed to enable the collection of soil water and the measurement of mineral N in that water. Two tubes per sampling site were installed; one at 600 mm and the other at 1 m. Pairs of tubes were installed at Nonpareil trees on each of the three rootstocks [Garnem (now Krymsk), Nemaguard and RP40] and in each N treatment (×½, ×1 and ×2) in blocks 1, 3 and 5.

The tubes were inserted by using a small augur of the same diameter as the tube on a long shaft to drill down to the appropriate depth and pushing the sampler down the hole with a wooden dowel. A 1:1 sand:bentonite clay slurry was poured down each hole to provide a 50-100 mm plug above the sampler to prevent a preferential path for water being provided. The rest of the hole was filled with a slurry of loose soil and water. The tubes and backfill were allowed to settle in for 2 months before the first samples were collected.

Young trees were trained to encourage straight trunks by tying to 1.5 m 25×25 mm hardwood posts hammered into the ground to 0.5 m. The trunks of all trees needed to be de-feathered to 0.5 m several times, and rootstock suckers needed to be removed regularly. The vase shape was encouraged by selecting suitable scaffold arms emanating from the trunk between 0.5 and 0.75 above the soil surface.

Tree damage due to strong winds, combined with termite damage to the wooden stakes supporting the tree (discussed in detail on p. 48), necessitated lopping all trees to about 600 mm in December 2019. Soil-borne disease further necessitated removal of all trees on Garnem at the start of 2020. The issues encountered related to biotic and abiotic stressors in general are discussed in more detail elsewhere (page 48).

Results from the assessments conducted in the planting are discussed in detail within the section *Horizon 1 – Improving resource use management.*

Horizon 3 platform

This planting was established in March 2019 to evaluate the suitability of scion cultivar/rootstock combination for future shake-and-catch harvesting systems based on closer tree spacings.

The planting covers 6.5 ha, and is comprised of 216 plots in six blocks of 36 plots each. Each plot has a 300 m^2 footprint. Three scion cultivars on four rootstocks were planted at three intra-row spacings in rows 5 m apart.

The planting occupies the middle of the site and stretches across the southern half of “Dune 1”, all of “Swale 2” and

[8] https://sentektechnologies.com/product-range/soil-data-probes/solusampler/

the northern half of “Dune 3” (Figure 14).

The experimental design is a split-split plot, where

block = block,

main plot = scion cultivar (*i.e.* A12, Carina or Vela),

sub-plot = spacing (*i.e*. 1, 2 or 4 m apart within rows, amounting to 500, 1000 or 2000 trees/ha), and

sub-sub-plot = rootstock (*i.e*. Garnem, Nemaguard, RP20 or RP40).

Plots are three rows wide, with the first and last row being buffer rows. The central nine, five and three trees are monitored in the 1, 2 or 4 m spacings, respectively, with the trees at the edges of the row acting as buffers. In total 432, 240 and 144 trees were monitored in the 1, 2 or 4 m spacings, respectively, across the first four blocks.

Rootstocks were randomised within spacing × cultivar combinations, cultivars were randomised across blocks and spacings were randomised along blocks.

As an example, a diagrammatic representation of Block 1 is presented in Figure 21

	4 m				1 m				2 m				
Vela	Gar	RP20	RP40	Nem	RP20	RP40	Nem	Gar	RP20	Nem	Gar	RP40	Vela
A12	RP20	Nem	RP40	Gar	Nem	RP20	RP40	Gar	Nem	Gar	RP40	RP20	A12
Carina	Nem	RP40	Gar	RP20	RP40	RP20	Gar	Nem	RP20	RP40	Gar	Nem	Carina

Figure 21 Diagramatic representation of Block 1 in the H3 planting

Young trees were trained to encourage a central leader and straight trunks were encouraged by also tying them to 1.5 m - 25×25 mm hardwood posts hammered into the ground to 0.5 m. As in the H1 the trunks of all trees needed to be de-feathered to 0.5 m several times, and rootstock suckers needed to be removed regularly. The trees were smaller than the H1 trees when the severe and persistent winds were experienced in the 2018-19 growing season. Unlike the H1 trees, the H3 trees did not have a vase shaped canopy that presented a large surface area to be buffeted by the multiple wind events. Nonetheless, there was a pronounced tendency for trees to bending away from the wind; a tendency exacerbated by the failure of many of the hardwood stakes due to termite damage. The failure of the hardwood stakes necessitated use of 3-m lengths of 10 mm steel rod as stakes. Initially plain rod was used, but quickly proved inadequate. Ribbed 10 mm reinforcing rod was subsequently shown to be suitable. The rods were hammered in at an angle of about 30° off the vertical and on the western side of the trees to counter the strong westerly winds that proved so damaging in the H1 planting. Two rods were frequently required to keep trees straight.

Resource availability and the group’s capacity necessitated reducing the scale of the trial from six to four blocks which is still scientifically robust for research outputs.

In winter 2020 the trees in blocks 1 to 4 were hedged using a cutter bar on a tractor-mounted hydraulic grape vine pruner. The blade was set vertically slightly away from the tractor at the top, and the trees hedged 0.5 m from the tree line on either side. The cutter bar was deemed unsuitable because many branches tended to be torn rather than cut and many prunings weren’t thrown away from the tree. The following winter (2021) blocks 1 to 4 were hedged to 0.75 m from the tree line on either side with a tractor-mounted hydraulic boom hedger with circular saws[9] which resulted in cleaner cuts and less pruning debris being left in the tree (Figure 22).

Blocks 5 and 6 were pruned horizontally at 100 cm in 2020 and 120 cm 2021 using the same equipment. The 2020 mechanical pruning was followed up with hand pruning to remove branches below the cut that were facing outward into the interrow and any downward orientated branches in the tree row.

[9] Ietto Contracting Services, Irymple, VIC, 3498

Figure 22 Dual boom hedger topper performing the hedging action at the start of the third leaf growing season.

A similar hedger, but with a single arm, has been procured to maintain canopy form in the higher density plantings in coming seasons.

The planting's 216 plots are spread over a part of the site where estimates of the amount of readily available water held in the rootzone varies by a factor of two or more (Figure 14). The different scion cultivar × rootstock × planting density could be expected to result in differing demands for water. The need – from a scientific perspective – to ensure that trees were neither under- or over-watered has been mentioned elsewhere (page 55), but the need for a more granular appreciation of RAW across the planting necessitated interpolating RAW values for each plot using the pit RAW values presented in Figure 14. The number of pits and hence the number of RAW estimates was insufficient to use any geostatistical software, which typically requires at least 100 points to make a reliable spatial interpolation.

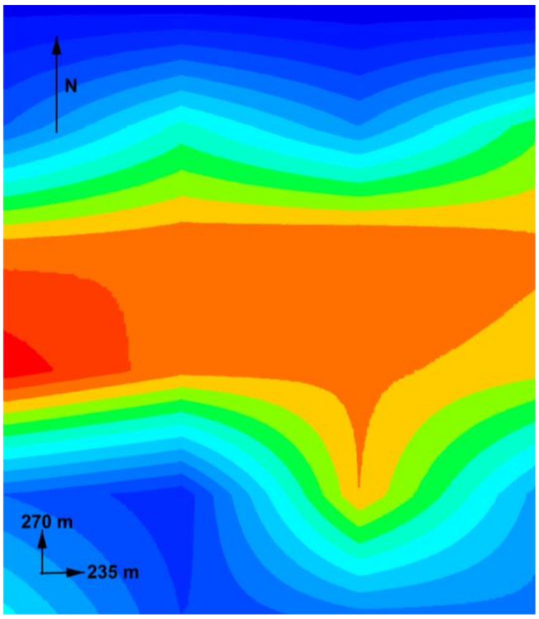
Estimates of each plot's RAW were made by interpolating between soil pits using an algorithm based on the assumption that plots near a soil pit were likely to be similar to that pit and far less similar to a pit 75 m away. Working in eastings and northings in 1 m steps the "influence" of each pit in a pair was diminished exponentially moving toward the other pit in a pair, and the influence of the other pit grew exponentially approaching that pit. The algorithm was applied between pits in an east-west and in a north-south direction. The resultant 5 m grid of RAW values was "filled" in by applying the algorithm in east-west and north-south directions using the interpolated grid values resulting in two estimates for each which were averaged. A crude projection of those RAW estimates appears in Figure 23.

Figure 23 Interpolated RAW (mm) across the 6.5-ha H3 planting

Interpolations are based on RAW estimates and likely rootzone depth in soil pits dug on a 75×75 m grid.

For reference, each of the planting's 216 plots covers 300 m^2 (i.e. 20 m × 15 m).

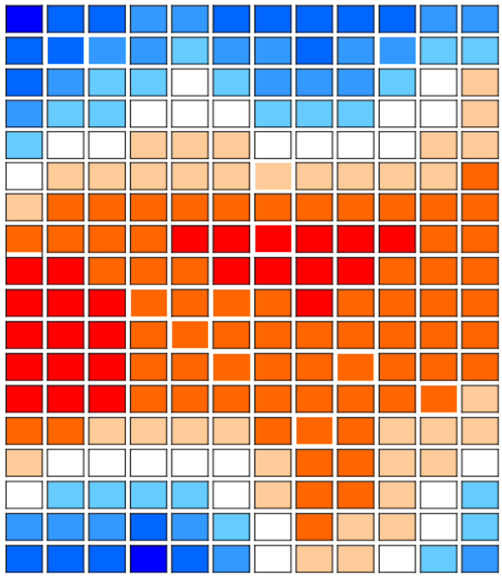
Key to colour coding: blue (highest RAW) ↔ red (least RAW).



The middle tree in the middle row of each plot was geo-located using co-ordinates in eastings and northings provided by a mobile phone app[10]. These were cross-referenced to the interpolated RAW values to identify each plot's RAW estimate. A projection of estimated RAW values for each plot appears in Figure 24, and the practical application of those interpolated plot-linked RAWs is described on page 36.

Figure 24 Distribution of interpolated RAW (mm) values for each plot in the H3 planting

Key to colour coding: blue (highest RAW) ↔ red (least RAW).



The H3 mineral nutrition program broadly followed industry best practice for establishing trees. Based on standard seasonal N, P and K input rates of 340, 170 and 340 kg/ha, respectively, inputs were 75% in the second leaf. The fertigation infrastructure to deliver dissolved mineral salts to trees in the H3 planting is less sophisticated than current industry norms, hence seasonal nutrient needs are split over only three applications: amounting to 30, 30 and 15% of the seasonal standard rates delivered in September, January and April. In the 2020-21 season magnesium nitrate was used both as a N source as well as a Mg source; the amount of Mg supplied was around 43 kg/ha.

Tree responses were determined through manual measurements and new technologies acquired not only to complement research outputs, but also to assist in managing the planting. The results are discussed in detail within the section *Horizon 3 - Suitability of new cultivars for more intensive production systems.*

Alternate nut platform

This trial was established to investigate and demonstrate some of the high-density concepts being explored in almond on alternate nuts on a limited qualitative basis. This trial will also serve to demonstrate the suitability of alternate nut types under the same edaphic and climatic conditions common in north west Victoria, south west NSW and much of the South Australian Riverland. Importantly, all the trees will be grown under the same management with modifications to reflect each nut type's particular growth, phenology and reproductive behaviour. As far as possible, scion cultivars were used that have contrasting fruit/nut-bearing structures. The same row spacing was used, but within row tree spacings were varied depending on the nut crop (Table 5). The trees will be hedged annually or bi-annually to maintain a 2-dimensional fruiting space to facilitate mechanical nut removal and collection.

Aside from the space and financial and human resources required, several considerations limit the depth to which any variable of relevance to the high-density orchard concept can be investigated.

Firstly, *Prunus* crops have an abundance of rootstock genotypes available to overcome soil-borne disease, hostile soils, limit scion size and shape and provide anchorage, amongst other traits. Rootstock usage – in Australia at least – in the other nut types is more limited; chestnut and hazelnut trees are grown on their own roots and pecan and macadamia trees grow on seedling rootstocks selected for nursery performance as opposed to agronomic performance, although that is changing for macadamia. The range of rootstocks available to the walnut and pistachio industry is quite limited. Hence, consideration of rootstock effects can only be limited.

[10] https://apps.apple.com/us/app/my-gps-coordinates/id1335952038

Secondly, there are wide disparities in the nut types' growth, phenology and reproductive biology. The latter can be summed up by the strategies many plants have to avoid self-fertilization. Dioeciousness – separate male and female trees – is one such strategy; pistachios are an example. Most other tree crops are monoecious; each tree carries both male and female reproductive structures. When male and female structures are present in the same structure (*i.e.* the flower), that structure is called perfect; macadamia is an example. In contrast, walnut, pecan, hazelnut and chestnut all have separate male and female structures; the male structure is called a catkin and the female structure is simply called the female flower. To prevent self-pollination, pollen release by the catkins is asynchronous with the receptivity of the female flower. The asynchrony can be exclusive – pollen release is completed before the female flowers are open – or there can be some overlap so at least some female flowers can be fertilised by pollen from a genetically different tree.

Nut producers get around these limitations by ensuring that there are catkins releasing pollen when female flowers are open. The timing of cultivars' pollen release and female flowers opening thus govern the mix of cultivars that need to be planted to ensure high productivity, and, given that pollen may be carried to the female flowers by wind, row orientation too plays a role. The pollen release and female flower opening timings of the hazelnut, pecan and walnut cultivars included in the alternate nut planting are presented in Figure 25, Figure 26 and Figure 27, respectively, to illustrate that strategy. The difference between the strategy used for hazelnut and pecan is that the pollen sources for the former are less than 10% of the total tree population, but the pollen source trees used in the latter make up 50% of the tree population making them significant nut producers in their own right. The proportion of male trees in a pistachio planting approximates that of the hazelnut pollen source trees in hazelnut orchards. The strategy employed by walnut producers is to plant a row of pollen source trees every 3rd or 4th row. The strategy used by chestnut producers is less clear.

Figure 25 Timing of pollen release and female flower opening of the two main hazelnut cultivars and pollen release by the two pollen source cultivars planted in the alternate nut trial

pollen release
pistal receptivity

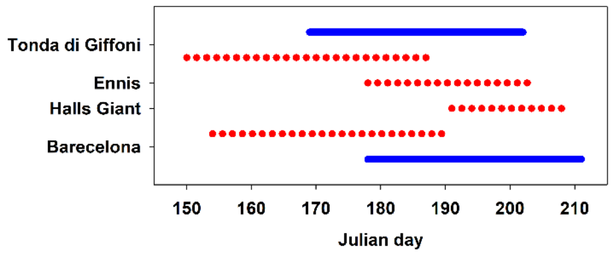


Figure 26 Timing of pollen release and female flower opening of the four pecan cultivars planted in the alternate nut trial

pollen release
pistal receptivity

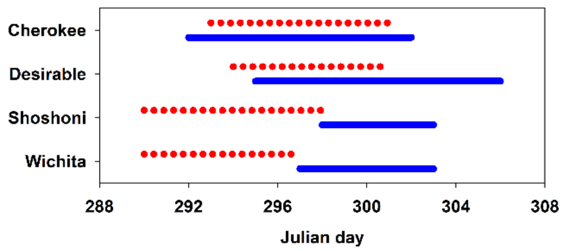
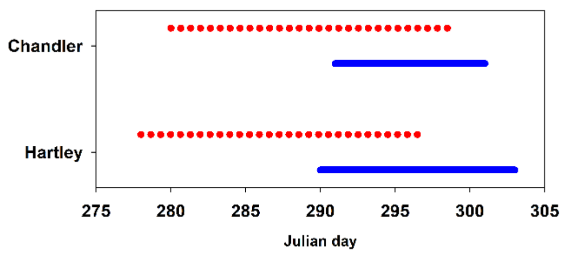


Figure 27 Timing of pollen release and female flower opening of the two walnut cultivars planted in the alternate nut trial

pollen release
pistal receptivity



Complete overlap of pollen release and female flower opening is not always possible, and suitable planting material not always available. In addition, cultivar selection was not based entirely on synchrony of pollen release and female flower opening for a nut crop type; for example, the walnut cultivars were chosen because one has a tendency to grow nuts at the tip of shoots and the other laterally. The macadamia cultivar selection was based on the long-term likely size of each cultivar; 'P'[11] trees are likely to be more compact than 'G'[12] trees.

A full list of cultivars planted and the intra-row planting distances are presented in *Table 5*. The spacings used reflect the amount of space available to accommodate the number of cultivars/rootstocks needed. The number of cultivars that could be planted was also a function of availability.

Table 5 Alternate nut types' cultivars and rootstocks and within tree row planting distances

Nut type	Variety	Rootstock	Within row spacing (m)
chestnut (*Castanea sativa*)	Red Spanish Purtons Pride Bouche de Betizac	(own roots)	3.33 & 6.67
hazelnut (*Corylus avellana* L.)	Ennis Halls Giant Tondi di Giffoni Barcelona	(own roots)	1, 2.1, 3.1 & 4.1
macadamia (*Macadamia integrifolia* & *M. tetraphylla*)	P G	(nursery-selected seedling)	2, 4 & 6
pecan (*Carya illinoinensis*)	Desirable Cherokee Shoshoni Wichita	(nursery-selected seedling)	3.3 & 6.6
pistachio (*Pistachio vera*)	Kerman Sirora G3 (♂)	UCB-1 (*Pistacia atlantica* × *P. integerrima*)	1.25, 2.5 & 5.0
walnut (*Juglans regia*)	Chandler Hartley	Paradox *(J. regia* × *J. hindsii)* American black walnut (*J. nigra*)	3.3 & 6.6

This trial will be far narrower in scope than the almond rootstock field experiments. At its simplest, the trials will demonstrate that other nut crops can be grown commercially in the region. On another level, the yield data produced will enable evidence-based gross margins to be prepared by prospective investors.

Training trial research platform

The limits of productivity possible in a 2D fruiting space are unknown, but are needed to design the orchards of the future and conduct economic projections of establishment costs and likely returns. Based on current productivity and tree spacing a target number of spurs per m of tree row has been identified, but it is unknown whether spur density is either physiologically or agronomically achievable. This trial was established to give trees the best possible opportunity to grow spurs and thereby estimate the upper limit of productivity that could be expected. Apical dominance relationships, tree-to-tree competition for water and nutrients and trees' carbon balance are being manipulating using novel tree training strategies to encourage/discourage axillary growth and the production of fruiting sites. This aim is not unrelated to the issues raised by the yield projections conducted as part of the higher

[11] https://macadamiainnovation.com.au/varieties/variety-p/
[12] https://macadamiainnovation.com.au/varieties/variety-g/

densities' component of this project (page 123). The trial was not established to compare tree training ideas *per se*, but rather to provide every opportunity for axillary growth to emerge and fruit sites to be produced.

In an area south of the H3 planting and on the western side of the site, 552 trees each of Rhea, A12 and A21 were planted in 24 120-m long trellised rows spaced 5 m apart. The same cultivar was planted down each row. A quarter of the trees of each cultivar were on Garnem, Nemaguard, RP20 and RP40, respectively. CCA-treated pine posts, 5 m long and with a 200 mm diameter, were buried to 3 m and used as strainer posts at either end of each row. Intermediate support was provided by 4-m 100-125 mm diameter CCA-treated pine posts jetted in to 1.9 m and placed every 4 m down each row. High-tensile 3.15-mm galvanised trellis wire at 0.5, 1.0, 1.5 and 2.0 m provides support for the canopy.

Four spacings were used down each row (4, 2, 1 and 0.5 m), and the four rootstocks were randomised within each spacing. For biometric purposes there were three blocks; each consisted of six rows of two groups of three rows (one of each cultivar).

Illustrative images are presented in Figure 28.The trees in one group of three rows were trained to a single leader which was trimmed to two m when it had reached three m and the laterals encouraged to grow horizontally along the trellis wires at 0.5, 1.0, 1.5 and 2.0 m.

Figure 28 Tree training treatments being applied in the tree training trial established on the Mildura SmartFarm

Top, central leader with lateral horizontal cordons established at 0.5, 1, 1,5 and 2 m above soil surface; middle: example of closely planted trees (0.5 m apart ≡ 4,000 trees/ha) trained as per trees in the top image, but cordons only extending 250 mm on either side of the central trunk; bottom: horizontal cordon established 0.5 m above soil surface and multiple leaders encouraged every 250 mm along the cordon.

Images recorded in March 2021.

Trees in the other group were trimmed to about 0.75-1.0 m and two laterals at about 0.5 m were trained onto the wire at 0.5 m above the soil surface and trimmed midway along the wire to the next tree's lateral trained onto the same wire. Those horizontal laterals were allowed to throw vertical laterals every 250 mm as multiple leaders.

The trial was a split-split-plot design where:

block = block,
main plot = tree training,
plot = cultivar,
sub-plot = spacing, and
sub-sub-plot = rootstock.

The trial covers approximately 2.7 ha. It will be a significant asset in the coming seasons.

Natural almond tree architecture

Three trees each of A12, A21, Carina, Carmel, Mira, Monterey, Nonpareil, Rhea and Vela, all on Nemaguard, were planted on an area to the west of the tree training trial in spring 2019. Tree spacing was 20 m × 20 m on an alternate diagonal arrangement. The trees had been acquired in 2018, re-potted into 10 L planting bags and grown in a shadehouse. The trees were supported with bamboo stakes to allow a central leader to grown straight up. The trees were staked with 10-mm ribbed steel rods to support the central leader. To encourage natural tree architecture the trees were not pruned before or after planting. The experiment is irrigated by the overhead spray system.

Light and spur fertility research platform

This experiment was set up to allow the quantification of the relationship between a spur's direct light exposure (quality and quantity) and its fertility. If the light exposure/spur fertility model holds up, a population of spurs that are mostly shaded during the period that floral bud primordia are initiated – thought to be late January-early February in Australia – should have a lower fertility than spurs that are mostly exposed to direct sunshine during this period.

The experiment consists of two rows of 50 Vela trees on Nemaguard planted two m apart. One row was oriented ESE-WNW at an angle of 110^o relative to magnetic north. The other row was oriented to be perpendicular, at an angle of 20^o relative to magnetic north. The orientation of the first row was such to lie predominantly under the path of the sun during late January-early February when floral primordia are believed to be initiated. Spurs on trees in this row would be shaded most of the day for the majority of the days during the period of floral bud initiation. Spurs on trees in the other row would be exposed to direct sunlight either in the morning or in the afternoon.

The trees were trained to a central leader that was trimmed off at two m to encourage laterals. The laterals were trained on trellis wires at 0.5, 1.0 1.5 and 2.0 m held up by CCA-treated pine posts every four m apart. The wires were strained at either end of each row using Walker strainers and 4-m 200-250 mm ø CCA-treated pine posts embedded two m into the ground. Galvanised screw-in anchors and threaded rod provided the strainer post with anchorage at both ends of each row.

Figure 29 Aerial image collected by a drone-mounted camera of the Light-X experiment

Note that the distortion of the rows' directions is an artifact produced by the camera's lens.

The orientation of the rows allows for the imposition of shading treatments on trees or particular parts of trees for specific periods of time. The uncertainty associated with "mostly" could be effectively minimised, allowing proportions of full sunlight to be excluded and in so doing being able to relate spur fertility to the quantity and quality of light received at the spur level during this critical period. This type of information will be relevant in designing the orchards of the future; for example, row width may be determined by the mount of light needed to encourage the fertility spurs at the bottom of a tree as well as at the top.

It is expected that this experiment will be a valuable experimental platform for at least a decade. The planting will be pivotal to providing knowledge to understanding the role that light plays in the reproductive behaviour of closely planted trees discussed on page 123).

Pollination

Beehives were placed along the plantings' central headland when trees started flowering at the standard time that industry would place beehives in the orchards (Figure 30). Each season 10-12 hives (a hive/hectare of plantings) were provided in-kind[13] to facilitate pollination.

Figure 30 Beehives supplied by Monsons Honey and Pollination services placed in the headland of the higher density plantings in 2021.

Managing biotic and abiotic stressors after establishment

Wind

Strong westerly winds were a prominent feature at the beginning of the 2019-20 season.

The H1 trees had been pruned to three or four scaffold arms the previous season and the classic vase shape used by the industry had developed on most of the trees. The trees had been staked to support the trunk and the vase using 25×25 mm 1.8 m kiln-dried hardwood stakes. These proved ineffective due to termites (Figure 31) weakening the below ground part of the posts and the posts' movement in moist soil as each tree's vase was buffeted by the wind.

Figure 31 Termite damage on hardwood stakes in the H1 planting

Image recorded in December 2020.

Two-m bamboo stakes proved slightly more effective due to their flexibility, but were prone to moving in the moist soil as the canopies were buffeted by the wind. The tree supports were upgraded to 1.5-m star pickets knocked into the ground to a depth of 0.5 m on the windward side of the tree and the trunk and a scaffold was attached. As the season progressed and the canopies developed the lack of give in the steel posts gave the canopies little capacity to deflect the wind. The wind on several days in November was sufficiently strong to cause the canopy/vase of a significant proportion of the trees to twist over generally at the point where the scaffold limbs emerged from the trunk (Figure 32). Possibly because the H1 site is flat and well exposed to westerly winds, the incidence of snapped trunks increased as the winds persisted during that month. Eventually the incidence of snapped trees was sufficient to compromise the biometric integrity of the experimental design and a decision was made to lop all the trees back to approximately 700 mm above the soil surface and let the stump throw new shoots. The lopping was conducted in December 2019, and by the end of January 2020 most trunks had new shoots from which potentially scaffolds were selected in the 2020 winter.

[13] Monsons Honey and Pollination, Buronga, NSW


Figure 32 Effect of wind on young almond trees in the H1 planting; cracked (left) and snapped (right) trunks

Images collected in November, 2019.

The termite problem was also evident in the H3 planting, but the wind effect was confined to pushing trees away from wind rather than snapping them over. The use of 3-m lengths of ribbed reinforced 10 mm steel rod proved effective – albeit costly – to prevent and/or correct that tendency.

Soil-borne disease

Aside from the weather-related issues referred to above, in the 2018-19 summer some trees in the H1 on Garnem began to display symptoms of gummosis; oozing sap, in other words. A few trees died, but the problem re-appeared in the 2019-20 summer and the incidence was much worse. Gummosis in *Prunus* can be attributed to multiple causes, but the principal cause in almond is *Phytophthora.* Foaming canker was also observed (Figure 33).

Figure 33 Symptoms of soil-borne disease infections observed on H1 trees

Below: congealed foam resulting from a foaming canker; Right: foaming canker; far right: foam and gum on trunk.

Images recorded in January, 2021.



Analyses by a plant pathologist[14] confirmed the presence of *Phytophthora* and remediation actions were taken to combat further tree losses. Phosphorus acid (H_3PO_3) was applied twice as a soil drench *via* the fertigation system

[14] Dr Len Tesoriero, NSW DPI, Menangle, NSW, 2568

during the course of the 2019-20 summer but failed to slow the rate of symptom appearance and tree death in the H1. By leaf fall that season the number of trees on Garnem to have died was such as to compromise the biometric integrity of the experimental design. A decision was made to replace the trees on Garnem with the same budlines on Krymsk-86, a *Phytophthora*-tolerant peach-plum hybrid rootstock that imparts greater vigour than Nemaguard, though not as great as Garnem. Krymsk rootlings had been obtained the previous season as "Plan B" if the phosphorus acid failed to stop tree death. These rootlings had been grown in a shadehouse and grafted over in February, 2020. The remaining trees on Garnem were excavated in June, 2020, and removed from the planting. Sufficient Krymsyk graftlings were available to plant the formerly Garnem measurement trees in late June 2020.

Birds

Large flocks of little corellas (*Cacatua sanguinea*) are not uncommon around the region over the late spring/summer period. Flocks may number many hundreds and collectively are capable of significant crop and infrastructure damage (Figure 34).

*Figure 34 Flock of little corellas (*Caatua sanguinea*) on the Mildura SmartFarm*

Image recorded in December 2020

The birds eat developing fruit as well as grass seeds[15].

A large flock began visiting the Mildura SmartFarm in 2019-20 season, possibly attracted to the winter crop residues, but were already in the habit of visiting other horticultural enterprises in the area to eat leaves and other developing fruit. The flock often nested overnight in a nearby tree lot used to dispose of winery wastewater.

Having fed the birds often chewed tree guards and drip tape causing leakages (Figure 35). Repairing the latter was a major diversion of support staff's time.

Figure 35 Damage to dripper tape caused by little corellas on the Mildura SmartFarm

Image recorded in December 2020.

Bird deterrence measures involving disturbance were largely ineffective, particularly as the flock would arrive at dawn or late in the afternoon when support staff were unavailable.

Lethal means of deterrence were unavailable given the proximity of occupied dwellings.

The questionable effectiveness of gas guns, restrictions on their time of usage and distance from dwellings precluded this option as well.

Laser bird deterrence capability[16] was acquired in January 2020. It's deployment and use are described on page 59. As the trees grew the unit was less effective because the light couldn't penetrate canopies. A succession of temporary structures to raise the unit to overcome that limitation was partially successful, but became increasingly cumbersome and not a long-term solution. Accordingly, local government approval was sought to erect a 12-m tower to mount the unit on to provide better coverage. Before approval was obtained, bird visitations increased in frequency to the point that by mid-December 2020 all fruit across the 21.5 ha were destroyed. The unit is now mounted on a 12 m tower.

[15] https://www.birdlife.org.au/bird-profile/little-corella
[16] https://www.birdxpeller.com.au/avix-autonomic

Snails

An infestation of vineyard or common white snails (*Cernuella virgata*) was observed November, 2020. The source of the infestation appeared to be vegetation along nearby roadside verge strips.

The snails nested on shaded trunks, in tree crotches and around developing fruit, but didn't appear to be feeding on the trees, and didn't move to the ground following irrigation or rain.

Their ongoing presence will pose a problem as trees produce fruit and need to be mechanically harvested.

A baiting program based on their movement – usually autumn and in response to rain – will continue to be part of the site's management program.

Figure 36 Common white snails (Cernuella virgata) nesting around developing almond fruit in the H3 planting

Image recorded in December, 2020.

Technologies to assist in orchard management

The term "AgTech" broadly covers any innovation or technology that improves efficiency, sustainability or profitability of food and fibre production systems[17]. It has become a vital part of many horticultural industries as they try to meet the challenges of climate change, input resource availability and the global demand for sustainably produced food and fibre. AgTech can provide producers with more timely information to assist in orchard management. It is now more affordable and accessible than before ever and the range available much wider.

Digital horticulture has also become a popular tool to virtually simulate the long-term performance of slow-growing perennial crops[18]. This approach enables researchers and producers to simulate novel tree establishment and management systems without investing time and money.

Multiple technologies have been installed or are being used at the Mildura SmartFarm to assist in the management of the plantings and for experimental purposes towards management improvement.

Technologies to assess tree performance - architecture and physiology

Tree architecture and physiology were assessed in relation to tree establishment and performance as affected by planting material and planting density. Specifically, the growth habits of new cultivars as modulated by rootstock and spacing, and how manipulation of the canopy by hedging influenced growth habits in the following seasons. This information is important to understand the capacity of canopies to produce fruit bearing structures (*i.e*. spurs), as well as how light interception will change in the canopy due to altered patterns of axillary growth.

Two technologies were used to define tree architecture and to describe tree growth across growing seasons.

Light detection and ranging (LiDAR)

The LiDAR system was acquired with funding provided by the Agriculture Infrastructure and Jobs Fund (AIJF) in 2019.

A Leica BLK360[19] static terrestrial laser scanner (Leica Geosystems, St Gallen, Switzerland) was used to create high-resolution 3D images of trees in the higher density planting for each of the treatments. The BLK360 scanner has a 360° horizontal and 300° vertical field of view, collecting up to 360 000 points per second. The scanner has a ranging accuracy of 4 mm and a 3D point accuracy of 6 mm at 10 m.

Figure 37 LiDAR unit used to scan trees

Scans were downloaded and registered in-field initially through the Recap Pro mobile app (discontinued in April, 2021) and the final scans with the Cyclone FIELD360 app. Images were

[17] https://launchvic.org/agtech
[18] https://www.goodfruitandvegetables.com.au/story/7413783/digital-modelling-to-influence-orchard-design/?cs=4917
[19] https://leica-geosystems.com/products/laser-scanners/scanners/blk360

processed in AutoDesk Recap and Recap Pro and Cyclone REGISTER360.

Additional images were collected in summer after active growth ended. With advances in image analyses the potential exists to model light interception from these images in the future.

This technology provides researchers with the capability to simulate growth in subsequent seasons in relation to canopy manipulation. Being able to predict canopy architecture and traits allow researchers to test for the suitability of advanced orchard systems. The need for field testing will remain, but the range of potential treatments can be narrowed.

However, the skills required to render and assess the images mean that this type of technology will unlikely see widespread adoption by industry. But, LiDAR technology on portable platforms is already accessible to industry through service providers to determine tree dimensions and for object identification (*e.g.* fruit).

LiDAR outcomes are discussed in detail on page 98 within the section on *Tree architecture*.

Remote sensing - unmanned aerial vehicle (UAV) high-resolution photogrammetry

The UAV platform was procured as part of AL14005 (*Identifying factors that influence spur productivity in almonds*) in 2019.

Aerial images of the H1 and H3 plantings were collected with a DJI Matrice 100[20] quadcopter fitted with a MicaSense Altum[21] multispectral and thermal sensor. The sensor's ground sample distance (GSD) is 5.28 cm per pixel at 120 m and the sensor's capture rate is an image per second for all bands.

The sensor captures five bands: blue (475 nm centre, 32 nm bandwidth), green (560 nm centre, 27 nm bandwidth), red (668 nm centre, 14 nm bandwidth), red edge (717 nm centre, 12 nm bandwidth) and near-infrared (842 nm centre, 57 nm bandwidth). In addition the sensor collects data in the long-wave infrared (LWIR) thermal band (8-14 µm).

Flight missions were planned and executed with the Pix4Dcapture (Pix4D S.A., Switzerland) mobile app and data were processed with Pix4Dmapper (Pix4D S.A., Switzerland) desktop software.

Tree dimension and volume data collected with a UAV platform are available to producers through service providers. These outputs are mainly used to detect areas of reduced growth in orchards. Producers are then able to diagnose the potential factors affecting tree growth and take action to ameliorate the issue.

High-resolution photogrammetry is also used for physiological assessments of the trees and can detect changes in tree health before it is visible with the naked eye. Multiple canopy indices (Wang *et al.* 2016) are available to estimate canopy chlorophyll content which is related to the nitrogen concentration of the leaves. The majority of service providers use this relationship to predict orchard nitrogen status from satellite imagery. The relationship between leaf spectral properties and nutrient contents is discussed in detail *in Leaf spectral properties and leaf mineral status.*

Figure 38 An Altum multispectral camera being connected to the DJI Matrice 100 with the Altum Skyport connection.

The GPS unit and light sensor, used to calibrate the images for changes in light during the flight, can be seen on top of the drone.

Thermal band outputs are not only useful in detecting irrigation leaks or blockages, but can also reveal output differences related to the irrigation infrastructure. The ability to do multiple flights during the season can elucidate these issues for rectification before tree health and productivity are adversely affected.

[20] https://www.dji.com/au/matrice100
[21] https://micasense.com/altum/

The technology does however require specialist skills and software for data extraction. The use of satellite imagery in higher-density plantings is currently not possible due to the resolution and the smaller canopy sizes. For mature commercial almond orchards satellite imagery resolution is satisfactory and constantly improving.

Validating the use of the UAV platform for tree height data

Similar to aerial LiDAR, terrestrial LiDAR can be used to determine tree dimensions, but data collection and extraction of information from those data are labour intensive and require specialised skills. The use of a UAV platform to determine tree height is standard practice in the forestry industry. The method allows for the collection of data across large areas and at multiple time-points negating the need for manual tree dimension measurements. The software also used for image rendering (Pix4D S.A., Prilly, Switzerland) is able to compute volumes, but as for tree dimensions requires ground truthing.

Following workflow development and method validation, this technology will be implemented for the rapid determination of tree heights and dimensions for a large number of trees and at multiple time-points over a growing season. The technology will have most use evaluating genotype suitability for higher density plantings. As discussed later excessive shoot growth, which is mostly a function of rootstock during the season, can increase the canopy size to an extent that an over-the-row harvester might not be able to be accommodated.

To determine the tree heights from aerial imaging double grid flights, ensuring an 80% frontal and side overlap, were conducted at 60 m above ground level (AGD) at 5.2 m/s, resulting in a ground sample distances (GSD) of 3.52 cm, with the sensor capturing an image every second. Tree heights were determined by subtracting the digital terrain model (DTM) from the digital surface model (DSM) in ArcGIS (Esri, West Redlands, USA) and ground-truthed with tree height measurements conducted manually at the same time as the flight. Trees for the validation (n = 118 and 72 for the H1 and H3 plantings, respectively) were selected to include all treatments to ensure that the relationship is validated for a wide range of tree heights and canopy densities. The workflow is shown in Figure 39.

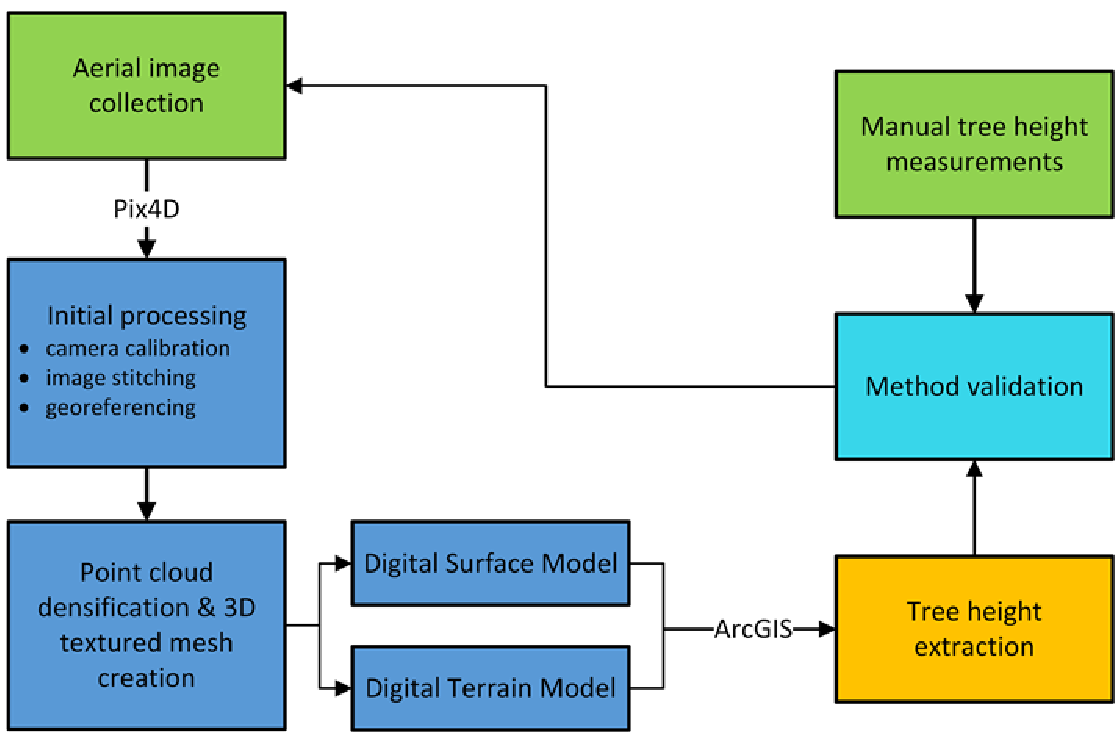


Figure 39 Workflow to validate the method to determine tree heights with images collected with a UAV platform

Examples of the outputs from point cloud densification and tree height calculations are shown in Figure 40.

