Hort Innovation

Final Report

Almond productivity: tree architecture and development of new growing systems

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Delivery partner:

Plant & Food Research Australia Pty Ltd

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Almond productivity: tree architecture and development of new growing systems AL14007

Disclaimer:

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Content

Summary

The Australian almond industry is undergoing rapid expansion, with extensive new "green field" plantings. The industry has grown from around 5,000 ha in 2001 to over 42,000 ha in 2018, and is expected to grow further to 50,000 ha by 2025. The rapidly increasing cost of water for irrigation is putting pressure on orchard profits and the industry has recognised, at a strategic level, that substantial changes are required in terms of orchard design and management to maintain and increase orchard profits.

Current planting regimes and management systems are based on Californian practices, with trees trained to produce multiple large scaffold branches that form a fully covered, closed canopy by Year 7. Growers are reluctant to change planting systems as this means changing orchard machinery. Smaller trees with narrow canopies, planted closer together, as adopted by many tree fruit industries, are more likely to lead to large improvements in orchard productivity and grower profits than incremental changes to existing systems. This need for change was recognised by Hort Innovation in 2014 when they contracted Plant & Food Research to establish the research programme "Almond productivity: tree architecture and development of new growing systems". Starting in 2014, the objective for the research was to "double yields but without increasing costs". Projects were established across the almond-producing regions of SE Australia, and most recently at the Almond Board of Australia (ABA) Almond Centre of Excellence in Loxton. Similar projects were established in California, with additional funding from the Almond Board of California to effectively have two seasons in one year.

The research demonstrated that in traditional orchards, while up to 90% of incoming sunlight is intercepted by the trees, most of this occurs in the upper canopy. There was insufficient light transmission to ensure cropping in the lower canopy. Although pruning selected limbs and using reflective ground covers increased light interception and thus yields in the lower canopy zones, the fruit in these zones were not ready for harvest until 2–3 weeks after the main crop, causing downstream problems for harvesters and processors. A novel, low cost pruning system was developed to produce trees with more light-efficient, narrower canopies to be managed with rows placed closer together than is traditional. Overall there were positive indications that a single "one-off" round of narrow-pruning when trees were 2-years-old would be a viable option, with trees planted in 6-m wide rows, and even with 5-m rows. In this system, estimated yield at 6 x 3 m spacing for 6-year-old 'Nonpareil' trees was 5.1 t/ha.

Several attempts were made to promote precocity and increase yields on young almond trees by trunk girdling, but none were particularly successful. The long-term response to trunk girdling was a reduction in tree size with no adverse effect on yield, which may be of interest to growers as an alternative to growth-controlling rootstocks.

Research also investigated the use of central leader trees and narrow pruning techniques across a range of scion/rootstock combinations. Rather than growers severely pruning their young trees to stimulate scaffold branch development, we believed that planting "unpruned" central leader trees would be an important step towards producing narrow tree canopies. Although trees in this project have not yet reached peak yields, the benefits of planting central leader trees were clear in terms of resilience to wind damage and ease of maintaining a narrow canopy. Interestingly, it was easier to maintain the central leader structure on the more vigorous than the less vigorous rootstocks.

Narrow pruning was also evaluated with the new, high yielding, self-fertile cultivars 'Carina' and BA2 (Shasta®). This project demonstrated the added complication of young trees bearing heavy crops of fruit causing branches to bend and break under the weight of fruit. It was estimated that the trial block, with 3-year-old 'Carina' and Shasta® trees spaced at 6 x 3 m, produced 2.3 and 2.9 t/ha, respectively.

Few of the existing almond cultivars are compatible with orchard intensification. New cultivars are required that naturally form a narrow, upright tree canopy. Working alongside almond breeders in Australia, California and Spain we identified important architectural traits needed to produce this tree structure, with most traits recognisable in trees less than 3-years-old. While shell and kernel quality are important breeding targets for almonds, as are self-fertility and pest and disease tolerance, new cultivars are required for the almond industry to make a step change in productivity, ones that are stacked with architectural traits that enable high productivity. Methodologies described in our research should help breeders achieve that outcome.

Tech transfer and extension activities during this 5-year program included 78 project related conferences and meetings with growers, nurseries, consultants, researchers and ABA staff; 15 formal presentations to workshops and conferences; two articles published in industry journals, seven conference proceedings and scientific posters, and six client and technical reports, in addition to 10 Hort Innovation milestone reports.

Keywords

Almond, productivity; tree architecture; breeding, cultivars, rootstocks, pruning systems; central leader trees; high density plantings; propagation; trunk girdling; reflective ground covers; light interception

Introduction

The Australian almond industry is undergoing rapid expansion, with extensive new "green field" plantings. The industry has grown from around 5,000 ha in 2001 to over 42,000 ha in 2018, and is expected to grow further to 50,000 ha by 2025. Almonds are the highest value fruit/nut crop and the most important exported horticultural crop in Australia. Typical yields from mature almond trees are generally 3–4 t of kernel/ha. With the rapidly escalating cost of water for irrigation, the industry has recognised at a strategic level that significant changes are required in terms of orchard design and management to improve on these yields and increase orchard profits.

Almonds tend to be grown in traditional low density 'large tree' orchard systems, with high vegetative vigour, poor light distribution and low partitioning of resources to fruiting. Tree architecture in these crops is poorly understood, leading to relatively unsophisticated canopy management. The objective of research described here was to provide growers with the knowledge, tools and confidence to intensify their orchard operations and to focus on more efficient and sustainable use of both capital and natural resources.

The Australian almond industry established itself by adopting the traditional growing methods developed and used by almond growers in California, by far the world's largest producer of almonds. To drive continual improvement across the industry and to increase yields beyond those currently produced using the California model, it was acknowledged that Australian growers would need to do something different. A fresh approach was required involving not only new planting systems but also new cultivars and rootstocks, and new pruning/training systems adapted to suit these.

Standard planting regimes and management systems are based on blocks with approximately 350 trees/ha. In these orchards, trees are trained to produce multiple large scaffold branches that form a fully covered, closed canopy by Year 7. Growers are reluctant to change planting systems as this means changing orchard machinery. Smaller trees, with narrow fruiting canopies, planted closer together within and between rows, are likely to be more suitable for orchard intensification than traditional systems.

Some newer "high density" blocks have been planted by growers with 556 trees/ha. However, without changes to pruning and training systems the trees in these blocks quickly become crowded without any yield benefit in the longer term. A "super high density" system developed in Spain is also being tested by some growers with up to 2,200 trees/ha. Although this system can be highly mechanised, it is costly to establish and in the absence of better ways to manage the canopy, grower experience is that long-term yields are similar to those from traditional blocks.

The need to increase orchard productivity and grower profits through orchard intensification was recognised by Hort Innovation in 2014 when they contracted Plant & Food Research (PFR) to establish this current program of research, "Almond productivity: tree architecture and development of new growing systems". Key research objectives in this program have been to identify almond cultivars, rootstocks and management strategies that are better suited to orchards with closer plantings, and to better understand how trees planted at high densities affect orchard light environment and crop maturity.

Several long-term projects were established during the course of the 5-year program, with trial sites located on commercial orchards across the main almond-producing regions in SE Australia and in California. It was recognised that while growers were happy to support these trials, we did not always have the option to change orchard row spacing to fully test high density growing systems. Initial projects in Australia were therefore designed to better understand principles and opportunities for change. It was not until the opening of the Almond Board of Australia (ABA) Almond Centre of Excellence in Loxton that we were able to have trials planted at high density in Australia.

Methodology

Fruit bud development depends on good exposure to sunlight. While the canopies of young almond trees are well illuminated and thus productive, light interception and productivity across the orchard block is low because of the wide planting distances and the large gaps between trees and rows. As trees get larger, orchard light interception increases but so too does internal shading within the trees. This means that there is a gradual movement of fruiting zones from the lower to upper canopy zones. Buds and spurs in the lower and central portions of the canopies die out completely and trees form an inverted pyramid shape, wider at the top than at the bottom. With this growing system orchards generally do not reach peak productivity until around Year 8, producing 3–4 t/ha.

Two issues highlighted here are the time it takes for traditional orchards to reach peak production and the inefficiencies of growing large trees with limited productive capacity. Research undertaken in this program to address these issues had three key objectives:

1. Better understand the limitations to traditional growing systems, based on existing cultivars and rootstocks, and to identify changes to increase orchard productivity over the longer-term
2. Investigate options to redesign orchards of the future, with new cultivars and rootstocks and new growing systems
3. Work alongside almond breeders to identify architectural traits associated with high productivity and suitability for more intensive growing systems.

Light management in traditional almond orchards (Appendix I)

With the current management systems for almonds, large trees develop an inverted pyramid structure forming a closed canopy across the top of the trees. It is the “shoulders” at the tops of these trees that help create the closed canopies and that shade the lower canopy zones of trees, including trees in adjacent rows. Our treatments used selective limb removal pruning to remove the large scaffold branches that create these shoulders. To accentuate this effect we also used reflective ground covers installed beneath the trees to reflect light back into the lower canopy zones. Trees were 6-year-old ‘Nonpareil’ planted at 6 x 3 m spacing. Our objective was to increase total tree yield over the longer term by increasing yields in the lower canopy zones.

Although we were able to increase the light and therefore the crop in the lower canopy zones, this did not increase total yield and actually created downstream issues with the fruit in the lower canopy taking longer to mature than the main crop.

Seasonal light interception by narrow-pruned almond trees (Appendix II)

In this project, also with ‘Nonpareil’ trees planted at 6 x 3 m spacing, we investigated the option of earlier intervention pruning to create narrower canopies on young trees, before crowding became an issue. Pruning involved removing any branches that, if left, would ultimately become large scaffold branches growing into the centre of the rows thus impeding machinery access.

The single round of narrow pruning we applied in 2014, when trees were 2-years-old, was sufficient to maintain narrower canopies for the 4-year duration of this project, without reducing yields. But the narrow-pruned trees were smaller, so in terms of cropping efficiency, narrow-pruned trees produced more fruit per canopy volume than the unpruned trees and would allow for closer row spacing. An interesting feature was how dynamic the canopies were during the season, with light interception reaching a peak in summer, around the time of floral initiation, when trees transitioned from relatively upright canopies to wider, spreading canopies as the branches bent downwards under the weight of the developing fruit.

Trunk girdling to increase cropping on young almond trees (Appendix III)

In this project we evaluated a range of girdling techniques in terms of timing and severity, to increase yields on young almond trees. Despite several attempts, none were routinely effective in increasing yields, but there were long term effects on tree size, similar to the effect one might expect from a growth-controlling rootstock. With more refinement in terms of timing and severity, trunk girdling might be a useful option for growers unable to source growth controlling rootstocks, or who already have young trees in the ground.

Pruning responses of traditional almond cultivars (Appendix IV)

In this project we evaluated four scion varieties, ‘Nonpareil’, ‘Carmel’, ‘Monterey’ and ‘Price’, chosen for their distinctive growth habit, budded on four rootstock varieties, ‘Nemaguard’, ‘Bright’s Hybrid’, ‘Cornerstone’ and

'Garnem', chosen for their vigour rating from medium to high vigour. Low vigour rootstocks were not available for this project. Half of the trees were planted in the traditional form headed back to 90 cm. The remaining trees were planted as unpruned, central leader trees, direct from the nursery, and narrow-pruned 2 years after planting.

Once planted in the orchard, the central leader trees maintained their shape for the first 3 months of growth. However, by the end of the season the basitonic growth habit, typical of almond trees, came into play and it became difficult to distinguish between central leader and control trees. But the benefits of having the structural limbs spread over a longer section of trunk, as with the central leader trees, were still apparent.

The different rootstocks expressed their expected influence over tree vigour, with trees on 'Garnem' and 'Bright's Hybrid' rootstocks being more vigorous than trees on the medium vigour rootstocks 'Nemaguard' and 'Cornerstone'. We also noted that it was easier to maintain a central leader growth habit with the higher vigour rootstocks than with the less vigorous rootstocks.

Yield potential of new cultivars (Appendix V)

Two projects were planted in 2016 to explore a range of new cultivars, tree types and pruning options for the establishment of almond orchards planted at high density. Three tree types were planted in these trials: 1) Control – trees cut back in nursery to 90 cm and all side shoots trimmed to two buds; 2) Central leader – trees planted with a single dominant trunk with multiple side branches; 3) Central leader - bare pole – trees planted with a single dominant trunk but with all side branches cut back to two buds.

Pruning regimes followed at each orchard included a combination of leader-release, dormant and in-season pruning. Leader-release pruning was used to maintain rapid extension of the central leader. Dormant, narrow-pruning was used to produce a narrow, palmette-style of tree. In-season, narrow-pruning to cut back vigorous, unbranched shoots was used to strengthen these shoots prior to cropping in the following season.

High yields on young trees of the new self-fertile cultivars 'Carina' and Shasta® demonstrated the pressures on young trees to support large crops and the need for pruning interventions to develop a stronger fruiting framework. Narrow pruning with a combination of dormant and in-season pruning starting in Year 2, helped mitigate some of these problems.

Tree architecture for future orchards (Appendix VI)

Understanding tree architecture and how trees respond to manipulation is fundamental to orchard system design and intensification. Studies involved working with almond breeders in Australia, California and Spain to access a range of novel genotypes and identify those with architectural features better suited to high density growing systems. The research demonstrated that it is possible, from the growth of 1-year-old trees in the nursery and the development of tree structure and bearing capacity of 2- and 3-year old trees in the orchard, to predict the growth habit and ultimate cropping potential of the mature tree.

An expected outcome from the research will be a set of architectural traits that breeders can use, at an early stage in the breeding cycle, to select/screen for or against in their breeding populations.

A legacy for on-going research

Several new trials testing ideas and concepts from our earlier research were planted in 2018 in Australia and California. These trials are only just starting to come into production. They will be a valuable resource for on-going research and collaboration with local and international researchers. Projects include:

<u>High Density Trial</u>

Here we are testing a model high density system against the more traditional high density blocks planted in Australia. Planted in July 2018, with the cultivars Shasta® and 'Vela' on 'Nemaguard' rootstock, the project is comparing planting densities of 513 (6.5 x 3 m), 769 (6.5 x 2 m), 741 (4.5 x 3 m) and 1,111 trees/ha (4.5 x 2 m). The objective is to grow tall, narrow "slender pyramid" shaped trees with minimal pruning to maintain a 2.0-m wide gap between the rows for machinery access.

<u>Pruning Responses Trial</u>

This study is looking at various tree management systems, starting in the nursery, and followed up in the orchard with different training/pruning methods to produce central leader trees. The project includes five mainstream cultivars ('Nonpareil', 'Maxima', 'Carina', Shasta® and 'Vela') planted in July 2018, at 4.5 x 3 m spacing. A similar project using a different set of cultivars, but the same pruning treatments, was established in California in February 2018.

Architectural Studies

This project is comparing a range of cultivars/genotypes to identify architectural traits suited to high density growing systems. We have 15 genotypes including the six new cultivars released from the University of Adelaide breeding program, as well as other unnamed genotypes identified to have growth habits suited to high density plantings. 'Nonpareil' is the control variety. All trees were planted in July 2018 on 'Garnem' rootstock at 4.5 x 3 m spacing. A similar project using a different set of genotypes from the UC Davis and Burchell Nursery breeding programs was established in California in February 2018. Data are being collected to identify cultivars and genotypes that easily form and maintain a strong central leader growth habit, which we believe is essential to forming the desired tall "slender pyramid" shaped tree.

Outputs

Formal presentations to industry or scientific meetings:

1. Thorp G. AL14007 Almond Productivity: Tree Architecture and Development of New Growing Systems. Invited presentation to 5th Australian Almond Research & Development Forum, Loxton, 30 October 2019.
2. Thorp G. Tree architecture and high density growing systems. Invited presentation to the 18th Australian Almond Conference in Melbourne, 1 November 2018.
3. Thorp G. Almond productivity – tree architecture and advanced production systems. Presentation to the ABA Production Research Committee, Mildura, 29 August 2018.
4. Thorp G. High density almond orchards – progress from down under. Invited presentation to the Almond Board of California (ABC) Annual Conference in Sacramento CA, 5 December 2017.
5. Thorp G, Traeger D, Smith A, Jenkins B, White N and Gradziel T. Using scion architecture of one-year-old budded trees as a guide to optimise almond orchard systems design using central leader trees. Presentation to ISHS VII International Symposium on Almonds and Pistachios in Adelaide, 5–9 November 2017.
6. Thorp G, Traeger D, Smith A, Jenkins B, Barnett A, van den Dijssel C, Périé E, Blattmann M, Snelgar P, Stanley J, Tustin. Use of pruning and reflective ground covers to improve light management in high density almond orchards. Presentation to ISHS VII International Symposium on Almonds and Pistachios in Adelaide, 5–9 November 2017.
7. Thorp G. Almond productivity – tree architecture and advanced production systems. Invited presentation to Almondco Australia Ltd growers in Virginia, 4 October 2017.
8. Thorp G. Almond productivity – tree architecture and advanced production systems. Invited presentation to Almond Growers of Australia Workshop in Renmark, 3 October 2017.
9. Thorp G. Almond: Tree architecture and development of new growing systems … what has and hasn't worked. Invited presentation to the Almond Board of California in Modesto CA, 2 May 2017.
10. Thorp G. Transforming almond orchards – tree architecture and advanced production systems. Presentation to the Almond Board of California (ABC) Annual Conference in Sacramento CA, 7 December 2016.
11. Thorp G. Transforming almond orchards – tree architecture and advanced production systems. Presentation to the Almond Board of California (ABC) Business Meeting in Modesto CA, 5 December 2016.
12. Thorp G. Transforming almond orchards – tree architecture and advanced production systems. Presentation to the 17th Australian Almond Conference in Melbourne, 10 November 2016.
13. Thorp G and White N. Using scion architecture of one-year-old budded trees as a guide to optimise almond orchard systems design. Presentation to XI International Symposium on Integrating Canopy, Rootstock and Environmental Physiology in Orchard Systems Bologna, Italy, 28 August – 2 September 2016
14. Thorp G and Granger A. Almond tree architecture: development of advanced production systems - mid-term review. Presentation to Almond Board of Australia's Advanced Production Systems Workshop in Adelaide, 19 May 2016.
15. Thorp G and Granger A. Investigating almond tree architecture for new growing systems. Presentation to Almond Board of Australia's Activated Almond R&D Forum, Renmark, October 2015 (presented by Brett Rosenzweig).

Conference Proceedings and Posters:

1. Thorp G and Smith A. Tree architecture – important traits for new almond varieties. Poster prepared for Almond Board of California (ABC) Annual Conference in Sacramento CA, 10–12 December 2019.
2. Thorp G. Tree Architecture and Development of New Growing Systems. Poster prepared for Almond Board of California (ABC) Annual Conference in Sacramento CA, 4–6 December 2018.
3. Thorp G. Transforming almond orchards – tree architecture and advanced production systems. Poster prepared for Almond Board of California (ABC) Annual Conference in Sacramento CA, 5–7 December 2017.
4. Thorp G, Traeger D, Smith A, Jenkins B, White N and Gradziel T. Using scion architecture of one-year-old budded trees as a guide to optimise almond orchard systems design using central leader trees. Proceedings ISHS VII International Symposium on Almonds and Pistachios in Adelaide, 5–9 November 2017.
5. Thorp G, Traeger D, Smith A, Jenkins B, Barnett A, van den Dijssel C, Périé E, Blattmann M, Snelgar P, Stanley J, Tustin. Use of pruning and reflective ground covers to improve light management in high density almond orchards. Proceedings ISHS VII International Symposium on Almonds and Pistachios in Adelaide, 5–9 November 2017.
6. Thorp G. "Transforming almond orchards – tree architecture and advanced production systems". Poster prepared for Almond Board of California (ABC) Annual Conference in Sacramento CA, 5–7 December 2016.
7. Thorp G and White N. Using scion architecture of one-year-old budded trees as a guide to optimise almond orchard systems design. Proceedings XI International Symposium on Integrating Canopy, Rootstock and Environmental Physiology in Orchard Systems Bologna, Italy, 28 August – 2 September 2016.

Popular articles in industry journals:

1. Thorp G. 2017. Unravelling tree architecture. PMA Produce Plus, Winter, 25: 68.
2. Thorp G, Granger A. 2015. Progress on the great Australian almond challenge. Australian Tree Crop, December: 14-15.

Client and Technical Reports (excluding Hort Innovation Project AL14007 Milestone Reports):

1. Thorp G, Smith A, Coates M, December 2019. Tree architecture and development of new growing systems. A Plant & Food Research report prepared for the Almond Board of California. Client Project No. 17-HORT30-Thorp. PFR SPTS No. 18937.
2. Thorp G. October 2019. Tree Architecture and Development of New Growing Systems. A Plant & Food Research report prepared for: Almond Board of California. Milestone No. 82995. Contract No. 34294. Job code: P/415081/01. SPTS No. 18719.
3. Thorp G December 2018. Tree architecture and development of new growing systems. Project No: 18-HORT30-Thorp. Almond Board of California, 2018.2019 Research Update: p27.
4. Thorp G, Smith A, Coates M, Hedderley D, Wirthensohn M. July 2018. Tree Architecture and Development of New Growing Systems. A Plant & Food Research report prepared for: Almond Board of California. Milestone No. 73933. Contract No. 34294. Job code: P/415081/01. SPTS No. 16739.
5. Thorp G, Brar G. December 2017. Tree architecture and development of new growing systems. Almond Board of California Research Update 2017: 29.
6. Thorp G. July 2017. Tree architecture and development of new growing systems: report to the Almond Board of California, July 2017. A Plant & Food Research report prepared for: Almond Board of California. Milestone No. 72268. Contract No. 34294. Job code: P/415081/01. SPTS No. 15249.

Note: a full list of project related conferences and meetings is included in Appendix VII

Outcomes

This project has contributed to the debate around orchard intensification for the almond industry. Almond growers rely on economies of scale with large plantings, relatively cheap land and long cropping cycles of more than 25 years before orchards are replanted. The orchards are highly mechanised and maintaining low labour costs is an imperative. One of the key challenges for growers, therefore, is how to increase productivity without increasing input costs. In this project we evaluated a low cost pruning system to produce trees with more light-efficient, narrower canopies that, with minimal additional cost, would increase orchard productivity.

The ambition was to "double yields but without increasing costs". Obviously this was a significant challenge, but one that has been achieved for other crops such as apple and kiwifruit. Successful outcomes from the research would be strong engagement by growers and researchers, both locally and internationally, to assist their respective industries make the transition to more intensive growing systems; and greater demand from industry for breeders will seek new cultivars with architectural traits compatible with orchard intensification. These new cultivars will naturally form narrow, upright tree canopies, providing the right fruiting platform for high productivity, with low cost, in high density orchards. An additional outcome would be for orchard machinery manufacturers to redesign equipment to suit these new orchards.

While the above outcomes are all long-term, in the short term we have developed a pilot model system for intensification of almond orchards. Based on trees planted in rows 4.5-m wide, with 2.0 m between trees along the rows, the model system will allow for trees to grow to 5.0 m tall and still be suitable for shake harvesting. The background research to this model started by working with existing orchards and growing systems with large, wide trees. It soon became obvious that we needed trees to have narrower canopies, with a clear gap between trees across the rows, to be able to increase yields without creating problems with mixed-maturities.

A key strength of the research was that new trials were planted using different combinations of scion cultivars and rootstocks, including new highly productive self-fertile cultivars recently released from breeding programs in Australia and California. New growing concepts were tested, including working with central leader trees planted at high density, and narrow-pruned to eliminate any branches that, if left, would ultimately become large scaffold branches growing into the centre of the rows. An important outcome was that we demonstrated a single round of narrow pruning to trees at the end of the second year's growth was sufficient to maintain narrower canopies for the 4-year duration of this project. This pruning did not reduce tree yields, meaning that yield per canopy volume was higher. Data showed that narrow-pruned trees intercepted less light than control trees, meaning there is definitely room to increase light interception and orchard yields with narrow-pruned trees planted closer together in 5-m wide rows.

Precocity, or the cropping potential of young almond trees, can have a negative effect on tree structure as high yields can cause the collapse of young fruiting canopies. The risk of tree collapse is especially evident with the new high yielding almond cultivars. While growers may want to sacrifice early yields in order to obtain stronger fruiting canopies, our research demonstrated alternative strategies, including planting central leader trees and intervening with combinations of leader-release pruning on new trees and dormant and in-season pruning of 2- and 3-year-old trees, to help mitigate the risks of over-cropping young trees.

Studies were also completed to describe the deficiencies in current cultivars in terms of tree architecture and what architectural traits are desired for high density growing systems. Almond breeders were the main target of these architectural studies. Our ambition was to encourage a shift in breeding targets to include tree architecture and productivity among current key selection criteria. While shell and kernel quality are important breeding targets for almonds, as are self-fertility and pest and disease tolerance, new cultivars stacked with architectural traits that enable high productivity will enable a step change in productivity and grower profits. Methods were demonstrated that breeders could use to identify positive and negative architectural traits within the first 3 years of tree growth, and so accelerate the breeding process.

Our research relied heavily on strong collaborations with almond breeders and physiologists in Australia, California and Spain, which offered the opportunity to consider a wider array of architectural phenotypes than would otherwise have been possible. A clear difference in approach was identified. While Spanish cultivars rely heavily on strong spur bearing types, the Californian and Australian cultivars tended more towards highly branched individuals. By simply raising awareness of this difference, and encouraging a better understanding of how these differences arose, our research has promoted discussion on how breeders might change selection criteria when choosing breeding parents and when screening large seedling populations.

Monitoring and evaluation

This research program did not have a formal "project reference group". Project monitoring and evaluation was facilitated through regular contact with Hort Innovation and ABA staff, senior consultants and growers in Australia and overseas. The program mid-term review was undertaken via a series of project review meetings with key collaborators, including ABA staff, growers, consultants and nurseries. Project outcomes were augmented through regular participation in industry events in Australia and overseas, with results presented at 78 project related conferences and meetings with growers, nurseries, consultants, researchers and industry peak body staff, and via 15 formal presentations to workshops, industry conferences and scientific symposia.

A constant challenge with the research was availability of suitable plant material for new trials. Each year, for various reasons that were not always under the control of the nurseries, a different calibre of plant was available for planting. While we consistently sought spring-budded, central leader trees at a minimum standard 1.6 m height, there were years when supply of budwood and rootstocks were delayed. This delay meant that trees were not budded until later in summer, and were well below the desired height and trunk diameter going into winter. A positive outcome from this was that we were forced to consider a wider range of tree types than previously considered. This of course is a reality for growers too. Delaying planting by a year while waiting for a new set of trees is not an option. If growers only had small trees available for planting, then they effectively became the nursery and expended significant time and cost pruning and training these small trees to develop a large tree during the first summer. This scenario basically rules out the option for growers to have central leader trees, as recommended from our research. An alternative option demonstrated to growers was to plant dormant budded trees, with a sleeping eye bud, that is forced to grow during spring to form a central leader tree, with no additional cost. This example of flexible and pragmatic project management ensured the continual improvement of the program and was key to the project moving forward and delivering quality outcomes for Hort Innovation and the Australian almond industry.

The cost of tree establishment was a constant source of concern in these projects. Standard systems with stakes and ties are expensive to install and remove, and can damage the trunks of trees leading to limb breakage and whole tree collapse. They were not compatible with central leader trees. Once again we were forced to develop systems that would be workable with the new tree types that we were promoting. The solution we found was to use 3.0 m long, 22–25 mm diameter bamboo stakes with plastic ribbon ties. These stakes were easily pushed by hand into the newly prepared soil. Once attached to the tree, the stakes provided sufficient support for the trees to withstand the constant very strong winds experienced in the Riverland and elsewhere in SE Australia. Importantly, the stakes were flexible allowing the tree to move with the wind and thus make the trees stronger. This is another example of the science project being able to work around issues and find practical solutions for industry.

The research program remained relevant and up to date with the latest developments overseas, largely because of the very strong collaborations formed with industry partners and the international almond science community. In Australia we worked closely with Dr Michelle Wirthensohn, who is Program Leader of the National Almond Breeding and Evaluation Program. Strategic links with international researchers and industry meant we could also establish research trials offshore, in parallel with similar projects in Australia, effectively having two seasons in one year. We established a strong and active collaboration with the Almond Board of California (ABC) who provided funding for research trials in California, including a high-density trial block in Fowler comparing pruning responses and tree architecture of a range of standard and new almond cultivars. The trials also included a range of advanced genotypes from the UC Davis and Burchell breeding programs led by Dr Tom Gradziel and Tom Burchell, respectively. This was important as many of the standard and new cultivars in these trials were also included in our Australian research, so the new knowledge gained in California was directly relevant to our trials in Australia and to Australian almond growers. In Spain, we collaborated with Dr Maria Rubio Cabetas at CITA in Aragón, where her interests are the selection of new almond cultivars and rootstocks and the study of genetic and physiological processes affecting tree architecture and productivity. We also collaborated with IRTA in Catalonia, Spain, mainly with Dr Ignasi Batlle at Mas Bové, who heads their almond breeding program, and with Dr Xavier Miarnau at Lleida who is a researcher and consultant on high density growing systems for almond.

These international collaborations were enhanced by members of the research team attending and presenting research results at international symposia and conferences, all of which provided continuous critical appraisal and validation of our research program objectives and outcomes. The task now is to build on this current program to develop a new suite of projects that will continue to deliver value for the Australian almond industry.

Recommendations

We recommend that Hort Innovation and the ABA continue to support the following projects and activities:

Traditional orchards:

1. Planting of central leader trees, available direct from the nursery, as a means to produce stronger, more wind resistant trees with lower establishment costs
2. Optimising the use of dormant budded trees as a cheap and effective solution for growers to establish central leader trees
3. Use of narrow pruning 2-year-old trees to produce more light efficient canopies and enable closer row spacing
4. Optimising dormant and in-season pruning to help stabilise and strengthen fruiting canopies, especially with highly precocious and productive new cultivars
5. Long-term studies on trunk girdling as a means to control tree growth, as an alternative or in addition to growth controlling rootstocks.