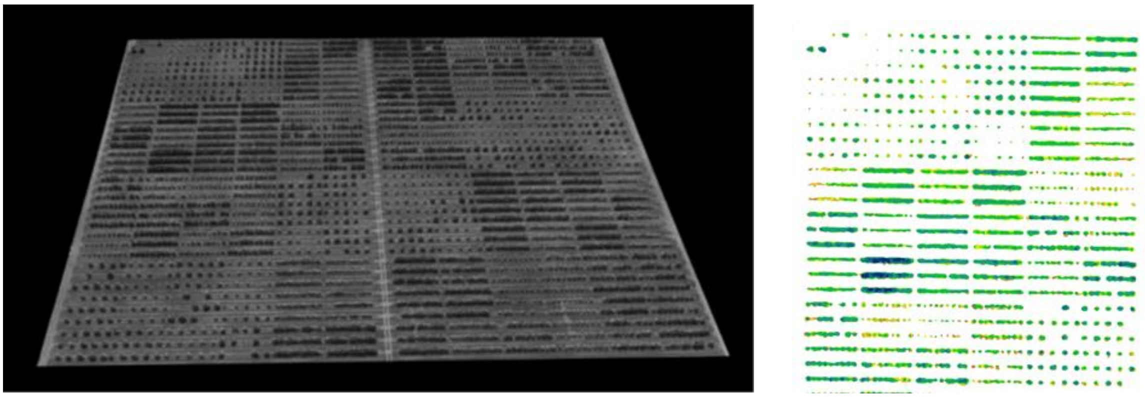


Figure 40 Examples of the outputs for the creation of the densified point cloud in Pix4D (left) and the resulting tree heights (m) calculated from the digital terrain and surface models in ArcGIS (right)

As the method to extract single trees have not yet been developed, tree heights were manually extracted from the spatial output and used as the dependent variable against the tree height measurements collected in the H1 and higher density plantings (H3). The relationships between tree heights determined from data collected by the drone in relation to absolute tree height measurements are shown in Figure 41.

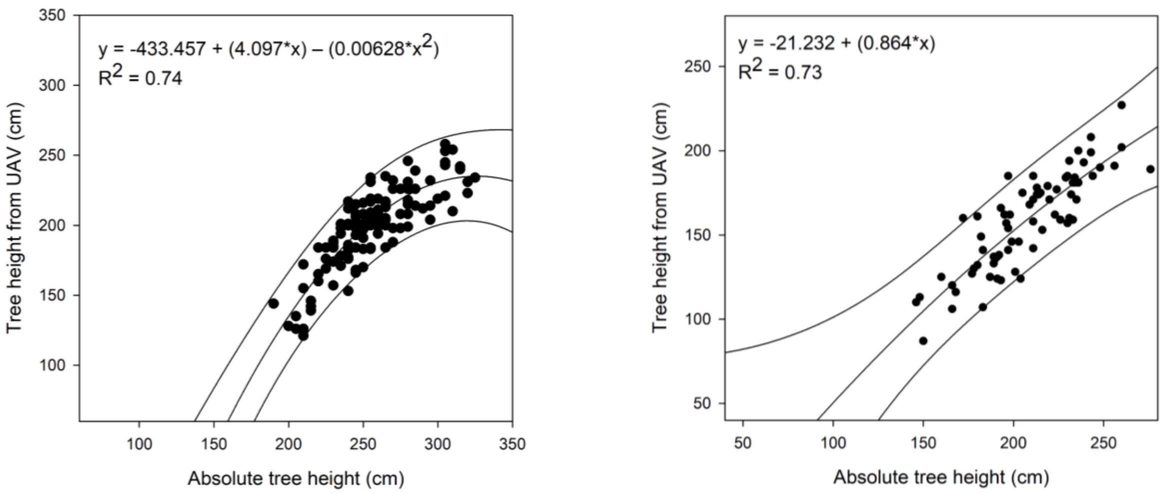


Figure 41 Relationship between the measured tree height values and the tree heights estimated from images collected by a UAV for trees in the H1 (left) and higher densities (H3) (right) plantings

A good relationship is seen between absolute and calculated tree heights in both plantings (Figure 41). The trees in the H1 planting are larger than trees in the H3 planting and have different shapes (*i.e.* vase versus hedged), and it appears that up until around 250 cm the relationship is linear between the absolute tree heights and the tree heights from the data collected by the UAV. As trees get taller the degree that tree heights are underestimated by the UAV increases. Absolute tree heights were measured to the top of the longest shoot. Depending on the density of vertical growth at this height this detail will be lost during processing of the aerial images due to loss in resolution during image processing. Furthermore, height values are categorised during processing and pixels represent more of an "overall mean" tree height per tree.

Even though the values are consistently lower for those collected by the UAV, the method is adequate to compare treatments and will be implemented in coming seasons.

Proximal sensing – spectroradiometric measurements

A Spectral Evolution RS 3500[22] spectroradiometer was acquired in 2017 with Victorian Government funding through Agriculture Victoria's SmartFarm initiative. The device is portable and robust; no moving parts make it suitable for both laboratory and field-based measurements.

Figure 42 Handheld leaf clip attachment used to measure light reflectance with SR 3500 spectroradiometer

The RS-3500 collects irradiance or radiance measurements across the ultraviolet, visible, near infrared and shortwave infrared regions of the spectrum in 1 nm increments. Three 100% diode array detectors cover the 350-2500 nm range: a 512 element Si detector (350-1000 nm) and two 256 element extended wavelength detectors (1000-1900 nm and 1900-2500 nm, respectively).

The instrument was supplied with handheld leaf clip (Figure 42), a pre-optic accessory specifically designed for leaf reflectance measurements. The integrated light source eliminates potential "noise" due to natural light variations and environmental effects, making it ideal for ground truthing hyperspectral or multispectral data.

The H1 trees provided a suitable platform to test whether a relationship could be established between leaf N content and the spectral characteristics of those leaves. The use of the instrument and the results obtained are discussed in detail in *Leaf spectral properties and leaf mineral status.*

Dendrometers

Six DE-1M[23] trunk dendrometers were acquired through Victoria's On-Farm Internet of Things Trial and installed in August 2021. The sensors connect to the EnviroEye[24] cloud platform through a Laird Sentrius RG191[25] LoRaWAN gateway. Real-time data can be connected to other platforms for public access. The aim is to make the data available for viewing by stakeholders and almond producers on the HIN Nut Network.

Figure 43 A trunk dendrometer installed on a tree in the higher density plantings

Dendrometers are precision sensors designed to measure very small movements such as the expansions and contractions of tree trunks that occur over a diurnal cycle. Those meaurements can be used in irrigation management, but also for diagnostic purposes because the long term trend in trunk diameter is a good indictor of tree growth. Used in combination with the soil moisture sensing technology that is already installed in the higher density plantings, the dendrometers will provide an additional level of insight into the tree water use in relation to soil moisture availability.

Technologies to assess the environment

Soil moisture

Overwatering is as much of a danger to tree health as under-watering is an impediment to tree growth. Adequate water supply is needed to ensure that the tree architecture measured and described reflected the genetic potential of the scion cultivars as modulated by rootstock and planting density in the case of the H3 planting and N supply in the case of the H1 planting. The influence of soil type (texture, depth *etc*.) on the degree of modulation a rootstock may exert on a scion cultivar's growth and physiology is accounted for by careful blocking based on a comprehensive soil survey and the experimental design. It is important from a scientific rigour viewpoint to be confident that trees' apparent responses are due to the treatments and not an artefact of under- or over-watering.

In the case of the H1 planting the amount of RAW that could be held in the rootzone was reasonably uniform (see

[22] https://spectralevolution.com/products/hardware/compact-lab-spectroradiometers/sr-3500/
[23] https://agriwan.com/product/trunk-stem-dendrometers-nbiot/
[24] https://www.enviroeye.com.au/
[25] https://www.lairdconnect.com/wireless-modules/lorawan-solutions

Figure 14), being mostly 24-32 mm but it could be up to 42 mm in some parts. The amount of RAW that could be held across the 6.5 ha H3 planting however varied from approximately 60 mm to slightly more than 20 mm. The trial's 216 plots (*i.e*. 3 cultivars × 4 rootstocks × 3 spacings × 6 blocks) were each valved separately as a result. To ensure that the plots were not over- or under-watered soil moisture sensor data were used to manage the irrigation schedules in both plantings. However, monitoring soil moisture in many plots represented a significant logistical difficulty.

Two different types of soil moisture sensor were installed and used for soil moisture monitoring: capacitance probes in the H1 and time domain transmissometry (TDT) in H3. TDT sensors are less sensitive to signal attenuation by soil texture, and accordingly the need for calibration less critical. The soil moisture sensors installed and used in irrigation management at the Mildura SmartFarm is discussed in detail in the next sections.

EnviroSCAN probes

EnviroSCAN[26] probes are widely used in industry in combination with climatic data for irrigation management.

Figure 44 Image showing the EnviroSCAN probe sensors at different depths

Image courtesy of https://en.npcagro.com/

Eleven probes were procured in 2018 and installed in the H1 planting. Nine sensors are installed in Nonpareil × rootstock × nitrogen treatment plots, and two sensors in Carmel and Monterey on Nemaguard in the ×1 nitrogen treatment to represent the industry standard plantings. Irrigation management is crucial in this orchard because of the soil properties (discussed in *Whole site soil survey* and *Whole site soil)* and the infiltration issues in certain areas of the planting. The sensors' outputs are used to ensure that irrigation is sufficient while avoiding over-watering those areas with a low infiltration rate; waterlogging has serious implications for disease, especially *Phytophthora*, in this planting.

The sensor data is available in real-time through the IrriMAX Live[27] online portal.

Aquaflex soil moisture and temperature sensors

The Aquaflex[28] soil moisture probe is a TDT sensor in a 3-m ribbon configuration that is laid horizontally to provide an integrated estimate of soil along the tree row. A network of 72 soil moisture sensors was acquired using project funds. The sensors were installed in 72 plots selected to cover the range of RAW values.

The sensors were installed in the winter of 2020. A 4-m long 150-mm wide trench was excavated 400 mm from the tree line to a depth of 400 mm. The trench was centred on the middle tree in each plot. The trench was cleared of loose soil with a trenching shovel, checked for depth consistency and modified as needed (Figure 44). The ribbon was laid flat in the trench and the trench backfilled. The sensors were hardwired to a datalogger which was in turn hardwired to a radio transmitter on a 3-m tower. Power to the logger is supplied by a solar panel on each tower. Each datalogger has the capacity to collect and transmit data from two sensors, and that option was exercised when the distance between two sensors was no greater than 20 m. In those cases, a 200-mm deep trench was dug between the plots to accommodate the connecting wire.

In three plots in the lighter soils and three plots in the swale an additional Aquaflex probe was installed at 1 m to assess water movement downward and possibly beyond the rootzone. In addition, six TDT sensors in the traditional vertical probe configuration[29] were installed in these locations that was acquired with additional funding provided under another Victorian Government initiative[30]. These sensors are described in more detail in a subsequent section.

[26] https://sentektechnologies.com/product-range/soil-data-probes/enviroscan/
[27] https://www.irrimaxlive.com/
[28] https://goldtecsystems.com.au/product/aquaflex-systems/
[29] https://www.gropoint.com/products/soil-sensors
[30] Agricultural Jobs and Infrastructure Fund

Figure 45 Aquaflex ribbon TDT soil moisture probe installation (left) and pole-mounted radio transmitter and power supply (right)

The soil moisture sensor network was used to monitor the soil moisture content over the 2020-21 season to gain experience with the sensor's integrated estimate of soil water. As an example, soil moisture traces for Carina on Garnem and RP20 in the 2 m spacing located in the swale is shown in Figure 46. The data is for the period between 21 and 27 January 2021 when high daily temperature maximas for consecutive days were recorded by the AWS (*MEA automatic weather station*) (Table 6).

Table 6 Mean daily weather data recorded by the automatic weather station from 21 to 27 January 2021

Date	T_{min} (°C)	T_{mean} (°C)	T_{max} (°C)	Mean wind speed (km/h)	Rainfall (mm)	ET_o (mm)
21/01	13.1	22.9	32.9	2.3	0	5.87
22/01	16.4	26.7	36.1	3.9	0	6.72
23/01	17.0	27.3	36.5	4.8	0	7.13
24/01	21.3	30.5	39.9	3.7	0	6.87
25/01	26.3	34.3	42.6	8.7	0	8.94
26/01	20.2	27.5	38.3	11.9	3.8	5.37
27/01	14.6	21.0	26.7	7.4	0.4	4.34

The plots in the lighter textured parts of the planting were watered separately and less frequently than plots in the swale that held less RAW, with plots in the swale being watered almost every day (Figure 46).

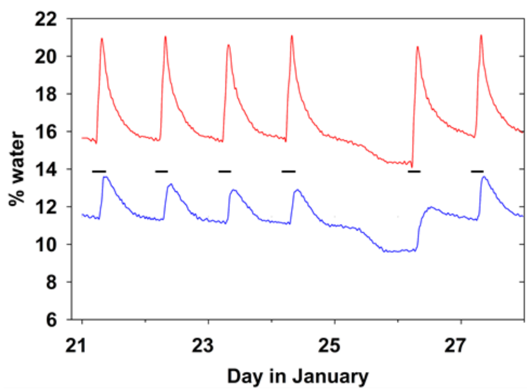


Figure 46 Soil moisture traces for a week in late January 2021 for 2-m spaced Carina trees on Garnem (blue) and RP20 (red) located in the swale

Short black bars indicate when irrigation was applied

The sensors interface wirelessly with the H3 irrigation control unit[31], which can act on the sensors' outputs to make decisions to open and close valves for individual plots of trees. Preliminary assessment of the data has been used to determine the fill and run of points. Open/close thresholds have been identified as experience grew interpreting the ribbon soil moisture traces.

"Like" plots without a sensor were grouped with an appropriate plot with a sensor and the system. The basis of the grouping was – in order of importance – plot RAW estimate, planting density, rootstock and scion cultivar. On these bases, less than a third of the sensors will only control irrigation decisions for their own plots and two of the sensors will control the irrigation decisions for themselves and seven other plots.

Essentially, the irrigation system will then be autonomous. Although the capability has been available for several years, it has not been widely adopted. On one level autonomous irrigation would represent a cost saving, and on another level would represent elimination of operators' subjectivity and eliminate staffing issues during holidays and long weekends *etc*. A *prima facie* case for water savings is reasonable, as is a case for more appropriate demand-driven water delivery, but both are unproven objectively at this point.

Ongoing research

The irrigation system installed in the higher density plantings has the capability to autonomously control the valves through the Dream 2 control system according to user defined soil moisture thresholds. This coming season the characterization of the soil moisture thresholds will continue and first trials on autonomous closed loop irrigation will commence. With the recent connectivity upgrades at the Mildura SmartFarm the potential now also exists to further improve irrigation by incorporating data on plant water needs and the environment through the SupPlant Growth Based Irrigation internet platform. Sensors that are already installed in the planting can also be connected to the platform.

GroPoint soil moisture sensors

Nine GroPoint Profile[32] soil moisture sensors were procured in 2020 through AIJF and installed in November 2020. The sensors measure soil water content and soil temperature at multiple depths. Soil moisture is measured up to a depth of 90 cm and the output is the average volumetric soil content for six 15 cm long segments along the probe.

Six of the sensors were installed in the higher density plantings plots where an Aquaflex sensor is installed at both 40 cm and 100 cm (each cultivar on Nemaguard and at 4-m spacing). Three sensors were installed on the dune and three in the swale to monitor the movement of water though the soil profile and corroborate values measured by the Aquaflex sensors.

The three remaining sensors were installed in the H1 planting. Two in locations where it is known that the soil had irrigation infiltration issues, and one a location which is considered to have good infiltration.

Sensors are manually downloaded via Bluetooth connection with the GP reader mobile app.

Climate

MEA automatic weather station

An MEA Junior[33] automatic weather station (AWS) was procured in 2018.

The real-time data is available on the Greenbrain online portal and is, amongst other applications, used to determine spraying conditions. The data is also available to internal AVR staff on the Virtual SmartFarm platform (https://smartfarms.agriculture.vic.gov.au/mildura).

TinyTag network

Temperature loggers were installed across the higher density orchard to investigate spatial temperature differences between treatments, and differences in temperature above and within the tree line in relation to the ambient temperature collected by the AWS.

[31] https://goldtecsystems.com.au/product/dream-2-irrigation-control-and-supervisory-system/
[32] https://www.gropoint.com/products/soil-sensors/gropoint-profile
[33] https://greenbrain.ag/documents/mea-weather-station-brochure.pdf

Twenty Tinytag Plus 2-TGP-4020 temperature loggers[34] were installed at a height of 1 m and 2m across the higher density orchards at the start of the 2020-21 season. The thermistor probes were positioned within gill screens and temperature and relative humidity data recoded every 15 minutes.

Figure 47 A TinyTag temperature probe installed at 2 m within a gill screen in the higher density plantings.

Data was manually downloaded with a portable device through TinyTag Explorer (Gemini dataloggers, Chichester, UK) software.

Outcomes from data collected this past season in the higher density plantings are discussed within the section on *Spatiotemporal differences in microclimate*.

Technology to assist in crop protection

The AVIX Autonomic Mark II bird deterrent system[35] was procured towards the end of 2019.

Visual bird deterrent systems have become popular in recent years and has shown to be effective in deterring birds in several horticultural crops. Factors that increased the popularity is the silent operation of the system, the ease of operation, that it can operate over a large area and that it's not harmful to animals.

The Mildura SmartFarm is located in a residential area making the use of acoustic deterrent systems discourteous. The Mildura SmartFarm is the perfect location to assess the effectivity of bird laser deterrent systems as large flocks of corellas are drawn to this area at dusk and dawn to feed because of the vicinity of nearby trees to roost on overnight and the availability of other edible horticultural crops.

Figure 48 The AVIX autonomic bird laser system installed on the temporary platform at the Mildura SmartFarm

An AVIX Autonomic Mark II was installed at the Mildura SmartFarm in January 2020. Due to the risks associated with the use of the laser (Class 3B) all OH&S policies and procedures had to be in place and the operational area defined before installation and operation. All users also completed the online training provided by AVIX.

Bird laser deterrent systems produce a green laser beam (between 520 and 532 nm) because green is the colour most visible to birds and the most effective for deterrent purposes. Birds perceive the green beam as a threat and as a result don't land on the area covered by the random laser light patterns.

The laser was programmed through the AVIX Connect app to run at dusk and dawn for 3-hour timeslots when birds were generally more likely visit the location. Two patterns were programmed to alternately run within the H1 and H3 planting. The patterns were changed at several timepoints across the season.

The system was initially installed on a temporary structure at 3 m which was sufficient in the first season when the trees were still small. The laser range is around 100 m for every metre above ground level that the device is positioned. The temporary structure became ineffective during the second season as tree heights increased. The process to install a 12-m pole was initiated early in the season to increase the efficiency and the area of coverage, but delays obtaining local government approval, as well as delays in delivery of the pole due to COVID, pushed the pole's installation forward to February 2021. Laser operation for the 2021-22 season was initiated in September 2021 and the increased height of the pole provides coverage of the whole orchard.

The system proved to be extremely effective and immediate results were seen after installation in the first season. It has been noticed that an increase in light intensity later in the morning dims the beam to a level that the birds can't detect it anymore, making it less efficient. This necessitates the use of other bird deterrent systems, *e.g.* acoustic systems, to sustain bird deterrence during daylight hours.

Connectivity at the Mildura SmartFarm

The recent upgrades to the facilities at the Mildura SmartFarm included infrastructure that provides farm-wide 5G WiFi coverage. This will enable real-time data collection from sensors and the capability to upload data directly to the

[34] https://www.geminidataloggers.com/data-loggers/tinytag-plus-2/tgp-4020
[35] https://www.avix.com/deter-birds-automatically/

cloud from anywhere within the experimental orchards. A Laird Sentrius RG191 LoRaWAN gateway was also acquired through Victoria's On-Farm Internet of Things Trial which extends the capability to connect to an array of different sensors other than to those that are already installed.

For now, two platforms have been identified for the visualisation of sensor data. Data will be accessible to industry on the Horticulture Industry Network's Nut Network webpage[36]) and internally on AVR's Virtual SmartFarm platform[37].

Horizon 1 – Improving resource use management

Nitrogen (N) fertiliser inputs into newly planted and established almond orchards are high in comparison to nitrogen inputs into other perennial horticultural systems and annual cropping. Rapid tree establishment is encouraged to hasten cropping and high inputs are required to maintain high productivity. Whilst partially explicable by logistical considerations, nitrogen fertiliser needs of all cultivars are generally considered to be the same despite ample empirical evidence that cultivars' growth habits and vigour differs. Equally, rootstock is seldom a consideration in fertiliser programs despite – again – ample empirical evidence of rootstock-related differences in scion vigour. This is also backed by experimental data showing agronomically important differences in scion mineral nutrient status related to rootstock.

Glasshouse trials

Summary	
Why?	• efficient use of resource inputs needed • rootstocks major resource gatekeeper for scions • rootstock/scion interactions poorly understood
How?	• sand culture (small scale glasshouse trials?) • controlled concentrations of mineral nutrients around roots • frequent rootzone rinsing and replenishment
What?	• optimum rootzone nitrogen concentration identified • branching suppressed by high phosphorus • branching enhanced at high potassium
So?	• upper limit for rootzone nitrogen concentration defined • tree architecture linked to mineral supply
Next?	• field test optimum rootzone nitrogen • synchronise water and nitrogen? • model system for scion / rootstock interactions

Growing plants in sand culture or nutrient solution offers the possibility of controlling the concentrations of mineral nutrients around the roots. It is concentration (*i.e*. the amount of a given solute per unit volume of water) that plant roots contend with, not absolute amounts supplied. Given that water is absorbed at greater rates than nutrients are taken up, in a normal soil situation the concentration of any dissolved plant mineral nutrient will change dynamically. The likelihood of being able to establish a manageable relationship between concentration and uptake under those circumstances is very low. Controlled environment experiments using sand culture circumvent that problem by frequent flushing of the rootzone. Glasshouse experiments are by their nature short term experiments: weeks/months, not years.

[36] http://www.hin.com.au/networks/nut-network#tab__178082
[37] https://smartfarms.agriculture.vic.gov.au/mildura

Materials and methods

A large cell in a AVR's glasshouse at the Irymple site was used. Given the cell's dimensions, and OH&S requirements for access *etc*., there was sufficient space for 210×40-L pots arranged in seven blocks of 30 trees each (Figure 49). An unbalanced design with six plots within each block, where each rootstock was included in a plot. Only five of the six N supply treatments appeared in each block and each treatment was applied the same number of times across an experimental run.

Figure 49 Almond rootstocks growing in sand culture in the first small-scale fertigation experiment at the Irymple glasshouse

Table 7 Modified Hoagland solution supplied to Prunus and Juglans rootstock genotypes in sand culture

The composition of the original solution was published by Hoagland and Arnon (1950), and, aside from variable N, P and K, modifications include the addition of Si, Co, Se and Ni and use FeEDDHA as opposed to FeEDTA

Nutrient	supplied as…	and…	and…	at ….	
N	NH_4NO_3			2.0 (0.25 – 16)	mM
P	KH_2PO_4			0.4 (0.02 – 2.5)	mM
K	K_2SO_4	KH_2PO_4	K_2SeO_4	0.7 (0.2 – 25)	mM
Ca	$CaCl_2.2H_2O$			3	mM
Mg	$MgSO_4.7H_2O$			0.5	mM
K	KH_2PO_4	K_2SO_4		1.8	mM
S	$MgSO_4.7H_2O$	K_2SO_4	$NiSO_4.6H_2O$	1.2	mM
Cl	$CaCl_2.2H_2O$	$CoCl_2.6H_2O$		6	mM
Na	$Na_2SiO_3.5H_2O$	$Na_2MoO_4.2H_2O$		4	mM
Si	$Na_2SiO_3.5H_2O$			2	mM
Fe	FeEDDHA			5	µM
B	H_3BO_3			5	µM
Mn	$MnSO_4.H_2O$			1	µM
Zn	$ZnSO_4.7H_2O$			0.1	µM
Cu	$CuSO_4.5H_2O$			0.1	µM
Mo	$Na_2MoO_4.2H_2O$			0.5	µM
Co	$CoCl_2.6H_2O$			0.02	µM
Se	K_2SeO_4			0.02	µM
Ni	$NiSO_4.6H_2O$			0.02	µM

The infrastructure required to impose seven different nutrient solution treatments was purpose built. Four hundred litres of nutrient solution were prepared using RO-grade (<10 μS/m) water supplied by a reverse osmosis unit capable of producing 6 KL of RO-water per day. Enough RO-water was always on hand to ensure sufficient solution to completely rinse depleted nutrient solution from the around the roots every two days.

A modified Hoagland solution (Hoagland and Arnon 1950) (Table 7) was used in all experiments and washed course river sand was used as the growth medium.

Eight separate experiments were conducted; some were run concurrently (Table 8).

Table 8 Summary of glasshouse sand culture/nutrient solution experiments

Note that experiments 2 and 3, 4 and 5, and 6, 7 and 8 were conducted concurrently

	Treatment variables				
Experiment	Rootstocks	Scion	[N]	[P_i]	[K^+]
1. Effect of rootzone nitrogen concentrations on shoot biomass and % N accumulated by almond rootstocks that impart a range of vigours to scion cultivars	Bright's hybrid Garnem GF677 Nemaguard RP40 Rootpac R	-	0.25 0.5 1.0 2.0 4.0 8.0 16.0	0.4	0.7
2. Almond rootstock responses to nitrogen concentrations in the rootzone	Garnem Nemaguard RP40	-	0.25 0.5 1.0 2.0 4.0 8.0 16.0	0.4	0.7
3. Walnut rootstock responses to nitrogen concentrations in the rootzone	American black walnut Northern Californian black walnut Paradox	-	0.25 0.5 1.0 2.0 4.0 8.0 16.0	0.4	0.7
4. Almond rootstock responses to inorganic phosphate concentrations in the rootzone	Garnem Nemaguard RP20 RP40	-	1.0	0.02 0.1 0.5 2.5	5.0
5. Almond rootstock responses to potassium concentrations in the rootzone	Garnem Nemaguard RP20 RP40	-	1.0	0.5	0.2 1.0 5.0 25.0
6. Rootzone nitrogen concentrations × rootstock × scion cultivar interactions: above ground biomass and branching	Nemaguard RP40	Nonpareil Carmel	0.5 1.0 2.0	0.5	1.0
7. Rootzone inorganic phosphorus concentrations × rootstock × scion cultivar interactions: above ground biomass and branching	Nemaguard RP40	Nonpareil Carmel	1.0	0.25 0.5 1.0	1.0
8. Rootzone potassium concentrations × rootstock × scion cultivar interactions: above ground biomass and branching	Nemaguard RP40	Nonpareil Carmel	1.0	0.5	0.5 1.0 2.0

The initial glasshouse fertigation experiments were designed to identify the concentration of N associated with maximum % N in the shoot dry matter. Three runs of the experiment were conducted. The first (experiment 1 in Table 8) involved six rootstock genotypes; Garnem, GF677, Nemaguard, RP40, Rootpac R and Bright's Hybrid.

The first experiment established that the maximum % N in the plants was achieved by a concentration of 1 mM NH_4NO_3 in the nutrient solution. This is generally considered to be at the lower end of the concentration range at which the low affinity transport system begins to operate. Below that concentration, the high affinity transport system operates exclusively (Miller *et al.* 2007).

Because of the importance of nitrogen in almond productivity the experiment was repeated, focussing on the three rootstocks that made up the H1 planting (experiment 2 in Table 8). The glasshouse capacity not being used for almond rootstocks was used to assess the response of walnut rootstocks to the concentration of nitrogen in the nutrient solution (experiment 3 in Table 8). The range of rootstocks available for walnuts was far more limited than the range of rootstocks available for almond; these included American black walnut (*Juglans nigra*), Northern Californian black walnut (*J. hindsii*) and 'Paradox' [a hybrid of Northern Californian black walnut and English walnut (*J. regia*)]. A logical inclusion in the list would have been 'Royal', a *J. nigra* × *J. regia*, a hybrid rootstock widely used in Europe and the USA that is not available in Australia.

Table 9 Concentrations (mM) of ammonium nitrate supplied to Prunus *and* Juglans *rootstock genotypes growing in sand culture*

TTT	mM NH_4NO_3	mM N	mg N L^{-1}
1	0.125	0.25	3.5
2	0.25	0.5	7.0
3	0.5	1.0	14
4	1.0	2.0	28
5	2.0	4.0	56
6	4.0	8.0	112
7	8.0	16.0	224

Responses of *Prunus* and *Juglans* rootstocks to N concentration in the rootzone (Experiments 2 and 3 in Table 8) were assessed across seven nutrient solution N concentrations (Table 9) supplied as ammonium nitrate (NH_4NO_3).

Table 10 Nitrogen treatments and concentrations in irrigation water supplied to Nonpareil trees in California for four seasons

Values are a function of total seasonal supply and proportion of total supply supplied at four time points each season

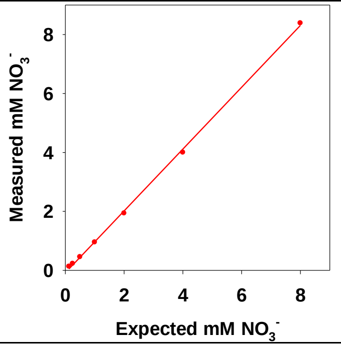
Based on Table 5 in Muhammad et al. (2015). 14.3 ML water supplied/ha/season in 1, 4, 14 and 4 irrigations in winter, spring, summer and autumn, respectively; 0.62 ML/ha supplied at each irrigation event.

	% seasonal N			
	20	30	30	20
	supplied at			
kg N/ha/season	mid-Feb	early April	mid-June	postharvest (Sept)
	kg/ha supplied at each application			
140	28	42	42	28
224	44.8	67.2	67.2	44.8
309	61.8	92.7	92.7	61.8
392	78.4	117.6	117.6	78.4
	mM N in irrigation water			
140	3.2	4.8	4.8	3.2
224	5.1	7.7	7.7	5.1
309	7.1	10.6	10.6	7.1
392	9	13.5	13.5	9

To put the N concentrations applied in the glasshouse trials into some industry context, the concentrations of N in the irrigation water supplied to Nonpareil trees in the field trial described by Muhammad *et al.* (2015), were calculated as set out in Table 10.

The concentration of nitrate applied by the fertigation system was checked by collecting nutrient solution being emitted by the drippers and using nitrate-sensitive test strips that was read with a Merck test strip reader calibrated against standard solutions. The correlation between expected versus actual application was very strong (Figure 50).

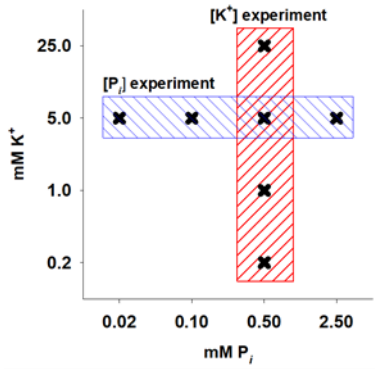
Figure 50 Relationship between expected and measured NO_3^- concentrations (mM) for the glasshouse fertigation system



The responses of four rootstocks (Garnem, Nemaguard, RP20 and RP40) to P and K concentrations were assessed in two experiments that ran concurrently (experiments 4 and 5 in Table 8). A standard N application of 1 mM nitrogen was supplied to the rootstocks and the P and K treatments that were imposed is set out in Figure 51.

The final three experiments (experiments 6 to 8 in Table 8) were conducted on grafted almond rootstocks and also ran concurrently. The responses of the two major almond scion cultivars (Nonpareil and Carmel) on two rootstocks (Nemaguard and RP40) were evaluated for biomass and axillary growth in relation to rootzone N, P and K concentrations. In each experiment one of the nutrient's concentrations were evaluated while the other two remained the same.

Figure 51 Concurrent treatments imposed to assess responses of seedling almond rootstocks to rootzone P and K concentrations in separate experiments conducted concurrently



Results

Effect of rootzone nitrogen concentrations on shoot biomass production by almond and walnut rootstocks

The initial glasshouse fertigation experiment was designed to identify the concentration of nitrogen (N) associated with maximum above ground dry matter production. Six rootstock genotypes were used; Garnem, GF677, Bright's Hybrid, Nemaguard, RP40 and Rootpac R (RPR). The relative vigour conferred on scion cultivars growing on these rootstocks lessens from Garnem through to RPR, though there is less experience with the Rootpac series in Australia.

All bar two (GF677 and Nemaguard) rootstock genotypes failed to survive when grown at 0.25 mM N. The data were analysed excluding that treatment accordingly.

Shoot biomass was affected by rootstock and by the concentration of N in the nutrient solution (Table 11). There was no significant interaction between those two experimental variables; above ground biomass production by all rootstocks increased as nutrient solution N concentrations rose to 2 mM N at which point above ground biomass was maximised. Beyond that concentration above ground biomass production was lessened by increasing nutrient solution N concentrations. Shoot biomasses did not reflect the generally understood relative scion vigours when grafted on these rootstocks; Garnem, GF677 and Nemaguard shoot dry weights were the same, and Bright's Hybrid and RP40 produced the same above ground biomass. Rootpac R did reflect the vigour, producing the least aboveground vigour compared to the other rootstocks. No rootstock responded at a different rate to increasing N concentration around the roots than any other rootstock.

Table 11 Rootstock and nutrient solution N concentration main effects on above ground biomass at harvest, shoot N content and shoot % N

Different letters following each mean within each main effect point indicate significant (P = 0.05) differences between means.

		g DM/shoot	mg N/shoot	% N
Rootstock	Garnem	10.6 a	316 b	2.98 b
	GF677	12.3 a	310 b	2.56 a
	Bright's Hybrid	7.1 b	208 cd	2.96 b
	Nemaguard	11.6 a	399 a	3.40 c
	RP40	6.5 b	225 c	3.58 d
	RPR	4.5 c	170 d	3.80 e
mM N	0.5	6.22 a	144 a	2.41 a
	1	8.68 b	231 b	2.79 b
	2	11.80 c	346 d	3.06 c
	4	9.92 b	301 c	3.18 c
	8	8.53 b	284 c	3.40 d
	16	8.69 b	315 cd	3.72 d

Nemaguard shoots accumulated the most N and Rootpac R the least (Table 12). Apart from the mean for the 16 mM treatment, the N concentration main effects suggest that maximum N was accumulated at 2 mM. Examination of the rootstock × mM N interactions (Table 12) indicated that that generalisation applied to Garnem and Bright's Hybrid, and that the amount of N accumulated by GF677 and Rootpac R shoots did not increase as the N concentration in the nutrient solution rose beyond 2 mM. The anomalous shoot N main effect at 16 mM N was due to the amount of N accumulated by Nemaguard.

Table 12 Rootstock × nutrient solution N concentration (mM) on shoot N content (mg N/shoot) at harvest

Means followed by different letters are significantly (P = 0.05) different.

	mM N					
Rootstock	0.5	1.0	2.0	4.0	8.0	16.0
Garnem	96 a-c	264 f-l	484 p	367 l-o	305 i-m	301 i-m
GF677	185 c-g	215 d-i	356 k-o	368 m-o	333 j-n	362 l-o
Bright's Hybrid	68 ab	210 d-i	305 i-m	211 d-i	153 a-d	172 c-f
Nemaguard	187 c-g	288 g-m	452 op	389 m-p	411 n-p	590 q
RP40	182 c-f	257 e-k	223 d-i	233 d-j	291 h-m	150 a-d
RPR	62 a	149 a-d	190 c-h	172 b-f	159 a-e	204 d-i

The % N in shoot dry matter was lower in those rootstocks considered to be vigorous and higher in those rootstocks considered to be dwarfing (Table 11). The mM N main effects show a gradual increase in shoot % N as the concentration of N in the nutrient solution rose. The rootstock × mM N interactions (Table 13) indicate that those N supply main effects were generally observed with the exception of Bright's Hybrid where % N did not change between 1.0 and 8.0 mM.

Table 13 Rootstock × nutrient solution N concentration (mM) on shoot % N

Means followed by different letters are significantly (P = 0.05) different.

	mM N					
Rootstock	0.5	1	2	4	8	16
Garnem	2.48 b	2.53 bc	2.93 d	2.90 d	3.28 ef	3.61 hi
GF677	2.03 a	2.43 b	2.39 b	2.46 b	2.87 d	2.99 d
Bright's Hybrid	2.32 ab	2.83 d	2.88 d	2.79 cd	3.04 d	3.33 e-h
Nemaguard	2.48 b	2.82 d	3.34 f-h	3.77 i-l	3.74 ij	3.93 j-l
RP40	2.49 b	2.98 d	3.38gh	3.76 i-k	3.81 i-l	4.29 mn
RPR	3.07 de	3.32 e-g	3.61 hi	3.76 i-l	4.04 k-m	4.50 n

The anomalous observations prompted a repeat of the experiment but focussing on the three rootstocks used in the H1 planting namely Garnem, Nemaguard and RP40. Additionally, unlike the first run, analyses could be confined to leaves due to the amount of leaf material available versus the amount of material need for analysis. In the previous run analyses were conducted on whole shoots. Analysing leaves only also enabled easier reference to published data and reference to interpretative standards.

Table 14 Rootstock and nutrient solution N concentration (mM) main effects on above ground biomass (g) at harvest

Rootstock × mM N interaction means followed by different letters are significantly (P = 0.05) different and means within each main effect followed by different letters are significantly (P = 0.05) different.

	mM N							Rootstock main effects
Rootstock	0.25	0.5	1	2	4	8	16	
Garnem	5.2 ab	21.5 gh	38.1 i	21.2 g	13.5 e	7.3 a-c	12 e	16.9 b
Nemaguard	10.3 de	27 h	41.2 i	24.6 gh	12.9 e	9.2 c-e	8.7 b-e	19.1 a
RP40	4.7 a	14.5 f	14.3 f	14.7 fg	8.6 a-d	4.9 a	4.8 a	9.5 c
mM N main effects	6.8 a	21.0 c	31.2 d	20.2 bc	11.7 bc	7.2 ab	8.5 bc	

Main rootstock and N concentration effects on shoot dry matter at harvest (Table 14) suggest firstly that the relative vigour imparted by Garnem on scions is not related to the inherent vigour it displays as an ungrafted plant. Secondly, shoot dry matter production was maximised at 1 mM N in Garnem and Nemaguard, with only a slight increase in biomass observed in RP40 at 2 mM. The interaction term indicated that that observation held for Garnem and Nemaguard but that above ground biomass production by RP40 was the same at 1 mM as it was at 2 mM and at 4 mM N.