Future high density orchards:

6. Detailed scientific studies on almond tree architecture and the opportunities for industry to set new production targets through orchard intensification
7. The effect of orchard intensification on orchard micro-climate and uniformity of crop maturation
8. Support the development of orchard machinery adapted to new intensive growing systems, including use of shake and catch harvest technology and on-farm hulling and drying
9. Promote architecture as a primary selection trait by breeders to deliver cultivars that will provide the tree structure and fruiting framework able to produce and support the high yields needed to obtain a step change in orchard yields and grower profits

Collaboration:

10. Continue to promote strong collaboration among international almond research groups
11. Continue to encourage strong collaboration between Australian almond research groups at Plant & Food Research, SARDI, Agriculture Victoria and The University of Adelaide
12. Support collaboration between almond researchers and the National Tree Genomics program (AS18000), to develop genomic prediction tools to accelerate the breeding pipeline for new cultivars with architectural traits associated with high productivity and orchard intensification.

Refereed scientific publications

The following papers are being prepared for submission to scientific journals:

Thorp G, Smith A, Traeger D, Jenkins B, Coates M, Granger A, van den Dijssel C, Barnett A, Blattmann M, Périé E, Mangin V, Snelgar P, Tustin S, Stanley J, Hedderley D, Wirthensohn M, Kolesik J and Brown B. Selective limb removal pruning and use of reflective ground covers to improve light distribution within 'Nonpareil' almond trees.

Thorp G, Smith A, Traeger D, Jenkins B, Coates M, Granger A, van den Dijssel C, Barnett A, Blattmann M, Périé E, Mangin V, Snelgar P, Tustin S, Stanley J and Hedderley D. Effect of narrow-pruned canopies on seasonal light interception and yield of 'Nonpareil' almond trees.

Thorp G, Smith A, Traeger D, Jenkins B, Coates M, Granger A, Barnett A, Blattmann M, Périé E, Mangin V, Snelgar P, Hedderley D, Roberts K and Slaughter J. Use of trunk girdling to promote flowering and increase cropping on young almond trees

Thorp G, Smith A, Traeger D, Jenkins B, Coates M, Granger A, Barnett A, Blattmann M, Mangin V, Snelgar P, Tustin S, Stanley J, Hedderley D, Kennedy J, Brown B. Pruning responses of almond cultivars budded on medium- and high-vigour rootstocks

Thorp G, Smith A, Traeger D, Coates M, Barnett A, Blattmann M, Mangin V, Tustin S, Stanley J, Hedderley D and Brown B. Yield potential of narrow-pruned almond trees

Thorp G, Smith A, Coates M, White N, Hedderley D, Wirthensohn M, Gradziel T, Lampinen B, Brar G, Slaughter J and Roberts K. Almond tree architecture – assisting breeders to redesign almond trees for future orchards

Intellectual property, commercialisation and confidentiality

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

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Appendices

APPENDIX I	Selective limb removal pruning and use of reflective ground covers to improve light distribution within ‘Nonpareil’ almond trees
APPENDIX II	Effect of narrow-pruned canopies on seasonal light interception and yield of ‘Nonpareil’ almond trees
APPENDIX III	Use of trunk girdling to promote flowering and increase cropping on young almond trees
APPENDIX IV	Pruning responses of almond cultivars budded on medium- and high-vigour rootstocks
APPENDIX V	Yield potential of narrow-pruned almond trees
APPENDIX VI	Almond tree architecture – assisting breeders to redesign almond trees for future orchards
APPENDIX VII	Project related conferences and meetings

APPENDIX I. Selective limb removal pruning and use of reflective ground covers to improve light distribution within 'Nonpareil' almond trees

Introduction

With traditional almond orchards, trees are spring- or winter-budded in the nursery and planted in the field as 1- or 2-year-old trees with a single trunk which is cut back to a strong lateral bud at approximately 90 cm above the bud union. This pruning stimulates growth of several strong scaffold branches that, with no or minimal pruning, quickly produce a large and spreading fruiting canopy. Trees are generally planted at relatively wide spacing between and within rows, for example 7 x 4.25 m spacing respectively (336 trees/ha), to allow room for the establishment of these large trees.

Growers are well aware that this current management system and planting distance are not optimal for light interception and cropping performance. Fruit bud development depends on good exposure to sunlight. The internal shading within these large trees means that the buds and spurs in the lower and centre of the canopies becoming non-viable and there is a gradual movement of fruiting zones from the lower to upper canopy zones as trees age.

More recently growers have experimented with closer planting distances, for example 6 x 3 m spacing (556 trees/ha). While this results in higher yields earlier in the life of the orchard, simply because there are more trees per ha, the end result is that the tree canopies become crowded earlier in the life of the orchard without any yield benefit in the longer term.

In this project we wanted to provide growers with options to better manage existing trees planted at higher densities. Previous research in California, following traditional approaches used in the stonefruit industry, aimed to establish trees with an open-vase structure and thus increase the amount of light passing through to the lower canopy zones. Experience has been that these approaches, when applied to almonds, did not provide any yield benefit over the long-term. We did not want to repeat that approach here.

With the current management systems for almonds, large trees develop an inverted pyramid structure forming a closed canopy across the top of the trees. It is the "shoulders" at the tops of these trees that help create the closed canopies and that shade the lower canopy zones of trees, including those of trees in adjacent rows. Our treatments used selective limb removal pruning to remove the large scaffold branches that create these shoulders. To accentuate this effect we also used reflective ground covers installed beneath the trees to reflect light back into the lower canopy zones. Our objective was to increase total tree yield over the longer term by increasing yields in the lower canopy zones.

Materials and methods

The research was established in 2014 at Orchard 1 at Lindsay Point in the Riverland region of Victoria, using 'Nonpareil' trees planted in 2009 on 'Nemaguard' rootstock at 6 x 3 m spacing (556 trees per ha).

Treatments were applied to blocks of six trees, with each block randomised in a complete block design and each treatment repeated once per row across seven rows to give seven replicates per treatment. Each 'Nonpareil' treatment row was separated on each side by one polliniser row ('Monterey' and 'Carmel') and one 'Nonpareil' row as guards, so 'Nonpareil' treatment trees were in every 5th row. Unless otherwise indicated, data were collected from the two central trees in each treatment block (14 trees per treatment) and the average value for each pair of trees used in data analysis (n=7).

Three treatments were applied:

1. No pruning
2. Pruned
3. Pruned + reflective ground covers

Winter pruning treatments were applied once in July 2014 (before flowering). This involved removing one or two of the largest branches forming the shoulders or widest points on each side of the trees (Figures 1 and 2). This pruning treatment was applied to the ‘Nonpareil’ trees as well as the adjacent ‘Monterey’ and ‘Carmel’ trees. Winter pruning treatments were reviewed during July 2015 and any additional cuts required were made. This involved the removal of just one or two additional branches from the occasional tree.

Reflective ground covers were installed in August 2014 (after flowering) beneath the ‘Nonpareil’ treatment trees. The covers were 5.0 m wide, sufficient to cover the inter-row space leaving a 1.0 m wide strip along the rows under the trees. The covers were removed after harvest and re-installed each year in spring (before flowering).

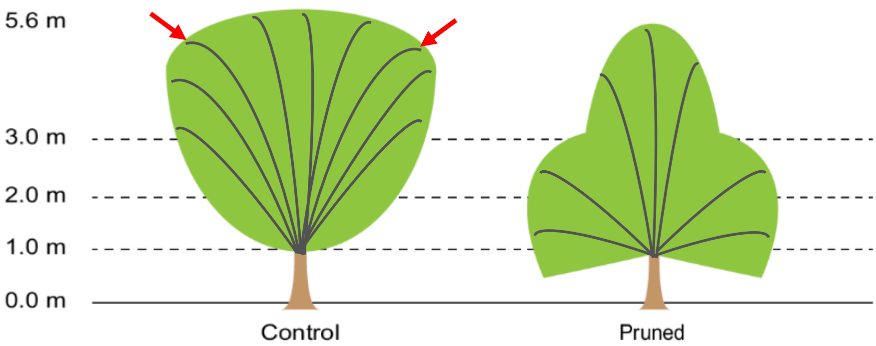

Figure 1. Schematic diagram describing selective limb removal pruning used to improve light distribution and cropping of ‘Nonpareil’ almonds. Arrows indicate location of branches removed during pruning. The pruning created a more open, spreading canopy as each year’s crop developed.

Figure 2. Selective limb removal pruning of ‘Nonpareil’ almond trees in July 2014 at Orchard 1. Trees were planted in 2009. The objective of the pruning was to remove one or two of the largest branches forming the shoulders or widest points on each side of the trees to improve light distribution within trees and reduce shading between trees.

Total yield and kernel quality

Yield and kernel quality data were collected over four successive years (2015, 2016, 2017 and 2018). The crops were machine harvested in February of each year and the total fresh weight per tree recorded. A 2.0 kg subsample was then taken from the harvested crop for hulling and shelling to provide an approximately 100 g subsample of kernels. The moisture content of this subsample was determined using a Burrows DMC-750 moisture meter and this information used to adjust the total kernel yield data to kg of kernel at 5.0% moisture content. Yields per ha were calculated at the planting density for the orchard (6 x 3 m, 556 trees/ha).

In 2015, fruit from the canopy zones 0 – 1.0, 1.0 – 2.0 and 2.0 – 3.0 m above the ground were harvested by hand from three trees each of the control and pruned + reflective covers treatments (n=3). Trees were divided into four sectors, NE, SW, SE and NW, and data combined to give an average value for each canopy zone. In 2017 and 2018, fruit were hand harvested from the lower canopy of each of the pruned + reflective covers treatment trees (n=7) up to a height of 2.5 m. In each year, hand harvests were done separately to the machine harvests so we could compare fruit from the lower hand-harvested zones with the shake-harvested fruit from the upper canopy.

In 2015, 2016 and 2017, a subsample of kernels from the lower and upper canopy zones of control and pruned + reflective covers trees were taken for vitamin E (tocopherols) and lipid analyses. Kernels were dried then ground to a fine powder prior to analysis by The University of Adelaide, using standard methods as described by Zhu et al. 2018 (Effect of enhanced solar UV radiation on almond (*Prunus dulcis*) tocopherols and fatty acids. Acta Hort 1219, 143-150).

Flowering and shoot growth

It was not feasible to record flowering in all canopy zones of these large almond trees so in winter we identified and tagged 2-year-old branches (eight branches per tree) in the lower canopy zone (0 to 2.0 m high) and counted the number of flowers on these branches in spring. The counts were made in July 2015 after budbreak (green tip) and before flower opening, when it was possible to distinguish between dormant, vegetative and floral buds. While not representative of the whole tree flower load, these branches did represent the potential fruiting wood in the lower parts of the tree canopies which we expected would be the wood most likely to show a response to improved light environment. The criteria for selecting the 2-year-old branches were that they had a basal diameter of approx. 1.0 cm, and they had not been damaged or pruned.

Additional measurements included an estimate of the number of "green" 1-year-old shoots in the canopies. A rating system was developed for this purpose:

0	zero green (1yr) shoots present, only spurs
1	≤ 10 green shoots, no water shoots (> 8.0mm basal diameter)
2	> 10 green shoots and 0 to 1 water shoots
3	> 10 green shoots and >1 water shoots

*Light interception (*2015)

<u>Spot measurements:</u>

Within-canopy light transmission data were collected in February 2015 and 2017 (before harvest) from three replicate trees for each of the control and the pruned + reflective ground cover treatments. Data were collected at solar noon (± 1 hour) using Li-Cor® LI-190 photosynthetically active radiation (PAR) quantum sensors placed in different zones (NE, SE, SW and NW) and heights (0.5, 1.5, 2.5 and 4.0 m) within the tree canopies. Within each zone the PAR sensors were placed

0.75 m away from the trunk along the row and 1.5 m away from the trunk between rows. Sensors were placed facing up to record incoming radiation and down to record the amount of light reflected into the canopy from the reflective ground covers. A reference sensor was placed above the canopies to record total incoming light. Data were an average of ten replicate readings made at each sampling location, and combined from the NE, SW, SE and NW sectors of each tree to give an average value for each canopy zone.

Fixed array:

Within-canopy light transmission data were logged continuously from 17 to 18 February 2015 using PAR quantum sensors in a fixed array. Data were collected from two replicate trees for each of the control and the winter prune + reflective ground cover treatments. PAR sensors were attached to steel rods in a fixed array of 16 sensors per tree, in the NE, SE, SW and NW sectors of each tree and at 0.5, 1.5, 2.5 m heights within the tree canopies. Within each zone (sector) the PAR sensors were placed 0.75 m away from the trunk along the row and 1.5 m away from the trunk between rows. In the NE and SW sectors, one sensor at 1.5 m high was placed facing up to record incoming radiation and one facing down to record the amount of light reflected into the canopy from the reflective ground covers. Additional sensors were placed facing up at 4.3 and 6.3 m directly above the trunk to give a total of 16 sensors per tree. Data collected from the NE, SW, SE and NW sectors of each tree were combined to give an average value for each canopy zone. Data are presented as average PPFD (µmol/m2/s) for the day, average % light transmission and the daily light integral (DLI) which is the total amount of light (PPFD) received in a single day at a particular location, expressed as moles of light per square meter per day (mol/m2/d). Total incoming radiation for the day is reported as total incoming DLI.

Statistical analyses:

Yield data were collected from the centre two trees in each group of six trees, with seven replicates per treatment (n = 7) for the control, pruned and pruned + reflective covers treatments. Light interception data using spot measurements or fixed arrays, as well as yield and kernel quality data, were collected from the upper and lower canopy of either two or three of the control and pruned + reflective covers treatment trees. Analyses were completed using analysis of variance with Minitab® v18.1. Mean separation was undertaken by the Tukey-Kramer method. Percentage data were arcsin transformed for analysis and then back-transformed for presentation.

Results and discussion

Total yield per tree

In the first 2 years of this trial we did not record significant differences in yield among our treatments (Table 1). We may have expected to find a yield reduction in summer 2015 in response to the winter 2014 selective limb removal pruning treatments, as these removed approximately 25% of the canopy, but it appeared the trees were able to compensate for this and still set a good crop.

The 2016 season turned out to be quite remarkable, with all trees producing exceptionally high yields when trees were in their 7th leaf, with 5.6 to 5.8 t/ha across our treatments. This compares with the current industry standard of 3 to 4 t/ha, clearly showing the early yield advantage when trees are planted at high density at a spacing of 6 x 3 m compared with the standard spacing of 7 x 4.25 m.

These high yields in 2016 were unexpected and were most likely the result of a favourable growing season, with similar high yields harvested that year from neighbouring orchards. So the question was, would these previous high yields be followed by low yields and would our treatments be able to offset these lower yields? We were not surprised then that yields were substantially lower on the control trees in 2017 and 2018 than in 2016, with 4.3 and 4.1 t/ha harvested in 2017 and 2018, respectively, compared with 5.6 t/ha in 2016. However, the grower had also responded to the high yields in 2016 and had come through in the following winter to mechanically prune all of the trees to create a small gap between the trees along the rows. This may have reduced the amount of fruiting wood and thus yields in the subsequent seasons.

Table 1. Fresh weight of whole fruit (hull + shell + kernel) at harvest, kernel moisture concentration and kernel yield per tree and per ha of 'Nonpareil' almond trees over 4 years in response to selective limb removal pruning and reflective ground cover treatments compared with unpruned control trees at Orchard 1. Trees were planted in 2009 and treatments applied in July 2014. Values are tree averages ± SE (n=7). Significance: NS = not significant; * = p<0.05; ** = p<0.01.

Treatment (Year/Tree age)	2015 6th leaf	2016 7th leaf	2017 8th leaf	2018 9th leaf
Fresh weight (kg/tree)				
Control	30.9 ± 2.2	31.1 ± 2.3	22.9 ± 1.1	22.9 ± 0.8 b
Pruned	28.5 ± 1.2	31.1 ± 1.0	21.0 ± 0.7	21.5 ± 1.2 b
Pruned + reflective covers	31.5 ± 2.8	30.4 ± 2.1	24.0 ± 1.0	28.1 ± 1.9 a
Significance	*NS*	*NS*	*NS*	**
p-value	*0.582*	*0.950*	*0.107*	*0.006*
Kernel moisture (%)				
Control	6.9 ± 0.7	4.9 ± 0.3	5.1 ± 0.7	4.3 ± 0.07
Pruned	6.8 ± 0.6	4.4 ± 0.2	4.7 ± 0.5	4.2 ± 0.06
Pruned + reflective covers	5.8 ± 0.2	4.7 ± 0.1	4.7 ± 0.4	4.2 ± 0.04
Significance	*NS*	*NS*	*NS*	*NS*
p-value	*0.252*	*0.306*	*0.803*	*0.198*
Kernel weight (kg/tree)[a]				
Control	4.5 ± 0.3	10.1 ± 0.8	7.6 ± 0.3 ab	7.3 ± 0.2 ab
Pruned	4.4 ± 0.3	10.4 ± 0.7	6.7 ± 0.3 b	6.9 ± 0.5 b
Pruned + reflective covers	5.4 ± 0.6	10.3 ± 0.9	8.2 ± 0.3 a	8.5 ± 0.6 a
Significance	*NS*	*NS*	*	*
p-value	*0.251*	*0.960*	*0.016*	*0.048*
Kernel weight (t/ha)[a,b]				
Control	2.6 ± 0.2	5.6 ± 0.4	4.3 ± 0.2 ab	4.1 ± 0.1 ab
Pruned	2.5 ± 0.2	5.8 ± 0.5	3.8 ± 0.2 b	3.8 ± 0.3 b
Pruned + reflective covers	3.1 ± 0.4	5.7 ± 0.5	4.6 ± 0.2 a	4.7 ± 0.3 a
Significance	*NS*	*NS*	*	*
p-value	*0.251*	*0.960*	*0.016*	*0.048*

[a] Adjusted to 5.0 % moisture content
[b] Based on 566 trees/ha (6.0 x 3.0 m spacing)

Although in our treatments, the trees that we pruned had less crop (p<0.05) than the pruned + reflective ground cover treatment trees in 2017 and 2018, the control trees were intermediate in yield and not significantly different from either treatment. These data could indicate lower yields on the pruned compared with the unpruned control trees that the use of reflective ground covers was able to mitigate. But as mentioned, these results could have been compromised by the mechanical pruning undertaken by the grower.

Note that the unusually high whole fruit fresh weight and kernel moisture values recorded at harvest in 2015 compared with subsequent years were a result of the crop being harvested relatively green/immature with high moisture content in 2015.

Flowering and shoot growth

We found no consistent difference in flower numbers per branch on the treated compared with the untreated control trees in spring 2015 (Table 2). Additional measurements included an estimate of the number of green 1-year-old shoots in the canopies which could become fruiting wood. These data showed more new shoot growth had been produced in the lower canopy zones of treated trees than of control trees.

Table 2. Number of flowers on selected 2-year-old branches and relative presence of green shoots on 'Nonpareil' almond trees at Orchard 1 in March 2015 in response to selective limb removal pruning and reflective ground cover treatments. Trees were planted in 2009 and treatments applied in July 2014. Values are tree averages ± SE (n = 7). Significance: * = p<0.05; *** = p<0.001.

Treatment	No. of flowers per 2-year-old branch	Presence of green 1-year-old shoots[a]
Control	46 ± 4	0.7 ± 0.1
Pruned + reflective covers	48 ± 6	2.0 ± 0.2
Significance	*NS*	***
p-value	*0.696*	*<0.001*

[a] Rating scale to record presence of one-year-old "green" shoots: 0 = zero green (1yr) shoots present, only spurs; 1 = ≤ 10 green shoots, no "water shoots" > 8.0mm basal diameter; 2 = > 10 green shoots and 0 to 1 "water shoots"; 3 = > 10 green shoots and >1 "water shoots"

Light interception, kernel yield and quality within canopy zones

Light distribution was improved within the canopies of trees that had been pruned and had reflective ground covers installed in the previous year. Light transmission through to the lower canopy zones was consistently higher in the treated than non-treated control trees when recorded at solar noon or when logged continuously over a 24-h period, before harvest in 2015 (Tables 3 and 4). And as expected the use of reflective ground covers increased light interception recorded by PAR quantum sensors placed facing down in the lower canopy zones.

Table 3. Photosynthetic photon flux density (PPFD) and % light transmission at different canopy zones on 'Nonpareil' almond trees at Orchard 1 in response to selective limb removal pruning and reflective ground cover treatments. Trees were planted in 2009 and treatments applied in July 2014. Data were collected at solar noon (± 1 hour) on 15 November 2015 using photosynthetically active radiation (PAR) quantum sensors. Average incoming radiation (PPFD) was 1859 µmol/m²/s. Values are canopy zone averages (n = 3). Significance: NS = not significant; (*) = p<0.10; * = p<0.05.

Treatment:		Canopy zone[a] 0 – 1.0 m	1.0 – 2.0 m	2.0 – 3.0 m
		PPFD (µmol/m²/s) (% light transmission in brackets)		
		(sensors facing up)		
Control		212 (11%)	187 (10%)	546 (30%)
Pruned + reflective covers		298 (16%)	416 (22%)	761 (41%)
	Significance	*NS*	*(*)*	*
	p-value	*0.426*	*0.060*	*0.047*
		(sensors facing down)		
Control		35 (2%)	32 (2%)	43 (2%)
Pruned + reflective covers		236 (13%)	179 (10%)	129 (7%)
	Significance	*	*(*)*	*NS*
	p-value	*0.048*	*0.059*	*0.105*

[a] Height above ground. PAR sensors placed at the mid-point for each zone (0.5, 1.5 and 2.5 m above ground)

Table 4. Photosynthetic photon flux density (PPFD), % light transmission and daily light integral (DLI) into different canopy zones of 'Nonpareil' almond trees at Orchard 1 in February 2015 in response to selective limb removal pruning and reflective ground cover treatments. Trees were planted in 2009 and treatments applied in July 2014. Data were logged continuously for 24 h using a fixed array of photosynthetically active radiation (PAR) quantum sensors located at different heights within the tree canopies. Average daily incoming radiation (PPFD) was 1017 µmol/m²/s and total incoming DLI was 56 mol/m²/d. Values are canopy zone averages for 24 h (n = 2).

Treatment	Canopy zone[a] 0.5 m	1.5 m	2.5 m	4.0 m
	PPFD (µmol/m²/s) (% light transmission in brackets)			
	(sensors facing up)			
Control	62 (6.6%)	50 (5.2%)	154 (16.5%)	131 (13.9%)
Pruned + reflective covers	72 (6.7%)	74 (6.9%)	248 (23.1%)	277 (25.8%)
	(sensors facing down)			
Control	-	7 (0.7%)	-	-
Pruned + reflective covers	-	47 (4.5%)	-	-
	Daily light integral (mol/m²/d)			
	(sensors facing up)			
Control	3.4	2.7	12.1	13.4
Pruned + reflective covers	3.8	3.8	9.5	8.5
	(sensors facing down)			
Control	-	1.0	-	-
Pruned + reflective covers	-	1.9	-	-

[a] Height above ground. PAR sensors placed at the mid-point for each zone (0.5, 1.5, 2.5 and 4.0 m above ground)

Very few kernels were produced in the 0 to 1.0 m canopy zone in 2015, with only two of the treated trees producing significant quantities in this zone (Table 5). However, there was clearly a shift in production of kernels from the upper to the lower canopy zones in the treated trees that had been pruned during winter and had reflective ground covers installed in spring. This probably reflected the difference in the amount of new fruiting wood produced in the lower canopy of the treated trees (Table 2). There were more fruit in the 1.0 to 2.0 m canopy zone on the treated trees than the control trees (1.29 and 0.72 kg, respectively); while the opposite was the case for the 2.0 to 3.0 m canopy zone where there were more kernels harvested from the untreated control trees than from the treated trees (1.89 and 3.2 kg, respectively; Table 5). On average, 18% of the crop harvested between 0 and 3.0 m high was produced in the 1.0 to 2.0 m zone of untreated control trees compared with 39% for the treated trees. This meant that 81% of the harvested crop was produced further up the tree, in the 2.0 to 3.0 m canopy zone on the control trees compared with 58% on the treated trees. Overall, however, total tree yields in 2015 were similar for the control and treated trees, so while our treatments were able to increase yields in the lower canopy zones this did not increase total tree yield (Table 1).

In 2017 and 2018 the fruit from the lower canopy zones were harvested separately from the upper canopy on the control and pruned + reflective ground cover treatment trees. The trees were approximately 6 to 7 m tall and we defined the lower canopy zone as between 0 and 2.5 m high. As with 2015, there were clear treatment effects, with more than twice as much crop produced in the lower canopy of treated trees, compared with control trees (Table 6). This additional crop in the lower canopy zone of trees in 2017 and 2018 represented approximately 10% of the total crop, but as in 2015, it was not sufficient to contribute to an increase in total yield compared with the control trees (Table 1).

Table 5. Yield of kernel harvested from different canopy zones on 'Nonpareil' almond trees at Orchard 1 in March 2015 in response to selective limb removal pruning and reflective ground cover treatments. Trees were planted in 2009 and treatments applied in July 2014. Values are canopy zone averages ± SE (n = 3). Significance: NS = not significant; (*) = p<0.10; ** = p<0.01; *** = p<0.001.

	Canopy zone[a]		
Treatment	**0 – 1.0 m**	**1.0 – 2.0 m**	**2.0 – 3.0 m**
	Kernel (kg) at 5.0% moisture content		
Control	0.013 ± 0.01	0.716 ± 0.10	3.196 ± 0.44
Pruned + reflective covers	0.100 ± 0.05	1.286 ± 0.19	1.889 ± 0.19
Significance	*NS*	*(*)*	*(*)*
p-value	*0.175*	*0.059*	*0.053*
	% of kernels in each canopy zone		
Control	0.3 ± 0.2	18.2 ± 2.5	81.4 ± 11.2
Pruned + reflective covers	2.5 ± 1.3	32.8 ± 4.9	48.1 ± 4.9
Significance	*NS*	*(*)*	*(*)*
p-value	*0.175*	*0.061*	*0.069*

[a] Height above ground

Table 6. Fresh weight of whole fruit (hull + shell + kernel) at harvest, kernel moisture concentration and kernel yield per tree and per ha of 'Nonpareil' almonds harvested from the lower canopy zone (0 to 2.5 m) of trees at Orchard 1 in response to selective limb removal pruning and reflective ground cover treatments. Data were collected in 2017 and 2018 Trees were planted in 2009 and treatments applied in July 2014. Values are tree averages ± SE (n=7). Significance: NS = not significant; * = p<0.05; ** = p<0.01; *** = p<0.001.

2017 (8th leaf) Treatment	Fresh weight (kg/tree)	Kernel moisture (%)	Kernel weight (kg/tree)[a]	Kernel weight (t/ha)[a,b]
Control	1.27 ± 0.2	16.3 ± 1.7	0.33 ± 0.02	0.18 ± 0.01
Pruned + reflective covers	2.81 ± 0.5	8.7 ± 1.7	0.81 ± 0.09	0.45 ± 0.05
Significance	**	**	***	***
p-value	*0.010*	*0.008*	*<0.001*	*<0.001*
2018 (9th leaf) **Treatment**				
Control	1.08 ± 0.28	25.3 ± 0.6	0.24 ± 0.06	0.14 ± 0.03
Pruned + reflective covers	4.17 ± 1.06	24.5 ± 1.1	0.92 ± 0.20	0.52 ± 0.11
Significance	*	NS	**	**
p-value	*0.016*	*0.585*	*0.006*	*0.006*

[a] Adjusted to 5.0 % moisture content
[b] Based on 566 trees/ha (6.0 x 3.0 m spacing)

Of concern, however, was that fruit in the lower canopy of the trees were much later maturing, with higher kernel moisture concentration at harvest, than the main crop on these trees (Figure 3). In 2017, the main crop in the upper canopy of trees had 5.1 and 4.7% moisture concentration at harvest for the control and treated trees, respectively, compared with 16.3 and 8.7% for fruit from the lower canopy of these trees (Table 1 and 6, Figure 3). So the lower canopy of the control trees had less crop with later maturing fruit while on the treatment trees the lower canopy had more crop with earlier maturing fruit. This difference in maturity between the main crop in the upper canopy and the lower canopy fruit was not a consequence of later flowering in the lower canopy (field observation) but is possibly a consequence of less air movement with higher humidity and lower temperatures in the lower canopy of these closely planted trees.

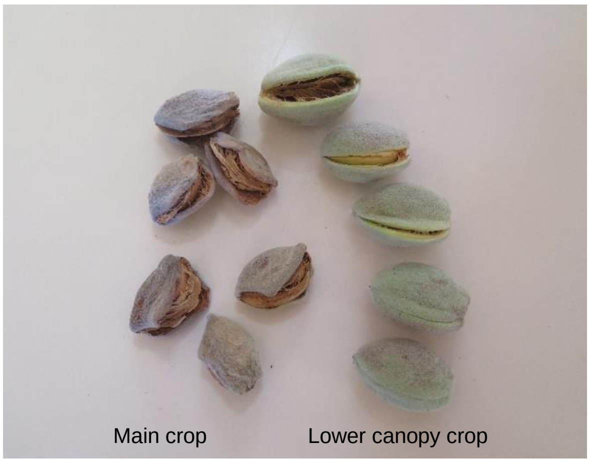

Figure 3. Selective limb removal pruning and use of reflective ground covers increased the number of fruit produced in the lower canopies of 'Nonpareil' almond trees but these fruit were later maturing by up to 3 weeks compared with the main crop produced near the tops of the trees.