The analysis of the leaf N data showed that rootstock as a main effect was not a significant source of variation and that leaf % N increased more-or-less steadily as the concentration of N in the nutrient solution increased from 0.25 to 16 mM (Table 15). The concentration of N in the leaves more than doubled as the concentration of N in the nutrient solution rose by a factor 64. The increases in leaf % N between 0.25 and 8 mM and between 8 and 16 mM were approximately of the same order; slightly more than a full percent in either case. The nutrient solution N concentration at which leaves % N on each of the rootstocks increased significantly varied by almost an order of magnitude; Garnem at 4 mM, Nemaguard 2 mM and RP40 at 0.5 mM. Leaves on all the rootstocks displayed the dramatic increase from 8 mM to 16 mM, the extent being greatest in Garnem leaves and the smallest in Nemaguard leaves.

Table 15 Rootstock × nutrient solution N concentration (mM) on leaf % N

Rootstock × mM N interaction means followed by different letters are significantly (P = 0.05) different and mM N main effect means followed by different letters are significantly (P = 0.05) different.

	mM N						
Rootstock	0.25	0.5	1	2	4	8	16
Garnem	2.27 ab	2.55 b-d	2.43 ab	2.51 a-c	3.32 f	3.57 g	4.95 k
Nemaguard	2.29 ab	2.29 ab	2.52 b-d	2.99 ef	3.53 g	4.12 h	4.69 ij
RP40	2.12 a	2.87 c-e	2.91 d-e	3.08 ef	3.06 ef	3.11 ef	4.37 hi
mM N main effects	2.23 a	2.57 b	2.62 b	2.89 c	3.30 d	3.60 e	4.67 f

This experiment established that maximum growth was achieved at 1 mM N and that shoot or leaf N increased as more N was made available to the roots. That rise may be a function of growth restrictions causing a concentration effect as well as more N being taken up. As pointed out above, there was a 64-fold difference in the amount of N available to the roots but only a 2-fold increase in leaf % N over that range and that shoot biomass production was the same at either end of the N supply treatments.

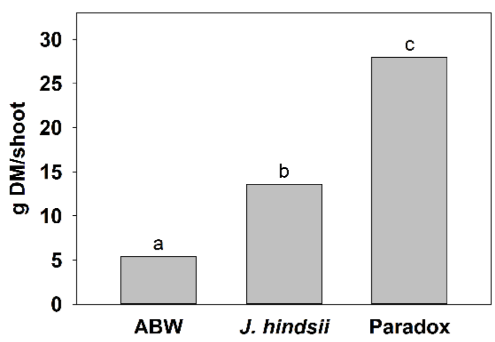
Restricting the second run of the experiment to the three rootstocks being used in the H1 trial allowed three walnut rootstocks to be included. The walnut rootstocks included in the experiment were American black walnut (ABW; *Juglans nigra*), Northern Californian black walnut (*J. hindsii*) and Paradox (a hybrid of Northern Californian black walnut and English —also known as Persian —walnut (*J. regia*)).

The seedling walnut rootstocks proved to be ill-suited to being grown in a glasshouse. Insect pests and fungal diseases were problematic, requiring active interventions. Nonetheless, 4 months of growth allowed the relative responses of the three rootstocks to rootzone N concentrations to be readily discerned.

The most vigorous rootstock, Paradox, produced 5-times as much shoot DM as ABW and about twice as much as *J. hindsii* (Figure 52).

Figure 52 Genotype main effects on seedling walnut rootstock shoot biomass (g) accumulation

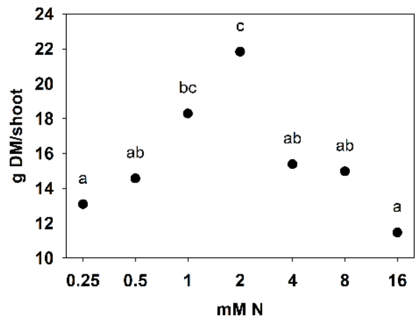
Different letters above each column indicate significant (P = 0.05) differences between means.



There was no evidence that any walnut rootstock seedling responded more or less to increasing rootzone N concentration than either of the other two genotypes. Across the three rootstocks, maximum shoot biomass production was observed when the rootzone N concentrations were 1-2 mM (Figure 53); a very similar response to that observed for almond rootstocks.

Figure 53 Rootzone N concentration (mM) main effects on shoot biomass (g) accumulation by seedling walnut rootstocks

Different letters above each mean data point indicate significant (P = 0.05) differences between means. Note that the x- axis is log_{10} scaled.



Effect of rootzone mineral nutrient supply on shoot biomass production, partitioning and architecture of almond rootstocks and grafted almond trees

In the experiments presented below phosphorus and potassium concentrations around the roots of four almond rootstock genotypes were manipulated in two experiments over realistic ranges to assess the impact on biomass production and branching. In another series of three experiments, the concentrations of nitrogen, phosphorus and potassium were manipulated over realistic ranges to assess the impacts on Nonpareil and Carmel trees growing on Nemaguard and RP40; two rootstocks that believed to differ in the vigour imparted to scion genotypes.

Phosphorus – Garnem, Nemaguard, RP20 and RP40

Rootstock and phosphorus supply main effects are presented in Table 16. Rootstock had a far greater influence on biomass accumulation than phosphorus supply. Nemaguard was the most vigorous; it partitioned more dry matter into leaves, laterals off the main stem and the roots, but was not the tallest. Biomass accumulation by the dwarfing rootstocks was partitioned mainly to leaves and not into the main stem or laterals. The root:shoot ratios indicated that the dwarfing rootstocks allocated more dry matter to the above ground parts. The dwarfing rootstocks' small root systems relative to the more vigorous rootstocks may have implications for trees growing on these rootstocks with respect to anchorage and nutrient and water uptake over time.

Table 16 Rootstock and inorganic phosphate concentration (mM) main effects on almond rootstocks' branching and biomass (g) at harvest

Different letters within a main effect indicate significant (P = 0.05) difference between means. An absence of letters indicates that there was no significant effect attributable to that treatment variable for that variate

	Rootstock				mM P_i			
	Garnem	Nemaguard	RP20	RP40	0.02	0.1	0.5	2.5
main stem cm	126 a	96 b	18 c	28 c	59	63	75	71
laterals/plant	2.3 b	8.1 c	1.8 b	0.6 a	2.8	3.4	3.6	3
g leaf/shoot	12.9 a	16.4 b	21.7 d	19.1 c	17.3	16.9	18.4	17.5
g stem/shoot	33.1 c	38.4 d	24.3 b	20.7 a	28.9	27.3	30.5	30
g shoot/plant	45 b	54.9 c	46.2 b	40.1 a	45.5	43.5	49.8	47.5
g root/plant	11.9 c	22.6 d	7.6 b	3.8 a	11.9	10.1	12.1	11.8
shoot:root	3.8 b	2.4 a	6.7 c	13.2 d	4.4 a	8.5 d	5.9 b	7.4 c

Varying the phosphate concentration in the rootzone by a factor of 125 had almost no effect on biomass accumulation or branching on the four rootstocks included in the experiment. Further, the rootstock × [P_i] interaction term was not significant, meaning that none of the rootstocks responded more or less than any other rootstock to the 5-fold increments in inorganic phosphate concentrations in the rootzone.

Because apical dominance diminishes basipetally with increasing distance from apical meristems, the possibility that the amount of branching observed was related to each plant's stature was explored by allowing for shoot height when analysing the number of laterals per main stem. The inclusion of stem height as a covariate failed to alter the relativities of the rootstock and phosphate concentration main effects and the interaction term remained non-significant.

Dry matter partitioning was affected by phosphorus supply but the trend over the range of rootzone phosphate concentrations was irregular and non-intuitive. Further, the rootstock × [P_i] interaction term for the biomass partitioning index was significant, and an examination of the rootstock × [P_i] means (Table 17) indicate that the unusual trend seen in the [P_i] main effects was attributable to RP40 plants.

Table 17 Interactive effect of rootstock × inorganic phosphate concentration (mM) on shoot: root ratios

Different letters within a main effect indicate significant differences between means at P = 0.05.

	mM P_i			
Rootstock	0.02	0.1	0.5	2.5
Garnem	3.5 ab	4.4 abc	3.2 a	4.3 abc
Nemaguard	2.4 a	2.5 a	2.4 a	2.5 a
RP20	6.1 cd	7.9 d	6.9 d	6.1 cd
RP40	5.7 bcd	19.4 g	11.2 e	16.6 f

Potassium – Garnem, Nemaguard, RP20 and RP40

Rootstock and rootzone potassium main effects on height, branching, biomass accumulation and partitioning are presented in Table 18. Nemaguard produced the most biomass, branched the most and partitioned proportionally more biomass to the roots. Biomass accumulation was generally maximised at rootzone potassium concentrations of 0.1 mM or less. Garnem grew the tallest though accumulating only as much biomass as the dwarfing rootstocks, but partitioned more of that biomass to the roots than the dwarfing rootstocks. The dwarfing rootstocks partitioned more biomass into the leaves relative to the more vigorous rootstocks both in absolute and relative terms.

Table 18 Rootstock and potassium concentration (mM) main effects on almond rootstocks' branching and biomass (g) at harvest

Different letters within a main effect indicate significant (P = 0.05) difference between means.

	Rootstock				mM K^+			
	Garnem	Nemaguard	RP20	RP40	0.02	0.1	0.5	2.5
main stem cm	116 a	96 b	20 d	40 c	89 a	61 b	59 b	63 b
laterals/main stem	2 a	7.7 b	1.9 a	1.1 a	4.2 a	3.7 a	2.8 ab	2 b
g leaf	8.9 a	14.1 b	20.5 c	19.7 c	18.7 a	16.5 b	17.3 ab	10.8 c
g stem	28.7 b	36.7 a	23.2 c	22.2 c	30.9 a	27.7 b	29.2 b	22.9 c
g shoot	37.7 a	51.2 c	43 b	41.7 ab	49.5 a	44.1 b	45.9 ab	34 c
g root	10.3 b	19.9 a	6.7 c	5.4 c	11.7 a	11 a	12.4 a	7.1 b
shoot:root	4.2 b	2.6 a	6.7 c	10 d	5.9 a	6.7 a	4.3 b	6.7 a

Increasing rootzone potassium concentrations from 0.02 mM to 2.5 mM was generally associated with smaller stature, less biomass accumulation and less branching on the main stem. With respect to the latter, the rootstock × potassium interaction was not a significant source of variation, but the inclusion of stem height as a covariate in that analysis enabled the identification of differential lateral production responses to increasing rootzone potassium concentrations across the rootstocks. Allowing for main stem height showed that Garnem produced about four lateral branches at the two lowest rootzone potassium concentrations and almost none at the two highest, whilst

Nemaguard produced double that number of laterals across the range of potassium concentrations (Table 19). The production of lateral shoots by RP20 and RP40 was similarly more-or-less unaffected by potassium concentration in the rootzone, but was less than half of that produced by Nemaguard despite these plants being about a fifth of the height of either Nemaguard or Garnem.

Table 19 Main and interactive effects of rootstock and potassium concentration (mM) on the number of almond rootstocks' laterals per stem adjusted for main stem height

Different letters within each main effect and within the interaction indicate significant (P = 0.05) differences between means.

Rootstock	mM K^+ 0.2	1	5	25	Rootstock main effects
Garnem	3.8 cd	4.3 cd	0 a	1.2 ab	2.3 a
Nemaguard	8.2 fg	10.0 g	9.6 fg	7.1 ef	8.7 c
RP20	5.2 de	4.9 c-e	4.8 c-e	4.4 cd	4.8 b
RP40	4.0 cd	3.2 b-d	4.8 c-e	2.6 a-c	3.6 ab
[K^+] main effects	5.3 a	5.6 a	4.8 ab	3.8 b	

Cultivar × rootstock × mineral nutrients' concentrations

Three separate experiments involving N, P and K concentrations in the rootzone were run concurrently making use of common treatments. Six-month old Nonpareil and Carmel trees grafted on Nemaguard or RP40 were grown in sand culture for 3-months in the glasshouse. At harvest main stem height, the number of laterals on the main stem and the biomass from the graft union upwards were determined.

The most consistent sources of variation across the three experiments were rootstock and mineral nutrient supply (Table 20). Rootstock and P or K generally accounted for 50 to 75% of the variation in tree size and lateral production. Rootstock and N accounted for half the variation in shoot biomass, but N supply explained very little of the variation in shoot height and lateral production. Trees on Nemaguard were consistently taller, accumulated more biomass and produced more laterals than trees on RP40. Biomass accumulation, stature and branching were positively related to the concentrations of K around the roots. Biomass accumulation and branching was also positively related to N concentration around the roots, but there was no main stem height increment when the N concentration around the roots increased beyond 0.5 mM.

Cultivar, either as a main effect or as an interaction term, was rarely a significant source of variation.

The direction of responses to increasing P concentrations around the roots was the opposite to that observed for N and K. The negative effect of greater P supply was observed between 0.5 and 1.0 mM. Growing the graftlings at 1 mM P was associated with significantly smaller plants, less biomass accumulation and much less branching. Additionally, biomass accumulation, plant stature and branching were the same at 0.25 mM as they were at 0.5 mM.

Table 20 Rootstock and rootzone a) N, b) P or c) K concentration main effects on scion biomass and architecture

An asterisk within rootstock main effects indicates a significant (P = 0.05) between rootstock means and different letters within N, P or K concentration main effects indicate significant (P = 0.05) differences between means. The absence of letters indicates a non-significant source of variation.

a) N

(P = 0.5 mM & K = 1 mM)	Rootstock		mM N		
	Nemaguard	RP40	0.5	1	2
g DM/shoot	53	22*	29 a	35 b	48 c
main stem height (cm)	122	67*	93	91	99
laterals/plant	9.1	2.8*	4.0 a	5.9 ab	7.9 b
laterals/m main stem	7.2	2.8*	3.6 a	5.0 ab	6.3 b

b) P

(N = 1 mM & K = 1 mM)	Rootstock		mM P		
	Nemaguard	RP40	0.25	0.5	1
g DM/shoot	38	16*	32 a	35 a	13 b
main stem height (cm)	92	50*	88 a	91 a	34 b
laterals/plant	5.7	2*	5.6 a	5.9 a	0.1 b
laterals/ m main stem	4.9	2.1*	5.4 a	4.9 a	0.1 b

c) K

(N = 1 mM & K = 1 mM)	Rootstock		mM K		
	Nemaguard	RP40	0.5	1	2
g DM/shoot	41	17*	15 a	35 b	37 b
main stem height (cm)	94	54*	40 a	91 b	91 b
laterals/plant	6	2*	0.1 a	5.9 b	6.3 b
laterals/ m main stem	5	2*	0.2 a	5.0 b	5.5 b

The analyses revealed few significant interactions, predominantly between rootstock and the concentration of P and K (Table 21); rootstock × N interactions were non-significant.

Examination of those significant interactions suggests that the response of graftlings on RP40 to increasing P in the rootzone started between 0.25 and 0.5 mM, whereas the negative impact of increasing P on graftlings on Nemaguard was not evident at 0.5 mM. Proportionally, the effect of high P on lateral production was greater for graftlings on Nemaguard compared to graftlings on RP40, but graftlings on both rootstocks produced almost no laterals at the highest rootzone P concentration imposed. As mentioned for the rootstock and P concentration main effects (Table 20), the inclusion in the analysis of main stem height as a proxy index of the likelihood of apical dominance reduced the variance ratio for the laterals/plant interaction term to below the threshold for statistical significance.

Table 21 Rootstock × P and rootstock × K interactions on scion biomass and architecture at 1 mM N.

For each measured/observed response different letters within each interaction indicate significant (P = 0.05) differences between means. The absence of letters indicates a non-significant source of variation.

	mM P			mM K		
	0.25	0.5	1	0.5	1	2
	g DM/shoot					
Nemaguard	44 a	51 a	18 bc	19 a	51 b	53 b
RP40	21 b	18 bc	8 c	12 a	18 a	21 a
	main stem height (cm)					
Nemaguard	114 a	119 a	43 ab	47 ab	119 c	115 c
RP40	61 b	62 b	26 a	32 a	62 b	66 b
	laterals/plant					
Nemaguard	7.8 a	9.1 a	0.3 c	0.1 a	9.1 b	9.7 b
RP40	3.4 b	2.6 bc	0 c	0.1 a	2.6 a	2.9 a
	laterals/m main stem					
Nemaguard	7.1	7.3	0.3	0.2 a	7.4 c	8.1 c
RP40	3.8	2.6	0	0.2 a	2.6 b	2.9 b

Generally, any positive effect of increasing rootzone K concentrations on biomass production, stature and the production of laterals was observed between 0.5 and 1 mM. Examination of the rootstock × K concentration interactions suggests that the main stem height and laterals per m of main stem of graftlings on RP40 were responsive to increasing K around the roots and that most of the response occurred between 0.5 and 1 mM, but biomass production or laterals produced per plant weren't increased by increasing K concentration. The inclusion of main stem height in the analyses reduced or relegated to non-significance the rootstock × K concentration interactions.

Table 22 Cultivar × rootstock × K interactive effects on plant height (cm) at harvest

Different letters indicate significant (P = 0.05) differences between means.

	Rootstock					
	Nemaguard			RP40		
	mM K					
Cultivar	0.5	1	2	0.5	1	2
Carmel	47 ab	115 d	131 d	38 a	76 bc	53 a-c
Nonpareil	48 ab	124 d	99 cd	27 a	48 ab	80 bc

Cultivar was only an important source of variation in the cultivar × rootstock × K concentration interactive effects on shoot height (Table 22). The length of main shoots of both cultivars on Nemaguard more than doubled between 0.5 and 1 mM, but did not increase further between 1 and 2 mM. The shoots of Nonpareil on RP40 responded positively with each increment in potassium concentration around the roots. The shoots of Carmel on both rootstocks were established between 0.5 and 1 mM potassium.

Discussion

The use of sand culture and frequent flushing of the pots with fresh nutrient solution ensured that the concentration of N planned to be imposed was imposed, and that readily available water around the roots was not limited. The reality is that concentrations of nitrate and ammonium in the readily available water in a field situation will vary because the rate of water uptake is much greater than the rate of nitrate and/or ammonium uptake. The rate of nitrification of ammonium to nitrate varies with soil temperature, aeration and water potential, and on denitrification (O'Sullivan et al, 2013), although it needs to be acknowledged that all those processes under frequent wetting drying cycles are less studied compared to broad acre dryland cropping situations. That said, the range of nitrate and ammonium concentrations that were imposed around the roots falls within the range of concentrations in soil water estimated by Miller *et al.* (2007) based on data published by Lark *et al.* (2004). The range of nitrate and ammonium concentrations also covered the concentrations that the high and low affinity nitrate and ammonium uptake systems function at (Miller *et al.* 2007). Further, the concentrations imposed have real world relevance based on what those concentrations might mean for the quantity of N supplied to trees in an orchard assuming credible irrigation water inputs (Table 4).

The major outcome was that across a 64-fold range of concentrations, a concentration of N in the rootzone was identified below which growth was limited by N and above which no further benefit was apparent or was in fact detrimental. The experimental design highlighted the strong ability of almond rootstocks to manage tissue N concentrations: leaf N rose from 2.4 to 3.7 % whilst biomass varied by a factor of two over the 32-fold range of N concentrations around the roots. That concentration of N – namely, 1 mM – amounts to 0.5 mM nitrate and 0.5 mM ammonium, and sits at the lower end of the concentration range that low affinity uptake systems for those two forms of N (Miller *et al.* 2007) operate at. Nitrogen uptake at that concentration is made up of uptake by the high affinity systems and the low affinity systems. Water uptake by roots causes a more negative water tension around the roots, which drives mass flow of water to the roots to equilibrate that tension; mass flow carries with it any solute in that water to roots. The data collected in the course of the glasshouse trials indicate that there is little advantage in allowing the concentration of N around the roots to exceed 1 mM, a concentration which when scaled up using current water usage (Table 4) maps well to current N fertiliser inputs based on Californian research (Muhammad *et al.* 2015). Given the Australian almond industry strategic aim of making better use of inputs, utilising the differential rate of water versus N uptake to reduce N inputs without sacrificing productivity may be a possibility. To that end, the upper limit on the concentration of N in the vicinity of the roots between irrigation events has been defined.

The experiments were conducted to provide a scientific basis to the treatments to be applied in the H1 planting and to gain an insight into the ability of rootstocks to modify tree growth and the extent to which that ability may be modulated by mineral nutrient supply. The N supply regime imposed on the trees in the H1 planting were based on the outcome of the glasshouse experiments, and amounted to 50, 100 and 200% of the concentration of N in the frequently replenished nutrient solution around the roots associated with maximum shoot biomass production. Effectively, the concentration of N in the readily available water supplied to the trees in the field was 0.5, 1 or 2 mM, or 7, 14, 28 mg N/L. The concentrations of either urea or ammonium nitrate needed to supply N at those concentrations at the dripper would need to be 30, 60 or 120 and 40, 80 and 160 mg/L, respectively.

A facet of glasshouse trials that assumed more importance over the course of the project was the ability of rootstocks to modify tree growth and the extent to which that ability may be modulated by mineral nutrient supply. This was in part driven by observation but also by advanced understanding in this area of plant science. Most of the work in this area is conducted on small annual plants with short life cycles, but the understanding developed using those model systems has been taken up by the researchers in other plant systems including perennial horticulture (for example in viticulture as discussed in Cochetel *et al.* (2018)), and the obvious connection made with the role that rootstocks may play in modulating scion architecture (Cookson and Ollat 2013). Hence, the expansion of the observations made on almond rootstock genotypes and young grafted trees in relation to N, P and K supply goes beyond simply biomass.

The study of the modulation of plants' natural architecture has historically been confined to annual plants, and chiefly the response to nutrient deficiency, particularly phosphorus. The contribution of Australian researchers in this field has been strong due to the poor fertility of most Australian soils used for crop production. The discovery of another class of phytohormone, the strigolactones, produced by the roots and which appear to modulate shoot branching (Gomez-Roldan *et al.* 2008, Umehara *et al.* 2008) has sparked interest in the potential role that a rootstock may have on scion architecture, for example in grapevines (Cochetel *et al.* 2018). A rootstock's tendency to produce and transport strigolactones upwards and the environmental conditions that modulate their production and acropetal transport and a scion's sensitivity to those compounds are key questions. Phosphorus availability is one of the key environmental factors implicated to date (Czarnecki *et al.* 2013), but nitrogen has also been mentioned (Cochetel *et* *al.* 2018). This field of research is still developing, and it seems likely that other environmental influences will be identified.

Whilst rootstock was the single biggest and most consistent source of variation across the experiments, it was observed that the production of laterals was discouraged by low K and high P supply and N supply only encouraged biomass production. There are some complexities involving plant responses to low P soils (Marschner 1995) and what happens when excessive tissue P alter plants' ability to utilise tissue Zn and Fe, but the observations point to some complex plant physiology that potentially may offer almond producers better ways to manage trees on different rootstocks to produce architectures more likely to bear fruiting sites. This development would require recasting the role of rootstocks beyond simply qualitative to a more nuanced appreciation of the interaction between two genetically different plants and how that interaction may be manipulated to industry's advantage.

Ongoing research

The control over the soil solution around plant roots is very difficult to replicate in the field. The approach as used in the experiments described have provided valuable insights and benchmarks around which orchard management options can be tested and extended to industry. The experiments also provided tantalising – but not entirely unexpected given the advances in this space using annual model plant systems – evidence of the influence of mineral nutrient supply can have on tree branching. Further experiments should be conducted to confirm those observations and explore the nature of the scion/rootstock interaction – which underpins much of perennial horticulture's production systems – by using techniques such as reciprocal grafting and split root culture.

Field trial

Summary	
Why?	• industry's strategic aim to use input resources more efficiently • nitrogen inputs significant • all cultivar/rootstock combinations managed the same • optimum rootzone nitrogen concentration in controlled environment
How?	• main industry cultivars on range of vigour-imparting rootstocks • fertigation • ×½, ×1 and ×2 optimum nitrogen in readily available water
What?	• rootstock and cultivar greater influence on early tree establishment • leaf nitrate more responsive that leaf total nitrogen to rootzone nitrogen • different cultivars and trees on different rootstocks manage nitrogen differently
So?	• cultivar- or rootstock-specific nitrogen management strategies needed? • more efficient use of major resource input?
Next?	• continue nitrogen supply treatments • continue observations/measurements • establish relative soil water and nitrogen depletion rates

Industry saw resource (principally fertiliser) use efficiency as an important issue due to the high inputs almonds require. Cost, availability and community expectations were significant drivers. Nitrogenous fertilisers make up a large proportion of almond enterprises' fertiliser budget, and it was for this reason that nitrogen was focussed on in the H1 planting.

Three considerations were critical in the set up and design of the H1 planting:

- observations that the three cultivars commonly planted together in the same irrigation unit and receiving the same fertiliser inputs grow and behave differently,
- a growing body of scientific evidence that different rootstocks exert different effects on scion cultivars and
- the more frequent use of size controlling rootstocks.

Hence the H1 was established with the aim of quantifying the effect of N supply treatments based on dissolved mineral N concentrations in the irrigation water. The N supply treatments imposed are based on measurements identified in glasshouse experiments under controlled conditions using sand culture as discussed in the section on the *Glasshouse trials.* Establishment and precociousness were priority responses for the project, but the planting and infrastructure have utility beyond the initial focus.

Materials and methods

The design and set up of the planting are described earlier (page 38).

Tree canopy dimensions were manually measured and recorded. Trunk diameters of the measurement trees (n = 540 trees in the 2018-19 season and 360 trees in 2020 and 2021) were measured at the end of the growing season in autumn with calipers at 40 cm above ground level.

Photosynthetically active radiation (PAR, µmol/m^2/s) intercepted by the canopy was measured monthly from January to April during the 2018-19 growing season. Twenty measurement were taken with a ceptometer[38] within each 133 m^2 planting square. No light interception measurements were conducted in 2020-21 because of extensive tree canopy manipulation to select the four scaffolding branches negated the effect of treatment on light interception.

Table 23 Interpretative mineral nutrient standards for almonds

Adapted from Robinson et al. (1997).

	Units	Concentration ranges					
		Deficient	Marginal	Critical deficiency	Adequate	High	Toxic or excessive
N	%	<1.8	1.8 - 1.9		2.0 - 2.5		
NO_3^--N	mg/kg			(Interpretive standards not available)			
P	%	<0.1			>0.1		
K	%	<1.0	1.0 - 1.3		1.4 - 1.7		
Ca	%				>2.0		
Mg	%				>0.25		
S	%			(Interpretive standards not available)			
Na	%				<0.25		
Cl	%				<0.3		
B	mg/kg	<12	12 - 24		25 - 65		>85
Cu	mg/kg				>4.0		
Fe	mg/kg			(Interpretive standards not available)			
Mn	mg/kg				>20		
Mo	mg/kg			(Interpretive standards not available)			
Zn	mg/kg	<15	12 - 24		25 - 30		

For leaf nutrient analyses leaf samples were collected from the measurement trees in each plot according to the industry standard method (Robinson *et al.* 1997). The leaves were washed in slightly acidified de-ionised water with a few drops of phosphate-free detergent to remove dust and other contaminants including foliar sprays, patted dry and then dried in a fan-forced oven at 60°C for 48 hours. The dried leaves were analysed by NATA-accredited analytical services[39]. Two sets of samples were collected from the H1; a complete set from the three rootstocks in 2019 before the trees on Garnem were removed, and another set in 2021 from the trees on Nemaguard and RP40.

[38] AccuPAR LP-80, Meter Group Inc., Pullman, USA
[39] https://www.csbp-fertilisers.com.au/services/lab

The analytical data were compared to the industry's interpretive standards (Table 23) as well as being subjected to analyses of variance. The comparison to the industry's accepted standards was to assess the overall nutritional state of the planting, ignoring cultivar, rootstock or N supply. It should be noted though that there are no interpretative stands for leaf nitrate, sulphur, iron or molybdenum.

To gain some insight into the soil N balance, soil water was extracted with SoluSamplers[40] from two depths (60 and 100 cm) beneath Nonpareil trees on Nemaguard and RP40 in November, 2020. The concentration of total N was measured spectrophotometrically following alkaline digestion with persulfate and a reaction with chromatropic acid. The digestion step completely oxidised all reduced (*i.e*. urea, ammonium and amino N; $CO(NH_2)_2$, NH_4^+ and $-NH_2$, respectively) and partially oxidised N (*i.e* nitrite, NO_2^-) to nitrate (NO_3^-). Thus, the assay measures all forms of mineral N and any organic N in the soil water extracted.

Results

Tree development: trunk diameters and tree dimensions

Trunk diameter measurements made at five points from October, 2018, through to April, 2020 (Table 24), and tree height and canopy width measurements conducted in September, 2021 (Table 26).

The trunks of trees on RP40 were always thinner than the trunks of trees on the other two rootstocks, and Carmel trunks were nearly always thinner. A four-fold range of N supply didn't alter those relative rankings or trunk growth at the final two measurement points.

Table 24 Cultivar, rootstock and N supply main effects on trunk diameters (mm) of trees in the H1 planting at five timepoints

Different letters indicate significant (P = 0.05) differences between means within a sampling point and main effect. An asterisk indicates that the trunk diameters of trees on RP40 were significantly different from the trunk diameters of trees on Nemaguard

Measurement timing	Cultivar			Rootstock			mM N		
	Carmel	Nonpareil	Monterey	Garnem	Nemaguard	RP40	×½	×1	×2
Oct 2018	6.1	6.4	6.4	7.1 a	7.3 a	4.5 b	z	6.4	6.2
Jan 2019	16 a	18 b	20 b	24 a	22 b	8 c	18 a	19 b	18 a
Jul 2019	34 a	40 b	40 b	48 a	44 b	22 c	37 a	39 b	38 ab
Jun 2020	44 a	53 b	54 b	-§	61	39*	48	52	50
Apr 2021	70 a	80 b	80 b	-	84	69*	75	75	79

§ Garnem trees were removed in 2020.

Cultivar × rootstock interactions were significant at every measurement point (Table 25). The dwarfing influence of RP40 was reasonably apparent from the first measurement point, and the tendency of Carmel trunks to be thinner was also apparent from that point. The trunks of Carmel trees on RP40 were thinner than the trunks of any other cultivar/rootstock combination at every subsequent measurement point. The tendency of Carmel trunks to be thinner than either Nonpareil or Monterey trunks was less apparent when the trees were growing on Garnem or Nemaguard.

[40] Sentek Sensor Technologies, Stepney, Australia

Table 25 Cultivar × rootstock interaction effects on trunk diameters (mm) of trees in the H1 planting at five timepoints

Different letters indicate significant (P = 0.05) differences between means within a sampling point.

Measurement point	Cultivar	Rootstock		
		Garnem	Nemaguard	RP40
Oct 2018	Carmel	6.8 c	7.6 d	4.0 a
	Monterey	7.4 d	7.1 cd	4.6 b
	Nonpareil	7.1 cd	7.3 cd	4.8 bc
Jan 2019	Carmel	22 cd	21 c	6 a
	Monterey	27 e	23 d	9 b
	Nonpareil	24 d	22 cd	9 b
Jul 2019	Carmel	46 de	41 c	16 a
	Monterey	49 ef	45 d	24 b
	Nonpareil	49 f	45 d	25 b
Jun 2020	Carmel	-	59 a	29 c
	Monterey	-	63 a	44 b
	Nonpareil	-	61 a	45 b
Apr 2021	Carmel	-	84 d	55 a
	Monterey	-	87 d	73 b
	Nonpareil	-	81 cd	78 bc

Re-growth following the lopping in December 2019, necessitated by severe wind, broadly reflected the trends in trunk diameter with the exception that Nonpareil tree height and canopy width on Nemaguard was indistinguishable from Nonpareil tree height and canopy width on RP40 by winter 2021 (Table 26). Prior to lopping, Nonpareil trees on RP40 were significantly smaller than Nonpareil trees on Nemaguard (data not shown). Data on Krymsk is not yet available as these trees were planted in the summer of 2021.

Table 26 Cultivar × rootstock interactions and cultivar and rootstock main effects on canopy (a) height and (b) width of H1 trees in September, 2021

Means followed by different letters within interactions or cultivar main effects are significantly different (P = 0.05). An asterisk indicates that a RP40 mean is significantly different to a Nemaguard mean. An absence of letters or an asterisk indicates that that source variation was non-significant.

Note that all trees in the H1 planting were lopped in Dec 2019 following devastating winds at the start of the 2019-20 growing season and that all trees on Garnem were removed in 2020.

		Rootstock		Cultivar main effects
	Cultivar	Nemaguard	RP40	
a) height (m)	Carmel	2.20 cd	1.44 a	1.82 a
	Nonpareil	2.11 bc	2.00 b	2.27 c
	Monterey	2.23 cd	2.31 d	2.05 b
Rootstock main effects		2.18	1.92 *	
b) canopy width (m)	Carmel	2.06 b	1.65 a	1.86 a
	Nonpareil	2.12 bc	2.29 d	2.21 b
	Monterey	2.06 b	2.18 cd	2.12 b
Rootstock main effects		2.08	2.04	

Canopy development: effective area of shade

Estimates of the effective area of shade (EAS) were made at 4-week intervals from January 2019 through to April of that year. The trees were planted in March 2018. The repeated measures analysis showed that approximately 88% of the variability across the dataset was accounted for by the time of the measurement interaction with the cultivar and rootstock. Cultivar (Table 27) and N (data not shown) supply significantly affected EAS as main effects, but their overall influence was small.

EAS increased nearly 4-times from January through to February, and the extent of that increase was greater for Nonpareil trees, and the least for Carmel trees. The extent of the increase over the measuring period was greatest for trees on Garnem and the least for trees on RP40. By the last measurement point (April), the EAS of trees on RP40 was comparable to EAS of trees on Garnem in March.

Table 27 Cultivar × time and rootstock × time interactions and cultivar, rootstock and time main effects on % effective area of shade of H1 trees in the 2018-19 season

Different letters within interactions or main effects indicate significant (P = 0.05) differences between means.

Time	cultivar			rootstock			time main effects
	Carmel	NP	Monterey	Garnem	Nemaguard	RP40	
January	1.16 a	1.38 ab	1.33 ab	1.58 bc	1.41 b	0.88 a	1.29 a
February	1.55 b	2.00 c	1.98 c	2.49 e	2.09 d	0.96 a	1.85 b
March	2.92 d	3.81 f	3.49 e	4.45 g	3.96 f	1.81 cd	3.41 c
April	4.27 g	5.63 i	4.95 h	6.50 i	5.71 h	2.65 e	4.95 d
cultivar & rootstock main effects	2.48 a	3.20 c	2.94 b	3.75 a	3.29 b	1.57 c	

The 4-fold range of N supplies imposed resulted in only a 10% increase in EAS from 2.69 to 2.96 as a main effect. Compared to the extent of the rootstock and cultivar main effects, the effect of N supply was minor.

Tree nutrient status

Graphical statistical summaries of the H1 trees' macro- and micronutrient data are presented in Figure 54 and Figure 55, respectively.

Compared to the industry standards (Table 23), the vast majority of trees in the H1 planting were in the acceptable range with respect to N, P, K, Ca and Mg. Sodium levels were below detection limits, but Cl levels were greater than 0.3% which is considered to be the threshold for concern. With respect to the micronutrients, leaf B, Cu and Mn were adequate, but Zn levels would be considered deficient.

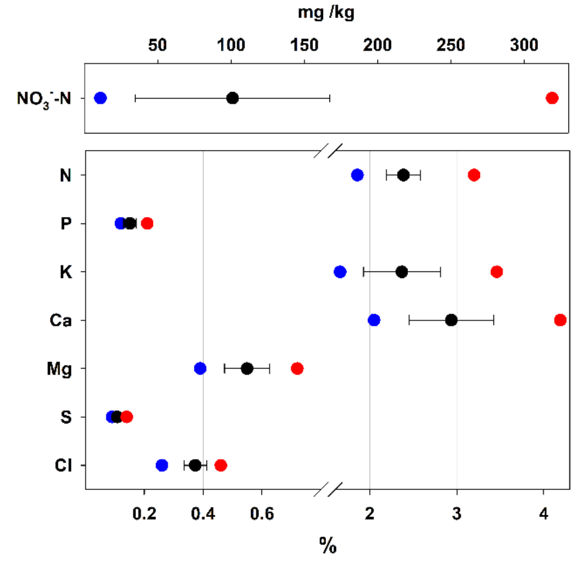


Figure 54 Statistical summary of macronutrient concentrations in leaves sampled from trees in the H1 planting in January 2019 *Minimum observation (●), mean of all observations (●) ± 1 × standard deviation, and maximum (●) observation.*

The impacts of cultivar, rootstock and N supply as main effects are set out in Table 28. With the exception of B and Mn, cultivar was a significant source of variation for most mineral nutrients. Rootstock was a significant source of variation for all mineral nutrients, but N supply only affected leaf nitrate-N, P, K, Ca and Zn.

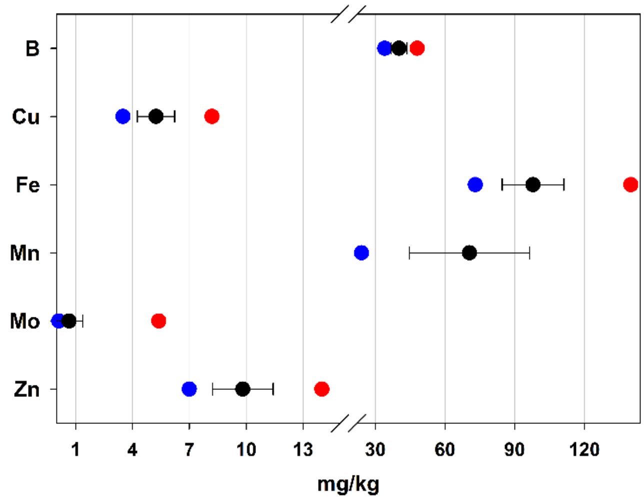


Figure 55 Statistical summary of micronutrient concentrations in leaves sampled from trees in the H1 planting in January, 2019 *Minimum observation (●), mean of all observations (●) ± 1 × standard deviation, and maximum (●) observation.*

As mentioned above, leaf N levels were adequate across the population of trees, and the 4-fold range in N supply did not raise leaf N in any meaningful way. However, leaf nitrate-N levels more-or-less doubled as N supply increased from the lowest to the next level of supply, and increased again by the same amount as N doubled again. The effects of N supply on the other mineral nutrients mentioned were not agronomically meaningful.