Kernel quality

Almonds are a good source of vitamin E and lipids with a high proportion of unsaturated fatty acids, mainly oleic and linoleic acid. In this project we did not find a consistent relationship between the total lipids in kernels from the upper and lower canopy zones (Table 7). In the 2015 whole tree samples and the 2017 lower canopy samples there were more total lipids in kernels from the control than the pruned + reflective covers treatment trees. In 2016, total lipids were similar across all treatments and canopy zones. The vitamin E content of kernels was similar across all years, canopy zones and treatments. Kernels from the pruned + reflective covers treatment trees tended to have more oleic acid and less linoleic acid, than kernels from the control trees. We found similar relationships with more oleic acid and less linoleic acid in kernels from the upper canopy zones where there is more light than from the shaded lower canopy zones (Tables 3 and 4). Our samples for vitamin E and lipid analyses were taken from combined samples harvested from within the different sectors and canopy zones. Light interception as a percentage of incoming radiation was generally low within these locations (Tables 3 and 4) which may have limited the differences in vitamin E and lipid concentrations we recorded between the different sampling locations, even with the reflective ground covers.

Table 7. Oil and vitamin E concentrations in the kernels of 'Nonpareil' almonds harvested from the lower canopy zone (0 to 2.5 m) of trees at Orchard 1 in response to selective limb removal pruning and reflective ground cover treatments. Data were collected in 2017 and 2018; Trees were planted in 2009 and treatments applied in July 2014. Values are tree averages ± SE (n=7). Significance: NS = not significant; * = p<0.05; ** = p<0.01; *** = p<0.001.

Year	Harvest	Treatment	Oil (lipids) (%)	Vitamin E (mg/100g oil)	Oleic Acid (% oil)	Linoleic Acid (% oil)
2015	**Whole canopy**	**Control**	49.8 ± 0.5	46.2 ± 2.2	60.7 ± 0.3	29.0 ± 0.5
		Pruned + reflective covers	48.7 ± 0.3	47.8 ± 2.0	61.9 ± 0.2	27.8 ± 0.3
		Significance	*	*NS*	*(*)*	*(*)*
		p-value	*0.050*	*0.618*	*0.087*	*0.065*
2016	**Lower canopy**	**Control**	50.0 ± 0.6	33.8 ± 1.3	62.9 ± 0.8 b	26.8 ± 0.7 a
		Pruned + reflective covers	51.0 ± 1.5	34.5 ± 1.5	63.2 ± 0.5 ab	26.7 ± 0.5 ab
	Upper canopy	**Control**	49.4 ± 0.8	31.1 ± 1.2	64.0 ± 0.4 ab	25.7 ± 0.3 ab
		Pruned + reflective covers	48.5 ± 0.7	32.9 ± 2.5	64.7 ± 0.2 a	25.1 ± 0.2 b
		Significance	*NS*	*NS*	*(*)*	*
		p-value	*0.349*	*0.556*	*0.079*	*0.048*
	Lower canopy	**Treatments combined**	50.5 ± 0.8	34.1 ± 1.0	63.0 ± 0.5	26.7 ± 0.4
	Upper canopy	**Treatments combined**	48.9 ± 0.6	32.0 ± 1.4	64.3 ± 0.2	25.4 ± 0.2
		Significance	*NS*	*NS*	*	**
		p-value	*0.120*	*0.219*	*0.015*	*0.007*
2017	**Lower canopy**	**Control**	51.8 ± 0.4 b	38.1 ± 1.2	66.2 ± 0.7	23.9 ± 0.7
		Pruned + reflective covers	50.4 ± 0.3 c	35.8 ± 1.6	67.3 ± 0.3	22.9 ± 0.3
	Upper canopy	**Control**	52.9 ± 0.3 ab	38.9 ± 1.1	66.8 ± 0.3	22.9 ± 0.3
		Pruned + reflective covers	53.8 ± 0.3 a	39.3 ± 0.7	66.6 ± 0.3	23.1 ± 0.3
		Significance	***	*NS*	*NS*	*NS*
		p-value	*0.000*	*0.162*	*0.370*	*0.239*

Concluding comments

Data collected over four consecutive years, from 6th to 9th leaf trees, demonstrate issues with high-density blocks where trees are planted at 6 x 3 m spacing and using standard management protocols. Significant treatment effects were expected in 2017 and 2018 because the increased proportion of direct and reflected sunlight recorded in the lower canopy zones during previous seasons had produced substantial new fruiting wood on our treatment trees. However, some of this wood was removed during a round of mechanical pruning in the block in winter 2016, to provide access for orchard machinery.

The shift in production from upper to lower canopy zones in the pruned trees with reflective ground covers was also a consequence of a gradual change in tree shape from a more upright to a more spreading canopy as the weight of the growing fruit dragged down the major bearing limbs (Figure 1). This effect was exaggerated on the pruned trees as these trees had fewer limbs and thus less opportunity for the limbs to become self-supporting. It was this growth response, with the wider canopies, that encouraged the grower to mechanically prune the trees.

Even though our treatments were able to increase kernel yield in the lower canopy zones of trees, the crops produced in these zones were later to mature than the main crop fruit at the tops of the trees. Observations in spring 2017 confirmed that flowering was not delayed in the lower compared with upper canopy zones. This suggests that environmental factors during the growing season, possibly low temperatures and/or high humidity, were contributing to delayed fruit maturation in the lower canopy. It would be interesting to install temperature and humidity sensors in the lower and upper canopy zones to further investigate this.

This situation with overcrowding is a consequence of older almond trees being grown with multiple scaffold branches so that trees inevitably develop a relatively wide, inverted pyramid shape with very poor light transmission to lower canopy zones. This shows the importance of re-designing high-density almond orchards by growing trees with a slender pyramid form to improve light interception and avoid development of a large shaded and barren volume in the centre of each tree canopy. This tree design would potentially produce higher yields with more uniform crop maturity and improved nut quality.

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APPENDIX II. Effect of narrow-pruned canopies on seasonal light interception and yield of 'Nonpareil' almond trees

Introduction

In traditional almond orchards, growers plant trees that have been either spring- or winter-budded in the nursery and then planted in the orchard with a single trunk. This single trunk is headed back at planting to a strong lateral bud at approximately 90 cm above the bud union. Several strong scaffold branches develop in response to this heading cut. With no, or minimal, pruning these branches quickly produce a large and spreading fruiting canopy. Trees are generally planted at wide spacing between and within rows, for example 7 x 4.25 m (336 trees/ha), to allow room for the establishment of these large trees.

More recently growers have experimented with closer planting distances, for example 6 x 3 m spacing (556 trees/ha), to obtain higher yields from young orchards. The risk with these higher density plantings is that the trees become crowded sooner than with traditional planting designs.

Of particular concern when trees become crowded is that large scaffold branches, growing out into the centre of the rows, restrict machinery access for normal orchard operations. These are the large branches that will "tear the windscreens out of tractor cabs". The standard remedy is that once trees become crowded, growers start a program of mechanical hedging to cut the trees back in winter and enable easier access for machinery. This pruning removes a lot of potential fruiting wood and can reduce the productive potential of trees and orchards.

In this project, with 'Nonpareil' trees planted at 6 x 3 m spacing, we investigated the option of earlier intervention pruning to create narrower canopies on young trees, before crowding becomes an issue. Pruning involved removing any branches that, if left, would ultimately become large scaffold branches growing into the centre of the rows and impeding machinery access. Our hypothesis was that these narrow-pruned trees would improve light interception and carbohydrate partitioning to the fruit and thus increase potential yield, compared with traditional growing systems. If successful the technique would be compatible with trees planted in 5 m wide rows with more trees per ha and thus even higher potential orchard yields.

Materials and methods

The project was established in 2014 on young 'Nonpareil' trees, spring-budded in 2011 on 'Nemaguard' seedling rootstock and field-planted in winter 2012 at Lindsay Point in the Riverland region of South Australia (Figure 1). Trees were planted in rows running in an east–west direction, with rows 6 m wide and trees 3 m apart within the rows (556 trees/ha).

Pruning in winter 2014 involved selectively removing any strong branches growing out towards the centre of the rows (Figure 1). This resulted in a narrow ellipsoid or informal palmette-style tree shape compared with the traditional more spherical shape. Treatments were reviewed in winter 2015 at which time it was decided that no additional pruning was required.

The pruning treatment was applied to five blocks of three trees each for pruned and unpruned control trees (total of 15 trees per treatment) in a systematic design with each block of three treatment trees alternating along a single row. The 'Nonpareil' treatment row was separated on each side by one polliniser row ('Monterey' and 'Carmel').

Figure 1. 'Nonpareil' trees planted in 2012 at 6 x 3 m spacing were pruned in winter 2014 to remove any large branches growing out towards the centre of the rows. The selected branches were the ones that if left would ultimately become large scaffold branches that would impede machinery access along the rows. Arrows indicate position of pruning cuts.

Tree dimensions and yield

Tree growth (tree height and canopy width) and kernel yield data were collected over four successive years (2015 – 2018).

Tree height and canopy width across the rows (N–S) and along the rows (E–W) were measured either directly (on young trees) or using digital images analysed with ImageJ software (imagej.nih.gov, v1.52r). Calculations for canopy volume were based on a truncated inverted cone with an elliptic base (https://keisan.casio.com/exec/system/15374075528834).

The crops were machine harvested in February of each year and the total fresh weight per tree recorded. A 2.0 kg subsample was then taken from the harvested crop for hulling and shelling to provide an approximately 100 g subsample of kernels. The moisture content of this subsample was determined using a Burrows DMC-750 moisture meter and this information used to adjust the total kernel yield data to kg of kernel at 5.0% moisture content.

Yields per ha were calculated at the planting density for the orchard (6 x 3 m, 556 trees/ha). Yields from pruned trees were also calculated with 667 trees/ha (5 x 3 m) and compared with the yield of unpruned trees at the standard planting density. This was done on the assumption that the narrow pruning treatment would mean the trees could be planted at the closer spacing.

Light interception

Light interception data were collected in January 2016 and at multiple dates during the 2017 and 2018 seasons, using Li-Cor® LI-190 PAR (photosynthetically active radiation) quantum sensors.

<u>Light bar measurements (January 2016)</u>

Total light interception of trees as a proportion of total incoming radiation was recorded on 12 January 2016 at approximately solar noon (± 1 hour) using an array of PAR quantum sensors placed facing up on a portable device passed in a series of sweeps just above ground level beneath the tree canopies (Table 1; Figure 2). The sweeps were made on each side of the trees in a north/south direction from the middle of the row towards the tree line. With trees 3 m apart and the light bar 1 m long it was possible to make six sweeps per side by starting/finishing at the trunk of the adjacent guard trees (12 sweeps per treatment replicate). Each sweep recorded approximately 10–15 data points which were compared with reference measurements taken at regular intervals in the open sky above the tree canopy. Data are presented as average photosynthetic photon flux density (PPFD; $\mu mol/m^2/s$) and % light interception.

Table 1. List of light interception studies recording seasonal changes in photosynthetic photon flux density (PPFD) in response to pruning treatments applied in 2014 to 'Nonpareil' almond trees planted in 2012. Photosynthetically active radiation (PAR) sensors were placed facing up either in a fixed array for continuous measurements or on a portable device passed in a series of sweeps or a single sweep just above ground level beneath the tree canopies.

				Data capture:			
				Light bar sweeps		Fixed arrays	
Year:	**Date:**	**Season**	**Growth stage:**	**Several sweeps across row**	**Single sweep along row**	**Vertical (in canopy)**	**Horizontal (on ground)**
2016	12-Jan-16	Summer	Fruit maturation	X			
	12 to 26-Jan-16	Summer	Fruit maturation			X	
2017	14-Feb-17	Summer	Fruit maturation	X			
	26-Jul-17	Winter	Dormant				X
	27-Sep-17	Spring	Early fruit growth	X	X		X
	28-Nov-17	Early summer	Kernel fill	X	X		X
2018	30-Jan-18	Summer	Fruit maturation	X	X		X
	22-Mar-18	Late summer	Postharvest	X	X		X

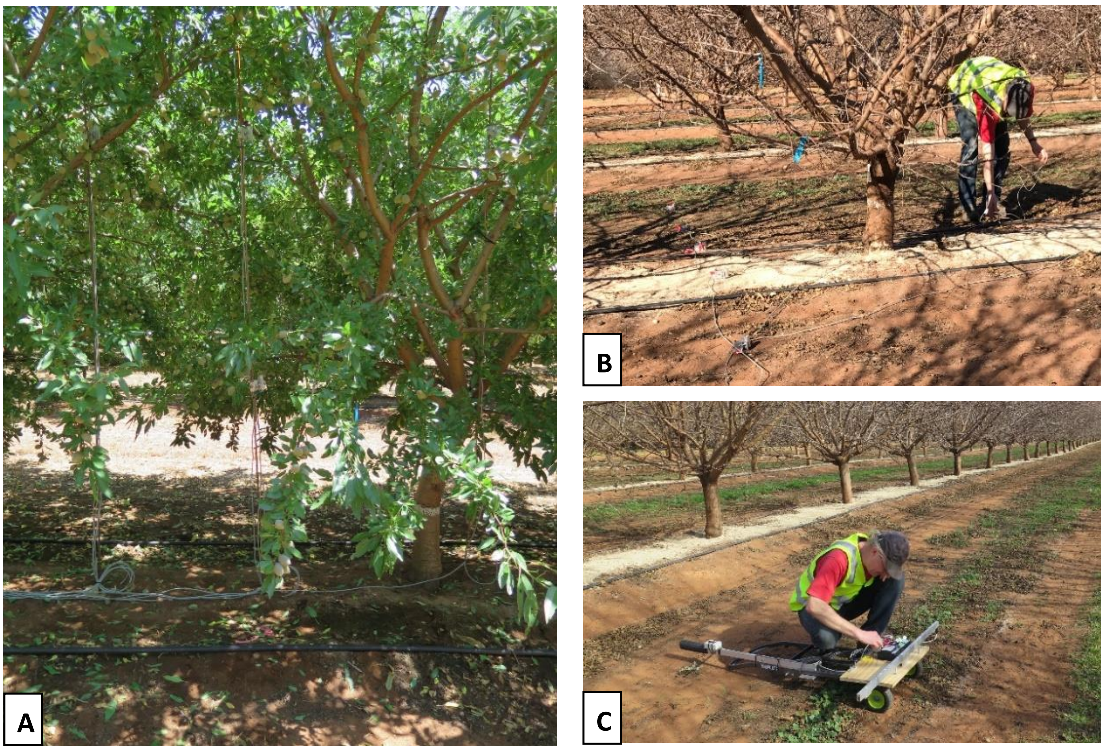


Figure 2. Photosynthetically active radiation (PAR) quantum sensors were used to compare light transmission through pruned and unpruned canopies of 'Nonpareil' almond trees planted in 2012 at 6 x 3 m spacing. PAR sensors were placed facing up attached to steel rods in a fixed array either within the tree canopy (A); placed on the ground beneath the tree (B) for continuous measurements; or on a portable device (C) passed in a series of sweeps beneath the trees.

Fixed array (January 2016)

Within-canopy light transmission for both treatments was measured in January 2016, approximately 1 month before harvest, using PAR quantum sensors placed facing up immediately adjacent to the trunks and at 0.75 and 1.5 m away from the trunks along the rows and at heights of 1, 2, 3 and 5 m above the ground within the tree canopies (Table 1; Figure 2). A reference sensor was placed above the canopies to record total incoming light. PPFD data were logged continuously for 2 weeks, from 12 to 26 January, using Campbell CR1000 data loggers set at 60s intervals. Only complete data sets recorded between sunrise and sunset (www.timeanddate.com) for each day were used in the analyses. Data are presented as average PPFD (µmol/m^2/s) for the day, average % light transmission and the daily light integral (DLI) which is the total amount of light (PPFD) received in a single day at a particular location, expressed as moles of light per square meter per day (mol/m^2/d). Total incoming radiation for the day is reported as total incoming DLI.

Light bar measurements (2017 and 2018)

Light interception was recorded at approximately solar noon (± 1 hour) on 14 February, 27 September and 28 November 2017 and on 30 January and 22 March 2018, using an array of PAR quantum sensors placed facing up on a portable device passed in a series of sweeps just above ground level beneath the canopies of each data tree (Table 1). In the first instance, the sweeps were made on the south side of the trees in a south/north direction from the middle of the row towards the tree line. With trees 3 m apart and the light bar 1 m long it was possible to make three sweeps per tree with each sweep recording approximately 10–15 data points. In the second instance a single sweep was run along the rows, also on the south side of each tree, 1.5 to 2.5 m out from the tree. Each sweep was 3 m long and recorded approximately 30–38 data points. Data are presented as average PPFD (µmol/m^2/s) and % light interception.

Fixed array (2017 and 2018)

Light interception was measured on five dates (26 July, 27 September and 28 November 2017 and 30 January and 22 March 2018), using PAR quantum sensors placed on the ground in a north/south line running at right angles to the row, 1 m out from the trunk on the eastern side of each data tree (Table 1; Figure 2). The first sensor was in the middle of the row (3.2 m out from the trunk) and then at 2 and 1 m out from the trunk on both the north and south sides of the trees. A final sensor was placed in line with the trunk to give a total of seven sensors per tree. A single sensor was placed above the tree canopies to record total incoming radiation. At each date, PPFD data were logged continuously over the 24-h period using CR1000 data loggers set at 60-s intervals. Only data recorded between sunrise and sunset (www.timeanddate.com) were used in the analyses. Data are presented as average PPFD (µmol/m^2/s) for the day, average % light interception and DLI (mol/m^2/d).

Statistical analyses

Tree dimensions and yield data were collected from the centre tree in each group of three trees (n = 5). Light interception and transmission data were collected from either four or five of the treatment replicates, as indicated previously. Analyses were completed using analysis of variance with Minitab® v18.1 with mean separation by Tukey's pairwise comparison method with $p \leq 0.05$. Year to year ANOVA comparisons were blocked by tree results. Percentage data were arcsin transformed for analysis and then back-transformed for presentation.

Results and discussion

Tree dimensions

The pruning treatments did not affect tree height but as expected the pruned trees were narrower by up to 1.2 m. This meant total canopy volume was also less on the pruned than the unpruned trees (Figures 3 & 4, Table 2). The effect of a single round of our narrow-pruning treatment in 2014 was still apparent in 2018. By 2017 the control trees were 5.6 m wide compared with 4.8 m for the pruned trees. This difference was slightly reduced in 2018 because during winter 2017 the grower had mechanically pruned the lower branches on all trees with an angled undercut.

Figure 3. 'Nonpareil' almond trees planted in 2012 at 6 x 3 m spacing were narrow-pruned in 2014, removing large branches growing out into the centres of the rows. The effects of this pruning treatment were still apparent in 2016 (left) and 2018 (right). The three trees in the foreground were narrow-pruned, the trees further along the row were not pruned.

Note that the measurements of canopy diameter were taken at the margins of the leaf canopy and did not take into account the location of any large scaffold branches growing out into the rows. These large branches were badly damaged by the harvesting equipment in 2017, hence the need for the mechanical prune in the subsequent winter. No damage was observed on the trees pruned in 2014 so it appeared that this single round of pruning in 2014 was able to contain the growth of the trees without further pruning and without impeding machinery access until at least 2019.

It was also noticeable that the mechanical pruning in winter 2017 was more severe on the large scaffold branches remaining on the unpruned control trees, than on the finer branches remaining on the pruned trees. These heavier cuts will stimulate more vegetative growth and thus will require more pruning in future years than will be required for the finer branches on narrow-pruned trees.

The overall impression was that the narrow-pruned trees would provide sufficient room for machinery access, including harvesters, in blocks planted with rows 5 m wide, however this still needs to be tested.

Seasonal changes in canopy diameter across the rows were recorded during the 2017/18 growing season. Pruned trees were always narrower than unpruned control trees, and trees tended to become wider (more spreading) during the middle part of the growing season as fruit matured and the weight of the crop became heavier (Table 3). Trees recovered and became narrower after harvest, once the crop had been removed.

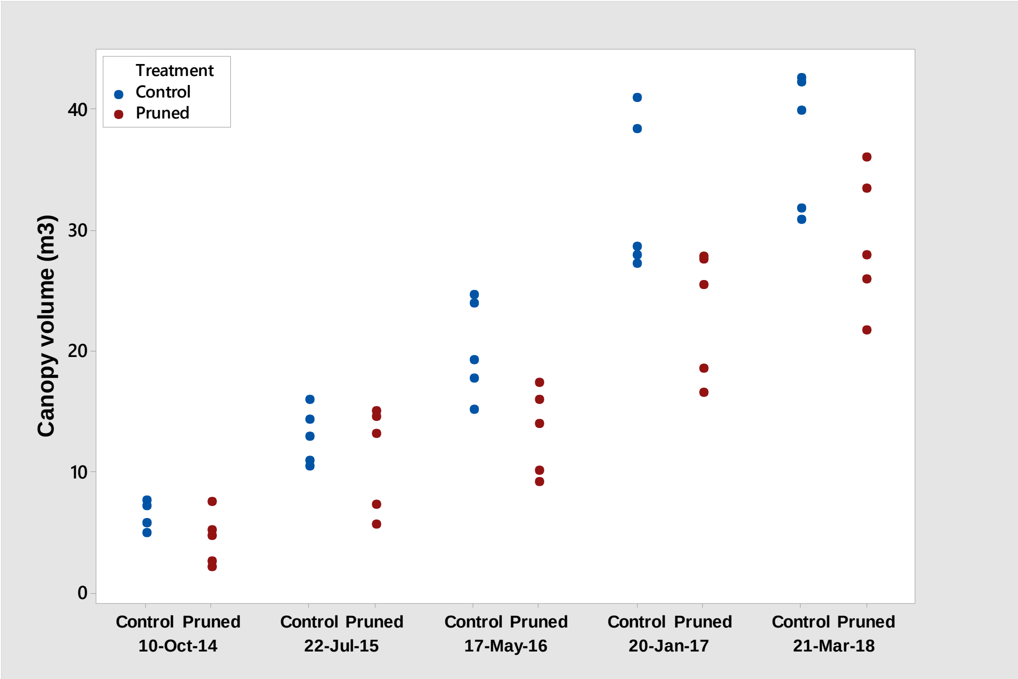


Figure 4. Canopy volume over 5 years, of 'Nonpareil' almond trees planted in 2012 and left unpruned (control) or narrow-pruned in 2014. Each data point represents data from a single tree.

Table 2. Tree height, width of leaf canopy across rows and canopy volume of 'Nonpareil' almond trees planted in 2012 at 6 x 3 m spacing and narrow-pruned in 2014, compared with unpruned control trees. Data were collected over 4 years. Values are treatment means ± SE (n = 5 trees per treatment). Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; * = p<0.05; ** = p<0.01; *** = p<0.001. Year to year ANOVA blocked by tree results.

	Tree height (m)				Tree canopy diameter - across the row (m)				Tree canopy volume (m^3)[a]			
Treatment:	**Control**	**Pruned**	*Significance*	*p-value*	**Control**	**Pruned**	*Significance*	*p-value*	**Control**	**Pruned**	*Significance*	*p-value*
Date:												
10 Oct 2014	3.4 ± 0.07 d	3.3 ± 0.12 d	*NS*	*0.592*	2.7 ± 0.10 d	2.0 ± 0.20 d	*	*0.012*	6.2 ± 0.5 e	4.4 ± 1.0 d	*NS*	*0.135*
22 Jul 2015	4.4 ± 0.08 c	4.5 ± 0.11 c	*NS*	*0.908*	3.6 ± 0.16 c	2.9 ± 0.19 c	*	*0.018*	12.9 ± 1.0 d	11.1 ± 2.0 c	*NS*	*0.440*
17 May 2016	4.6 ± 0.24 c	4.5 ± 0.09 c	*NS*	*0.510*	4.8 ± 0.16 b	3.7 ± 0.22 b	**	*0.003*	20.1 ± 1.8 c	13.3 ± 1.6 c	*	*0.022*
20 Jan 2017	5.2 ± 0.12 b	5.0 ± 0.06 b	*NS*	*0.343*	5.6 ± 0.15 a	4.8 ± 0.16 a	**	*0.005*	32.6 ± 2.9 a	23.2 ± 2.4 b	*	*0.036*
21 Mar 2018	6.0 ± 0.24 a	6.0 ± 0.16 a	*NS*	*0.873*	5.5 ± 0.23 a	4.9 ± 0.07 a	*	*0.042*	37.4 ± 2.6 a	29.0 ± 2.6 a	*	*0.049*
Significance	***	***			***	***			***	***		
p-value	*<0.001*	*<0.001*			*<0.001*	*<0.001*			*<0.001*	*<0.001*		

[a] *Calculations for canopy volume were based on a truncated inverted cone with an elliptic base*

Table 3. Canopy diameter (m) across the row during the 2017/18 growing season of 'Nonpareil' almond trees planted in 2012 and narrow-pruned in 2014, compared with unpruned control trees. Trees were planted in 6 m wide rows in an east–west direction with trees 3 m apart within the rows. Data were collected over the 2017 /18 growing season. Values are tree averages ± SE (n = 5 trees per treatment). Values in each column followed by the same lower-case letters were not significantly different. Significance: * = p<0.05; ** = p<0.01.

		Tree canopy diameter, m (across the row)			
	Treatment:	**Control**	**Pruned**	*Significance*	*p-value*
Date:	**Growth stage:**				
9 Aug 2017	Dormant	5.58 ± 0.15 ab	4.74 ± 0.16 b	**	*0.005*
26 Sep 2017	Fruit growth	6.10 ± 0.16 ab	5.22 ± 0.12 ab	**	*0.002*
29 Nov 2017	Kernel fill	6.17 ± 0.16 a	5.30 ± 0.14 a	**	*0.003*
13 Feb 2018	Fruit maturation	5.99 ± 0.15 ab	5.24 ± 0.05 a	**	*0.002*
21 Mar 2018	Postharvest	5.52 ± 0.23 b	4.94 ± 0.07 b	*	*0.042*
	Significance	*	*		
	p-value	*0.040*	*0.011*		

Kernel yield:

Although a small crop was produced in 2015, the first year after trees were pruned, the first commercial crop was not harvested until 2016 (Figure 5, Table 4). Although not statistically significantly different (p=0.179 in 2016), there were consistent differences in yield of kernel (kg/tree) harvested over the 3 years from 2016 to 2018, with the pruned trees tending to have less crop than the unpruned control trees. More treatment replication with more trees may have shown these differences to be significant.

Although yield per tree may have been less on the pruned trees, the canopies of narrow-pruned trees were smaller than the unpruned control trees (Table 2, Figure 4). This meant that cropping efficiency, in terms of yield of kernel vs canopy volume (g/m^3), was higher for the pruned than the unpruned control trees (Figure 5, Table 5). At least this was the case in 2016 and 2017. The difference was not apparent in 2018, probably because of the mechanical prune undertaken by the grower in winter 2017.

All trees in this trial block and adjacent blocks with older trees produced unusually high yields in 2016 (Table 4, Figure 5). This was probably a consequence of a favourable growing season, however, it may have had a negative impact on canopy growth and cropping in the following season as cropping efficiency peaked in 2016 and dropped away in subsequent years (Table 5, Figure 5).

Field observations also indicated that the narrow-pruned trees produced less fruit in the lower canopy zones than the unpruned control trees, as a consequence of poor shoot development and lack of new fruiting wood in the lower canopy of the pruned trees (Figure 3). A slight change in pruning style, by heading back instead of complete removal of the selected shoots, might be sufficient to encourage more fruiting wood and crop in the lower canopy of narrow-pruned trees. Our initial pruning technique was deliberately targeted to avoid this type of regrowth.

By 2018, the trees in this project were producing 5.1 and 4.5 t/ha of kernel from control and pruned trees, respectively. The estimated yield from narrow-pruned trees planted at 5 x 3 m spacing (667 trees/ha) would have been 5.36 t/ha. These are substantial yields compared to industry averages of 3–4 t/ha and demonstrate the benefits of closer plantings. The narrow-pruned trees have maintained their narrow ellipsoid shape and so are still an option for closer row spacing, for example 5.0 m between rows. We anticipate being able to increase yields beyond 6 t/ha following adjustment to the pruning method as described above.