Table 28 Cultivar, rootstock and N supply main effects on leaf mineral nutrient concentrations in leaves sampled from the H1 planting in January, 2019

Different letters within each main effect/mineral nutrient combination indicate a significant (P = 0.05) difference between means. An absence of letters indicates that there were no significant differences between the means in that main effect/mineral nutrient combination.

		Cultivar			Rootstock			N		
		Carmel	Nonpareil	Monterey	Garnem	Nemaguard	RP40	×½	×1	×2
N	%	2.37 ab	2.40 b	2.40 a	2.32 a	2.40 b	2.45 b	2.38	2.39	2.39
NO_3^--N	mg/kg	113 a	71 b	113 a	122 a	112 a	63 b	56 a	100 b	141 c
P	%	0.15 a	0.15 a	0.16 b	0.14 a	0.14 b	0.18 c	0.15 a	0.15 b	0.15
K	%	2.2 a	2.6 b	2.3 a	2.2 b	2.0 a	2.9 c	2.3 a	2.3 a	2.4 b
Ca	%	3.1 a	2.8 b	2.9 b	3.3 a	2.7 b	2.8 b	3.0 a	2.9 ab	2.8 b
Mg	%	0.56 a	0.53 b	0.55 a	0.58 b	0.59 a	0.48 c	0.56	0.54	0.54
S	%	0.11 a	0.11 b	0.1 a	0.10 a	0.11 b	0.11 c	0.11	0.11	0.11
Cl	%	0.38 a	0.36 b	0.38 a	0.37 b	0.40 a	0.35 c	0.38	0.37	0.37
B	mg/kg	40	40	40	38 a	44 c	39 b	40	40	40
Cu	mg/kg	5.3 b	5.7 c	4.8 a	4.9 b	4.6 c	6.3 c	5.1	5.3	5.3
Fe	mg/kg	98 b	106 c	90 a	99 a	101 a	94 b	100	98	95
Mn	mg/kg	73	67	67	66 b	56 a	86 c	64	71	73
Mo	mg/kg	0.80 a	0.40 b	0.57 b	0.35 a	0.29 a	1.13 b	0.60	0.58	0.58
Zn	mg/kg	9.5 a	10.5 b	9.5 a	10.4 a	9.9 b	9.2 c	9.3 a	9.5 a	10.6 b

Two significant interaction terms – cultivar × N supply (Table 29) and rootstock × N supply (Table 30) – shed some light on the effects of each source of variability. Leaf nitrate-N in all three cultivars was responsive to increasing N supply, but to varying degrees. The increases in nitrate-N seen in Monterey leaves approximate the increments in N supply. The increases in Carmel leaves less so, and no increase in leaf nitrate-N levels was seen after the first doubling of supply. On the other hand, nitrate-N levels in leaves of trees on Garnem and Nemaguard increased significantly and by approximately the same amount with each increment in N supply, but leaves of trees on RP40 responded more modestly.

Table 29 Cultivar × N supply interactive effects on mg NO_3^--N/kg in leaves harvested from trees in the H1 planting in January 2019

Different letters indicate significant (P = 0.05) differences between means.

	N supply		
Cultivar	×½	×1	×2
Carmel	78 b	104 cd	157 e
Nonpareil	41 a	85 b	86 bc
Monterey	47 a	112 d	180 f

Table 30 Rootstock × N supply interactive effects on mg NO_3^--N/kg in leaves harvested from trees in the H1 planting in January 2019

Different letters indicate significant (P = 0.05) differences between means.

	Rootstock		
N supply	Garnem	Nemaguard	RP40
×½	63 ab	58 ab	46 a
×1	125 c	113 c	64 ab
×2	178 d	165 d	80 b

Reference to the interpretative standards (Table 23) suggests that in 2021, as for the 2019 samples, the N status of most trees was adequate, but a proportion of trees had N levels above 2.5 % N which is believed to be the upper limit of adequate (Figure 56). Phosphorus, K and Ca levels were adequate and Mg was high. Sodium levels were below detection and Cl levels were below 0.3% considered the threshold for concern (Figure 56).

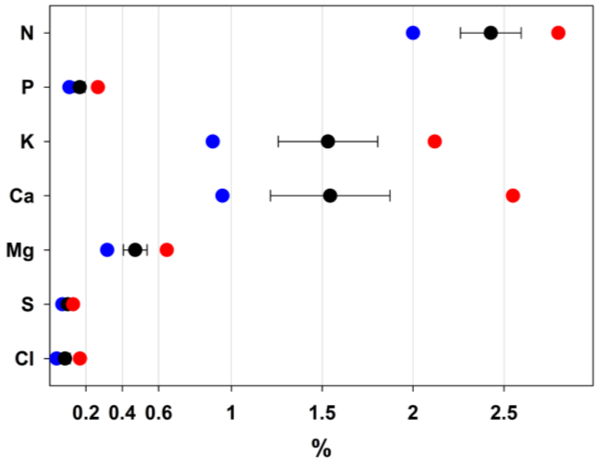


Figure 56 Statistical summary of macronutrient concentrations (%) in leaves sampled from trees in the H1 planting in January 2021

Minimum observation (●), mean of all observations (●) ± 1 × standard deviation, and maximum (●) observation.

As mentioned earlier, there are no interpretative standards for S in almond leaves; the same situation applies to two other *Prunus* tree crops, namely apricot and cherry. The interpretive standards for peach – another *Prunus* tree crop – defines adequate S between 0.2 and 0.4%. In the absence of any other yardstick, the S status of the almond trees in the H1 planting are arguably low. Levels of S in leaves has not improved since the 2019 sampling despite two heavy applications of single strength super phosphate (11% S) with the cereal cover crops sown each autumn, and the retention of the crop residues *in situ*.

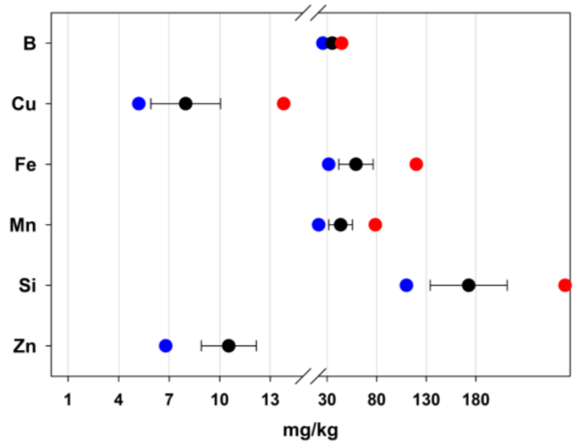


Figure 57 Statistical summary of micronutrient concentrations (mg/kg) in leaves sampled from trees in the H1 planting in January, 2021

Minimum observation (●), mean of all observations (●) ± 1 × standard deviation, and maximum (●) observation.

The trees' micronutrient status in 2021 was reasonably consistent with the situation in 2019, and for those micronutrients for which an interpretive standard was available, the trees were in the adequate range (Figure 57). The analytical service also provided Si, but there are no interpretive standards available. The trees would still be considered Zn deficient (Figure 57) despite several applications of zinc sulphate over the course of the 2020-21 growing season.

Cultivar, rootstock and N supply as main effects were significant sources of variability in the levels of most mineral nutrients in the leaves sampled in January, 2021 (Table 31). There were very few significant interaction terms. Excluding N, no main or interactive effect on any mineral nutrient was of agronomic concern. In contrast to the 2019 leaf samples, neither cultivar nor rootstock significantly influenced leaf N. Leaf N was increased by increasing N supply, and at the highest N supply leaf N was marginally above the threshold between adequate and high.

[41] https://www.altsa.com.au/

Table 31 Cultivar, rootstock and N supply main effects on leaf mineral nutrient concentrations in leaves sampled from the H1 planting in January, 2021

Different letters within cultivar/mineral nutrient or N supply/mineral nutrient combination indicate a significant (P = 0.05) difference between means. An asterisk following an RP40 mean indicates that it is significantly (P = 0.05) different from the accompanying Nemaguard mean. An absence of letters or an asterisk indicates that there were no significant differences between the means in that main effect/mineral nutrient combination.

Mineral nutrient	Cultivar			Rootstock		N supply		
	Carmel	Nonpareil	Monterey	Nemaguard	RP40	×½	×1	×2
N (%)	2.46	2.37	2.44	2.44	2.41	2.35 a	2.41 a	2.52 b
P "	0.16	0.16	0.17	0.16	0.17	0.16	0.17	0.17
K "	1.44 a	1.58 b	1.60 c	1.36	1.72*	1.50	1.54	1.58
Ca "	1.8 a	1.5 b	1.4 b	1.4	1.7*	1.6 a	1.6 ab	1.5 b
Mg "	0.50 a	0.46 b	0.45 b	0.5	0.44*	0.49 a	0.45 b	0.46 b
S "	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cl "	0.08	0.09	0.08	0.10	0.07*	0.09 a	0.09 a	0.08 b
B (mg/kg)	34 a	37 c	35 b	36	34*	35	35	35.57
Cu "	8.6 a	8.6 a	7.5 b	7.6	8.8*	7.9	8.4	8.4
Fe "	61	55	61	58	59	62 a	63 a	52 b
Mn "	49 a	41 b	42 b	39	49*	44 a	40 b	48 a
Si "	186	162	171	183	163*	184 a	185 a	150 b
Zn "	11	10	11	10	11	10 a	10 a	11 b

Nitrogen in soil water

The extensive soil sampling and analyses conducted at the outset of the project indicated that total N in the top m was typically less than 0.1% on a dry weight basis, and that mineral N constituted less than 15% of that total. The vast majority of N in the soil at any depth is present in organic matter and living soil biota. Typically also, total and mineral N levels in soils decline exponentially with depth, and very low levels of either are measured below 1.5 m. The concentrations of total N in the soil water samples extracted from below Nonpareil trees in November, 2020, were extremely variable (Table 32); the standard deviations were generally half the magnitude of the means or greater, meaning co-efficients of variation were typically 50% or greater.

Table 32 Total N concentration (mg/L) mean ($\bar{x}$) and standard deviations (σ) in soil water extracted at two depths beneath Nonpareil trees in the H1 trial in November, 2020

		N supply					
		×½		×1		×2	
rootstock	depth (cm)	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Nemaguard	60	22	15	29	33	31	13
	100	12	11	18	17	25	18
RP40	60	16	9	21	19	32	33
	100	17	21	20	14	11	5

With that qualification, mean total N concentrations in soil water extracted at 60 cm trended upward with each doubling in N concentration in the irrigation water. No such trend was apparent in the soil water extracted at 100 cm.

Further, N could not be detected in another set of soil water samples collected in April, 2021, after the season's fertigation program had been concluded but irrigation was still being applied. As such, these data amount to qualitative evidence that in these soils mineral N was not building up excessively after being supplied with urea in the irrigation water. There was also no indication that there was a trend for higher concentrations of total N to be found at depth.

Discussion

Despite the setbacks, the observations made demonstrate that the cultivars do grow at different rates, and that rootstock genotype modulates that tendency to some extent. The known relative vigour imparted by the three rootstocks planted was confirmed by the trunk diameter measurements (Table 25), as well as the canopy measurements (Table 26). Also confirmed was the relative vigour of Carmel versus Nonpareil and Monterey.

Despite the concentration of N in the irrigation water varying by a factor of four, growth responses were modest and it took three seasons of treatment imposition to move leaf N status significantly. The leaf N measurements conducted in the 2020-21 season however may represent the beginning of a population of trees with divergent tree N status.

The almond industry's tree N status index is % N in normal sized leaves taken from non-fruiting spurs in mid-late January (Robinson *et al.* 1997). In the case of young trees, as was the case for the H1 trees, it is recommended that leaves are sampled from extension growth. Leaves collected in H1 trees' first and third leaf indicated that despite a four-fold range in the amount of N supplied it is very difficult to move % N in any agronomically significant manner despite there being obvious signs that aspects of tree growth respond to increasing N supply. For example, % N in leaf samples collected in January, 2019 showed no evidence of responding to the four-fold range in N supply, and leaves sampled in 2021 only varied between 2.35 and 2.75. An inference may be that % N is a relatively blunt instrument for assessing tree N status. Further, the focus on a single sampling point means timely decision making is difficult.

The efficacy of % N as an index of tree N status aside, the lack of more timely methods to assess tree N status during the growing season is a limitation shared with other tree crop industries. Advances in the robustness and utility of spectrophotometric equipment raised the possibility that other approaches could be developed that could serve to provide orchard managers with better means of assessing tree N status in more or less "real time". The population of trees in the H1 planting offered a suitable platform to quantify the relationship – if any – between leaf N status and leaf spectral properties. This has been investigated during the course of the project and discussed in detail on page 83.

On-going research

The H1 planting was established in 2018, but over the first two seasons was subject to a number of abiotic and biotic stressors that reduced the achievable outputs significantly. Strong persistent winds coupled with termite damage to hardwood stakes being used to support the trees resulted in canopies being twisted and trunks being snapped over. The proportion of trees that were damaged was sufficient to compromise the biometric robustness of the trial and all trees were lopped to allow new scaffold limbs to develop and canopies to re-establish; in other words, the trial was effectively re-started. The trees on Garnem needed to be removed due to the number of tree losses attributable to soil-borne disease. These trees have been replaced by trees on Krymsk 86, a rootstock more tolerant of soil-borne disease and reputedly imparting more vigour to scion cultivars than Nemaguard. These trees will likely not be able to be compared to the remaining trees in the planting for several seasons.

Nonetheless, two-thirds of the cultivar × rootstock experimental strategy remains intact, and a bespoke irrigation/fertigation system capable of imposing three different fertigation regimes on a meaningful scale has been installed. Further, a population of trees differing with respect to N status is being generated, and providing a robust platform to develop and test new technologies and approaches to managing resource inputs and to assess the impact of genetics and management on kernel quality. The original aims of improving resource use efficiency (to wit, nitrogen fertiliser) similarly remain on track and achievable, and are arguably more relevant now than at the project's outset.

Leaf spectral properties and leaf mineral status

Summary	
Why?	• real-time fertigation assessment decision support needed • availability of new generation robust spectral equipment • suitable sampling platform
How?	• leaves sampled from nitrogen fertigation × rootstock × cultivar trees • conventional analysis versus leaf reflectance • multivariate statistics
What?	• total nitrogen versus reflectance relationship's predictive power promising • water complicates relationship development • narrowness of total nitrogen range a hinderance
So?	• leaf total nitrogen range currently limiting relationship development • industry total nitrogen too coarse measurement
Next?	• continue nitrogen supply treatments to widen range of leaf total nitrogen • leaf nitrogen pools or other nitrogen-related indirect indicator? • other advanced "black box" multivariate approaches?

Almond orchards can contain several rootstock/scion combinations, as well as a number of soil and topographical variations across a single management unit adding complexity to efficient nitrogen fertiliser management. The ability to track crop nitrogen status in real-time with significant spatial dimension would improve objectivity and timeliness of management decisions.

Currently almond crop nutrient status is generally assessed once towards the end of the growing season. This assessment, together with information on the crop load, is used to determine the nutritional needs for the following season. Some producers do perform an additional assessment earlier in the season.

The multi-stepped sampling and analysis process to assess leaf nutrient status is not only time consuming but has a high associated cost and does not provide information in real-time. New remote sensing technologies could potentially provide almond producers with rapid non-destructive crop nitrogen status information on a large scale for a fraction of the cost of traditional methods, meaning that the frequency of assessment could be significantly increased, facilitating improved efficiencies in management during the season.

There are three main types of sensing platforms currently utilised in horticultural crops including proximal active transmission sensors which contain their own light source and measure a single leaf, proximal passive reflectance sensors that measure part of a crop canopy, and remote passive reflectance sensors that measure whole tree canopy profiles.

UV-vis NIR spectroradiometry is a developing technology that has various applications within the agricultural sector although few studies have focused on almonds (Zarate-Valdez *et al.* 2015). Remote sensing technologies mainly utilise reflective sensors to measure crop canopies on a large scale and rely on natural light resulting in a large external environmental influence on the signal. This 'sampling noise' could limit the ability of statistical methods to extract relationships between measured leaf nitrogen concentrations and tree canopy spectral profiles and hinder the development of an accurate predictive model. Accordingly, a proximal sensor with its own light source were used in this study to measure spectral profiles of leaves directly and thereby eliminating natural light variations and environmental effects.

The Horizon 1 platform at the Mildura SmartFarm was used as the platform to assess the link between leaf spectral properties and leaf mineral content. The nitrogen treatments applied in this orchard (Table 10) had the potential to provide a population of leaves with a diverse range of nitrogen values to allow for investigation into the functional relationships between leaf spectral profiles and laboratory-based determinations of leaf nitrogen.

Materials and methods

Spectral analyses were performed with a Spectral Evolution SR-3500 spectroradiometer (instrument details on page 55) on leaf samples collected for nutrient analyses. A subsample of 20 leaves was randomly selected from each bulk sample and each leaf scanned using the instrument's leaf clip accessory. Each leaf was scanned at the same position on the leaf; with the petiole facing away and the leaf clip positioned to the right of the main vein, half-way down the leaf. After scanning the subsample was weighed to determine fresh mass at the time that spectra were collected, dried for 24h at 60°C and weighed to obtain the dry mass. The water content for the scanned subsample was calculated from the fresh and dry masses. These data were used to convert leaf % total nitrogen reported on a dry mass basis (N_{DM}) by the analytical service to % total nitrogen on a fresh mass basis (N_{FM}).

Spectral data were evaluated using the multivariate statistical analysis program Aspen Unscrambler[42]. The 20 spectral profiles for the individual leaves were averaged to give one spectral profile for each of the measured nitrogen values. The averaged data were randomly separated into two sets; 80% of the data was used as a training set for calibration and 20% as a test set for prediction. Multiple pre-processing techniques were applied to account for potential additive and multiplicative scattering effects common to spectroscopic data.

Partial least squares regression (PLS) analyses were performed using mean-centred pre-processed spectral data, with N_{DM} or N_{FM} as the response variable, to determine the potential for leaf reflectance data to be used for the prediction of total nitrogen content. A leave-one-out cross validation method was utilised to estimate the validation residual variance of the final multivariate models. Briefly, in each iteration of the cross validation a single data point is removed from the calibration and used for prediction. This is repeated until all samples had been excluded once from the calibration. The 20% test sets excluded from the PLS regression models were then used to give an indication of the prediction accuracy of each model.

Results

Typical reflectance spectra for four random samples are presented in Figure 58 and show that differences between leaves are expressed across the complete spectral range detected by the instrument.

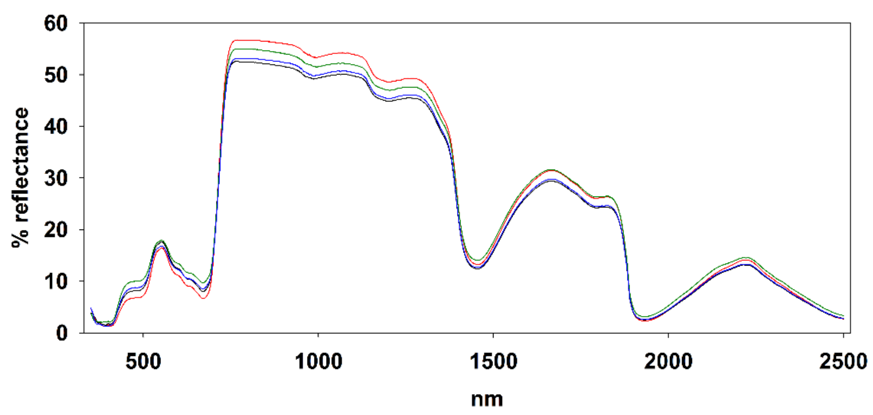


Figure 58 Reflectance spectra for four randomly selected leaf samples

The PLS model generated from the raw data (no pre-processing applied) for N_{DM} showed a better correlation to leaf spectra (R^2 = 0.71) compared to N_{FM} where R^2 = 0.64 (Table 33). Based on this, N_{DM} was selected as the response variable for further processing. The selection of N_{DM} is relevant as critical nitrogen levels are stated on a dry mass basis (Robinson *et al.* 1997) and leaf nitrogen concentrations are reported on a dry mass basis by analytical services.

Selected pre-processing techniques [Savitzky-Golay smoothing using a second order polynomial (SGS), standard normal variate (SNV) and multiplicative scattering correction (MSC)] were trialled on the N_{DM} data and compared to the original raw data model; the results are shown in Table 33. A slight increase in R^2 for calibration and validation was seen when both the SNV and MSC corrections were used (data not shown).

[42] Aspen Technology, Inc., Bedford, MA, USA

Table 33 PLS models generated from raw and pre-processed data sets, with both N_{DM} and N_{FM} (%) as the independent variable.

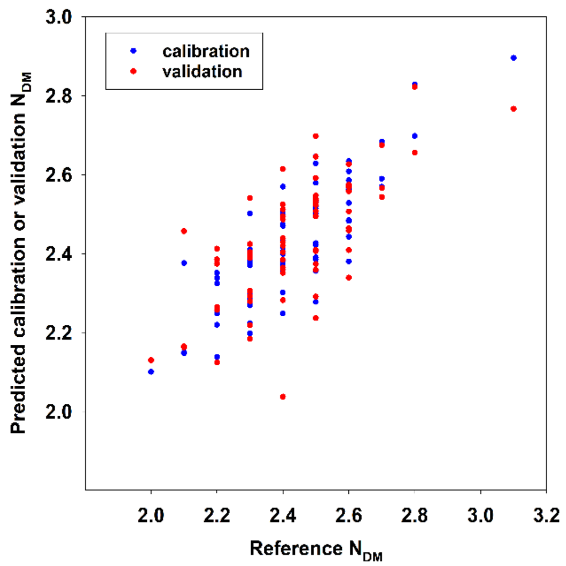
Also shown are their associated optimal number of factors, R^2 and error of calibration (RMSEC), R^2 and error (RMSEV) of validation, R^2 and error (RMSEP) of prediction. Note that the number of optimal factors were 7 in every pre-processing comparison run.

		calibration		validation		prediction	
Pre-processing	**Independent variable**	**R^2**	**RMSEC**	**R^2**	**RMSEV**	**R^2**	**RMSEP**
none	N_{FM}	0.64	0.04	0.41	0.05	0.04	0.04
none	N_{DM}	0.71	0.10	0.50	0.13	0.31	0.14
SGS	N_{DM}	0.71	0.10	0.50	0.13	0.31	0.14
SNV	N_{DM}	0.73	0.10	0.53	0.13	0.22	0.15
MSC	N_{DM}	0.73	0.10	0.53	0.13	0.22	0.15

When the test set was used to estimate the predictive accuracy of the models both the raw data model and the model generated using the SGS pre-processed data showed a better correlation (R^2 = 0.31) and a slightly lower associated error (RMSEP = 0.14) between predicted and reference N_{DM} values than the other pre-processing methods (Table 33). The results for calibration and validation of the raw data training set are shown in Figure 59.

Figure 59 Reference versus predicted plot for calibration and validation of the % N_{DM} PLS model obtained from the mean-centred raw data training set

R^2 = 0.71 and RMSEP = 0.14 for the calibration model whereas R^2 = 0.50 and RMSEP = 0.13 for the validation model.



The predicted N_{DM} values when the raw data test set was projected back into the raw data model are reported in Table 34. Predicted values differed up to 12% from the respective reference values (Table 34).

Table 34 Predicted N_{DM} values (%N) calculated using a PLS model based on the raw data test set

% N_{DM}		residual	
reference	predicted	absolute	relative
2.1	2.36	0.26	12.4
2.2	2.18	-0.02	-0.9
2.3	2.28	-0.02	-0.9
2.3	2.36	0.06	2.6
2.4	2.25	-0.15	-6.3
2.4	2.39	-0.01	-0.4
2.4	2.39	-0.01	-0.4
2.5	2.21	-0.29	-11.6
2.5	2.65	0.15	6.0
2.5	2.58	0.08	3.2
2.5	2.65	0.15	6.0
2.5	2.62	0.12	4.8
2.6	2.6	0	0
2.6	2.55	-0.05	-1.9
2.6	2.53	-0.07	-2.7
2.6	2.4	-0.2	-7.7
2.8	2.64	-0.16	-5.7

Morphological and biochemical differences between the leaves of cultivars could potentially have contributed to the prediction errors of the raw data model. For this reason, Nonpareil samples were extracted as a subset from the raw data set and a new PLS model developed (Table 35). The R^2 for calibration, validation and prediction all increased but it did not reduce the error associated with the model.

Table 35 Nonpareil PLS model with % N_{DM} as the independent variable, R^2 values and errors associated with the calibration, validation and prediction

Note that the number of optimal factors were 4 in this case.

calibration		validation		prediction	
R^2	RMSEC	R^2	RMSEV	R^2	RMSEP
0.76	0.09	0.58	0.12	0.62	0.15

The optimal number of factors were reduced to four in the Nonpareil model. The predicted %N_{DM} values when the Nonpareil test set was projected back into the Nonpareil model are reported in Table 34. Predicted %N_{DM} values differed up to 9% from their respective reference values (Table 36) which was an improvement from the 12% seen for the raw dataset.

Table 36 Reference and predicted % N_{DM} values estimated for the Nonpareil test set within the Nonpareil PLS model

% N_{DM}		residual	
deference	**predicted**	**absolute**	**relative**
2.1	2.25	0.15	7.14
2.3	2.41	0.11	4.78
2.4	2.43	0.03	1.25
2.6	2.53	-0.07	-2.69
2.8	2.54	-0.26	-9.29

The weighted regression coefficients for the first four factors of the Nonpareil model showed multiple areas across the spectrum that contributed to % N_{DM} with the strongest contribution observed in the 350-800 nm range (Figure 60).

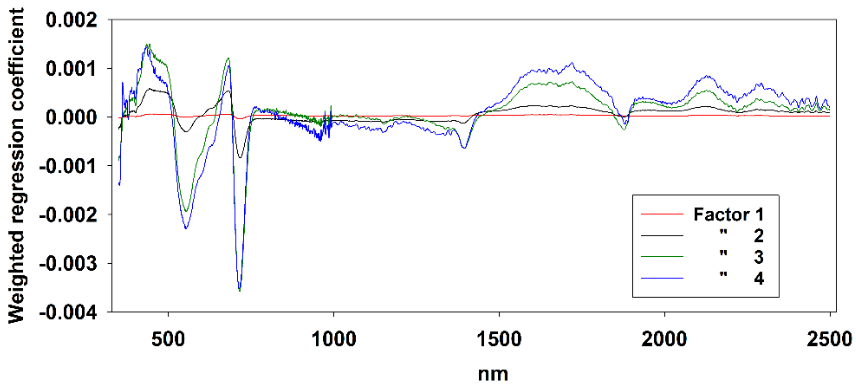


Figure 60 Weighted regression coefficients for the four factors in the Nonpareil PLS model obtained from mean-centred data

Water contributes around 70% to the fresh mass of leaves (data not shown). As the spectral data is collected from fresh leaves, compared to the nutrient analyses performed on dry leaves, water content (on a % w/w basis) was included as a covariate with % N_{DM} to take advantage of possible correlations or collinearity between the two. The resultant model showed a decrease in the respective R^2 values associated with % N_{DM}, as well as an increase in the error of calibration and validation (Table 37).

Table 37 PLS models generated with both % N_{DM} and % moisture as covariates and their associated R^2 values and errors

Four factors were identified as optimal in both models.

	calibration		validation		prediction	
Covariate	**R^2**	**RMSEC**	**R^2**	**RMSEV**	**R^2**	**RMSEP**
% N_{DM}	0.39	0.14	0.28	0.16	0.24	0.14
% moisture	0.77	0.90	0.72	0.10	0.76	0.71

However, it was demonstrated that spectral leaf data have the potential to accurately predict leaf water content seeing that the R^2 for calibration, validation and prediction was higher than 0.70.

A PLS model generated with only water as the independent variable showed little if any improvement in R^2 and error associated with calibration and validation compared to that of the previous covariate model (Figure 61).

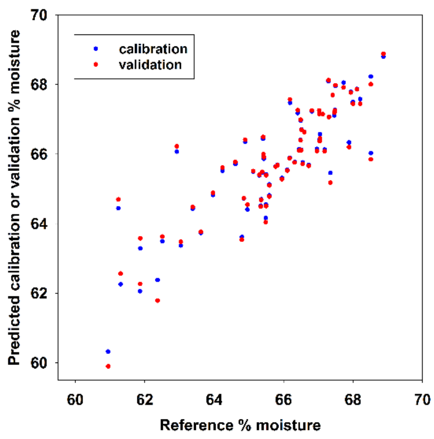


Figure 61 Reference versus predicted plot for calibration and validation of the leaf moisture (%) PLS model for the training set

A test set used to estimate the predictive accuracy of the model predicted leaf moisture differing at most 2.4% from the reference values (Table 38).

Table 38 Reference and predicted % leaf moisture calculated using the raw data PLS model for the test set

% moisture		residual	
reference	predicted	absolute	relative
62.5	61.3	-1.2	-1.9
63.8	63.2	-0.6	-0.9
64.2	63.5	-0.7	-1.1
64.4	64.8	0.4	0.6
64. 5	66.0	1.5	2.4
64.6	64.6	0	0
65.0	65.8	0.8	1.2
65.3	64.8	-0.5	-0.7
65.8	66.2	0.4	0.6
65.9	64.7	-1.2	-1.8
66.1	65.3	-0.8	-1.3
66.4	66.6	0.2	0.3
66.4	66.0	-0.4	-0.6
67.2	66.4	-0.8	-1.1
67.3	67.3	0	0
67.6	67.5	-0.1	-0.2
68.1	67.9	-0.2	-0.3

Discussion

The model showed that there is a relationship between laboratory-based determinations of the total % N and proximal leaf spectral measurements. However, the prediction accuracy of the model, without incorporating differences between genotypes, showed that N could be over- or under-estimated by up to 12% from the absolute value. In an orchard situation this will mean that it would likely not be possible to discriminate between two samples with respective N_{DM} values of 2.4% and 2.6%, but possible between two samples with N_{DM} values of 2.0 and 2.8%.

The total % N in samples in this study ranged from 2.1 to 3.1% with the majority falling between 2.3 and 2.6%. The H1 was selected as the platform for this study because of the nitrogen fertigation treatments applied.; the assumption being that because N supply differed by four-fold leaf N values would vary significantly between treatments and provide a sample population with N_{DM} values below, at and above the optimal range currently used as a guide for industry (Robinson *et al.* 1997). Up to now trees were in the early stages of establishment and as trees mature and treatment effects on the canopy size and yield become more apparent, leaf N ranges between treatment applications may become more discernible. It should be noted here too that during the spur productivity trial (AL14005) a 46% reduction in the standard nitrogen application imposed for four years on mature Nonpareil trees, did not result in leaf N levels falling below the level considered adequate in almonds.

Considering that the average of the predicted N values is close to the average of the absolute N values (Table 34) a relatively close prediction of the % N for a whole orchard is possible when the predicted % N for individual trees or sections are averaged out. In commercial orchards blanket N applications are applied to single plantings because of infrastructure limitation.

Removal of potential variability between cultivars by limiting the model to only Nonpareil samples did result in an improvement of the R^2 of calibration and validation as well as that of prediction. However, the small number of samples limited the size of the test set used to determine prediction error and as such care must be taken when interpreting these results. More weight can be given to the R^2 and error associated with the leave-one-out cross validation in this case. Developing a model based only on Nonpareil would have limitations for an industry based around multiple cultivars and with an increased interest in new cultivars, but it would still provide a valuable tool for N management for 50% of standard Australian orchards.

In terms of the current study the narrow range of N_{DM} used to develop the PLS model is limiting the likelihood of success at this point. Incorporation of additional samples with N_{DM} values in the deficient range (*i.e*. below 2.0%) mand values that would be considered supra-optimal (*i.e.* above 2.5%) and even excessive would provide a more robust base on which to build a more accurate model and one that has a greater application in industry. The H1 planting remains the most likely source of such a range of N_{DM} underscoring the need for ongoing imposition of the N supply treatments.

Total % N analyses includes a digestion step indicating that all leaf compounds that contain N are reflected in the value. This raises the question as to whether there is an inherent limitation around using leaf total N as a tool for N fertiliser management in almond orchards as it may not be the best indicator of leaf N concentration. Indeed, examination of the PLS model's weighted regression coefficients (Figure 60) showed that wavelengths between 350 to 800 nm had the strongest relationship with N_{DM}. Vegetation indices – *e.g.* NDVI, NDRE and CCCI – are generally used in remotely sensed canopy spectra as an indication of N status of orchards using wavelengths between 670 nm and 800 nm, the red-edge band (*i.e.* 680-730 nm) particularly. Reflectance spectra collected from leaves off trees in the H1 planting displayed at approximately 437, 497, 551, 676 and 716 nm. Chlorophyll A and B are expressed in these bands and as these bands fall outside of the range commonly used in N prediction there is a potential to develop a new N-based indices for almonds that incorporates wavelengths in the lower regions of the visible spectrum.

The identified bands also suggest that other classes of compounds such as the carotenoid pigments and anthocyanins, may be contributing to the model. There is the possibility that changes in these compounds could indicate changes in leaf N, but it needs to be emphasized too that correlation does not necessarily indicate causation. Using alternative metabolites or classes compounds for N prediction in leaves will need thorough investigation to establish their suitability, especially because some classes of compounds and cellular components are affected by tissue levels of other mineral nutrients as well (*e.g*. chlorophyll and iron).

A strong correlation (R^2 = 0.77) was found between leaf water content and leaf reflectance spectra. Predicted leaf water content varied by up to 2.3% from the respective reference values suggesting that a model built on that correlation may have potential as an orchard management tool. Sample leaf water content only ranged between 61.0 to 68.9% possibly because trees were well watered. The generating a wider data set by including leaves from trees at hydric constraint, optimum or luxury would provide a more robust model for prediction of leaf water content in an almond orchard context and opens up the opportunity to manage irrigation and nitrogen in real time based on reflectance scans collected off leaves. Qualitative assessments of tree water status is most commonly based on thermal data but the resolution of remotely sensed thermal data outputs is coarse. In orchards with small canopies, as will be the case in higher density plantings, a large portion of the thermal signal will originate from the soil. As a water model uses the same spectral data set as a N model would, both water and N may possibly be estimated at the same time.

Ongoing research

The conduct of the field trial was severely affected by environmental circumstances beyond the control of the project team, and completion of some outputs adversely affected as a result. Nonetheless, the trial's infrastructure is unique in that a range of fertigation treatments can be supplied to plots at a statistically robust scale. The planting is also unique because a population of trees is being generated that is differing in their N status. The need to remove all trees on Garnem doesn't negate the usefulness of the remaining trees on Nemaguard and RP40, as the most recent analytical data attest.

Further nutrient and spectral datasets consisting of % N over a wide range of values will be added to the current dataset over coming seasons to increase the robustness of the datasets and improve the model's predictive power.

It is further possible to conduct small trials on the relationship between spectral data and the water content of leaves. These can be conducted concurrently with water withholding and recovery trials (discussed on page 114).

Identifying spectral bands that contain information about leaf N (and pools therein) or classes of compounds indirectly related to leaf N is complex and additional skill sets may need to be developed or accessed externally to improve this part of model development. Potentially, collaboration within AVR and/or SARDI may be appropriate, and as mentioned, the H1 planting is a unique fit-for-purpose platform for this type of analyses because of the different scions/rootstock and nitrogen fertigation treatments being applied.

Horizon 3 - Suitability of new cultivars for more intensive production systems

The higher density planting was established to evaluate the suitability of some of the new Australian-bred cultivars within closer plantings with the view that denser plantings will be needed for future shake-and-catch harvesting systems. The architecture of Almond 12 (A12), Carina and Vela, as modulated by two commercial (Garnem and Nemaguard) and two growth reducing [Rootpac 40 (RP40) and Rootpac 20 (RP20)] rootstocks were investigated. Because it is unknown what growth habit or tree architecture would be preferable in a higher density planting, these self-fertile cultivars with different growth habits were selected.

Tree architecture and light interception as a function of scion cultivar/rootstock and planting density

Summary	
Why?	• suitability of scion/rootstock/spacing for overhead shake and catch harvest technology • tree architecture vs light interception and ultimately yield • changes in tree architecture to canopy manipulation
How?	• tree and shoot architecture • light interception • LiDAR
What?	• scion/rootstock tree architecture and vigour • % canopy removed through hedging • scion/rootstock response to hedging
So?	• regular vs reduced vigour rootstocks axillary growth • suitability in relation to canopy dimensions • canopy light interception in scion/rootstock
Next?	• changes in tree architecture across multiple seasons • changes in canopy light interception over multiple seasons • tree architecture simulations

Tree growth

Tree dimensions are important during the first stages of development as this indicates the rate that the scion/rootstock combination will fill the tree line. At the later stages of development tree growth, which will largely be modulated by rootstock, will dictate the percentage of the canopy removed during mechanical pruning operations. The long-term effects of tree hedging on the canopy in subsequent seasons needs to be assessed as it will have implications for light interception, the degree of canopy management required to maintain canopy dimensions and on kernel yield.

The degree of expansion of the canopy during the growing season also has repercussions during the harvest period. The trees are "sculpted" in winter to allow for an over-the-row harvester (Figure 62). An additional hedging operation may need to be conducted prior to harvest should the canopy size increase during the summer growth period to such a degree that the dimensions are too large for a harvester. The additional canopy manipulation action will also add to management costs.

Depending on the severity required, a late season hedging may stimulate axillary growth – likely more prominent in some cultivars on some rootstocks. Carbohydrates destined for the storage pool will be utilised in late seasonal growth instead of being allocated to the permanent structures which will impact flowering and budburst the following season.

Figure 62 Mechanical over-the-row harvesters available for almonds

On the left is a modified grape harvester harvesting high-density almond plantings at the SuniTAFE SmartFarm (Mildura) and on the right an example of a currently available commercial almond harvester.

To accommodate the grape harvester the canopy height should not exceed 2 m and the canopy width should be a maximum of 1.5 m. For the commercial harvester (image from https://tenias.com) orchard row spacing needs to be 5.5 m, trees need to have a maximum height of 5.5 m and have maximum trunk height of 0.9 m.

Two measures were used in the trial to assess tree growth and how genotype and tree spacing affected the changes in tree size following hedging. Tree dimension measurements were used as an indication of the expansion of the tree canopies whereas trunk diameter measurements were used as an indication of the increase in biomass. To support these measurements shoot architecture assessments were conducted in the 2020-21 season to determine where along the shoot reproductive zones were located and where on the shoot axillary growth primarily occurs.

Materials and methods

Preliminary assessment of tree dimensions commenced in the 2019-20 season. The first hedging action was performed in the winter of 2020 and first assessments of the response of trees to the hedging action, both in growth and the degree and manner of branching, were conducted at the end of the 2020-21 season. Due to the small size of the trees at the end of the first growing season (refer to LiDAR section – page 51) a small percentage of canopy was removed by the hedging. The hedging action at the end of the second growing season was more severe than the first because tree size and shoot numbers and lengths were greater.

Hedging in the first season was performed by a private contractor using a tractor-mounted hydraulic cutter bar commonly used in vineyards. This was sufficient at the end of first leaf because the trees were still small.