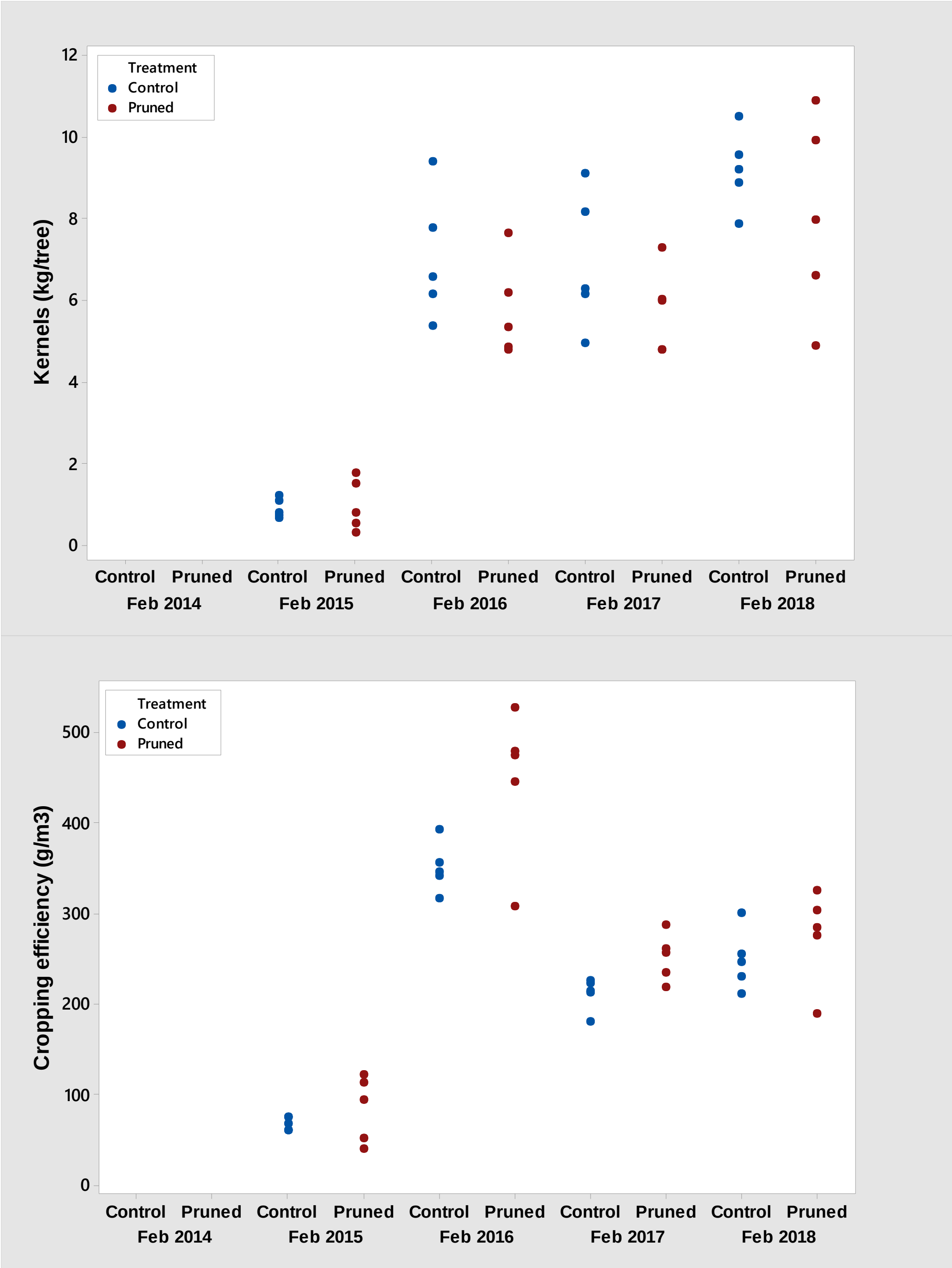


Figure 5. Kernel yield and cropping efficiency (weight of kernel per canopy volume) over 5 years, of 'Nonpareil' almond trees planted in 2012 and left unpruned (control) or narrow-pruned in 2014. Each data point represents data from a single tree. Kernel yield data are adjusted to 5% moisture content.

Table 4. Yield of kernel harvested from 'Nonpareil' almond trees planted in 2012 at 6 x 3 m spacing and narrow-pruned in 2014, compared with unpruned control trees. Yields per ha for control trees were calculated at the planting density for the orchard (6 x 3 m, 556 trees/ha) and compared with yields from narrow-pruned trees at 556 trees/ha and assuming 667 trees/ha (5 x 3 m). Data were collected over 4 years. Values are treatment means ± SE (n = 5 trees per treatment). Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; *** = p<0.001. Year to year ANOVA blocked by tree results.

	Kernel (kg/tree)[a]				Kernel (t/ha)[a] at 6 x 3 m spacing (556 trees/ha)				Kernel (t/ha)[a] at 5 x 3 m spacing (667 trees/ha)			
Treatment:	**Control**	**Pruned**	*Significance*	*p-value*	**Control**	**Pruned**	*Significance*	*p-value*	**Control**	**Pruned**	*Significance*	*p-value*
Date:												
18 Feb 2015	0.9 ± 0.1 c	1.0 ± 0.3 c	*NS*	*0.784*	0.5 ± 0.1 c	0.5 ± 0.2 c	*NS*	*0.784*		0.7 ± 0.2 c	NS	0.456
15 Feb 2016	7.0 ± 0.7 b	5.8 ± 0.5 b	*NS*	*0.179*	3.9 ± 0.4 b	3.2 ± 0.3 b	*NS*	*0.179*		3.8 ± 0.4 b	NS	0.882
28 Feb 2017	6.9 ± 0.8 b	5.8 ± 0.5 b	*NS*	*0.225*	3.8 ± 0.4 b	3.2 ± 0.3 b	*NS*	*0.225*		3.8 ± 0.3 b	NS	0.989
22 Feb 2018	9.2 ± 0.4 a	8.0 ± 1.1 a	*NS*	*0.355*	5.1 ± 0.2 a	4.5 ± 0.6 a	*NS*	*0.355*		5.4 ± 0.7 a	NS	0.746
Significance	***	***			***	***				***		
p-value	*<0.001*	*<0.001*			*<0.001*	*<0.001*				*<0.001*		

[a] Adjusted to 5.0% moisture content

Table 5. Cropping efficiency (yield of kernel vs canopy volume) of 'Nonpareil' almond trees planted in 2012 at 6 x 3 m spacing and narrow-pruned in 2014, compared with unpruned control trees. Values are treatment means ± SE (n = 5 trees per treatment). Data were collected over 4 years. Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; * = p<0.05; *** = p<0.001.

	Kernel[a] (g/m^3 canopy)			
Treatment:	**Control**	**Pruned**	*Significance*	*p-value*
Date:				
18 Feb 2015	68 ± 3 d	84 ± 17 c	*NS*	*0.362*
15 Feb 2016	351 ± 12 a	447 ± 37 a	*	*0.039*
28 Feb 2017	211 ± 8 c	252 ± 12 b	*	*0.022*
22 Feb 2018	249 ± 15 b	276 ± 23 b	*NS*	*0.361*
Significance	***	***		
p-value	*<0.001*	*<0.001*		

[a] Adjusted to 5.0% moisture content

Light interception studies

Fixed array (2016):

This array of PAR quantum sensors was installed on 14 January 2016 and data logged until 27 January 2016. The arrays were arranged vertically at three heights (1, 2 and 3 m high) within the tree canopies and data averaged for each zone (Figure 2). Only complete "full day" data sets collected from 15 to 26 January are presented here.

PAR, light transmission (% of incoming radiation) and daily light integral (DLI) were similar in the 1- and 2-m canopy zones of the narrow-pruned and unpruned control trees, with on average 4.5 and 9.6 % light transmission, respectively (Table 6). However, in the 3 m canopy zone, PAR, light transmission and DLI were higher in the control trees than in the narrow-pruned trees indicating a more open canopy at this zone in control trees compared with the pruned trees. These data were collected in January at a time when the trees were under maximum crop load before the onset of fruit maturation and drying leading up to harvest. This crop load causes the tree canopies to open up as the major limbs bend outwards under the weight of the fruit (Table 3). It would seem that the narrow-pruned trees were less susceptible to this and the branches remained relatively upright.

Table 6. Photosynthetic photon density (PPFD), % light transmission and daily light integral (DLI) in different canopy zones of 'Nonpareil' almond trees planted in 2012 and narrow-pruned in 2014, compared with unpruned control trees. Trees were planted in 6 m wide rows in an east–west direction with trees 3 m apart within the rows. Data were logged continuously for 2 weeks, from 12 to 26 January 2016, using a fixed array of PAR sensors located in different canopy zones. Average daily incoming radiation (PPFD) was 986 µmol/m²/s and total incoming DLI was 50.8 mol/m²/d. Values are canopy zone averages ± SE (n = 4 trees). Significance: NS = not significant; * = p<0.05.

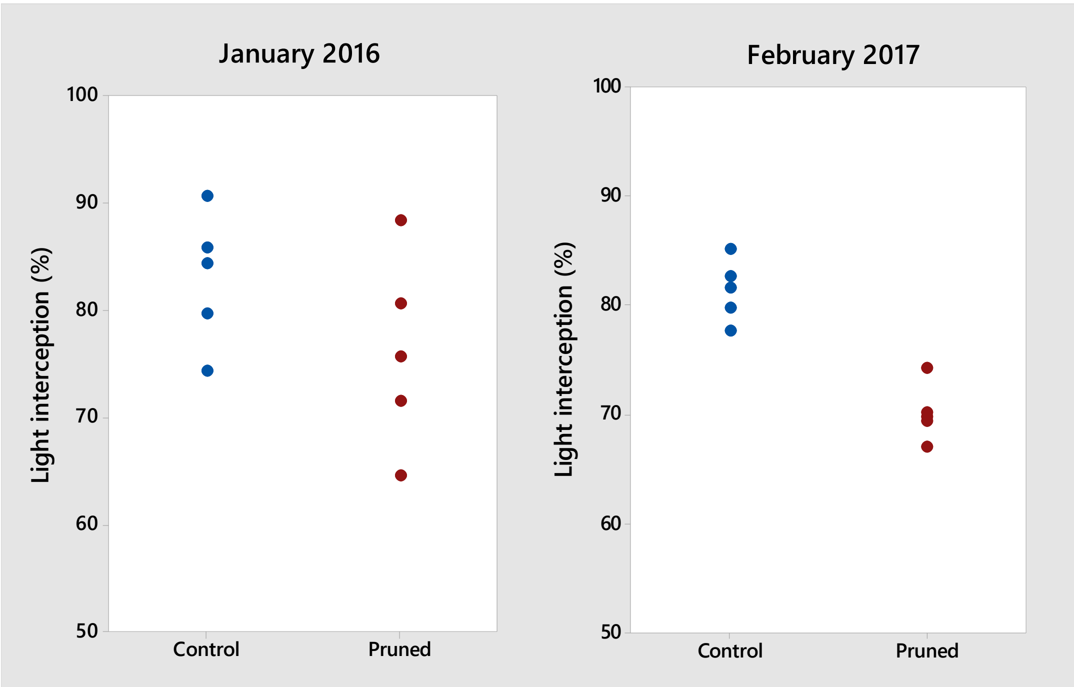
	Canopy zone (height above ground)					
	1 m	**2 m**	**3 m**	**1 m**	**2 m**	**3 m**
Treatment:	**PPFD (µmol/m²/s)[a]**			**Light transmission (% of incoming radiation)**		
Control	43 ± 2.4	97 ± 3.5	453 ± 17	4.4 ± 0.2	9.9 ± 0.2	46.1 ± 1.3
Pruned	45 ± 2.8	91 ± 6.3	262 ± 17	4.6 ± 0.3	9.3 ± 0.6	26.5 ± 1.5
Significance	*NS*	*NS*	*	*NS*	*NS*	*
p-value	*0.888*	*0.800*	*0.028*	*0.860*	*0.804*	*0.025*
Treatment:	**Daily light integral (mol/m²/d)**					
Control	2.25 ± 0.2	5.01 ± 0.30	23.4 ± 2.0			
Pruned	2.33 ± 0.5	4.69 ± 1.10	36.9 ± 3.9			
Significance	*NS*	*NS*	*			
p-value	*0.889*	*0.798*	*0.022*			

[a] PAR quantum sensors in each canopy zone were placed facing up in line with the trunk of the trees 0, 0.75 and 1.5 m away from the trunk.

Light bar measurements (2016)

PAR was recorded at approximately solar noon on 12 January 2016 using a portable device passed in a series of sweeps under the tree canopies (Figure 2B). Although not significantly different, in 2016 the canopies of pruned trees intercepted 76% of incoming radiation compared with 83% for the unpruned control trees (Figure 5). So although the canopies were wider on the control trees than the narrow-pruned trees (4.8 m compared with 3.7 m, respectively; Table 2), total light interception was similar for both sets of trees because the pruned trees intercepted more light (less transmission) in the upper canopy zone compared with the control trees (Table 6). These data once again support the concept that the narrow-pruned trees could have been grown at closer row spacing than the control trees.

It is not clear why there was more variability in light interception between individual trees in 2016 compared with 2017 (Figure 6). It is possible the unusually high crop load on relatively young trees in 2016 compared with 2017 may have been a factor, with the scaffold branches not yet fully developed. Note that the trees were mechanically pruned in winter 2017, so this would not have made a difference to the trees in summer 2017, as presented in Figure 6.



PAR: Control 152 ± 85 Pruned 234 ± 119 P = 0.592	PAR: Control 343 ± 27 Pruned 550 ± 32 P = 0.001
LI (%): Control 83 ± 2.8 Pruned 76 ± 4.1 P = 0.215	LI (%): Control 81 ± 1.3 Pruned 70 ± 1.2 P = 0<0.001

Figure 6. Light interception (LI, % of incoming radiation) and photosynthetic photon flux density (PPFD; µmol/m²/s) of 'Nonpareil' almond trees planted in 2012 and narrow-pruned in 2014, compared with unpruned control trees. Trees were planted in 6 m wide rows in an east–west direction with trees 3 m apart within the rows. Data were collected at approximately solar noon on 12 January 2016 and 14 February 2017 using an array of photosynthetically active radiation (PAR) quantum sensors placed facing up on a portable device passed in a series of sweeps just above ground level beneath the tree canopies. The sweeps were made on each side of the trees in a north–south direction from the middle of the row towards the tree line. Average incoming radiation was 1933 and 1074 µmol/m²/s for 2016 and 2017, respectively. Values are tree averages ± SE (n = 5).

Fixed array (2017 – 2018)

A fixed horizontal array of PAR quantum sensors was used to record light transmission on five dates covering different stages of tree growth from winter 2017 until after harvest in March 2018. The sensors were placed on the ground in a north/south line running at right angles to the row (Figure 2).

Narrow-pruned trees intercepted less light than control trees (Figure 7, Table 7).The amount of light (PAR) recorded beneath trees reached a peak around midday, as expected, with less light passing through the control than the pruned trees. The diurnal variation was most obvious in November, earlier in the growing season, than in September or January, however, the January data were possibly compromised by the conditions on the day of measurement with intermittent cloud cover and thus low PAR and low DLI.