At the end of the second leaf a large percentage of canopy had to be removed, especially in the plots with high vigour rootstocks, and the scaffolding branches were more robust. For these reasons, hedging was performed with a dual boom hedger-topper[43] (Figure 22). To maintain tree form in coming seasons a hedger-topper has been procured for the Mildura SmartFarm using RRDP and Victorian State Government funding.

Tree dimensions were measured manually and the tree height and the canopy diameters along and within the tree row noted. Manual tree dimensions measurements are labour intensive and as tree size increase the potential for measurement error increases. For this reason, the potential to define tree dimensions with the use of a UAV platform was evaluated (refer to page 53) to increase the accuracy and efficiency of data collection and to enable measurements at multiple phenological time-points during the season.

The trunk diameters of the measurement trees (n = 816) were measured at the end of the growing seasons with S_Cal EVO Form E digital calipers[44]. A model with a 30 cm measuring range and extended jaws was procured so that measurements can also be conducted on larger mature trees. This model also has Bluetooth capability; data can be directly logged into a spreadsheet. The time spent conducting trunk diameter measurements was drastically reduced as a result of acquiring these calipers. The measurement height (40 cm) was permanently marked to ensure consecutive measurements were taken at the same position on the trunk.

Results and discussion

Tree growth

As expected, trees in the 1-m spacing filled the intra-row space by the end of the second leaf irrespective of scion/rootstock combination (Table 39). The majority of trees spaced at 2 m also filled out the tree line, but there were still gaps between several trees on RP20. Overall, RP20 trees still had to fill around 9% of the tree line space at the end of the second growing season which was significantly lower (P = 0.05) than the approximately 3% of trees on Garnem (Table 39). At the end of this coming season all trees in the 2-m spacings will likely have filled the intra-row space.

Table 39 The effect of cultivar and rootstock on the intra-row canopy diameter (m)

Values are the mean (n = 16 per cultivar and n = 12 per rootstock) and letters denote significant differences (P = 0.05) between cultivars or rootstocks within tree spacings. Where letters are absent no differences were found between measurements.

		Tree spacing (m)		
		1	**2**	**4**
Cultivar	**A12**	1.00	1.94 a	2.38 b
	Carina	1.00	1.77 b	2.35 b
	Vela	1.00	2.00 a	2.55 a
Rootstock	**Garnem**	1.00	1.95 a	2.74 a
	Nemaguard	1.00	1.91 ab	2.49 b
	RP20	1.00	1.83 b	2.13 d
	RP40	1.00	1.92 ab	2.34 c

Cultivar also played a role in closing the tree line space in the 2-m spacing, likely because their growth habits dictate the degree of horizontal growth. Vela trees closed the intra-row space by the end of the season but Carina canopies, which grow upright compared to Vela's weeping growth habit (discussed in *Tree architecture* on page 98), were significantly (P = 0.05) narrower compared to Vela at only 1.77 m (Table 39).

[43] Ietto Contracting Services, Mildura

[44] https://www.sylvac.ch/products/calipers/caliper-s_cal-evo-form-e

Irrespective of scion/rootstock, trees filled out around two thirds of the intra-row space in the 4-m spacings (Table 39). Possibly because there was no competition for space in the 4-m plots trees were able to grow without restriction and the tree width along the tree line reflected the vigour of the rootstocks and the growth habits of the cultivars (Table 39). This was also noticeable in the tree heights.

Table 40 The effect of genotype and tree spacing on the increase in height of trees and expansion into the interrow space

Values are the mean (n = 48 for cultivar and tree spacing and n = 36 for rootstock) and letters indicate significant (P = 0.05) differences between measurements within main effects.

		Height (m)	Interrow (m)
Cultivar	**A12**	0.68 b	1.98 a
	Carina	0.81 b	1.93 a
	Vela	0.98 a	2.06 a
Rootstock	**Garnem**	1.08 a	2.17 a
	Nemaguard	0.76 b	1.96 b
	RP20	0.71 b	1.81 c
	RP40	0.75 b	2.01 b
Tree spacing (m)	**1**	0.78 b	1.77 c
	2	0.78 b	1.95 b
	4	0.91 a	2.24 a

The degree to which trees extended into the interrow space again was related (P = 0.05) to tree spacing because of competition between trees planted 1 m and 2 m apart not only for intra-row space, but potentially also water and nutrients that may have limited growth compared to trees in the 4-m spacing. As expected, rootstock also played a role because of different vigours imparted on the scions.

Table 41 Variation accounted for by the cultivar, rootstock and tree spacing, and interactions thereof, on the canopy volume (m^3) and the percentage of canopy removed during the hedging action

Canopy volume was determined at the end of the second leaf and the % canopy removed estimated from the hedging dimensions

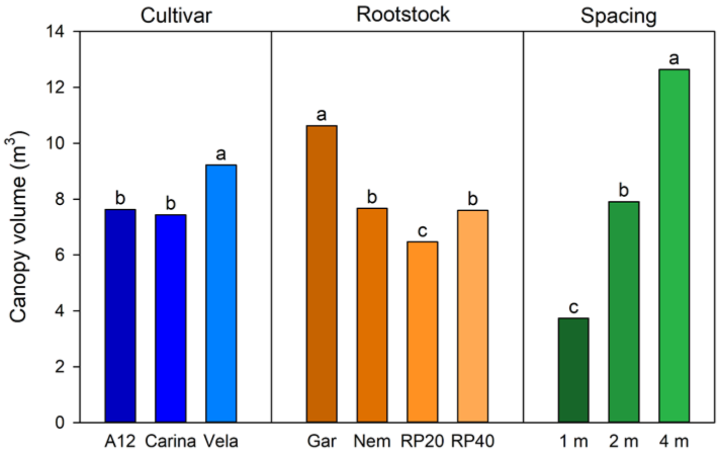
Source of variation	Canopy volume		% canopy removed by hedging	
	% sums of squares	Significance (p-value)	% sums of squares	Significance (p-value)
Block	1		5	
Cultivar	3	**0.015**	8	**0.012**
Rootstock	12	**< 0.001**	20	**< 0.001**
Tree spacing	64	**< 0.001**	21	**< 0.001**
Cultivar × rootstock	2	**0.001**	8	**< 0.001**
Cultivar × tree spacing	1	0.121	1	0.897
Rootstock × tree spacing	7	**< 0.001**	2	0.251
Cultivar × rootstock × tree spacing	1	0.194	2	0.922
Residual	9		33	

Canopy volume was estimated from the tree dimensions at the end of second leaf by assuming that the tree shape is a rectangular cuboid. Canopy volume was significantly (P = 0.05) influenced by the genotype and tree spacing and also by the interaction between cultivar and rootstock, likely driven by the rootstock-related scion vigour, as well as the spacing and rootstock interaction (Table 41).

Tree spacing was the strongest source of variation in tree volumes (Table 41) and accounted for 64% of the variation observed. Trees in the 1-m spacing had the smallest canopies because of the competition for space, followed by trees in the 2-m spacing for a similar reason (Figure 63). As discussed, the unfettered growth of trees in the 4-m spacing resulted in significantly larger canopies that were almost double the size of trees in the 2-m spacing and three times larger than trees in the 1-m spacing.

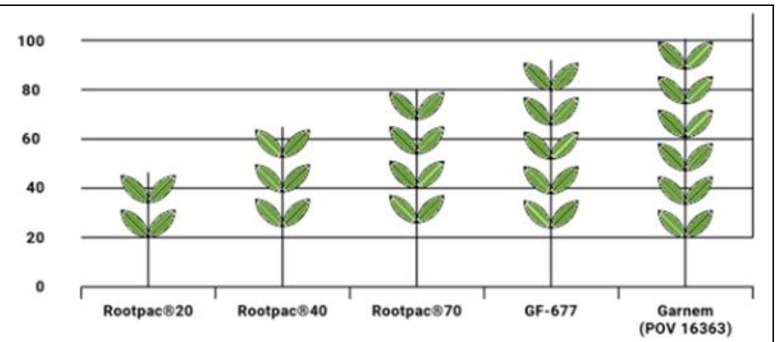
Figure 63 Cultivar, rootstock and spacing main effects on the canopy volume at the end of the second leaf growing season

Values are the means (n = 48 for cultivar and tree spacing and n = 36 for rootstock) and different letters above columns within main effects indicate significant (P = 0.05) differences between canopy volumes



Rootstock also played a role in the volume of the canopies at the end of the second leaf, albeit not as large a role as tree spacing played (Table 41). As expected, the canopies of trees on Garnem were significantly (P = 0.05) larger than the canopies of trees growing on the other rootstocks, and trees on RP20 had the smallest canopies (Figure 63). The differences in canopy volumes for RP20 and RP40 trees in relation to Garnem trees decreased as plant spacing narrowed, with the canopies in the 4-m spacing being around 50 and 40% smaller in RP20 and RP40, respectively, compared to Garnem. This is in broad agreement with the information available to industry (Figure 64). Trees on RP20 and RP40 were, however, only around 35 and 17% smaller, respectively, in relation to Garnem when trees were 1 m apart (data not shown).

Figure 64 Scion vigour imparted by RP20 and RP40 relative to scion vigour imparted by Garnem (www.agromillora.com/rootpac/, accessed 29 September 2021).



Interestingly, casual empirical observation during the growing season suggested trees on Nemaguard and RP40 had very similar canopy sizes, and this was verified by detailed measurements (Table 40). Ostensibly, RP40 is a dwarfing rootstock (Figure 64).

As mentioned, a substantial hedging action was performed at the end of the second leaf to prepare the canopy to accommodate an over-the-row harvester. Topping height was raised from 2 to 2.3 m to minimise OH&S risks associated with the operation of the hedging equipment and the potential hazards should the blades hit infrastructure in the tree line. Canopy width was maintained at 1.5 m.

Figure 65 shows Vela on Nemaguard trees planted 2 m apart before and after the hedging action. Also shown is the precision of the vertical cut (0.75 m) on one side of the canopy.

Figure 65 Image of Vela on Nemaguard in the 2 m spacing before (left) and after (middle) hedging and the vertical hedging cut (right) the side of the canopy

The percentage of canopy removed by hedging was determined by subtracting the extent of the canopy after hedging from the canopy volume determined at the end of the previous growing season. In some experimental plots – specifically trees growing on RP20 – canopies had not yet fully expanded to the "hedging box" and very little canopy needed to be removed as a result.

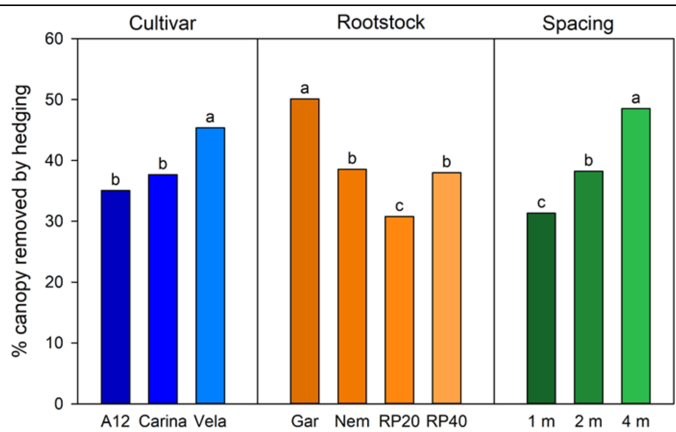
The percentage of canopy removed by hedging follows the same trend as for canopy volume, but severity of the hedging action, which can be measured as the percentage of canopy that was removed, depended on the extent of tree growth during the previous season.

Compared to A12 and Carina, 17% more of the Vela canopy was removed during the hedging action (Figure 66) possibly because of the weeping growth habit of this cultivar as seen in the lateral canopy dimensions (Table 40) and subsequently the canopy volume (Figure 63).

The largest percentage of canopy removal can however be attributed to the extra vigour imparted by Garnem, with half of the canopy volume needing to be removed (Figure 66) to maintain the target canopy dimensions. This indicates that the trees on Garnem will probably have to be managed during the growing season to accommodate an over-the-row harvester at the end of the season, which in turn increases the potential for stimulation of excessive axillary growth and densification of the canopy (discussed further in *Shoot architecture* on page 100).

Figure 66 Cultivar, rootstock and tree spacing main effects on the predicted percentage of canopy removed through hedging at the start of the third leaf growing season

Values are the means (n = 48 for cultivar and tree spacing and n = 36 for rootstock) and different letters above columns within main effects indicate significant (P = 0.05) differences between percentages.



Biomass

Trunk diameter is a non-destructive and repeatable measurement to determine the growth of trees over time and the response of different cultivars to rootstock and spacing. It is a good indicator of the biomass increase and can provide additional insight into the trees' vigour.

Figure 67 shows trunk diameters, as modulated by the cultivar, rootstock and spacing five months after establishment (August 2019), and at the end of the first (June 2020) and second leaf (May 2021). Trunk diameter measurements in the first season can mainly be used as the baseline as the size of the planting material received from the nursery would have greatly affected these measurements.

Trunk diameters started to separate according to the treatments when the trees were 15 months old. Rootstock was the strongest influence, accounting for 25% of the variability in trunk diameter increments between 2019 and 2020 (Figure 67). At the end of the second leaf the variability in the data also started following more-or-less similar trends as was seen in the canopy volume. Of interest to note is that at the end of the growing season the main effects were not as significant for the trunk diameters as was seen for the canopy volumes even though these measurements were carried out close together. It has to be remembered that tree dimension measurements will not capture differences in the density of the canopy; it does not show the degree of axillary growth within the canopy which may be reflected in the trunk diameter data. For example, trunk diameters do not differ between Vela and A12, whereas the canopy volume measurements indicate that Vela has a larger canopy than A12. Mention has been made of the two cultivars' different growth habits, and so a large percentage of A12 growth may be angled vertically or angled inward which may account for similar trunk diameters but different canopy volumes.

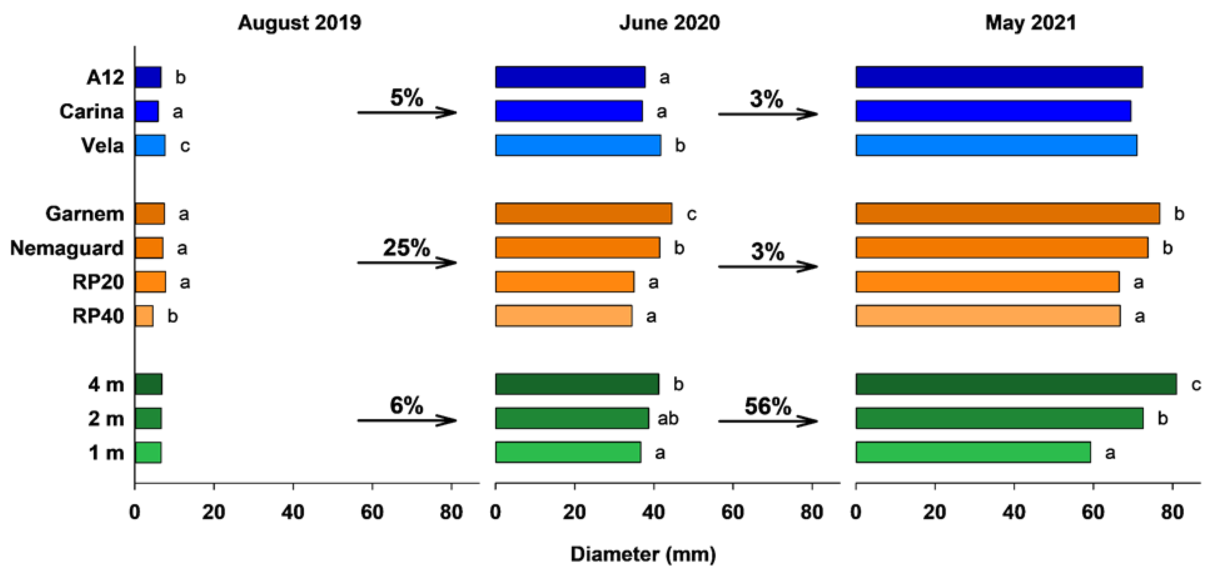


Figure 67 Cultivar, rootstock and spacing main effects on trunk diameter at three time points

Measurements were conducted after establishment (August 2019), the end of first leaf (June 2020) and then of second leaf (May 2021).

Data presented are means (n = 48, 36 and 48 for cultivar, rootstock and spacing, respectively). Within main effects and measurement times different letters indicate significant differences between means (P = 0.05). Percentages above arrows indicate the proportion of variability in trunk diameter increments between measurement times accounted for by each main effect.

Measurements at the end of the final growing seasons showed that trunk diameters in the reduced vigour rootstocks were smaller than for the regular rootstocks, and that trees in the 1-m spacing had thinner trunks than trees in the 4-m spacing, which underscores the extent of the canopies in these two spacings and the role that competition for space plays in the increase in biomass (Figure 67). Note too that even though trees on RP40 had similar canopy volumes to that of trees on Nemaguard, the relative trunk diameters were more in accordance with the widely held belief that RP40 is a growth reducing rootstock.

Ongoing research

The next step is to develop a method and automated workflow to identify individual trees for tree dimension data collection. Specialist skills are needed to create the algorithms required; estimates are currently extracted manually. Images will be collected with the UAV platform in the coming seasons to determine tree expansion at multiple timepoints after the first more severe hedging action and to determine whether additional hedging actions are needed before harvest. Manual width and length measurements will however need to continue until the methodology has been validated.

The team was approached by a service provider who has the capability to identify individual tree canopies from aerial imaging. Similar sensors are used by both parties and collaborative linkage may be possible.

Trunk diameter measurements will continue in coming seasons to assess changes in biomass and whether tree spacing limits the expansion of the above-ground biomass.

Tree architecture

Light detection and ranging (LiDAR) was used to render digital 3D representations of the trees in the higher densities planting. The instrument works by pulsing laser beams and determining the time that the reflected beam takes to return to the detector. A highly accurate 3D-point cloud is then produced from the variable distances.

The first set of point cloud data was collected after leaf fall in winter 2020, prior to the first hedging action, to define the natural growth habits of the treatment combinations. The second set of data was collected in winter 2020 (again after leaf fall) to determine the effect of the first hedging on axillary growth and to simulate the impact of the upcoming hedging.

Materials and methods

Equipment details are described on page 51 under Light detection and ranging (LiDAR).

Four high-resolution scans were conducted per treatment from both sides of the trees with the scanner placed 2.5 m from the tree and at a height of 1.2 m. Eight calibration targets were placed at random positions and heights to assist in image registration. Scans were downloaded and registered in-field and images were rendered in AutoDesk Recap (Autodesk Inc., San Rafael, CA, USA) and Cyclone REGISTER360 (Leica Geosystems, St Gallen, Switzerland). Hedging simulations were performed in AutoDesk Recap.

Results and discussion

Point cloud representations of trees after the first leaf are shown in Figure 68; the cultivars' natural growth habits were already apparent after the first year of establishment. The three scion cultivars are shown on Nemaguard, the industry standard rootstock, and RP20 which should impart the lowest vigour (as discussed under *Tree growth*).

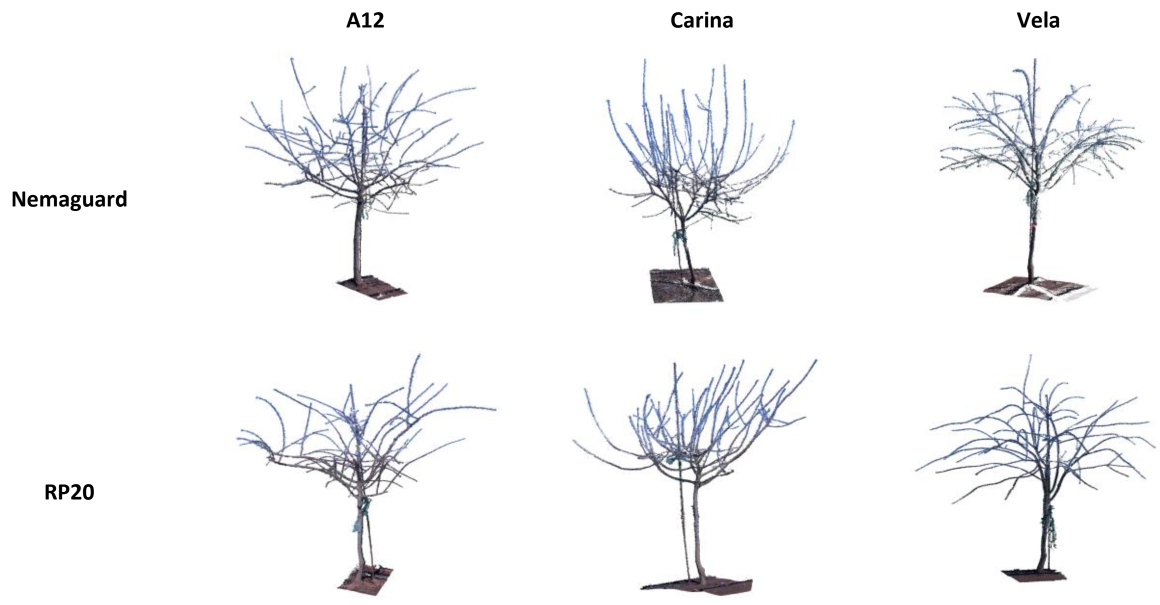


Figure 68 Point cloud images showing the natural growth habits of Almond 12 (A12), Carina and Vela on the industry standard (Nemaguard) and a growth reducing rootstock (RP20)

Images were collected in the winter after first leaf when trees were 14 months old and before the first hedging.

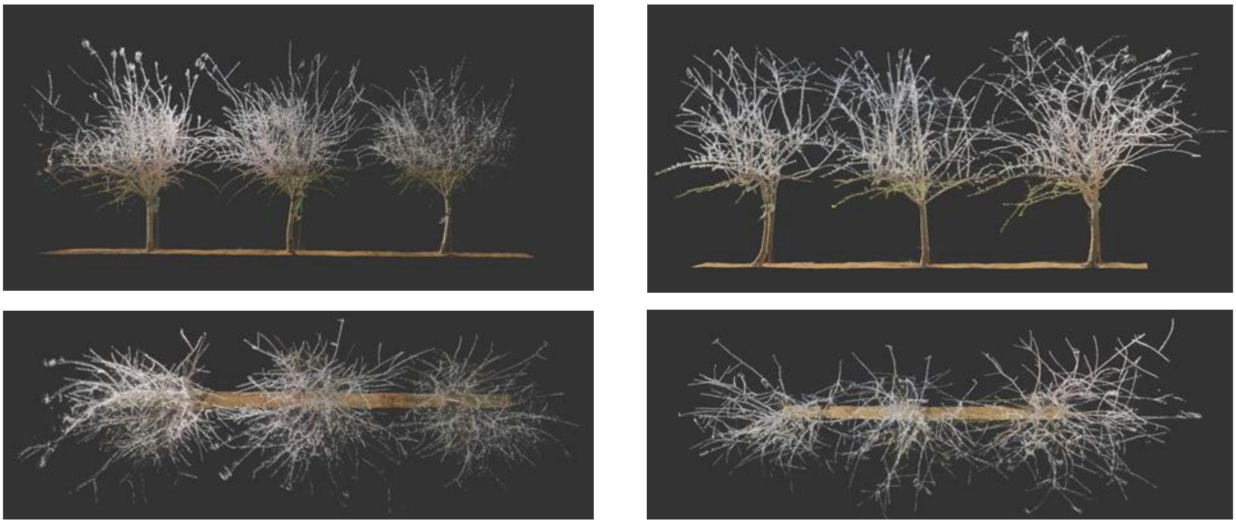
At first glance A12's branch orientation is obviously more horizontal compared to the other two cultivars. Axillary growth on a A12 branch is also mostly perpendicular to the shoot that it originated from. This observation was even more noticeable on A12 trees on RP20, and a box-like appearance became more common as the shoots grew.

Carina's growth is the most vertical of the three cultivars, with Vela's branch orientation being between that of A12 and Carina and described as "weeping".

Closer examination of the rendered images indicated that at the end of the first leaf trees on RP20 were not only smaller, but had less axillary growth compared to trees on Nemaguard. This may be part of the mechanism(s) by which RP20 confers dwarfing. Further investigation of the dwarfing phenomenon is warranted given the importance that tree size control is likely to play in the future.

These growth habits, both the branch orientation and tendency for axillary growth, have implications for their suitability in higher density plantings as discussed in the section on *Tree growth*, and will be discussed further in subsequent sections. Branch orientation and axillary growth will not only affect light interception in the canopy, thereby affecting productivity, but will also play a role in the trees' response to hedging.

Point clouds taken at the end of the second leaf confirmed the growth habits of the trees (data not shown for all scion cultivars and rootstocks). For discussion purposes images of the tree architecture of Vela on Nemaguard and RP20 are presented in Figure 69.



Nemaguard *RP20*

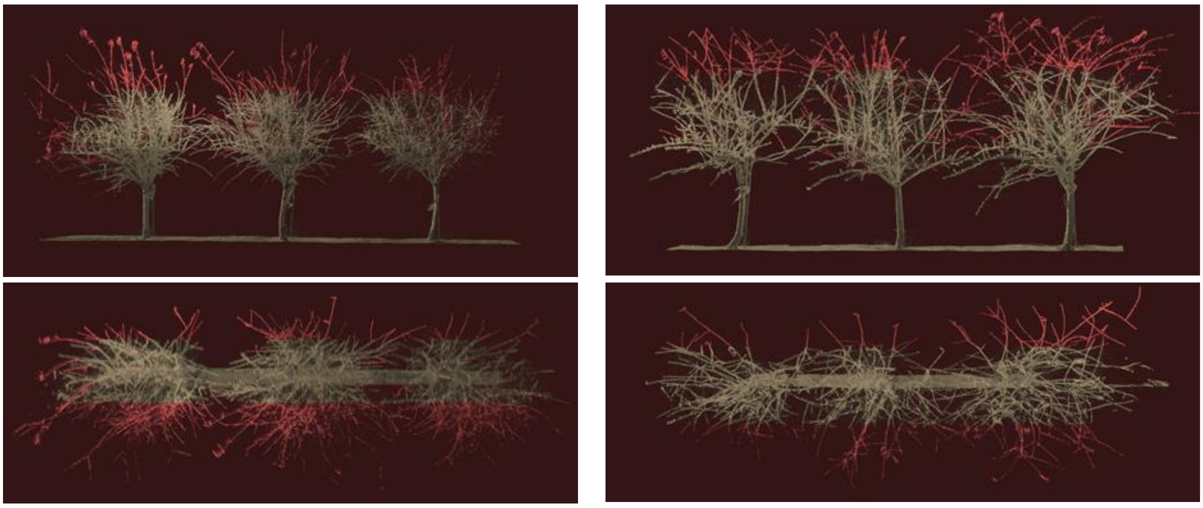
Figure 69 Side and top view of point cloud images of 2 m spaced Vela trees on Nemaguard and RP20 at the end of second leaf and prior to the second hedging

From Figure 69 it can be seen that Vela has largely filled the tree line (and as shown in Table 39). The sprawling growth of Vela shoots may be the reason that it seems that Vela trees on RP20 filled the space as well from the images provided, but large gaps were still visible in the field between trees.

The top view is included to show the importance of branch orientation on light penetration through the canopy. Compared to an upright cultivar like Carina, the sprawling nature of Vela should improve light penetration into the internal parts of the canopy, which – depending on the number of flowering locations within the canopy – should improve this cultivar's yield. These aspects are discussed in more detail in *Shoot architecture* and *Projected productivity*.

Preliminary observations after the first season's establishment on the influence of rootstock on axillary growth were reconfirmed after the second leaf; trees on Nemaguard having a higher degree of axillary growth compared to trees on RP20 (Figure 69). This is evident in both views, and, as noted, will have implications for light interception in the lower parts of the canopy in the longer term.

Furthermore, it is possible to simulate the hedging action and determine the amount of canopy that will be removed, as well as where the hedging cuts will made, as all structures on the tree are captured in the images. In combination with the insights set out in *Shoot architecture*, the potential for axillary growth, and where that axillary growth is more likely to occur, growth in following seasons can be predicted, which in turn will give insights into future canopy densification.



Nemaguard RP20

Figure 70 Simulation of the hedging action of Vela on Nemaguard and RP20 to show the extent of canopy removed and where on shoots hedging cuts will be made

Green defines the simulated tree dimensions after hedging, and red the canopy that will be removed during the action.

Ongoing research

Canopy images will be collected across multiple seasons to ascertain the effect of treatments and intensive canopy management on tree architecture. Further assessments will show the changes in branching (axillary growth) and the loss or gain in potential fruiting space.

Shoot architecture

Shoot architecture assessments were performed to assess the growth habit of shoots across seasons. The natural habit was assessed as well as the growth response to the first hedging action, specifically the location and degree of axillary growth after apical dominance was removed, and if genotype or plant spacing affected these.

The growth response in relation to canopy manipulation is important in the selection of genotypes that are suitable for higher density plantings as discussed throughout this and previous sections.

Materials and methods

Shoot architecture assessments were performed in June 2021 after leaf fall. Four shoots, two hedged and two non-hedged shoots were randomly chosen from the central measurement tree in each plot (n = 576 shoots). One shoot of each type was selected from the north and south face of the tree to accommodate for the potential influence of the wind (as discussed on page 48) on shoot growth and development (n = 288 per shoot type).

The shoot length was recorded and each node noted if it had a latent, vegetative or floral bud, or an axillary shoot. Axillary shoots were further classified as short (< 5 cm), medium (> 5 cm but < 15 cm) and long (> 15 cm) and if it was vegetative or reproductive.

Proportional data were normalised using arcsine transformation.

Results and discussion

Non-hedged shoots

Non-hedged shoots were assessed to determine the natural growth habits of the cultivar and whether rootstock and spacing modulated those natural traits to any extent. Cultivar, rootstock and spacing main effects on non-hedged shoots' characteristics are presented in Table 42.

Non-hedged shots were also assessed to determine where reproductive zones are naturally located along the shoot. This knowledge will assist in not only determining how many reproductive nodes may be removed during hedging, but also if the reproductive zones will potentially be shaded out in the higher vigour scion/rootstock combinations and higher tree density plots. The natural tendency of a cultivar or rootstock to produce axillary growth, especially at the base of the shoot, has implications for canopy density but potentially also providing more fruiting sites.

Table 42 Cultivar, rootstock and spacing main effects on non-hedged shoot characteristics

Values are means (n = 96 shoots for cultivar and n = 72 shoots for rootstock and spacing) and letters indicate that values significantly (P = 0.05) differ within main effects.

	Cultivar			Rootstock				Spacing (m)		
	A12	**Carina**	**Vela**	**Garnem**	**Nemaguard**	**RP20**	**RP40**	**1**	**2**	**4**
length (cm)	92 b	103 a	96 ab	91 b	104 a	97 ab	95 ab	95 a	95a	101 a
nodes/shoot	63 c	73 a	66 b	61 c	74 a	71 ab	64 bc	65 b	65 b	72 a
cm/internode	1.51 a	1.42 b	1.48 ab	1.54 a	1.43 b	1.40 b	1.51 a	1.51 a	1.49 a	1.40 a

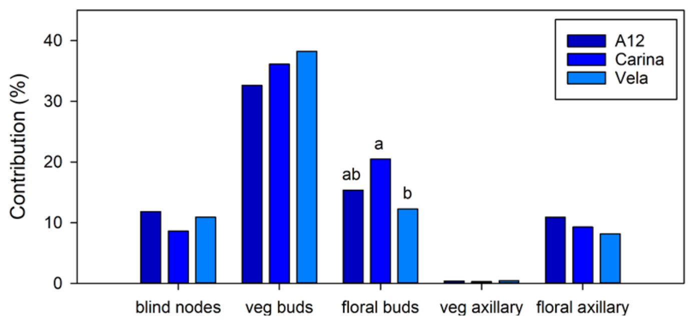
Non-hedged shoots on trees in the 4-m spacing were longer, had more nodes and those nodes were closer together that non-hedged shoots on trees spaced at 1 and 2 m. The shorter internode lengths may be indicative of competition for water and nutrients.

Shoot length was significantly (P = 0.05) affected by both cultivar and rootstock. Trees on Garnem did not present relative shoot lengths consistent with that rootstock's vigour; unhedged shoots on trees growing on this rootstock were the shortest with the least nodes. As mentioned, the nature of rootstocks' effects on scion vigour warrants further investigation.

Spacing did not play a significant role (P = 0.05) for most of the shoot attributes quantified; the exception being the percentage of vegetative axillary growth where the highest percentage vegetative axillary growth was recorded in the 4-m spacing (P = 0.05). This too may be indicative that competition for water and nutrients are playing a role.

Figure 71 Effect of cultivar on the percentage of blind, vegetative and floral buds and vegetative and floral axillary growth per shoot

Values are means (n = 96) and different letters above columns indicate that values significantly (P = 0.05) differ between cultivars. The lack of letters indicates that there were no significant differences between means.

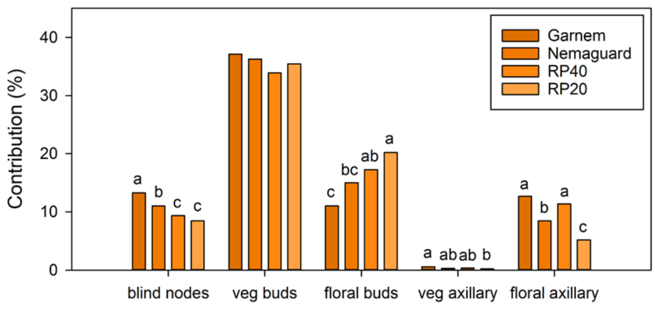


Cultivar only significantly (P = 0.05) affected the percentage of nodes that bore floral buds (Figure 71), an effect related to the differences in the number of nodes per shoot (Table 42). Other shoot attributes were not significantly affected.

A large percentage (96%) of the axillary growth had floral buds present with the potential to bear fruit. Because the population of these shoots will not be altered during hedging due to their position in the canopy, the presence of these shoots will increase the trees' number of fruiting positions.

Figure 72 Effect of rootstock on the percentage of blind, vegetative and floral buds and vegetative and floral axillary growth per shoot

Values are means (n = 72) and different letters above columns indicate that means within an attribute differ significantly (P = 0.05) between rootstocks. The lack of letters indicates that there was no significant effect



Nodes on non-hedged shoots were more likely to be floral but axillary shoots were less likely to be floral on trees on RP20 than shoots on trees growing on the other rootstocks (Figure 72). This is consistent with the observation that in general non-hedged shoots of trees on RP20 have a significantly (P = 0.05) lower percentage of axillary shoots compared to trees on other rootstocks (5% compared to 13% for trees on RP20 and Garnem, respectively – data not shown).

Hedged shoots

The trees were first hedged 17 months after planting and after their first leaf. The trees had not put on extensive growth at this point (as discussed on pages 92 and 98) and only a small percentage of material was removed during the first hedging action.

Removing the apical bud during hedging precluded further shoot elongation and stimulated axillary growth. But the low number of nodes per hedged shoot (26 on average, data not shown) limit the number of potential fruiting positions and locations for axillary growth in subsequent seasons.

The number of axillary shoots and the number of those axillary shoots longer than 15 cm was a function of cultivar and rootstock (Table 43). Twice the number of axillary shoots arose from hedged shoots on A12 trees on RP40 compared to A12 on RP20. Rootstock exerted no influence on the number of axillary shoots to arise on hedged Vela shoots or the number of those axillary shoots being longer than 15 cm.

Table 43 Interactive effects of cultivar and rootstock on the number of axillary shoots on hedged shoots and the number of axillary shoots longer than 15 cm

Values are means (n = 288 shoots) and different letters following each mean indicate significant differences between means at P = 0.05 between rootstocks within cultivars. The lack of letters indicates that there was no significant effect.

An asterisk (*) indicates that the value differs significantly (P = 0.05) between cultivars within a rootstock.

	Axillary shoots/hedged shoot				Axillary shoots >15 cm			
	Garnem	**Nemaguard**	**RP20**	**RP40**	**Garnem**	**Nemaguard**	**RP20**	**RP40**
A12	7.0 bc	8.8 b	5.8 c	11.6 a*	4.5 b	5.5 b	3.8 b	8.5 a*
Carina	8.1 a	6.5 a	5.4 b	8.8 a	5.2	4.6	4.1	5.8
Vela	7.2	6.2	5.2	6.5	4.6	4.5	3.6	3.6

A12 showed the widest variability in axillary growth in relation to the rootstock it was grafted on (Table 43). Hedging seemed to stimulate axillary growth on A12/RP40 and produced on average twelve axillary shoots per shoot of which nine were longer than 15 cm. Hedged shoots on A12/RP40 had 44 nodes on average so around a quarter of the nodes on the assessed shoots produced axillary shoots, and three-quarters of the axillary shoots would have been longer than 15 cm. This observation was only evident on A12 trees with no differences seen between Carina and Vela on RP40 in axillary growth. The number of long axillary shoots (> 15 cm) also did not differ between rootstock in Carina and Vela.

Hedged shoots on trees growing on RP20 generally had fewer axillary shoots, but the rootstock's effect was not evident on Vela trees (Table 43). Although RP20 also seemed to have the least number of long axillary shoots, it was not significant. These differences in axillary growth were also evident from the LiDAR images (as discussed on page 98).

Trees on Garnem, the high vigour inducing rootstock, did not show excessive axillary growth after the hedging action compared to trees growing on other rootstocks (Table 43). This observation is in contrast to what was observed for tree growth and architecture (pages 92 and 98). It has to be remembered that only four shoots out of the total shoot population per tree were assessed which does not account for the total number of shoots per tree. Unhedged shoots of tress on Garnem did produce a larger number of axillary shoots compared to the other rootstocks (Figure 72), which could partially account for the higher vigour observed for this rootstock. Hedged shoots on trees on Garnem also had four times more vegetative axillary shoots compared to hedged shoots on trees on RP20 (data not shown).

On average only 4% of axillary shoots on hedged shoots were vegetative with an even smaller percentage (3%) of long axillary shoots being vegetative with rootstock significantly (P = 0.002) affecting the number of vegetative axillary shoots (data not shown). This indicates that axillary shoots were significantly more likely to have been fertile (96% of shoots having floral buds compared to 4% being vegetative) at the end of the second leaf.

Table 44 Effect of cultivar and rootstock on the total number of fertile axillary shoots on hedged shoots

Values are the mean value (n = 288 shoots) and letters denote that numbers differ significantly (P = 0.05). An asterisk (*) indicates that the value differs significantly (P = 0.05) between cultivars within a rootstock.

	Fertile axillary shoots				Fertile axillary shoots > 15 cm			
	Garnem	**Nemaguard**	**RP20**	**RP40**	**Garnem**	**Nemaguard**	**RP20**	**RP40**
A12	6.4 b	8.5 b	5.6 c	11.5 a*	4.2 b	5.4 b	3.7 b	8.3 a*
Carina	7.8 ab	6.4 ab	5.4 b	8.5 a	5.1 a	4.6 a	4.1 a	5.7 a*
Vela	6.4 a	6.2 a	4.9 a	6.0 a	4.1 a	4.5 a	3.4 a	3.3 a*

Because most axillary shoots were fertile, the effect of cultivar and rootstock on the occurrence of fertile axillary shoots were similar to the overall axillary shoot numbers. The main difference is that the number of long fertile axillary shoots on hedged shoos on trees growing on RP40 differed significantly between the three cultivars (Table 44).

Ongoing research

Shoot assessments during the 2022 winter will throw further light on the cultivars' growth habits as influenced by the rootstock and spacing and the second more severe hedging in the 2021 winter. Observation continuity is critical as trees mature over the coming seasons and as the multiple hedging actions changes the architecture of the shaped trees. Changes in tree architecture over the coming seasons in response to hedging will in turn affect other important yield parameters; *e.g.* the light penetration through the canopy. This point is critical because it is the long-term effect of multiple hedging actions on not only the tree architecture, but also productivity that are unknown. This information needs to be established to confidently make recommendations for potential cultivars/rootstocks/spacings to industry. The degree to which each cultivar/rootstock combination responds to regular axillary growth stimulating events (*i.e.* hedging) and constraints of light, space, water and nutrients need to be quantified over multiple seasons.

Canopy light interception

The effective area of shade (EAS) measures the proportion of light intercepted by the canopy, and is an indication of the size of the canopy. Fundamentally, EAS is an index of the size of the transpiration area, and has been shown to be well correlated with tree water requirements. In combination with the reference crop evapotranspiration (ET_o), EAS can be used to optimise irrigation to avoid over-or underwatering trees.

Materials and methods

Photosynthetically active radiation (PAR, µmol/m^2/s) intercepted by the canopy was measured with a ceptometer (AccuPAR LP-80, Meter Group Inc., Pullman, USA) over a 20 m^2 planting square (*i.e.* 4 × 5 m). Measurements were carried out at five timepoints during the season and EAS calculated as the average of three measurements taken at solar noon and solar noon ± 3 hours. Measurements were taken in three to five bands (depending on the extent of the canopy) of five measurements each to capture the shaded area within the planting square.

Results and discussion

Effective area of shade was determined at the end of the 2019-20 season as an indication of potential differences between canopies in relation to scion cultivar/rootstock/spacing treatments after the first year of growth and prior to the first hedging action. Based on the sums of squares, spacing contributed the most (43%) to the variation in EAS, with rootstock playing a less prominent (7%) but still significant (P = 0.05) role (data not shown).

Changes in the EAS over the second leaf indicated the increase in canopy size and density during the second year of growth in relation to the genotype and tree spacing. Because of the rapid growth of the trees during the season EAS differed significantly (P = 0.05) between treatments within measurement dates. Within measuring dates spacing and rootstock contributed most to the variability in EAS with the rootstock × cultivar interaction coming into play only from December onwards after canopy closure (data not shown).

Spatial variability (*i.e*. the block effect) was minor at the outset of the second leaf season, but drastically increased by the end of the season to explain 44% of the variability by February 2021 (data not shown). The spatial variability is most likely due to the changes in soil texture and RAW holding capacity; soil texture and RAW would be most critical during the warmest months.

Trees were 19 months old at the start of the second growing season and the majority of trees, especially trees on the

Rootpac rootstocks, had not filled out the tree rows. The EAS at the end of the 2019-20 season was close to the EAS measured in October 2020 (data not shown).

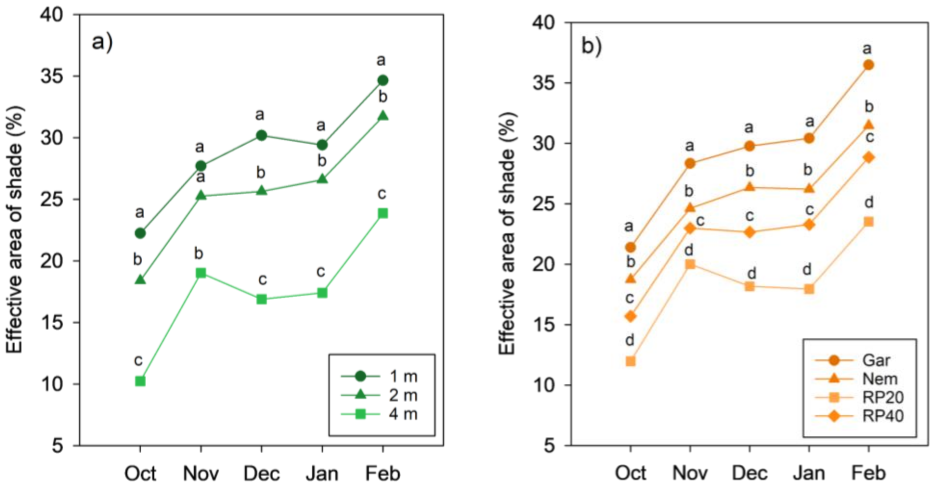


Figure 73 Effect of (a) spacing and (b) rootstock on the effective area of shade (EAS) in the second leaf growing season from October 2020 to February 2021

Values are the means (n = 48 for spacing and 36 for rootstock) and letters indicate significant (P = 0.05) differences between effects within a date.

Between October and November 2020 EAS increased rapidly, reflecting the fact that this is the period of active growth in almond. The plateauing of EAS from November to January for trees on all rootstock or apparent decline for trees at the widest spacing coincides with the period of canopy closure when active vegetative growth ceases. The increase in EAS after January 2021 can be attributed to growth being stimulated after the crop was removed and is visible in both spacing and rootstock (Figure 73).

Trees spaced 1 m and 2 m apart consistently had higher EAS than trees in the 4-m spacings because trees in the closer plantings had already filled out most or all of the tree line the previous season, whereas trees in the 4-m spacing had only filled around two-thirds of the distance between trees along the tree row (Table 39) by that time. Despite the fact that trees in the 4-m spacing extended more into the interrow space, a third less of the planting space was shaded. This indicates that trees in the 4-m spacing have less leaf area per unit ground surface area and therefore less transpirational area than trees in the other row spacings and hence a lower water requirement. The water potential measurements (Figure 76 and Figure 77) support this idea; trees in the 4-m spacing showed lower levels of water stress in both the Ψ_{PD} and Ψ_{SWP} readings.

The relativities of EAS more-or-less followed the same order as canopy volume (Figure 66). This agreement was especially noticeable for the ranking of rootstocks in terms of the vigour imparted to scion cultivars: Garnem having the highest EAS and RP20 the lowest [Table 51 (b)]. Note too that because trees on Nemaguard and RP40 had similar canopy sizes (Figure 66) but trees on RP40 had lower EAS than trees on Nemaguard, it can be inferred that trees on RP40 had a less dense canopy. This is consistent with RP40 reducing scion vigour and this was evident in the LiDAR renderings.

When irrigation volumes are determined it has to be noted that because of the spatial variability in the microclimate within the orchard (see page 112) a blanket ET_o cannot necessarily be assumed. As a larger proportion of the soil is exposed to the sun in the 4-m tree spacings it also means that more water will evaporate from the soil surface compared to the 1-m spacing where the irrigated area is mostly shaded. This will especially be evident where drippers are spaced at 0.5 m and water is applied to the open spaces between trees. It is unlikely that these trees will fill the tree line space during the course of the trial as the aboveground tree volume will be continuously manipulated. These observations are being taken into account with the implementation of autonomous irrigation and rootstocks and tree spacing will be incorporated together with soil water holding capacities (Figure 14, Figure 23 and Figure 24) in the decisions on valve groupings (see discussion starting on page 56).

Ongoing research

Light interception measurements will continue to be assessed over the coming seasons to evaluate changes in EAS in relation to the treatments. The first two seasons after establishment canopy density was low and enough light would've penetrated the internal parts of the canopy for floral bud initiation. This will change however as the canopies become denser in the next seasons in response to hedging. The degree of densification will depend on the degree of axillary growth, which in turn will be determined by the respective scion/rootstock combination's propensity to produce axillary shoots after apical dominance is removed during hedging.

The light interception thresholds for floral bud initiation are however still unknown, but a PhD scholarship has been offered in collaboration with the University of Melbourne to investigate this relationship using the planting designed for that very purpose (see page 47). A suitable applicant has been identified, but due to unforeseen delays in the approval process the student has not yet commenced. Two bespoke light spectroradiometers, able to measure light quality and quantity *in situ* from sunrise to sunset, have been procured to define the temporal light environment within the canopy in relation to ambient light conditions. These sensors will be used to define the light characteristics and quantities needed for floral bud initiation. Initial assessments on the performance of the prototypes have been conducted and design improved and construction materials changed. Due to COVID travel restrictions the electronic engineer[45] that designed and built the sensors has been unable to travel up to Mildura to make final adjustments.

Tree physiology as affected by genotype and planting density

	Summary
Why?	• impact scion/rootstock/spacing on phenology • scion/rootstock/spacing resource use • spatial impact on resource use
How?	• phenological assessments • tree water use measurements • leaf nutrient analyses
What?	• differences in phenology between scion/rootstock • reduced water use by growth reducing rootstocks • rootstock/spatial effect on mineral nutrient content of leaves
So?	• adaptation of management programs • adjusted inputs in relation to rootstock/spacing and soil
Next?	• validate input needs as trees mature and carry a crop • incorporate spatiotemporal microclimatic differences in irrigation management • investigate RP40 tree water use efficiency

Phenology

Phenological assessments were undertaken in the higher density plantings to assess any impact rootstock and spacing may have on the flowering behaviour of the three self-fertile cultivars, and to extend the range of observations of those cultivars' flowering behaviour beyond the South Australian Riverland where the breeding program's initial and advanced selection observations were made.

As the cultivars in the higher densities planting are self-fertile, flowering dates are not *per se* as critical as flowering dates for non-self-fertile cultivars might be, but flowering dates do have implications for cultivar selection in areas that may be prone to frost. Furthermore, large disparities in flowering time are generally accompanied by differing phenologies which has implications for plant protection spray programs.

[45] Daniele Pelliccia, Instruments & Data Tools, Melbourne, VIC, Australia.

Materials and methods

Phenological assessments were initiated in the 2020-21 season and repeated in 2021-22 at the start of the third leaf season. Detailed assessments were conducted weekly on the scion/rootstock combinations in the 2-m spacing according to the methodology recommended to industry[46].

The three central measurement trees were visually assessed for flowering, leaf out and nut development stages. The following floral bud stages were noted: swollen buds, calyx visible, corolla visible, 'popcorn', stamens visible and open flowers. In 2021-22 the percentage of flowering was also assessed for the remainder of the plant spacings.

The key flowering behaviour milestones – *viz*. start of flowering (1%), full bloom (80%) and when 100% of the flowers had flowered – were identified as day-of-year (DoY). Timing of flowering milestones that occurred between assessment dates were estimated by interpolation using the daily rate of flower opening between assessments.

Results and discussion

There was large spatial influence on when flowering milestones were reached (data not shown) despite the experimental layout (discussed under page 40) allowing for spatial variability by blocking in an east-west direction rather than north-south.

Figure 74 Flowering periods for A12, Carina and Vela on standard (Nemaguard and Garnem) and growth reducing rootstocks (RP20 and RP40) in the 2-m spacings for the first and second leaf

Horizontal lines represent the estimated start (1% flowering) and end (100% flowering) dates (day of year). Circles and triangles represent the estimated full bloom (80% flowering) dates for the 2019-20 and 2020-21 seasons, respectively.

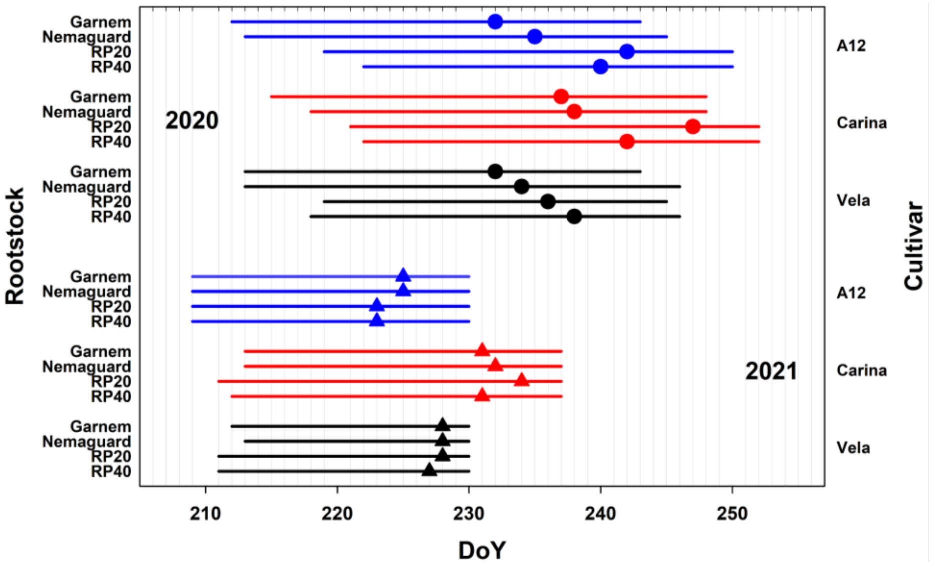


Figure 74 is a visual representation of the differences in the flowering period and the date of full bloom between cultivars and rootstocks and also between seasons. Main effects are shown in Table 45 for the 2019-20 season and Table 46 for the 2020-21 season.

The flowering period in the second season of assessments was compressed in comparison to the first (Figure 74). In the second season flowering was completed in just over 3 weeks (an average of 22 days for all treatments), whereas the flowering period was just under 5 weeks in the first season of assessment (an average of 30 days for all treatments).

In the 2019-20 season neither cultivar nor rootstock significantly affected the flowering period (Table 45). The start date of flowering was however significantly (P = 0.05) influenced by both cultivar and rootstock, with rootstock contributing to 54% of the variability seen between timings. Carina was the last cultivar to start flowering with A12 and Vela starting one day apart. Trees on the higher vigour rootstocks started flowering six days earlier than trees on the reduced vigour rootstocks.

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[46] Thomas, D. and J. Connell. 2018. Assessing Phenology of Almonds. Government of South Australia. p. 7.

Table 45 Scion and rootstock main effects on the start, peak and end of flowering (days of year) and length of the flowering period (days) in the 2-m tree spacing in the 2019-20 season

Different letters within a main effect/flowering stage combination indicate a significant (P = 0.05) difference between means.

	Cultivar			Rootstocks			
	A12	**Carina**	**Vela**	**Garnem**	**Nemaguard**	**RP20**	**RP40**
start	217 b	219 a	216 b	213 b	215 b	220 a	220 a
peak	237 b	242 a	235 b	233 b	235 b	241 a	240 a
end	247 b	250 a	245 b	245 b	246 ab	249 a	249 a
length	30 a	29 a	28 a	30 a	31 a	28 a	28 a

The same trends in separation between the dates for the cultivars and rootstocks for the start of flowering were seen for the timing of the peak of flowering as well as the DoY that flowering ended, except that the dates when 100% flowering was reached was closer together between the rootstocks than seen for the start and peak of flowering. The higher vigour rootstocks reached the end of flowering in around 12 days, whereas the reduced vigour rootstocks reached the end of flowering earlier than expected after around nine days.

In the 2020-21 season the length of the flowering period significantly (P = 0.001) differed between cultivars; cultivar accounted for 73% of the variation in the length of the flowering period. Carina had the longest flowering period (25 days) and Vela the shortest at only 19 days (Table 46). The shorter flowering period this past season was also experienced in industry and may have been partly driven by climate during the flowering period, but possibly also because cooler conditions early in winter satisfied all cultivars' chilling requirements earlier than normal meaning that all cultivars started flowering more-or-less at the same time. This observation suggests that warming requirements following the satisfaction of chilling requirements may be similar across the three cultivars.

Table 46 Scion and rootstock main effects on the start, peak and end of flowering (days of year) and length of flowering period (days) in the 2m tree spacing in the 2020-21 season

Different letters within a main effect/flowering stage combination indicate a significant (P = 0.05) difference between means.

	Cultivar			Rootstocks			
	A12	**Carina**	**Vela**	**Garnem**	**Nemaguard**	**RP20**	**RP40**
start	209 b	212 a	211 a	211 a	211 a	210 a	210 a
peak	224 c	233 a	227 b	228 b	229 a	228 ab	227 c
end	230 b	237 a	230 b	232 a	233 a	234 a	235 a
length	21 b	25 a	19 c	21 a	21 a	22 a	22 a

The order in which the cultivars started flowering in 2020-21 also changed from 2019-20 with A12 being the first to present flowers. The order in which the cultivars started flowering is in accordance with that observed in AL17005 (*National almond breeding and evaluation program*). Anecdotal evidence that A12 was the first cultivar to go into dormancy at the end of the previous season further indicates that A12 might have an earlier phenological cycle compared to Carina and Vela. The degree of the difference will have implications for the timing of orchard management practices as mentioned previously. Rootstock was not seen to account for a significant amount of the variation in the date that flowering started.

The number of days between the cultivars that the peak of flowering (80%) was reached was more than was seen for the start of flowering which contributed to the large differences in the length of the flowering periods (Table 46). There was a small but significant (P = 0.001) 3-day difference in full bloom timing by trees on different rootstocks (Table 46).

Possibly because of the seasonal conditions referred to earlier, the end of flowering was reached within a week of full bloom, except by trees on RP40 that reached the end of flowering 8 days after full bloom (Table 46). Contrary to 2019-20 observations, the period between the peak and end of flowering was around seven days in the reduced vigour rootstocks, but the higher vigour rootstocks reached the end of flowering within only four days.

Table 47 Variation accounted for by cultivar, rootstock and tree spacing, and interactions thereof, for the dates of full bloom (80% flowering) for trees in the higher density planting

Source of variation	% variation accounted for	Significance (p-value)
block	1.5	
cultivar	80	**< 0.001**
rootstock	1.5	**0.003**
tree spacing	0	0.971
cultivar × rootstock	4	**<0.001**
cultivar × tree spacing	0.5	0.245
rootstock × tree spacing	1	0.312
cultivar × rootstock × tree spacing	0.5	0.894
residual	11	

Empirical observations suggested flowering behaviour was similar across the spacings, and a full assessment of the flowering rate of all the plots in 2020-21 confirmed that this was indeed the case. Tree spacing did not significantly contribute ($P = 0.971$) to the date of full bloom (80% flowering) in the 2020-21 season (Table 47) for all the plots.

Variability in the timing of full bloom was mainly driven by cultivar which contributed to 80% of the variability in full flowering timing. Rootstock played a small (2%) but significant ($P = 0.003$) role in the differences seen in the timing of full bloom, with the cultivar × rootstock interaction contributing significantly ($P = 0.001$) to 4% of the data variation. These data validate the phenological assessments conducted on the 2-m spacing plots as representative of the remainder of the spacings for the 2020-21 season and in-depth assessments of the 2-m spacings will continue in coming seasons.

The phenological observations were used to time the 'pink bud' micronutrient spray application and when the beehives were placed in the orchard and removed. These data are also important in planning assessment schedules.

Ongoing research

Seasonal phenological assessments will continue as the trees mature to confirm the flowering time for the cultivar × rootstock combinations in the 2-m spacing and to determine whether spacing has an effect on flowering behaviour. These data will also be used to determine the phenological cycles of the cultivars to expand the geographic bases for flowering behaviour timings for these new cultivars.

The relationship with Monsons Honey and Pollination will continue in coming seasons and there is interest to conduct pollination experiments in the planting.

Tree water use efficiency

Water potential (Ψ) is an accurate and well accepted indicator of plant water status.

Pre-dawn Ψ (Ψ_{PD}) indicates how much water in the soil is available to the tree, and is measured before sunrise when the tree is in equilibrium with the soil water and before the tree starts transpiring. The measurement will not be affected by conditions that will affect measurements during the day such as temperature and wind. Well-watered trees will have a higher Ψ_{PD} compared to under-irrigated trees.

Stem Ψ (Ψ_{SWP}) is an indicator of the efficiency with which the tree is using the water at solar noon when photosynthetic activity and hence transpiration will be at the highest rate.

To assess the resilience of trees when water availability is low, either due to water being unavailable or during extreme events, an experiment was conducted to measure the changes – as a function of cultivar, rootstock and spacing – in tree water status (*i.e.* Ψ_{PD} and Ψ_{SWP}) as soil water was depleted.

Materials and methods

All plots were well watered up the point when irrigation was withheld. Prior to the start of the water withholding period the soil profile was filled as close as possible to field capacity. This point was determined through examination of the soil moisture content as indicated by the soil moisture sensors. Thirty-six research plots representing each scion cultivar/rootstock/spacing combination and distributed across the planting were selected for measurements. Due to time-limitations on the period that Ψ_{SWP} can be conducted treatment combinations could not be replicated. Spatial variability has been accounted for by selecting plots across the planting.

Water potential was determined with a Scholander pressure bomb (Plant Water Status Console 3005 series, Soil Moisture Equipment Corp., Santa Barbara, USA).

Ψ_{PD} measurement were conducted prior to sunrise at the start and end of the soil drying out period. Three leaves were randomly selected per experimental plot and Ψ_{PD} measured as soon as possible after the leaf was removed from the tree.

Ψ_{SWP} measurements were conducted according to the method of Fulton and Buchner (2014). Measurements were taken every second day in the hour around solar noon until Ψ_{SWP} values presented stress values. At least half an hour before the measurements were taken three randomly selected exposed healthy leaves per experimental plot were covered with a foil laminate bag (PMS Instrument Company, Albany, OR, USA). A single leaf at a time was collected from the tree, the base of the petiole removed with a sharp blade and a Ψ_{SWP} determined with the leaf still enclosed in the bag. The degree of water stress that the trees experienced was classified according to the guidelines presented in Fulton and Buchner (2014).

At the end of the drying out period the trees were irrigated and a final Ψ_{SWP} measurement performed a day after re-watering to assess the tree recovery response.

To assess the potential changes in temperature as modulated by the orchard's characteristics and topography – which may have implications for ET_0 – 20 TinyTag temperature loggers (details on page 58) were installed across the orchard at a height of 1 m and 2 m (representing conditions within and above the tree line, respectively). Temperature and humidity were recorded every 15 minutes.

Results and discussion

Trees did not have a crop at the time of measurement so the effect of crop load has been excluded as a factor that may have affected tree water use. Trees did however differ in canopy size (as discussed on page 92 and 103) which would have influenced the canopy transpiration rate and subsequently the water requirements of the trees and how quickly soil water was depleted.

The following climatic conditions were recorded for the trial period by the AWS (details on page 58) located on the Mildura SmartFarm adjacent to the orchard.

Table 48 Mean daily weather data for the trial period as recorded by the automatic weather station

An asterisk next to the date indicates the days that Ψ_{SWP} measurements were performed.

Date	T_{mean} (°C)	RH (%)	Mean wind speed (km/h)	Solar radiation (W/m²)	Degree days	ET_o (mm)
12/04/2021*	11.6	55.4	5.6	193	2.9	2.54
13/04/2021	13.6	53.4	3.8	209	3.6	2.61
14/04/2021*	19.7	33.2	10.9	107	9.7	4.27
15/04/2021	15.2	60.3	6.7	185	5.7	2.86
16/04/2021*	15.0	61.0	5.3	179	5.2	2.54
17/04/2021	11.9	56.9	3.4	201	3.1	2.28
18/04/2021*	12.6	58.9	3.7	200	3.1	2.30
19/04/2021	13.7	62.9	3.1	144	3.8	1.95
20/04/2021*	13.9	58.8	4.4	174	4.2	2.34

Overall, the trial period was mild, but on 14 April (as seen in Table 48), one of the measurement days, the weather was warm and windy which reflected in the reference evapotranspiration rate (ET_o). A mean wind speed of 10.9 km/h was recorded on that day, but gusts of up to 25 km/h were recorded during the measurement period around solar noon. No rain fell during the measurement period.

Soil moisture

The degree of change in soil moisture content between the first (12 April) and last day (18 April) of Ψ measurements was only significantly (P = 0.006) affected by rootstock which also contributed the largest percentage (37%) to the variability seen in the data (data not shown).

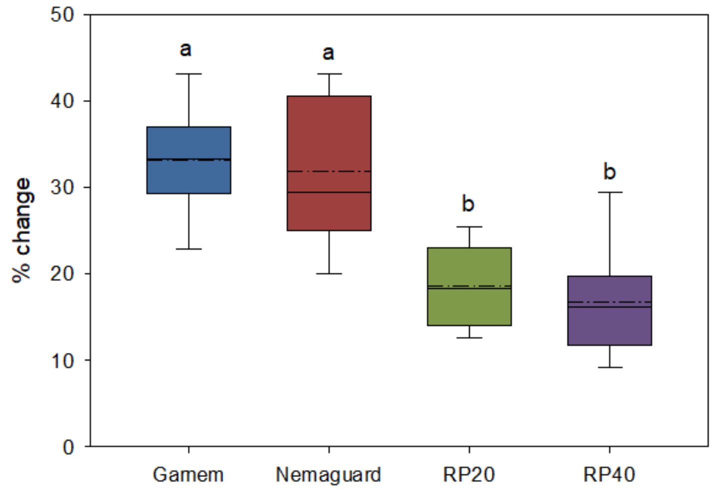


Figure 75 Boxplots for the relative changes (%) in soil moisture content between the first (12 April) and last (18 April) Ψ measurement dates as recorded by the soil moisture sensors

Solid lines show the median and dashed lines the mean within rootstocks. Boxes encompass the central 50% of measurements and whiskers denote the upper and lower 25%.

Different letters indicate that means differed significantly (P = 0.05).

There was a clear separation in the change in the soil moisture content between the higher and reduced vigour rootstock plots (Figure 75), and RP20 and RP40 removed a smaller percentage of soil water compared to Garnem and Nemaguard during the trial period.

The high variability in the data seen in the extent of the boxplots reiterates the spatial differences in soil moisture dictated by the soil differences across the Mildura SmartFarm.

Predawn leaf water potential (Ψ_{PD})

Ψ_{PD} measurements for all treatments significantly (P = 0.001) differed between the two measurements dates. In the week between measurements the mean Ψ_{PD} decreased by around 40%.

Table 49 Variation accounted for by cultivar, rootstock and tree spacing, and interactions thereof, on the two Ψ_{PD} measurement dates

	12 April 2021		19 April 2021	
Source of variation	**% variation accounted for**	**Significance (p-value)**	**% variation accounted for**	**Significance (p-value)**
block	13	0.223	24	**0.001**
cultivar	7	0.162	5	**0.016**
rootstock	19	**0.047**	22	**0.001**
tree spacing	11	0.068	16	**0.001**
cultivar × rootstock	4	0.781	11	**0.018**
cultivar × spacing	11	0.211	12	**0.006**
rootstock × spacing	15	0.245	5	0.122
cultivar × rootstock ×	10	0.500	2.5	0.500
residual	10		2.5	

At the first measurement date (12 April) only rootstock had a significant (P = 0.047) effect on the Ψ_{PD} measurements (Table 49). This could be attributed to the larger canopy (refer to page 92) of the higher vigour rootstocks that would have required a larger amount of water to recover and would have depleted a larger percentage of the soil water after the plots have been irrigated up to the fill point the day before. At the second measuring date several factors emerged as the source of variation, including the block which indicates that the spatial distribution of the measurement plots affected the readings (Table 49). This observation reiterates the differences in soil type across the planting with the capacity to hold different amounts of water (Figure 14), as well as the position within the topography (on the dune or swale).

Considering the degree of change in the Ψ_{PD} readings between the first and last measurement date firstly, only rootstock and tree spacing significantly contributed (P = 0.020 and 0.033 for rootstock and tree spacing, respectively) to the change in Ψ_{PD} over the 8-day experiment (data not shown).

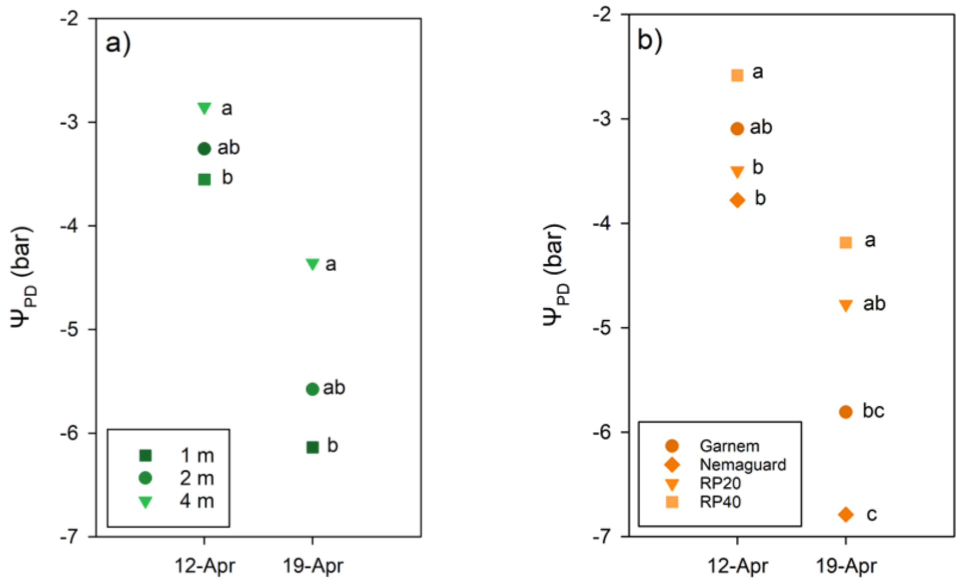


Figure 76 (a) tree spacing and (b) rootstock main effects on Ψ_{PD} measurements at the start (12 April) and end (19 April) of the soil drying out period

Values are the mean (n = 36) and letters indicate significant (P = 0.05) differences between Ψ_{PD} values within a measurement date.

Trees in the 4-m spacing had the least negative Ψ_{PD} likely because there was not as much competition between trees for resources [Figure 76(a)]. At the end of the drying out period trees in the 2-m and 1-m spacing had the lowest Ψ_{PD} readings which confirms that tree spacing plays a large role in soil moisture depletion most likely because of the greater competition for water. This was especially evident in the 1-m tree spacing where the trees' root systems are in much closer proximity and likely exploiting all of the soil profile. This needs to be taken into consideration in irrigation management in higher density plantings.

The term "hydric" refers to the amount of water a plant transpires and the amount of water a plant absorbs. Hydric constraint or stress arises when the former is greater than the latter. Isohydric plants avoid that situation by reducing transpiration to maintain a more-or-less constant Ψ_{SWP}.

Trees on RP40 showed the least signs of hydric constraint (*i.e*. less negative Ψ_{PD}) at the start and end of the soil drying out period (Figure 76(b)) even though it has a similar canopy size to the higher vigour rootstocks (refer to page 92). Water stress in trees on RP40 also increased at about half the rate observed in trees on Nemaguard and Garnem (data not shown). This may be interpreted that RP40 is an "optimistic" water user – isohydric, in other words – and may have the potential to confer some degree of drought resistance to scions. The rate of change in soil moisture points towards RP40 also extracting less water from the profile, which further suggests a mechanism that regulates water use by the tree. Further investigation is warranted to determine the mechanism that controls water use by trees on RP40.

Nemaguard had the lowest Ψ_{PD} reading at the start and end of the trial period and had the fastest rate of decrease in Ψ_{PD} between the first and final measurements date together with Garnem (data not shown). On the other hand, RP20 had the slowest rate of decrease, but not significantly different to RP40; a result attributable to that cultivar's small sparse canopies (discussed on page 92) which will reduce transpiration and tree water use and in turn reduce the rate of soil water depletion.

Midday stem water potential (Ψ_{SWP})

Neither cultivar nor spacing significantly affected the rate of increase in water stress of the trees during the soil drying out period from the first to the last measurement point. Rootstock, however, was a significant source of variation for Ψ_{SWP} at every time-point (Figure 77). From these data it can be inferred that the growth reducing rootstocks are more tolerant of limiting soil water conditions. The Ψ_{SWP} of trees on RP40 in particular, which not only had the least water stress across all the measurement periods, but also did not fluctuate by more than 1.5 bar. If the second measurement date (14 April – see Table 48) was discounted because of the weather, Ψ_{SWP} of trees on RP40 had only started decreasing by the final measurement date, emphasising that RP40 may have a mechanism to control tree water use that warrants further investigation.

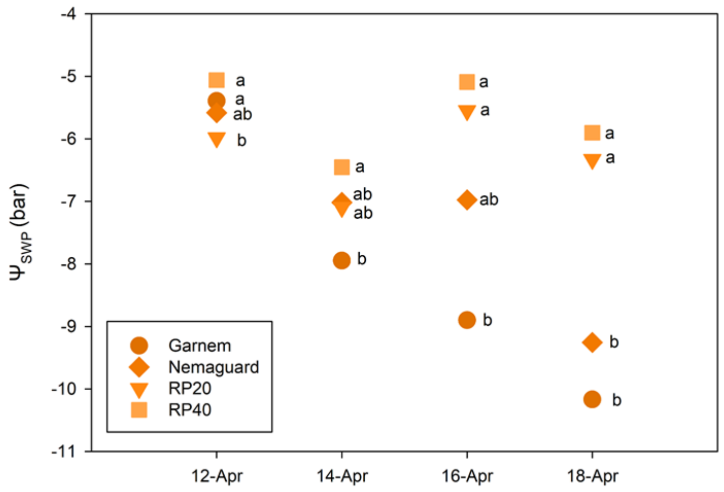


Figure 77 Rootstock main effects on Ψ_{SWP} measurements at each measurement date

Values are means (n = 27) and different letters within a measurement dates indicate significant (P = 0.05) differences between means.

As for Ψ_{PD}, the location of the experimental plot also significantly contributed to the variability in Ψ_{SWP} towards the end of the trial period (P = 0.019 and P = 0.011 for the last two measurement dates respectively). The variability in relation to the location could again be attributed to each experimental plot's soil type and readily available water holding capacity (Figure 24).

The baseline Ψ_{SWP} values indicated that the trees did not experience any water stress (Ψ_{SWP} > -6 bar) confirming that trees were well-watered (Figure 77). During the soil drying out period the Ψ_{SWP} of trees started separating on the basis of rootstock, with trees on the commercial higher vigour rootstocks (Garnem and Nemaguard) indicating more negative Ψ_{SWP}, but the trees still only experienced low levels of water stress of between -6 and -10 bar (Figure 77).

The lower Ψ_{SWP} readings at the second measurement point (14 April) can be attributed to the weather conditions that day because enough water would still have been available in the soil as evidenced by soil moisture sensor readings (data not shown). The higher temperature and wind speeds compared to the other measurement days (Table 48) would have increased the transpiration rate and subsequently the water use of the trees. The trees' Ψ_{SWP} were still only lightly water stressed (between -6 and -10 bar), confirming that enough water was still available in the soil for the trees to function optimally under these conditions.

The Ψ_{SWP} values for Nemaguard did not separate at the third measurement date because of the high spatial variability in Ψ_{SWP} readings (Figure 77).

At the final measurement date, after irrigation had been withheld for eight days, rootstock still significantly (P = 0.004) contributed to the variability seen in Ψ_{SWP} (Figure 77) and more water was left in the soil under the Rootpac rootstocks (Figure 75). The higher vigour rootstocks were at the threshold of mild water stress (-10 bar) when looking at the mean Ψ_{SWP} values, and also removed the largest % of soil moisture up to this date (Figure 75). The rapid decrease in Ψ_{SWP} readings in Garnem, also seen in the Ψ_{PD}, can be attributed to the larger and denser canopy (refer to pages 92 and 98), needing more water to sustain tree function. Interesting to note though is that trees on Garnem rapidly recovered to around -7 bars within a day of the plots being re-watered (data not shown).

Spatiotemporal differences in microclimate

Differences in temperature, relative humidity and wind speeds within the orchard in relation to the ambient conditions can be brought on by planting density, cultivar/rootstock combinations affecting tree dimensions and density and/or the position within the landscape (the dune or swale in the case of the higher density plantings). These differences can potentially affect ET_0 and the transpiration rate of the trees which in turn will have implications for irrigation management. The ET_0 used for irrigation management, in combination with other values such as the crop factor, is mostly calculated using measurement collected by a weather station located as close as possible to the planting, but may also be located in an area which is not representative of the planting's area, or the conditions within the planting itself. For this reason, a network of temperature loggers was deployed across the higher density planting to investigate the potential microclimatic spatial variability.

As an example of the extent of spatiotemporal differences in temperature within the orchard temperatures on the dune (row 5) and in the swale (row 35) were compared. The loggers' temperatures and relative humidity readings were also compared to the values registered by the AWS. Temperature differences within and above the tree line were further compared through placing loggers at 1 m (within the tree line) and 2 m (above the tree line) above ground level. The results are shown in Figure 78 and Figure 79.

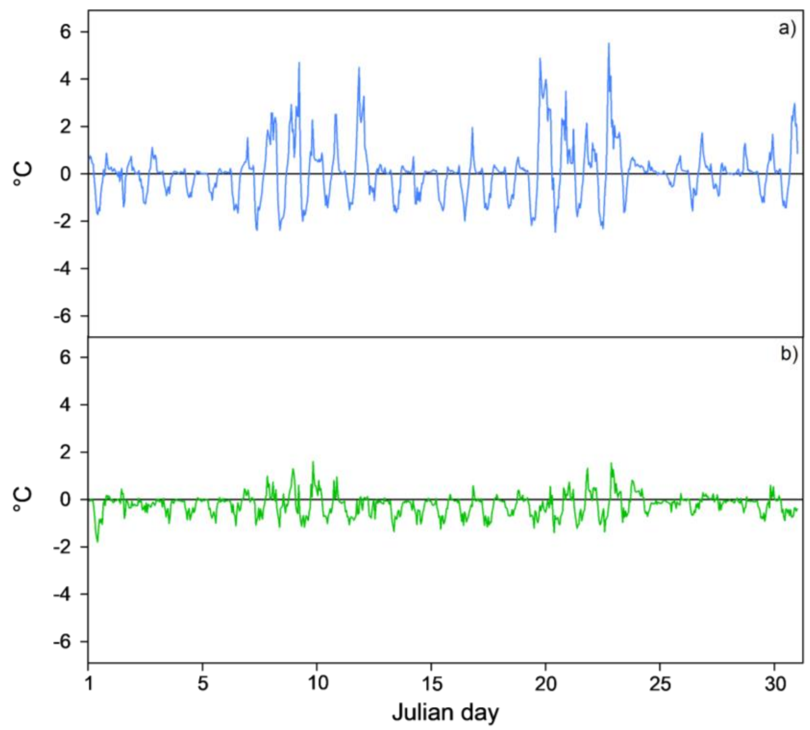


Figure 78 Hourly differences in temperature during January 2021 between loggers positioned at a height of 1 m in relation to loggers positioned at 2 m on the a) dune and in the b) swale

Values above the line indicate that temperatures at 2 m were higher than measured at 1 m, and similarly, values below the line that temperature at 2 m were lower than measured at 1 m.

When considering the differences in temperature within (1 m) and above (2 m) the tree line temperatures at 2 m were up to 5 °C warmer than measured at 1 m and could be up to 2 °C cooler (Figure 78). There is a clear diurnal pattern in temperature differences, with temperature within the canopy usually being less than measured above the canopy during the day, generally during the morning hours. Temperatures above the tree line were almost always warmer during the night than the temperature measured within the tree line (Figure 78). Interesting to note is that differences in temperature above and within the tree line did not differ as much in the swale as was observed on the dune (Figure 78), likely because the dune is more exposed and therefore prone to changes in temperature. Temperatures measured on the dune were also generally higher than those observed in the swale.

Mean daily temperatures in the swale were generally more differentiated in comparison to the AWS, and recorded noticeable lower and higher temperatures of up to 4 °C in relation to the AWS on several occasions (Figure 79). Differentiation in the temperature measure on the dune was less pronounced, likely because of the closer vicinity of the logger to the AWS, but nevertheless the proximity logged clear differences in temperature to the AWS on several occasions.

Interesting to note is that the mean daily relative humidity recorded by the weather station was higher than recorded by the logger located on the dune for the majority of the days, and similarly lower than recorded by the logger in the swale. These differences in relative humidity may have implications for the transpiration rate of trees in these locations.

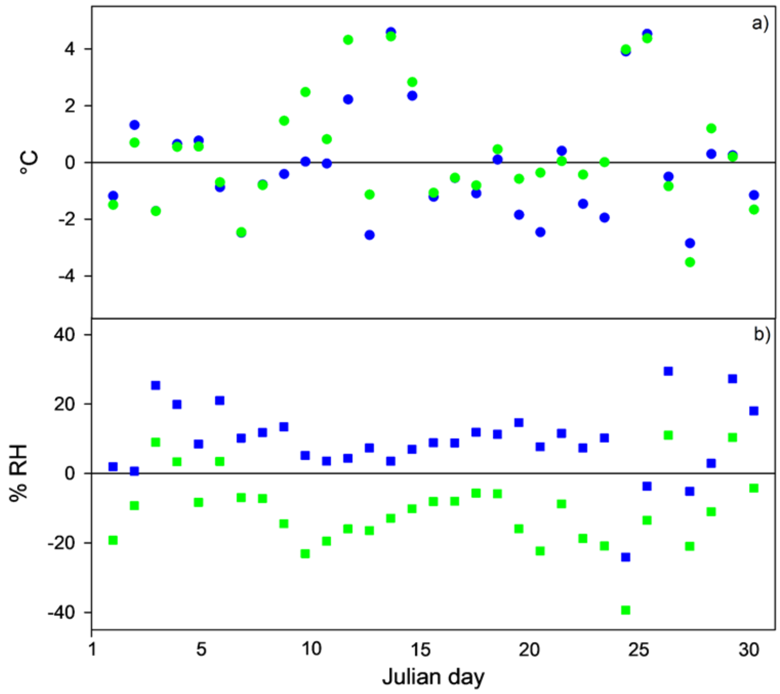


Figure 79 Spatial differences in mean daily a) temperature and b) relative humidity measured above the tree line in relation to values measured by the AWS for January 2021.

Shown are the differences in temperature on the dune (blue) and swale (green). Points above the line mean temperature or RH values were higher than measured on the dune or in the swale, and points below the line indicate values were lower than measured on the dune or in the swale.

These observations have major implications in irrigation management where ET_0 is used to calculate tree water needs, especially in plantings where spatial variability in the meso- and microclimate are more pronounced. These observations have the potential to be used to further "fine-tune" irrigation management in combination with other soil and plant water indicators in the irrigation system currently installed in the H3 planting.

Ongoing research

Water potential measurements will continue this year to validate the current findings of genotype and tree spacing on tree water use as trees mature. Measurements will also be conducted during different phenological status to determine water requirements during different growth stages in the season.

In addition to the response of trees to periods of low soil water availability, more detailed "recovery" trials will be conducted to investigate how the trees respond when the profile is refilled to field capacity after a drying out period.

After the thresholds for autonomous closed-loop irrigation are finalised from this coming season's data and the system is active, Ψ_{SWP} measurements will confirm if the irrigation is sufficient for trees to function optimally. It will also confirm that the thresholds are correct. Dendrometers (details on page 55) will add another dimension to the Ψ_{SWP} data and show the trees' diurnal trunk responses. The potential exists to expand the datasets further by overlaying canopy attributes (*e.g.* LAI – an indication of canopy density – and canopy size) as covariates.

Tree nutrient status

Leaf analysis is an important tool to manage fertigation in almond orchards. As discussed on page 83 leaf spectral properties to aid fertigation were investigated in this project, specifically for nitrogen. The analyses of the site's soil chemical properties conducted as part of the soil survey (see page 33) indicated large variation in the chemical indices of soil fertility. To assess whether that variation contributed materially to variation in tree mineral status across the higher densities planting, leaf samples were collected and analysed.

Materials and methods

Leaf samples were collected in early March 2020 and sample preparation conducted as described for the H1 leaf samples (see page 75). Leaf nutrient analyses were performed by a local NATA accredited analytical service[47].

Results and discussion

The data presented in Figure 80 are for leaf nutrient analyses at the end of the first leaf and before fertigation regimes were implemented.

The majority of nutrients, irrespective of treatment, were in the adequate range according to the interpretative standards for almonds shown in Table 23. The exceptions were calcium, which was on the deficiency threshold, and zinc that was slightly deficient (data not shown). The propensity for zinc deficiency was rectified with foliar spay applications in following seasons.

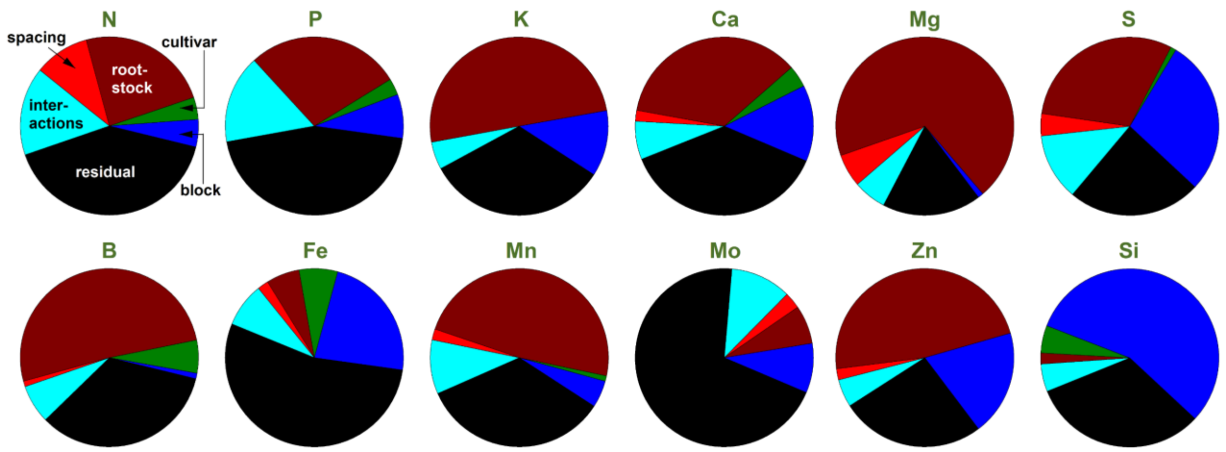


Figure 80 Proportions of sums of squares attributable to known (cultivar, rootstock, spacing, interactions thereof and block) and unknown (residual) sources of variation for mineral concentrations in leaves sampled from H3 trees in February, 2020

Figure 80 shows the contribution of the fixed sources of variation (*i.e*. the cultivar *etc.*) to the variation in leaf mineral nutrients across the planting, as well as the proportion attributable to blocks (*i.e*. the spatial effect) and the proportion attributable to unknown factors (*i.e.* the residual). For the most part, spatial variability did not have an important influence on leaf mineral nutrient levels, but leaf silicon (Si) and chloride (Cl) were the notable exceptions, and leaf sulphur (S) to a lesser extent. Silicon is not classified as an essential mineral nutrient, rather as a beneficial element (Marschner 1995); its role in abiotic stress tolerance is an active area of research (Frew, Weston, Reynolds, & Gurr, 2018). The spatial influence on leaf Cl levels can perhaps be attributed to the soil textural change from Block 1 (deep well drained sandy loam on the dune) to Block 4 (shallow poorly draining heavier textured soil in the swale).

Rootstock played a consistently significant and large role in the variation seen for each nutrient (Figure 80). Amongst the micronutrients, rootstock was a very strong influence for boron (B), manganese (Mn) and zinc (Zn); latent, but agronomically important deficiencies, of these elements are not uncommon on Mallee soils and toxicity of B easy to achieve. The observation that the likelihood of those deficiencies occurring is greater or lesser depending on rootstock is therefore of interest in avoiding these deficiencies, particularly given the important roles B and Zn play in

[47] Analytical Laboratories & Technical Services Australia, Merbein South, VIC, Australia.

reproductive biology. Interesting to note though is that cultivar did not really affect variation seen in the leaf nutrient concentrations, except maybe for B and Fe, where even though it is was significant source of variation, the contribution of the cultivar was minor compared to the other sources of variation.

The large percentages of variation that the residual accounts for indicates that there are large unknowns that were not tested for that contributed to differences seen in the leaf nutrient levels between trees in each of the treatments and treatment combinations. Given the crucial role that Mo plays in nitrate reductase – the first step in the conversion of nitrate to a form that can be used to make proteins in plants – the observation that 75% of the variation in leaf Mo levels is unexplained is perhaps relevant to managing N use efficiency at a level not generally considered.

It was hypothesized on page 92 that trees that are spaced closer together had smaller canopies due to competition for nutrients but results from the first season of establishment did not fully support this idea because leaf nutrient levels were still adequate. Tree spacing also played a minor and generally non-significant role in the variability seen in for all the nutrients. The nitrogen levels did however separate between the spacings with higher levels of nitrogen observed in the 4-m spacing compared to the 1-m spacing (Table 50). Nitrogen is an essential macronutrient and plays a major role in plant growth, development and yield determination and realisation.

Table 50 The effect of cultivar, rootstock and tree spacing on the concentration of nitrogen (N), phosphorous (P) and potassium (K) in leaves collected in the higher density plantings at the end of the first growing season

Values are the means (n = 48, 36 and 48 for cultivar, rootstock and spacing, respectively) and letters within main effects indicate significant (P = 0.05) differences within nutrients. An absence of letters indicates that that main effect had no impact on the concentrations of that nutrient in leaves.

	Cultivar		Rootstock		Spacing (m)	
% N	*A12*	2.66	*Garnem*	2.57 c	*1*	2.62 c
	Carina	2.83	*Nemaguard*	2.65 c	*2*	2.74 b
	Vela	2.74	*RP20*	3.01 a	*4*	2.87 a
			RP40	2.75 b		
% P	*A12*	0.25	*Garnem*	0.24 c	*1*	0.26
	Carina	0.26	*Nemaguard*	0.24 c	*2*	0.26
	Vela	0.27	*RP20*	0.30 a	*4*	0.26
			RP40	0.27 b		
% K	*A12*	1.95	*Garnem*	1.70 c	*1*	1.95
	Carina	1.95	*Nemaguard*	1.67 c	*2*	1.94
	Vela	1.91	*RP20*	2.13 b	*4*	1.92
			RP40	2.25 a		

The mechanisms by which dwarfing rootstocks limit the growth of scions are unknown and a disruption in mineral movement across the graft is one of the many possible explanations offered. From these initial data it is possible that this hypothesis does not apply to RP20 and RP40 because higher levels of N, P and K were consistently found in the leaves, well within the adequate levels needed for optimal plant growth and functioning.

As trees mature, canopy size and density increases, and as trees start to produce agronomically significant yields, these relationships will potentially change due to differing nutritional needs in response to the treatments.

Ongoing research

The effect of crop load on the differences between leaf nutrient levels in relation to the treatments will be determined from this season onwards and as trees mature. Nutrient analyses of leaf samples taken from the higher density plantings will also be used in coming seasons to optimise fertigation strategies for the individual treatments and, along with the analyses on leaves sampled from H1 tree, feed into the work on developing alternate means of assessing tree nutrient status (details from page 83 onwards).As the understanding of the role of Si on plant abiotic stress responses improves, the spatial element of tree Si status in relation to tree stress warrants will need consideration.

Projected productivity as affected by genotype and tree planting density

Summary	
Why?	• yield prediction • productivity of scion/rootstock/spacing
How?	• flower prediction • yield projection
What?	• number of flowers per tree differ for scion/rootstock/spacing • cultivar yield trends inconsistent • yield driven by kernel mass
So?	• accurate yield predictions from flowers for industry • productivity of higher density planting systems
Next?	• confirm nut retention rate for cultivar/rootstock/spacing • absolute yield values • changes in yield as trees mature

Potential yield predictions based on flower counts is an important basis for predicting a season's N fertiliser demands to avoid under- or over-fertilising. Tools to conduct flower counts will therefore be a valuable tool for industry. The higher densities planting on Mildura SmartFarm is a unique platform to contribute to the development of such a tool because of the multiple scion cultivar/rootstock and tree spacing combinations potentially providing a wider range of flowering intensities than may normally be the case in a commercial setting. The hedging imposed also resulted in open uniform structures across the planting (Figure 65) reducing any potential influence of different tree sizes on flower number estimates.

By the 2021-22 season (*i.e*. third leaf) the trees had attained a canopy size suitable for flower number estimates and using those estimates to project potential yields as affected by scion cultivar/rootstock/tree spacing. As trees mature fertility will change because of changes in the light environment in the internal canopy and changes in the number of fruiting locations due to canopy management (as discussed in the section on tree architecture, page 91).

The work described in this section was a collaborative exercise involving AV research teams at Irymple and Tatura. Each team's skills and resources were brought to bear on applying new technologies on a unique platform to achieve the project aims and to extend the application range of the technologies used. Because the trees have been hedged into a shape likely to be more amenable to over-the-row shake-and-catch harvesting, caution needs to be applied when interpreting the projected yield or extrapolating to current production systems.

Materials and methods

A day prior to the flower assessments all experimental plots were visually assessed for the percentage of flowering and twelve plots at around 70% flowering selected for manual flower counts.

As described in the section on phenological observations (see page 105), A12 trees' flowering period began earlier than that of Vela and Carina in the 2021-22 season (Figure 74). At the time of assessment A12 trees had already reached 100% flowering in the majority of the plots and were excluded from the calibration manual flower counts. Covid-related travel restrictions at that time (August, 2021) and the short notice that could be provided to coordinate staff and transport equipment from Tatura at a certain stage of flowering – especially given the compact flowering period in 2021 – it was not possible to conduct scans at two time-points (one for A12 trees and one for the other two cultivars' trees, for example).

Twelve plots (Vela and Carina on Garnem and RP20 at the three spacings) were selected. An 8-m length of the tree line was marked out in each of the plots resulting in 2, 4 and 8 trees assessed in the 4-m, 2-m and 1-m plant spacings, respectively. The number of flowers per tree were manually counted over two days. Manual flower counts are time-consuming, labour intensive and need to be conducted within a very short timeframe. Ideally, triplicate counts would be conducted, but this level of scientific rigour was precluded by resource availability at that time.

Figure 81 The Cartographer instrument mounted on an electric side-by-side vehicle and scanning the higher density plantings for development of the flower count prediction model

All the plots were simultaneously scanned with a Green Atlas Cartographer mounted on an electric side-by-side 4-wheel vehicle (Figure 81) on 17 August 2021. The scans and the manual flower counts were used by Green Atlas[48] to develop an almond flower prediction model[49].

A Navcom Land-Pak SF-3040 GNSS Survey System[50] GPS was used to collect the georeferencing points for the individual plots. The GPS co-ordinates were downloaded with a Trimble Nomad 900 handheld computer[51]. A spatial grid of the boundaries of each treatment plot and containing the metadata for the treatments was created in QGIS Open-source Geographic Information System from the GPS coordinates.

Projected spatial flower count numbers were supplied by Green Atlas from the calibrated flower count prediction model and flower counts per research plot were extracted by Dr Alessio Scalisi (Senior Technical Officer, Tatura SmartFarm).

Based on the number of trees per hectare (500, 1000 and 2000 for the 4-m, 2-m and 1-m spacings, respectively, at a row width of 5 m) the number of flowers per tree were extrapolated to the number of flowers per ha.

Average fruit set estimates were not available for the three cultivars that make up the planting so a uniform 35% was used. Anecdotally, fruit set percentages of 30-35% are observed in industry, and similar values were also observed in AL14005 (*Identifying factors that influence spur productivity in almonds*)(Coetzee 2019).

The kernel yield per hectare was estimated from the number of potential fruit per ha and the mean kernel mass for A12, Carina and Vela as determined in AL12015 (*Australian almond variety evaluation and commercialisation program*). Vela has a larger kernel (1.8 g[52]) compared to the other two cultivars with A12 having the second largest

[48] https://greenatlas.com.au/
[49] Green Atlas intellectual property
[50] NavCom Technology, Inc., Torrance, USA
[51] Trimble, Sunnyvale, USA
[52] (anonymous). 2017. Australian Almond Variety - Vela. All About Almonds - Establishment. Australian Almond Board, Loxton, South Australia

kernel at 1.64 g[53]. Carina has a small kernel (1.13 g[54]) compared to the other cultivars, but is classified as having a medium kernel size.

Results and discussion

The results presented in this section should be viewed as qualitative in nature, and are intended to highlight variability between the fixed sources (*i.e.* cultivar, rootstock and spacing) across the planting and interpreted accordingly. The projected flower numbers and yields results can be revisited and updated as the Green Atlas model is refined and new insights come to light.

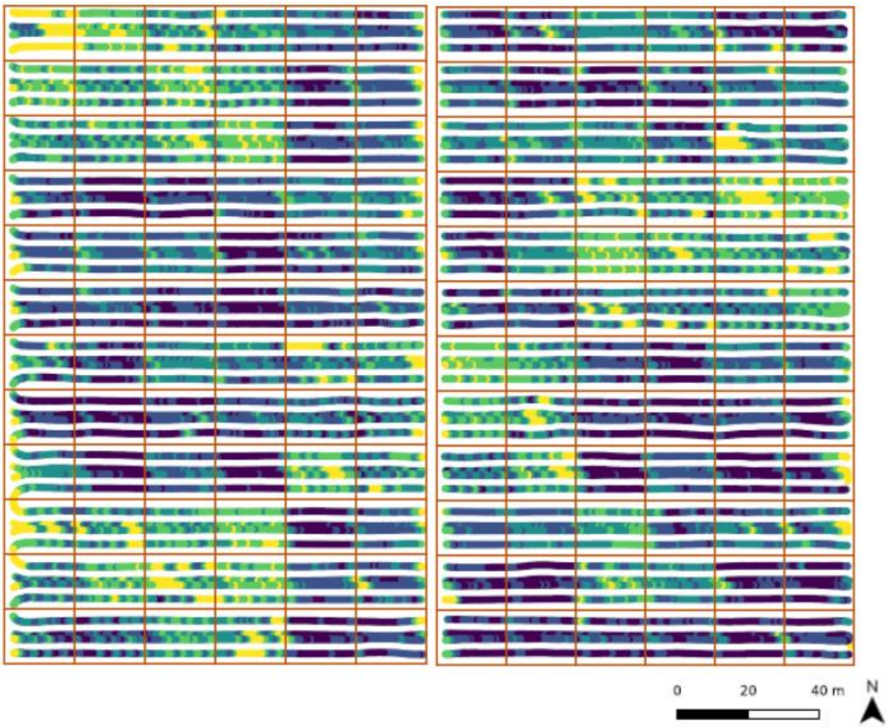
Flower counts in relation to genotype and tree spacing

Flower number projections from the first flower count prediction model look promising with an error of ±4% when all tree spacings are considered (data not shown - Green Atlas). A spatial map projection covering the whole planting generated by the Green Atlas model using the geo-referenced scan data is presented Figure 82.

Figure 82 Projection of the spatial variation in flower counts per m of tree row in the higher densities planting on the Mildura SmartFarm

The grid designates the extent of the research plots. Yellow indicates areas with low flower numbers (0-177) and dark blue areas with more than 1241 flowers/m.

Flower numbers were derived from images collected by the Cartographer and processed by Green Atlas' almond flower prediction model.



At first glance the yellower areas where fewer flowers/m were predicted coincides with the 4-m spacing plots. The number of flowers was expected to be less in these plots because of large gaps between the trees (Table 39). Distinguishing between the 2-m and 1-m plots is more difficult, but the plots with slightly fewer flowers/m within these spacings generally coincide with the reduced vigour rootstocks.

The flower numbers per research plot were extracted and the sources of variation in the number of flowers per tree and the projected yield per hectare are shown in Table 51.

All main effects and the interactions thereof significantly (P = 0.05) contributed to the differences seen in the predicted number of flowers per tree. Tree spacing had the largest effect on the number of flowers and contributed to 45% of the variation. Opposite to the results per metre tree row, trees in the 4-m spacing had more flowers (2299 flowers/tree) compared to trees in the 2-m and 1-m spacings (1095 and 1066 flowers/tree, respectively). Extrapolating flowers per tree projections to flowers per hectare, however, shows that trees spaced 1 m apart will produce around double the number of flowers per hectare than trees that are 4 m apart (data not shown).

[53] Personal communication, Dr Michelle Wirthensohn, University of Adelaide

[54] (anonymous). 2017. Australian Almond Variety - Carina. All About Almonds - Establishment. Australian Almond Board, Loxton, South Australia.

Table 51 Variation accounted for by cultivar, rootstock and tree spacing, and interactions thereof, on the predicted number of flowers per tree and projected yield

	Number of flowers		Projected yield per ha	
Source of variation	**% variation accounted for**	**Significance (p-value)**	**% variation accounted for**	**Significance (p-value)**
block	3		2.5	
cultivar	6	**0.031**	39	**< 0.001**
rootstock	10	**< 0.001**	6	**< 0.001**
spacing	44	**< 0.001**	33	**< 0.001**
cultivar × rootstock	9	**< 0.001**	8	**< 0.001**
cultivar × spacing	2	**0.027**	2.5	**< 0.001**
rootstock × spacing	6	**< 0.001**	1	0.099
cultivar × rootstock × spacing	5	**< 0.001**	1.5	**0.035**
residual	15		8	

Cultivar, rootstock and tree spacing, as well as the interaction between cultivar and tree spacing, and rootstock and tree spacing were significant sources of variability seen in the predicted kernel yield/ha. The variability seen in the predicted yield was, however, mainly accounted for by cultivar (39%) which can be attributed to the large differences in kernel size between cultivars. The mean kernel yield per hectare decreased in the same order as kernel mass with kernel yield in Vela being 50% higher than in Carina (data not shown). Tree spacing played the second largest role at 32% which can be attributed to the differences in the total number of flowers borne per hectare.

The effect of the interaction between the genotypes and spacing on the average number of flowers per tree is shown in Table 52.

Table 52 The effect of cultivar, rootstock and tree spacing interaction on the number of flowers per tree in the higher densities planting

Values are the mean and letters indicate that values differ significantly (P = 0.05) within combinations.

		Tree spacing (m)		
Cultivar	**Rootstock**	**1**	**2**	**4**
A12	**Garnem**	1190 a-e	2097 h-k	2220 i-k
	Nemaguard	1276 a-e	2557 jk	3069 l
	RP20	956 ab	1465 c-e	1537 c-f
	RP40	987 a-c	1558 d-g	1325 a-e
Carina	**Garnem**	926 ab	1376 b-e	2357 i-k
	Nemaguard	847 a	1648 e-h	2409 i-k
	RP20	894 ab	1360 b-e	1318 a-e
	RP40	1205 a-e	2120 h-k	2297 i-k
Vela	**Garnem**	1000 a-c	2069 h-k	2154 i-k
	Nemaguard	1197 a-e	2155 i-k	3458 l
	RP20	1085 a-d	1966 f-i	2049 g-i
	RP40	1228 a-e	2488 jk	3391 l

To reiterate, differences in flower numbers per tree can't be attributed to differences in canopy size as the assessment was done after the hedging action when canopy dimensions would have been similar between treatments. That qualification does not however encompass canopy density; denser canopies will carry more locations to bear flowers.

As seen for the main effects, generally trees in the 4-m spacing consistently bore more flowers than trees in the 1-m or 2-m spacings; the exceptions being A12 on RP40 and to a small degree in Carina on RP20, where more flowers were predicted per tree in the 2-m than the 4-m spacing. Fewer flowers were also detected on trees on the lower vigour rootstocks in the 4-m spacing compared to trees on the other two rootstocks, with the exception of Vela on RP40 that had similar flower numbers to that seen on trees on Nemaguard for which the highest numbers of flowers per tree were detected on each cultivar. On the other hand, with exception of trees on Garnem, this trend was not observed in the number of flowers per tree in the 1-m and 2-m spacings. Different physiological and abiotic conditions most likely play a role in the flowering potential in trees at these spacings.

Flower numbers per tree were significantly (P = 0.05) higher on Vela trees compared to the other cultivars, with about 20% fewer flowers detected on A12 and Carina compared to Vela. It needs to be acknowledged too that the predicted flower numbers for A12 may have been underestimated because that cultivars advanced stage of flowering during the scanning period and because petal fall had already started. A12 also has tighter clusters with multiple flowers (Figure 83) compared to either Carina or Vela, which may further have contributed to the underestimation of flower numbers. Earlier flower counts and scanning will be conducted on A12 in coming seasons if circumstances allow. The number of flowers per cluster also needs to be considered in follow up assessments in coming seasons.

Figure 83 Flower clusters along the main shoots on A12

The tight clusters of multiple flowers are clearly visible that potentially contributed to an underestimation by the flower count model of flowers in this cultivar. The degree of petal fall is also visible in the image which would have further contributed to a smaller number of flowers being detected.

Image recorded the day prior to Cartographer scans being conducted.

Projected yield in relation to genotype and spacing

Productivity estimates are presented in Figure 84 and Figure 85 and need to be confirmed, particularly over multiple seasons as trees mature and the capability of the trees to retain and mature nuts through to harvest settles down. Results from the Australian breeding cultivars shown that the yield more than doubles in these three cultivars after the third or fourth leaf. The results presented are only intended to be an indicator of the potential productivity differences between the scion cultivar/rootstock combinations in relation to the tree spacing and should not be the basis of any recommendation to industry at this point. Observations over multiple seasons are needed to confirm the long-term suitability of particular scion cultivar/rootstock combinations in higher density plantings and subject to hedging at least every winter.

Even though the number of flowers/ha is a good indication of the potential yield, several factors affect the percentage of flowers that are pollinated and set fruit and retain those fruit until harvest. For this reason, the projected yield results discussed in this section may be either over- or underestimates because the age of the trees precludes definitive statements. These factors will also change in the coming seasons in relation to the treatments and the potential confounding of canopy management actions over multiple seasons.

As mentioned, cultivar and tree spacing accounted for 39 and 33%, respectively of the variation in projected kernel yield/ha (Table 51). Differences in the projected yield between cultivars can be attributed to the differences in kernel size in combination with the number of flowers per tree. Vela's greater flowers numbers per tree (1999) and larger kernels resulted in a projected yield of 1213 kg of kernels per hectare. This was followed by A12 at 983 kg. Carina, having a substantially smaller kernel than both Vela and A12, and carrying a flower load similar to A12, was predicted to produce only 608 kg of kernels per hectare (data not shown).

It should be noted too that the mean kernel masses for those three cultivars were determined using kernels from mature trees. It is possible that each cultivar's mean kernel mass may change as trees mature and interactions between spacing/rootstock/scion become greater or lesser.

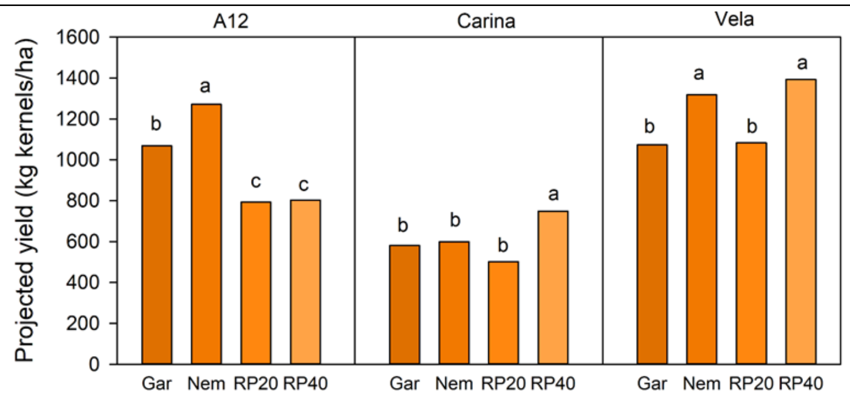


Figure 84 Projected impact of rootstock on kernel yield (kg kernels/ha) for the three cultivars in the third leaf

Data generated by the flower count model was extrapolated to a per hectare basis using a 5-m interrow spacing, assuming a 35% pollination, set and nut retention success rate and kernel masses observed in AL12015. Data are means (n = 36) and different letters above columns within cultivars indicate significant differences (P = 0.05) between rootstocks.

Differences attributable to the kernel size are noticeable in the mean projected yields across rootstocks within cultivars (Figure 84). There was no definite trend in the projected effect that rootstock may have on yield, except that trees on RP20 are projected to consistently produce one of the lowest yields irrespective of cultivar. Even though RP20 bore the highest number of floral buds (Figure 84) the less dense canopies (page 98) reduce the number of locations to carry flowers and fruit. Trees on RP20 may, however, not have reached their full potential yet.

On the other hand, Carina and Vela on Garnem, having a multitude of shoots to carry fruit, had very similar projected yields compared to trees on RP20 and a lower projected yield than predicted for trees on Nemaguard. Garnem had the lowest number of floral buds and likely put more energy into reproductive axillary growth which would have been removed during hedging.

Hedging potentially may cause these canopies to densify over the next few season and possibly to a higher degree in the trees on the rootstocks that encourage higher scion vigour. Should this mainly be in the internal parts of the canopy this could result in less light penetrating these parts potentially creating unproductive zones in the canopy.

Interesting to note though is that Vela on RP40 is projected to produce a similar yield to that of trees on Nemaguard at a 35% nut retention rate, but this also needs confirmation. Projected yields may be significantly higher or lower in relation to Vela on other rootstocks and spacings depending on whether the trees are able to retain and ripen that many fruit.

As expected, tree spacing played a role in the projections of kernels yield per ha within cultivars (Figure 85), possibly because of the gaps between the trees in the 4-m plots particularly for trees on the growth reducing rootstocks (Table 39).

These differences may however narrow or reverse. For instance, the actual yield in the 1-m tree plots could be substantially lower because the trees could either have a low pollination success rate or abort most of the nuts after pollination. This may occur due to competition between the trees for nutrients and water in such a close spacing (also discussed on page 115 under *Tree nutrient status*) restricting photoassimilate production.

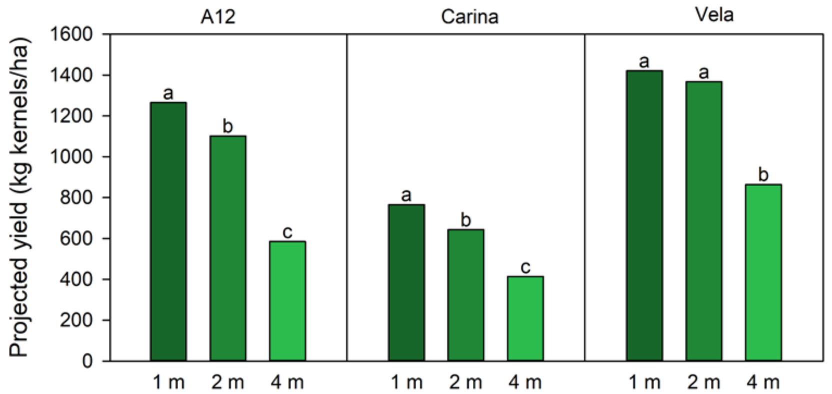


Figure 85 Projected impact of tree spacing on kernel yield (kg kernels/ha) by the three cultivars in the third leaf

Data generated by the flower count model was extrapolated to a per hectare basis using a 5-m interrow spacing, assuming a 35% pollination, set and nut retention success rate and kernel masses observed in AL12015. Data are means (n = 36) and different letters above columns within cultivars indicate significant differences (P = 0.05) between spacings.

Ongoing research

Nut counts will be conducted in November after "June drop" to confirm the overall pollination/set/retention rate between treatments. Estimated yield will be recalculated to determine potential differences that can be attributed to genotype and spacing. Pending COVID-related travel and other restrictions and instrument availability canopies will also be simultaneously be scanned using the Cartographer to start the development of a nut detection model.

Flower counts and yield data in following seasons will indicate the changes in floral numbers in response to the treatments and canopy management as trees mature.

Projected yield data will be validated at harvest when nuts will be harvested from the individual plots. Nut retention percentages for all the treatments can be estimated from the kernel yield and flower counts from the Cartographer data. It has to be emphasized too that these outputs are qualitative because the number of flowers is estimated and not quantified. It does, however, serve as an indicator of the potential yield differences between treatments. Mean kernel mass will also be determined and monitored over coming seasons to see how these change as trees mature.

Not unconnected to the issues raised above and identified early in the project was the need for purpose designed plantings to address some of the specific issues. The tree trellising trial (page 45) and the light and spur fertility trial (page 47) were established to provide an upper limit to how many spurs could be expected on per m tree basis when trees were trained to maximise the number of axillary shoots, and to quantify the light versus spur fertility relationship, respectively. The findings stemming from these trials will be contribute substantially to understanding the nature of responses that will be observed in the higher densities planting over coming seasons.

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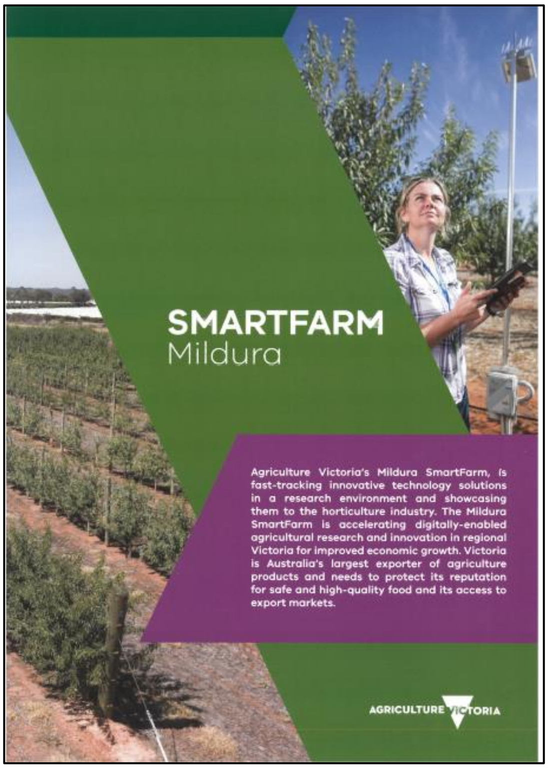
Appendix B: Communication outputs



SMARTFARM
Mildura

Agriculture Victoria's Mildura SmartFarm, is fast-tracking innovative technology solutions in a research environment and showcasing them to the horticulture industry. The Mildura SmartFarm is accelerating digitally-enabled agricultural research and innovation in regional Victoria for improved economic growth. Victoria is Australia's largest exporter of agriculture products and needs to protect its reputation for safe and high-quality food and its access to export markets.

AGRICULTURE VICTORIA

The **Mildura SmartFarm** has been developed to provide a research and innovation environment to design and test more intensive temperate nut production systems for Australia, with a focus on almonds. The SmartFarm is ideally located in north west Victoria, an area that accounts for more than 60 per cent of the Australian almond industry's annual production.

The Mildura SmartFarm aims to develop and demonstrate knowledge and technologies to support the Australian temperate nut industry to continually develop and grow with next generation orchard designs for production and resource use efficiency, along with crop protection and biosecurity through integrated pest management.

The Australian Almond Industry
The Mildura SmartFarm has a focus on the almond industry's strategic aims, which include next generation high-density orchards and new cultivars. The outcomes sought are new opportunities for industry to improve production efficiency. This includes encouraging adoption of shake-and-catch harvesting, better use of labour, fertiliser and water and effective pest and disease management.

"Horizon 1"
Set up as a conventionally spaced orchard with the industry's main cultivars growing on the main rootstocks as well as a size-reducing rootstock. The short to medium term aim is to improve nitrogen fertiliser use. The longer term aim is to provide a environment to test new generation proximal and remote sensing technologies to support real time fertigation decision making.

"Tree training"
Radical tree training techniques are being applied to a range of new cultivars that differ in their growth habits, growing on different rootstocks and planted at standard (500 trees/ha) through to ultra-high (4000 trees/ha) densities.

"Light-X"
Designed to enable quantification of the relationship between light exposure and spur fertility. One row of trees has been planted to ensure unfettered exposure to sunlight during the floral bud initiation period. Spurs on the trees in the row planted perpendicular to the exposed row are mostly shaded during this period. The light received by trees in each row is being measured by purpose designed and built sensors.

AGRICULTURE VICTORIA

SMARTFARM
Mildura

Other temperate nuts
Set up to demonstrate the suitability of the region for the production of other temperate nut types including hazelnuts, walnuts, pecans, chestnuts, macadamia and pistachio.

"Horizon 3"
Designed to assess the impact of rootstock and planting density on the tree architecture and spur production of three mechanically hedged new self-fertile Australian cultivars. LiDAR is being used to visualise branching patterns in 3-D.

The site also features a range of soil textures with different water holding capacities; new generation soil moisture sensors are being used to avoid under- and over-watering and to draw inferences about water use by different cultivar/rootstock/spacing combinations. The sensors will also enable demonstration on a significant scale of closed-loop autonomous irrigation.

Connectivity
The Mildura SmartFarm is served by LoRaWan and 4G providing connectivity across the site and remote access to sensors and irrigation controllers.

Integrated Pest Management
Research and innovation to improve orchard hygiene, new powerful insect traps, improved knowledge of pest populations, biocontrol and biopesticides, and post-harvest disinfestation.

About Agriculture Victoria SmartFarms

Victoria has an opportunity to grow a productive, sustainable and profitable agriculture sector by pairing its world-leading science capabilities with advances in agricultural technology.

While the true benefits of digital disruption and advances in agricultural technology are yet to be fully realised, Victoria is well-positioned to take advantage of these opportunities to drive a new era of productive, sustainable and profitable agriculture. Applications of innovative technology can lead Victoria's agriculture to new climate change solutions.

Agriculture Victoria is partnering with industry, agribusiness and communities to build SmartFarms in key regional centres across Victoria. The SmartFarms capture and bring together smart technology and big data to support smart information and new opportunities for agriculture. Each SmartFarm is a gateway to research, innovation, technology and skills development for Victoria's major agriculture industries. SmartFarms actively engage in multidisciplinary collaborative research and are connected to each other and to the leading-edge big data, genomics and metabolomics capabilities at AgriBio, Centre for AgriBioscience, in Bundoora. Together, they form a research ecosystem that enables transformative science and technology developments and fast-tracks adoption of innovations in agriculture.

Figure B 1 Mildura SmartFarm brochure

AGRICULTURE VICTORIA

SMARTFARM
Mildura

With Commonwealth and Victorian State Government support, Agriculture Victoria has developed a temperate nut experimental orchard to provide a research and innovation environment to design, test and demonstrate more intensive production systems for Australian temperate nut industries using almonds as a model crop.

The focus is on generating knowledge for the next generation of orchards.

Linkage with the Australian almond industry
The 20-ha experimental orchard is located near Mildura in north west Victoria, an area that accounts for more than 60 per cent of the Australian almond industry's production. The majority of the plantings on the Mildura SmartFarm are designed to address aspects of the Australian almond industry's strategic aims, which include increased productivity based on higher density plantings and new cultivars. The industry also wants to see more efficient production. This includes encouraging adoption of shake-and-catch harvesting, better use of labour, fertiliser and water, and effective pest and disease management.

Horizon 1
Horizon 1 is a conventionally spaced planting of three of the industry's current main cultivars. The trees are growing on the industry's standard rootstock, a size-reducing rootstock and a rootstock more resistant to soil-borne disease.

The planting is a platform to study of ways to improve nitrogen fertiliser use in this widely adopted production system. It is also being utilised as a platform to test new generation sensing technologies to support real-time fertigation decision making.

A medium- to longer-term use could include research on managing nut composition, particularly in relation to nutrition and health.

Horizon 3
The Horizon 3 block was established to allow the assessment of the impact of rootstock and planting density on tree architecture and spur production of three new Australian-bred self-fertile cultivars with differing growth habits.

The planting covers a wide range of soil types capable of holding different amounts of water. This presents an opportunity because new generation soil moisture sensors, wirelessly integrated (LoRaWAN and 4G networks) with an irrigation control unit, can be utilised to deliver appropriate amounts of water to each plot, avoiding under- or overwatering. Being in a position to demonstrate closed-loop autonomous irrigation on a significant scale to industry is an added bonus.

Inferences about crop water requirement by different cultivar/rootstock/spacing combinations may also be made. This information may help guide irrigators as access to water supply assumes greater importance.

LiDAR is being used to visualise branching patterns in 3-D. This capability is important because it captures very complex tree growth patterns that may be ameliorated by rootstock and spacing in ways that aren't readily discernible from visual observations.

Tree training
Radical tree training techniques are being applied to a range of new almond cultivars that differ in their growth habits, growing on a range of vigour-imparting rootstocks and planted at standard (500 trees/ha) through to ultra-high (4000 trees/ha) densities.

The aim is to test the productivity limits of the 2-dimensional fruiting space concept. In other words, how many nuts can be produced per metre of tree row?

Knowing the productivity limit will be important in designing novel orchard layouts.

Light-X
Perennial fruit and nut tree canopies are managed to improve light penetration to the lower parts of the trees. Almonds are no exception; shaded spurs — spurs are short shoots on which almonds are produced — and spurs closer to the ground are less productive.

This trial was designed and established to investigate the relationship between light exposure and almond spur fertility. Two rows of trees are planted perpendicular to each other in a cross arrangement orientated so that one row of trees has unfettered exposure of all parts of the tree to sunlight during the period when floral buds are formed in spurs. The second row of trees lies under the path of the sun during this period so that spurs on these trees are mostly shaded during this period.

Other temperate nuts
A planting of hazelnut, walnut, pecan, chestnut, macadamia and pistachio has been established primarily to assess and demonstrate the suitability of different cultivars and — where possible — different rootstocks for higher density plantings.

Uniquely, the planting will allow producers and potential investors to assess the suitability of the region for each crop and cultivar under the same climatic, soil and management conditions.

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Acknowledgement: The plantings have been established as part of project ST16001, a co-investment between the Victorian Government and the Federal Department of Agriculture, Water and the Environment through the Rural Research and Development for Profit program. The Commonwealth funds are managed by Horticulture Innovation Limited. The initial light interception methodology development was conducted with support from the Victorian Government's Agriculture Infrastructure and Jobs Fund.

ALMOND BOARD OF AUSTRALIA
Australian Government Department of Agriculture, Water and the Environment
Hort Innovation
AGRICULTURE VICTORIA

Figure B 2 Mildura SmartFarm fact sheet

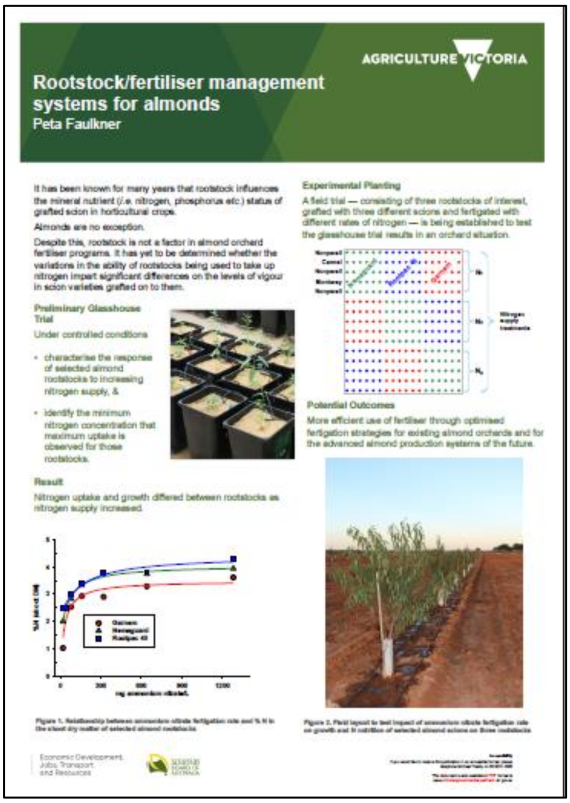


Figure B 3 Mildura Field days poster 2017

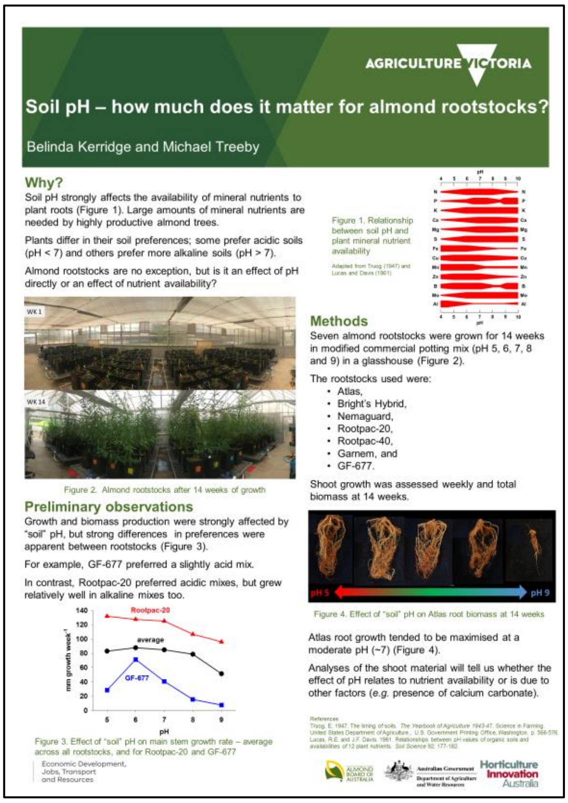


Figure B 4 Mildura Field days poster 2018

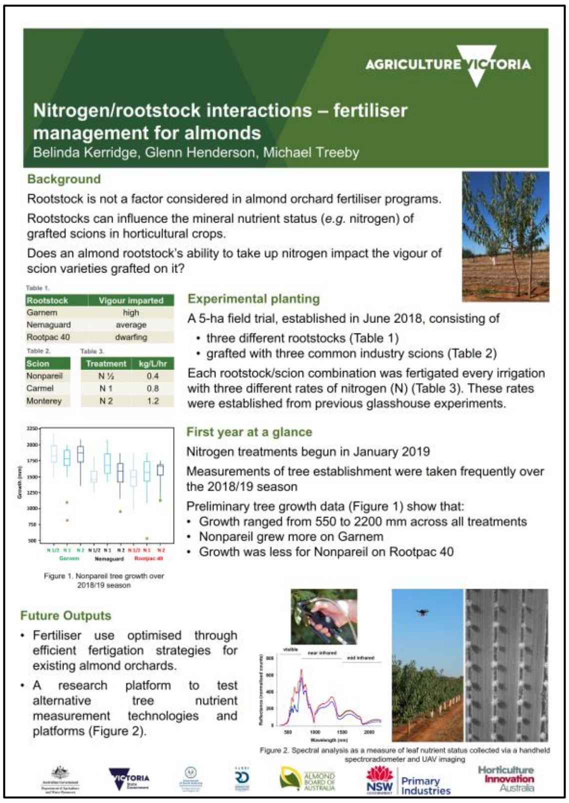


Figure B 5 Mildura Field days poster 2019 (1)

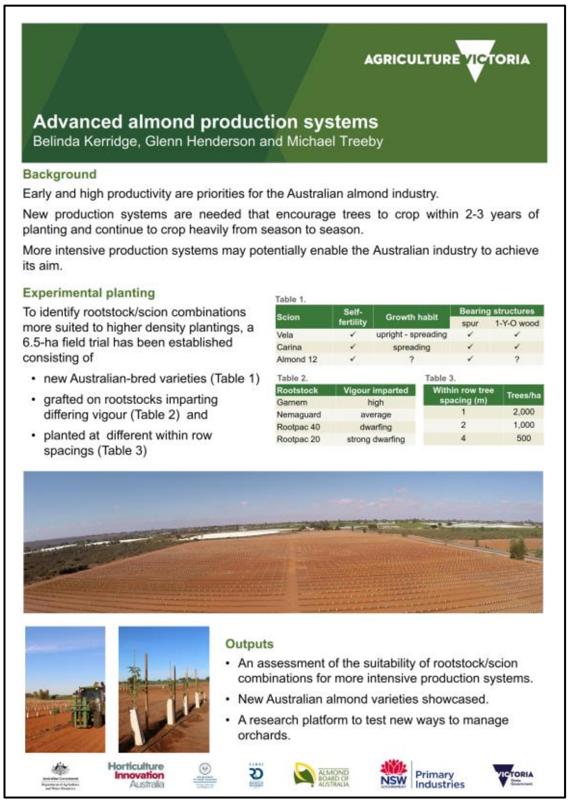


Figure B 6 Mildura Field days poster 2019 (2)

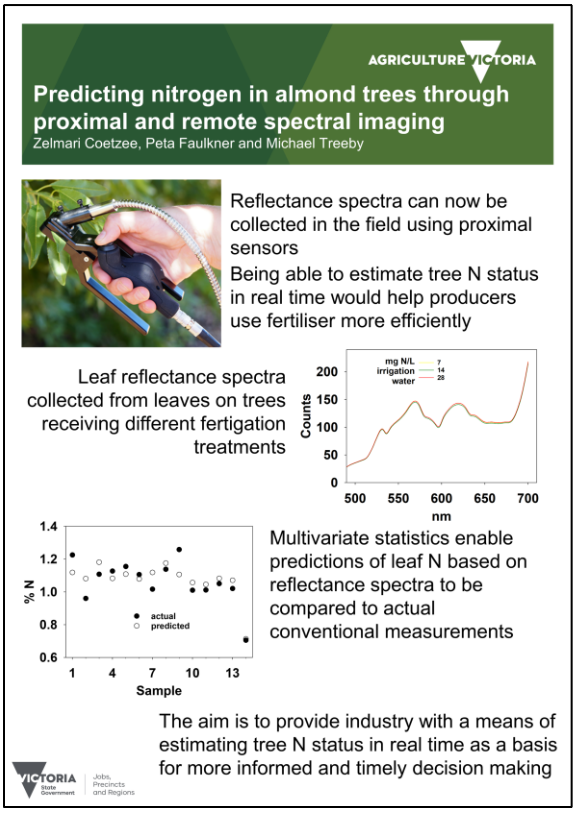


Figure B 7 Mildura Field days/minister's launch poster 2021 (1)

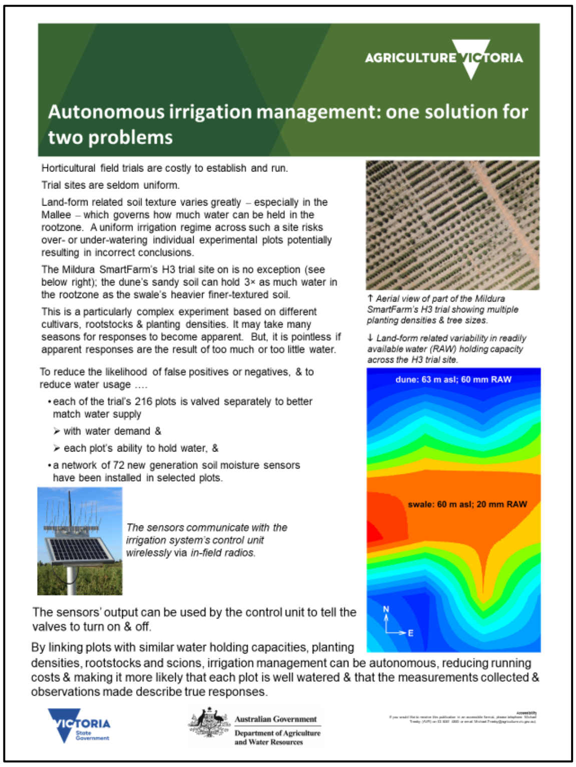


Figure B 8 Mildura Field days/minister's launch poster 2021 (2)

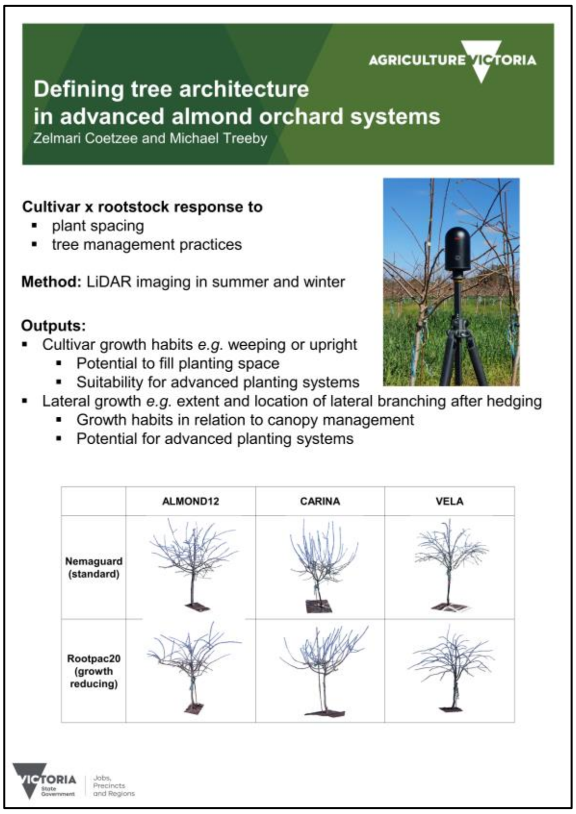


Figure B 9 Mildura Field days/minister's launch poster 2021 (3)

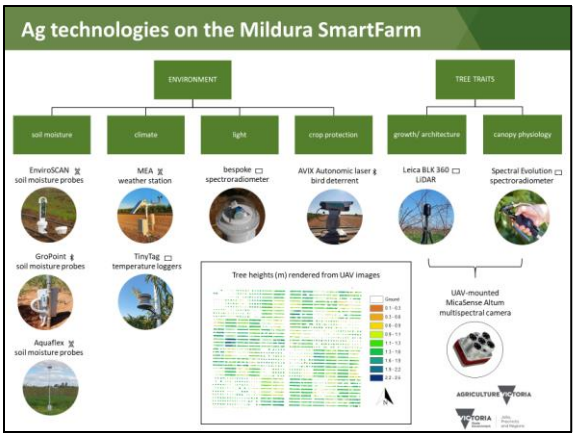


Figure B 10 Mildura Field days/minister's launch poster 2021 (4)

FERTILISERS & NUTRITION

It's nuts not to future-proof nitrogen

Peta Faulkner, Zelmari Coetzee & Michael Treeby

In an effort to remain competitive in international markets, there has been a push in recent years by the temperate nut industry to improve the precocity and productivity of orchards.

As temperate nuts require large fertiliser inputs to achieve high productivity, efficient fertiliser programs are vital for ensuring sustainability and the continued viability of the industry.

Nitrogen is one of the main nutrient requirements of both almonds and walnuts; its efficient management is critical to maximising productivity.

Newly planted trees, compared to mature trees, are highly dependent on nitrogen application due to more vigorous growth and limited storage reserves as a result of their smaller size.

The amount of nitrogen applied to a crop can be tailored to maximise the efficiency of its use by the crop as nitrogen uptake by roots generally plateaus at a particular concentration in the soil solution.

Generally, there is nothing more to be gained by pushing the concentration of nitrogen above that concentration, and in some cases further increases can even be detrimental.

Regulation of nitrogen uptake and its utilisation are complex and differ considerably between crops, and cultivars within crops.

Walnut and almond rootstocks growing in sand culture medium, supplied with nutrient solutions containing varying amounts of nitrogen via a purpose-built fertigation system.

Nitrogen uptake and utilisation regulation in the horticultural world is particularly complex due to the use of rootstocks that may be quite different genetically from the scion cultivar (grafted onto the rootstock) and its nitrogen uptake and utilisation abilities. Rootstocks supply water and mineral nutrients to scions.

Some rootstocks are better suited to certain soil types (eg: light textured, high pH, calcareous etc) and some are more tolerant or resistant to soil-borne pathogens.

Rootstock choice is therefore an important decision to ensure healthy tree growth and high productivity.

Young trees, consisting of nine different rootstock/scion combinations, planted in a randomised whole block design at Agriculture Victoria's experimental orchard near Mildura.

30 AUSTRALIAN TREE CROP OCTOBER/NOVEMBER 2019

FERTILISERS & NUTRITION

Agriculture Victoria researcher Michael Treeby planting almond rootstock seedlings as part of the controlled glasshouse experiment.

There is no single "best" rootstock; rather, the physical and biological conditions of each orchard, and management blocks within orchards, have to be considered during orchard design.

There is ample evidence across many horticultural crops that the same scion grafted on different rootstocks will have significantly different mineral nutrient statuses and temperate nuts are no exception.

Despite this, rootstock is not considered as a factor in orchard fertiliser programs. It has yet to be determined whether the variations in the ability of rootstocks to take up nitrogen impart significant differences on the vigour in scion cultivars grafted onto them.

Research being conducted by Agriculture Victoria at Mildura aims to determine whether there are differences in the ability of different almond and walnut rootstocks to take up and transport mineral nutrients, and to assess the impact of these differences on scion mineral nutrient status, early tree growth and the time to the first significant crop.

A preliminary glasshouse experiment was conducted under controlled conditions to investigate the nitrogen requirements of six temperate nut rootstocks.

Almond and walnut rootstocks were grown in sand culture and seven different nitrogen solutions were applied through the nutrient solution.

The vigour response of rootstocks to the nitrogen supply was characterised by the above ground biomass.

The almond seedling rootstocks used included RootPac 40 and Garnem, *Prunus dulcis* × P. persica hybrids that impart low and high vigour in scions, respectively, and Nemaguard (*Prunus persica*), the industry standard. The walnut rootstocks used were American black walnut (*Juglans nigra*, but commonly referred to as "ABW"), Northern Californian black walnut (*Juglans hindsii*, and commonly referred to as "NCBW") and Paradox (a J. hindsii × J. regia hybrid), the industry standard.

All three almond rootstocks exhibited maximum growth at the same nitrogen concentration in the soil solution (about 14 mg/L), with above ground biomass declining beyond that point.

The walnut rootstocks behaved similarly, albeit reaching maximum aboveground biomass at 28mg /L; twice that needed for the almond rootstocks to achieve maximum above ground biomass.

Production of above ground biomass by ABW and NCBW at nitrogen concentrations beyond 28 mg/L was less compared to the production at the optimal concentration. Interestingly, Paradox was able to reach maximum growth at all concentrations of 28 mg/L and above.

These results demonstrate that in addition to the well documented environmental effects of excessive nitrogen supply, a significant reduction in rootstock growth is likely, as seen with five of the six rootstocks tested. This may result in a delay in tree establishment and hence a potential economic cost.

A follow-up field trial has been established at Agriculture Victoria's experimental orchard near Mildura to test the glasshouse trial results under field conditions.

Three almond cultivars (Nonpareil, Carmel and Monterey), each grafted on the same three almond rootstocks used in the glasshouse experiment (Rootpac 40, Garnem and Nemaguard) were planted in a randomised complete block design.

Nitrogen at the optimal, half the optimal and double the optimal concentration (as determined in the glasshouse trial) is being supplied through the drip irrigation system to the young trees.

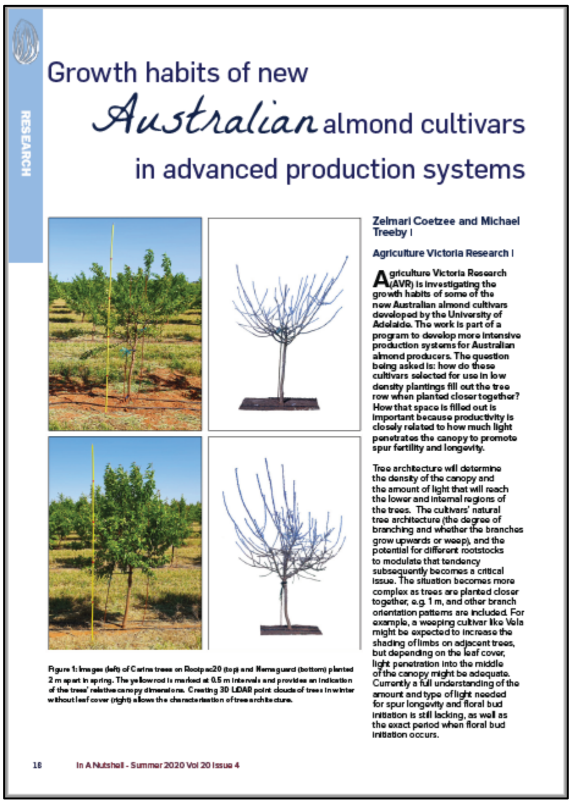
The impact on tree establishment, mineral nutrient status and reproductive behaviour of the different rootstock/scion combinations are being assessed.

This research will lead to a better understanding of rootstock-scion interactions and more efficient use of fertiliser through optimised fertigation strategies for existing almond orchards, and for the advanced production systems of the future.

Acknowledgement: Developing advanced production systems for temperate nut crop industries research is funded by Agriculture Victoria Research with co-investment from the Australian Government's Rural Research and Development for Profit programme via Hort Innovation.

OCTOBER/NOVEMBER 2019 AUSTRALIAN TREE CROP 31

Figure B 11 Faulkner, P., Coetzee, Z. & Treeby, M. 2019. It's nuts not to future-proof nitrogen. Australian Tree Crop, Oct/Nov, 30-31



RESEARCH

Growth habits of new Australian almond cultivars in advanced production systems

Zelmari Coetzee and Michael Treeby | Agriculture Victoria Research |

Agriculture Victoria Research (AVR) is investigating the growth habits of some of the new Australian almond cultivars developed by the University of Adelaide. The work is part of a program to develop more intensive production systems for Australian almond producers. The question being asked is: how do these cultivars selected for use in low density plantings fill out the tree row when planted closer together? How that space is filled out is important because productivity is closely related to how much light penetrates the canopy to promote spur fertility and longevity.

Tree architecture will determine the density of the canopy and the amount of light that will reach the lower and internal regions of the trees. The cultivars' natural tree architecture (the degree of branching and whether the branches grow upwards or weep), and the potential for different rootstocks to modulate that tendency subsequently becomes a critical issue. The situation becomes more complex as trees are planted closer together, e.g. 1 m, and other branch orientation patterns are included. For example, a weeping cultivar like Vela might be expected to increase the shading of limbs on adjacent trees, but depending on the leaf cover, light penetration into the middle of the canopy might be adequate. Currently a full understanding of the amount and type of light needed for spur longevity and floral bud initiation is still lacking, as well as the exact period when floral bud initiation occurs.

Figure 1: Images (left) of Carina trees on Rootpac20 (top) and Nemaguard (bottom) planted 2 m apart in spring. The yellow rod is marked at 0.5 m intervals and provides an indication of the trees' relative canopy dimensions. Creating 3D LiDAR point clouds of trees in winter without leaf cover (right) allows the characterisation of tree architecture.

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Describing tree architecture in anything other than qualitative terms (e.g. upright versus weeping etc.) is difficult, but technologies have been developed that make it easier than it was in the past. High-resolution terrestrial LiDAR (Light Detection and Ranging) can produce highly accurate 3D point clouds of objects by illuminating complex targets, such as trees, with timed bursts of laser light. The timing of the return signal is proportional to where in space, relative to the laser source and sensor, the surface that reflected that light is. By illuminating trees from multiple perspectives, point clouds are compiled that allow 3D representations of the target. The renderings of the architectural features of trees in winter (Figure 1) allow the characterisation of their natural branching habits, their tendency to throw lateral shoots and the orientation of branches or shoots, which in turn allows us to simulate how the tree will fill the space as trees mature. Preliminary work shows that LiDAR images collected in summer can further be used to model what the likely light receipts in the different parts of the canopy might be.

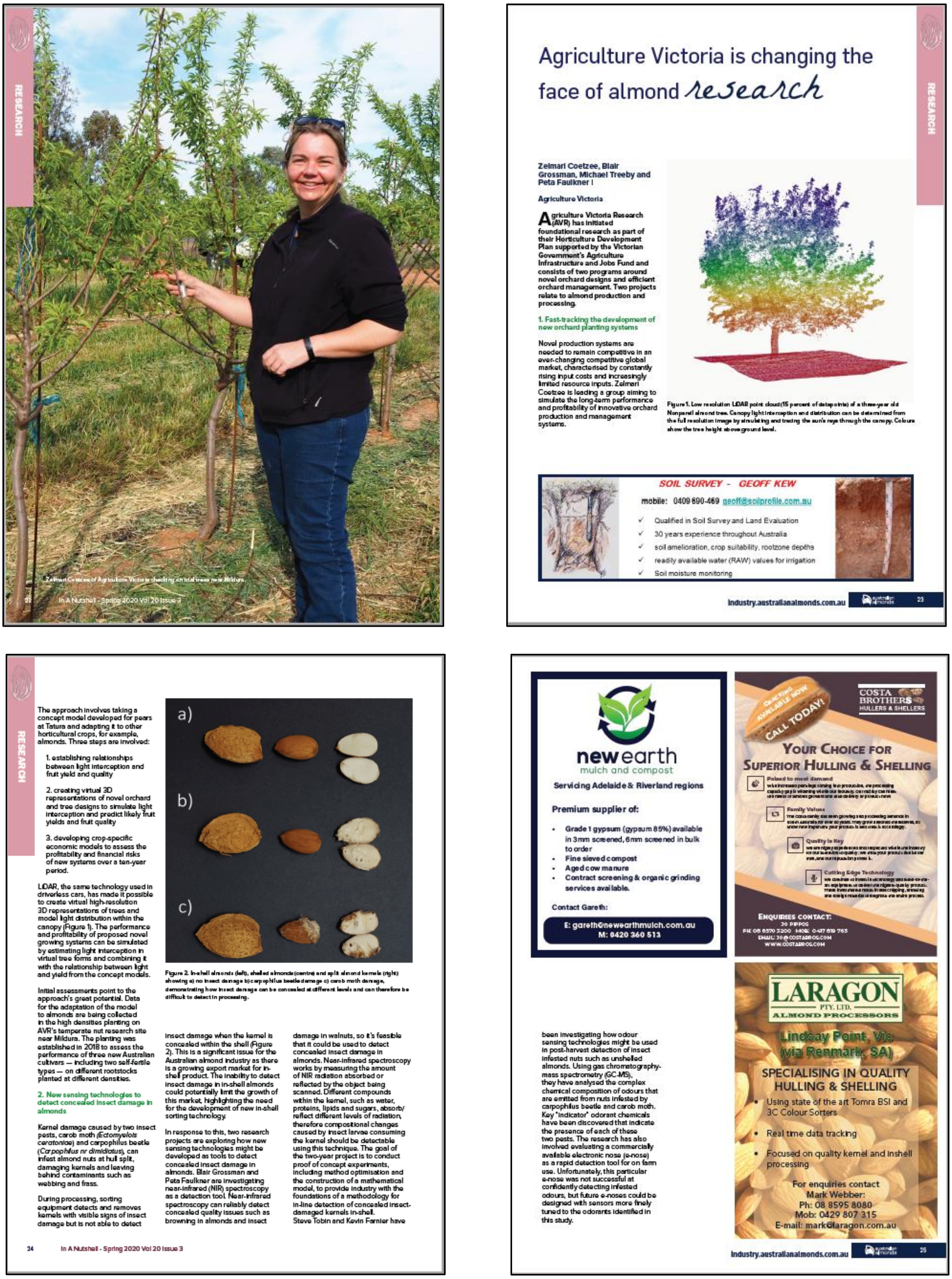
The planting being used was established in 2018 on AVR's Mildura SmartFarm in north west Victoria. The planting consists of Vela, Carina and Almond 12, which are all self-fertile, budded on industry standard rootstocks (Nemaguard or Garnem) and two size-reducing rootstocks (Rootpac20 or Rootpac40). Within-row tree spacings range from 4 m - more or less current industry standard - to 1 m, which is considered ultra-high density.

Figure 1 shows examples of the point clouds created with LiDAR in winter for Carina on two different rootstocks. The differences in canopy density between trees on Rootpac20 and Nemaguard is clear and is emphasised by the gaps in the trees' shadows. From the LiDAR images we can infer that the differences in density can be attributed to Rootpac20 limiting lateral branching in the scion compared to Nemaguard. LiDAR images collected this coming winter will allow us to determine the degree of branching over seasons and where new growth occurs, which in turn will allow us to predict what the trees will look like as they mature.

Acknowledgement

The plantings have been established as part of project ST16001; a co-investment between the Victorian Government and the Federal Department of Agriculture, Water and the Environment through the Rural Research and Development for Profit program. The Commonwealth funds are managed by Horticulture Innovation Limited. The initial light interception methodology development was conducted with support from the Victorian Government's Agriculture Infrastructure and Jobs Fund.

Figure B 12 Coetzee, Z. & Treeby, M. 2020. Growth habits of new Australian almond cultivars in advanced production systems. In a nutshell, 20 (4), 16-17



RESEARCH

Zelmari Coetzee of Agriculture Victoria checking on trial trees near Mildura.

Agriculture Victoria is changing the face of almond research

Zelmari Coetzee, Blair Grossman, Michael Treeby and Peta Faulkner I

Agriculture Victoria

Agriculture Victoria Research (AVR) has initiated foundational research as part of their Horticulture Development Plan supported by the Victorian Government's Agriculture Infrastructure and Jobs Fund and consists of two programs around novel orchard designs and efficient orchard management. Two projects relate to almond production and processing.

1. Fast-tracking the development of new orchard planting systems

Novel production systems are needed to remain competitive in an ever-changing competitive global market, characterised by constantly rising input costs and increasingly limited resource inputs. Zelmari Coetzee is leading a group aiming to simulate the long-term performance and profitability of innovative orchard production and management systems.

Figure 1. Low resolution LiDAR point cloud (15 percent of datapoints) of a three-year old Nonpareil almond tree. Canopy light interception and distribution can be determined from the full resolution image by simulating and tracing the sun's rays through the canopy. Colours show the tree height above ground level.

The approach involves taking a concept model developed for pears at Tatura and adapting it to other horticultural crops, for example, almonds. Three steps are involved:

1. establishing relationships between light interception and fruit yield and quality
2. creating virtual 3D representations of novel orchard and tree designs to simulate light interception and predict likely fruit yields and fruit quality
3. developing crop-specific economic models to assess the profitability and financial risks of new systems over a ten-year period.

LiDAR, the same technology used in driverless cars, has made it possible to create virtual high-resolution 3D representations of trees and model light distribution within the canopy (Figure 1). The performance and profitability of proposed novel growing systems can be simulated by estimating light interception in virtual tree forms and combining it with the relationship between light and yield from the concept models.

Initial assessments point to the approach's great potential. Data for the adaptation of the model to almonds are being collected in the high densities planting on AVR's temperate nut research site near Mildura. The planting was established in 2018 to assess the performance of three new Australian cultivars — including two self-fertile types — on different rootstocks planted at different densities.

2. New sensing technologies to detect concealed insect damage in almonds

Kernel damage caused by two insect pests, carob moth (*Ectomyelois ceratoniae*) and carpophilus beetle (*Carpophilus nr dimidiatus*), can infest almond nuts at hull split, damaging kernels and leaving behind contaminants such as webbing and frass.

During processing, sorting equipment detects and removes kernels with visible signs of insect damage but is not able to detect insect damage when the kernel is concealed within the shell (Figure 2). This is a significant issue for the Australian almond industry as there is a growing export market for in-shell product. The inability to detect insect damage in in-shell almonds could potentially limit the growth of this market, highlighting the need for the development of new in-shell sorting technology.

a) b) c)

Figure 2. In-shell almonds (left), shelled almonds (centre) and split almond kernels (right) showing a) no insect damage b) carpophilus beetle damage c) carob moth damage, demonstrating how insect damage can be concealed at different levels and can therefore be difficult to detect in processing.

In response to this, two research projects are exploring how new sensing technologies might be developed as tools to detect concealed insect damage in almonds. Blair Grossman and Peta Faulkner are investigating near-infrared (NIR) spectroscopy as a detection tool. Near-infrared spectroscopy can reliably detect concealed quality issues such as browning in almonds and insect damage in walnuts, so it's feasible that it could be used to detect concealed insect damage in almonds. Near-infrared spectroscopy works by measuring the amount of NIR radiation absorbed or reflected by the object being scanned. Different compounds within the kernel, such as water, proteins, lipids and sugars, absorb/reflect different levels of radiation, therefore compositional changes caused by insect larvae consuming the kernel should be detectable using this technique. The goal of the two-year project is to conduct proof of concept experiments, including method optimisation and the construction of a mathematical model, to provide industry with the foundations of a methodology for in-line detection of concealed insect-damaged kernels in-shell.

Steve Tobin and Kevin Farnier have been investigating how odour sensing technologies might be used in post-harvest detection of insect infested nuts such as unshelled almonds. Using gas chromatography-mass spectrometry (GC-MS), they have analysed the complex chemical composition of odours that are emitted from nuts infested by carpophilus beetle and carob moth. Key "indicator" odorant chemicals have been discovered that indicate the presence of each of these two pests. The research has also involved evaluating a commercially available electronic nose (e-nose) as a rapid detection tool for on farm use. Unfortunately, this particular e-nose was not successful at confidently detecting infested odours, but future e-noses could be designed with sensors more finely tuned to the odorants identified in this study.

Figure B 13 Coetzee, Z., Grossman, B., Treeby, M. & Faulkner, P. 2020. Agriculture Victoria is changing the face of almond research. In a nutshell, 20 (3), 23-25

Appendix C: Project related documentation

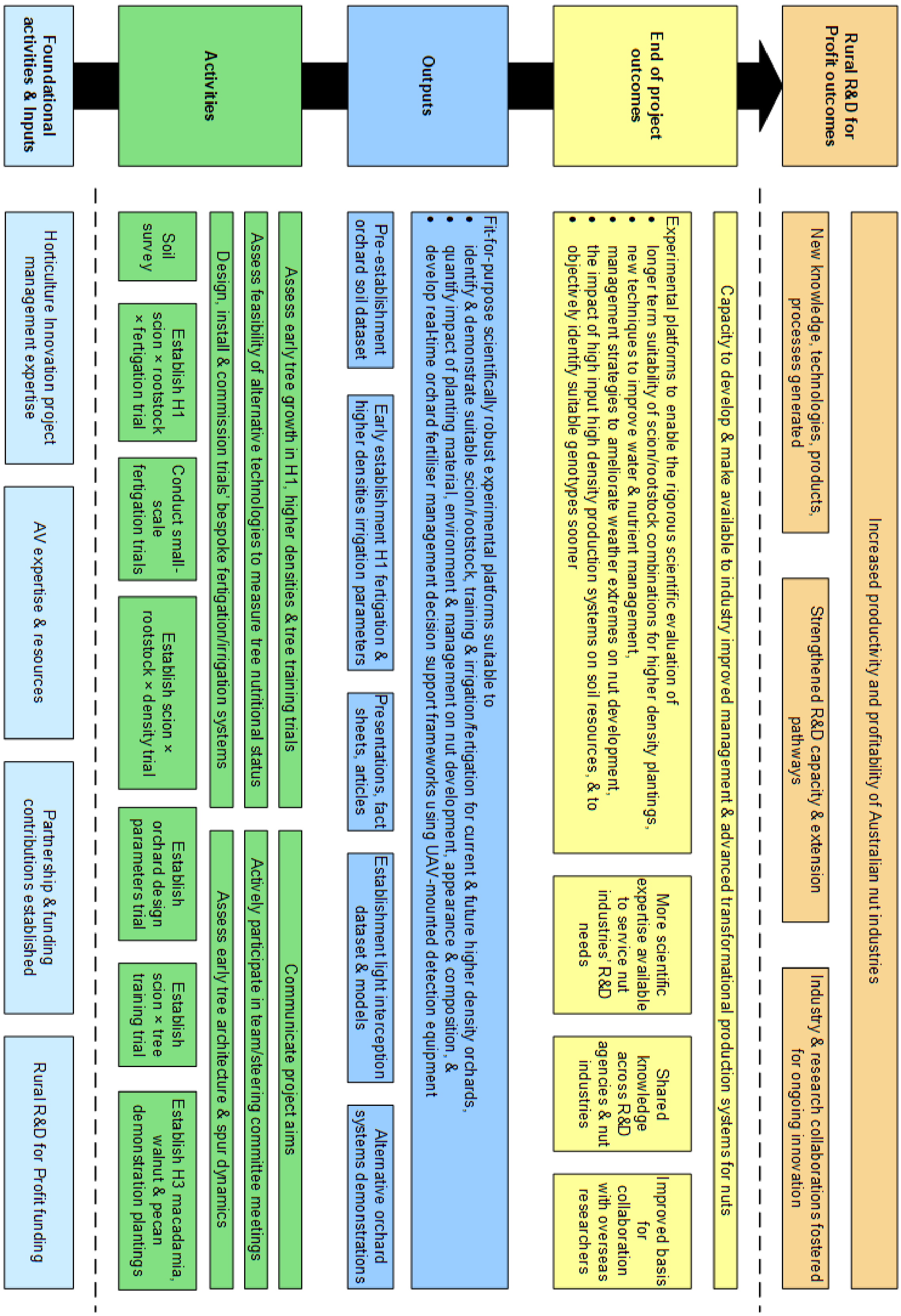


Figure C 1 Project logic framework developed at the outset of the project