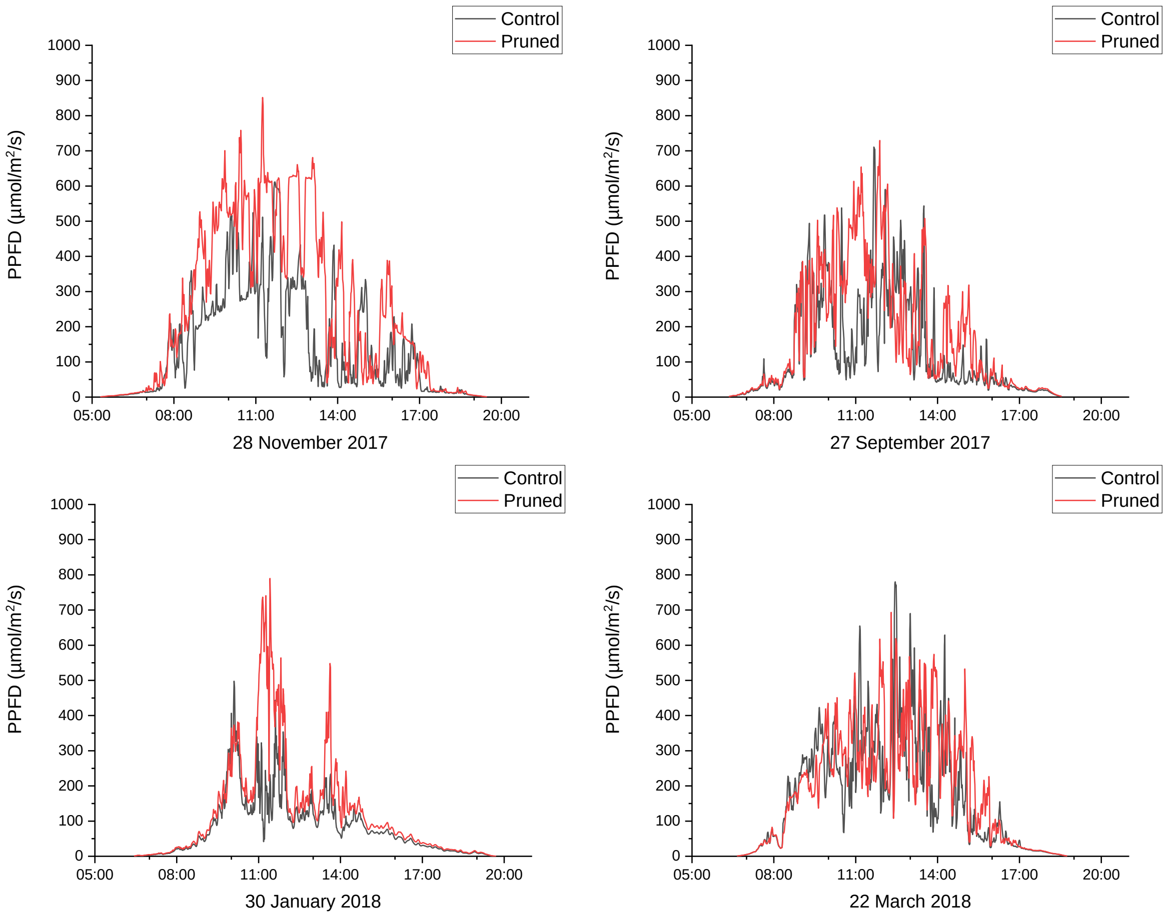


Figure 7. Seasonal changes in daily photosynthetic photon flux density (PPFD, µmol/m^2/s) by canopies of 'Nonpareil' almond trees planted in 2012 and narrow-pruned in 2014, compared with unpruned control trees. Trees were planted in 6 m wide rows in an east–west direction with trees 3 m apart within the rows. A fixed array of photosynthetically active radiation (PAR) sensors was placed on the ground in a north/south line running perpendicular to the row of trees, starting 1 m out from the trunk on the eastern side of each data tree. Values are tree averages (n = 4).

Light interception was obviously higher on the trees once they had developed their leaf canopies, and values tended to increase during the early part of the season and then decreased after harvest. As well as continued canopy growth increasing light interception, the November to January period is when trees develop maximum crop load and leaf canopies are at their widest, with branches bending under the weight of the growing fruit (Table 3). Light interception in March, after harvest, was less than during summer, not only because there was significant loss of leaf during shake harvesting but also because the trees became more upright once the crop was removed.

Data collected in winter (July 2017) when the trees were dormant with no leaf cover showed 53% and 52% light interception by the canopies of narrow-pruned and unpruned control trees, respectively (Table 7). This means the branching framework alone substantially reduced the amount of light passing through the trees. It is not clear how this might influence interpretation of light interception data by leaf canopies collected during spring and summer.

Light bar measurements (2017 – 2018)

Light interception was recorded using a portable light bar with an array of PAR sensors at approximately solar noon during the 2017/18 growing season (Figure 2). The sensors were passed beneath the tree canopies in a series of sweeps across the rows or in a single sweep along the rows.

As with the fixed arrays, data from the multiple sweeps across the rows indicated maximum light interception during January on both the pruned and control trees, with 91% and 92% light interception, respectively (Table 8). Using this method, light interception data were similar between dates in September, November and March, but at each date, light interception was higher on the control than the pruned trees. These data represent the total allocated space for the trees. It is likely that there was more shading from the trunks of the trees with multiple sweeps across the rows as these sweeps ended in line with the trunks; this would have artificially increased light interception values with this method.

Data collected using a single sweep along the rows, on the south (shaded) side of the trees, approximately 2 m out from the trunk of each tree, also showed that light interception was higher on the control than the pruned trees (Table 8). But in contrast to the multiple sweep data, the single sweep data indicated minimum light interception during January, on both the pruned and control trees.

Regardless, at all stages during the season, light interception was highest by the control than the pruned trees, which once again is consistent with the smaller canopy footprint on the narrow-pruned trees.

Table 7. Seasonal changes in photosynthetic photon flux density (PPFD), % light interception and daily light integral (DLI) for canopies of 'Nonpareil' almond trees planted in 2012 and narrow-pruned in 2014, compared with unpruned control trees. Trees were planted in 6 m wide rows in an east–west direction with trees 3 m apart within the rows. A fixed array of photosynthetically active radiation (PAR) quantum sensors were placed on the ground in a north/south line running perpendicular to the row of trees, starting 1 m out from the trunk on the eastern side of each data tree, with one array per tree. Values are tree averages ± SE (n = 4). Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; (*) = p<0.10; * = p<0.05; ** = p<0.01; *** = p<0.001.

		PPFD (μmol/m²/s)[1]				Light interception (% of incoming radiation)			
	Treatment:	**Control**	**Pruned**	*Significance*	*p-value*	**Control**	**Pruned**	*Significance*	*p-value*
Date:	**Growth stage:**								
26 Jul 2017	Dormant	290 ± 9 a	295 ± 10 a	*NS*	*0.685*	53 ± 1.3 c	52 ± 1.3 c	*NS*	*0.834*
27 Sep 2017	Fruit growth	138 ± 10 b	184 ± 4 c	**	*0.005*	87 ± 0.7 ab	83 ± 0.3 ab	**	*0.002*
28 Nov 2017	Kernel fill	137 ± 4 b	230 ± 15 b	**	*0.004*	92 ± 0.6 a	86 ± 1.0 a	**	*0.007*
30 Jan 2018	Fruit maturation	80 ± 4 c	126 ± 7 d	**	*0.001*	90 ± 0.6 a	84 ± 0.7 a	**	*0.001*
22 Mar 2018	Postharvest	160 ± 15 b	200 ± 4 bc	*	*0.041*	84 ± 1.5 b	80 ± 0.3 b	(*)	*0.070*
Significance		***	***			***	***		
p-value		*<0.001*	*<0.001*			*<0.001*	*<0.001*		

		Daily light integral (mol/m²/day)			
	Treatment:	**Control**	**Pruned**	*Significance*	*p-value*
Date:	**Growth stage:**				
27 Sep 2017	Fruit growth	6.08 ± 0.4 a	8.09 ± 0.2	**	*0.005*
28 Nov 2017	Kernel fill	6.81 ± 0.2 a	9.57 ± 1.4	*NS*	*0.122*
30 Jan 2018	Fruit maturation	3.80 ± 0.2 b	7.67 ± 0.6	**	*0.001*
22 Mar 2018	Postharvest	7.00 ± 0.7 a	8.27 ± 0.1	*NS*	*0.103*
Significance		***	*NS*		
p-value		*0.001*	*0.271*		

[1] Average daily incoming radiation (PPFD) was 579, 1038, 1267, 729 and 912 μmol/m²/s and total incoming daily light integral (DLI) was 22, 46, 65, 35 and 40 mol/m²/day for the July, September, November, January and March measurement dates, respectively.

Table 8. Photosynthetic photon flux density (PPFD) and % light interception beneath 'Nonpareil' almond trees planted in 2012 and narrow-pruned in 2014, compared with unpruned control trees. Trees were planted in 6 m wide rows in an east–west direction with trees 3 m apart within the rows. Data were collected using an array of photosynthetically active radiation (PAR) sensors placed on a portable device passed either in a series of sweeps across the rows or in a single sweep along the row, on the south side of trees. Values are tree averages ± SE (n = 5). Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; * = p<0.05; ** = p<0.01; *** = p<0.001.

Multiple sweeps across row		**PPFD, (µmol/m²/s)[1]**				**Light interception (% of incoming radiation)**			
	Treatment:	**Control**	**Pruned**	*Significance*	*p-value*	**Control**	**Pruned**	*Significance*	*p-value*
Date:	**Growth stage:**								
27 Sep 2017	Fruit growth	244 ± 18 ab	390 ± 31 b	**	*0.003*	86 ± 1.0 ab	77 ± 1.8 b	**	*0.003*
28 Nov 2017	Kernel fill	339 ± 53 a	574 ± 18 a	**	*0.003*	84 ± 2.5 b	73 ± 0.9 b	**	*0.003*
30 Jan 2018	Fruit maturation	128 ± 25 b	155 ± 13 c	*NS*	*0.383*	92 ± 1.5 a	91 ± 0.8 a	*NS*	*0.383*
21 Mar 2018	Postharvest	272 ± 27 ab	391 ± 31 b	*	*0.021*	84 ± 1.6 b	77 ± 1.9 b	*	*0.021*
Significance		**	*			***	***		
p-value		*0.007*	*0.019*			*< 0.001*	*< 0.001*		
Single sweep along row		**PPFD (µmol/m²/s)[1]**				**Light interception (% of incoming radiation)**			
	Treatment:	**Control**	**Pruned**	*Significance*	*p-value*	**Control**	**Pruned**	*Significance*	*p-value*
Date:	**Growth stage:**								
27 Sep 2017	Fruit growth	221 ± 42 bc	450 ± 60 ab	*	*0.014*	87 ± 2.4 a	74 ± 3.5 ab	*	*0.014*
28 Nov 2017	Kernel fill	379 ± 76 ab	717 ± 81 a	*	*0.016*	82 ± 3.6 ab	66 ± 3.9 bc	*	*0.016*
30 Jan 2018	Fruit maturation	437 ± 50 a	731 ± 104 a	*	*0.034*	74 ± 3.0 b	56 ± 6.2 c	*	*0.034*
21 Mar 2018	Postharvest	122 ± 7 c	216 ± 33 b	*	*0.022*	93 ± 0.4 a	87 ± 2.0 a	*	*0.023*
Significance		***	***			***	***		
p-value		*0.001*	*<0.001*			*0.001*	*0.001*		

[1] Average incoming radiation (PAR) was 1730, 2100, 1675 and 1668 µmol/m²/s for the September, November, January and March measurement dates, respectively.

Concluding comments

Almonds are not a high value horticultural crop per land area utilised. Growers rely on economies of scale with large plantings, relatively cheap land and long cropping cycles of more than 25 years before orchards are replanted. The orchards are highly mechanised and maintaining low labour costs is an imperative. One of the key challenges for growers, therefore, is how to increase productivity without increasing input costs. In this project we evaluated a low cost pruning system to produce trees with more light-efficient, narrower canopies that, with minimal additional cost, would increase orchard productivity.

Experience from other horticultural crops is that light interception by narrow canopies is more efficient than with larger canopies that have heavy internal shading. Our hypothesis was that narrow-pruned almond trees could be planted closer together, with narrower than traditional rows, and thus obtain higher yields earlier in the life of the orchard. The more efficient narrow canopies could also produce higher orchard yields over the longer term than current traditional growing systems.

While some growers are already experimenting with rows 6 m apart, compared with 7.25 m in traditional blocks, we wanted to investigate the opportunities and issues with managing rows 5 m wide. The trial block was on a commercial orchard and had been planted with 6 m wide rows. We monitored light interception and canopy development in response to narrow pruning to be able to predict what the responses would be in blocks with 5 m wide rows.

The single round of narrow pruning we applied in 2014, at the end of the second year's growth, was sufficient to maintain narrower canopies for the 4-year duration of this project. A most interesting feature was how dynamic the canopies were during the season with trees transitioning from relatively upright canopies to wider, spreading canopies as the branches bent downwards under the weight of the developing fruit. Postharvest, these branches would resume their more upright form. This meant light interception reached a peak in summer, around the time of floral initiation, which could be regarded as a positive feature. But it is also the time when trees are most prone to damage from machinery moving along the rows.

The narrow-pruned trees appeared to remain more upright than the control trees, as indicated by less light transmission and higher DLI at 3 m height in the canopies of the pruned trees compared with the unpruned control trees but not further down in the canopies. With PAR sensors positioned on the ground beneath the trees, data showed that narrow-pruned trees intercepted less light and had higher DLI, especially in January, than control trees. So there was definitely room to increase light interception with narrow-pruned trees planted closer together in 5 m wide rows.

While there was a trend for higher yields on the control than narrow-pruned trees, at no stage over the 4 years were the differences significant. But the narrow-pruned trees were smaller, so in terms of cropping efficiency, in the second and third year of the project the narrow-pruned trees produced more fruit per canopy volume than the control trees. The first year was the first season after pruning, when differences would not be expected, and the fourth year was after the grower had mechanically hedged all trees which may have affected the results.

Overall there were positive indications that a single "one-off" round of narrow-pruning at the end of year 2 would be a viable option with trees planted in 6 m wide rows and even with 5 m rows. Improvements to the narrow-prune method used here would be for growers to use heading cuts to cut back selected branches and thus stimulate the production of new fruiting wood low down in the tree canopies, rather than the flush cuts we used in this current project to totally remove the selected branches (refer Appendices IV and V). The other opportunity is to start with central leader trees, direct from the nursery, as these could require less pruning intervention to maintain a narrow canopy (Appendix IV).

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APPENDIX III. Use of trunk girdling to promote flowering and increase cropping on young almond trees

Introduction

Increasing yields from young trees and thus reducing the time to first commercial harvest is a key target for growers establishing new orchards. With almonds and other nut crops, for a harvest to be considered as commercial, there must be sufficient crop on the trees to warrant the use of mechanical harvesters to collect it.

Trunk girdling, i.e. removing a strip of bark from the trunk of trees, is one technique used in several fruit industries to increase flowering and cropping on young plants. Timing of girdling is critical to obtaining the desired response. Trunk girdles applied in late winter before flowering can increase fruit set, when applied after flowering can increase fruit size, and when applied in mid-summer can increase carbohydrate accumulation and thus the sweetness of fruit. A trunk girdle applied later in summer, at the time of floral initiation, can increase the number of flowers in the subsequent spring. This project evaluated the use of trunk girdling young almond trees on orchards in Australia and California in summer, to increase flowering on trees about to set their first commercial crop.

Materials and methods

Girdling treatments

<u>Orchard 1 (Victoria)</u>

One trunk girdling treatment was applied in December 2014 to young 'Nonpareil' trees planted in 2012, with 10 girdled and 10 non-girdled "control" trees in a systematic design, with girdled and control trees alternating along the same row. Trees had been budded on 'Nemaguard' seedling rootstock and planted at 6 x 3 m spacing (556 trees per ha) in Orchard 1orchard at Lindsay Point in the Riverland region of Victoria. Trunk girdling treatments were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. The objective of our treatment was to increase flowering in spring 2015 on the girdled trees and thus increase commercial yield in 2016 (Year 2). Application of trunk girdles in December was timed to coincide with the latter stages of kernel growth and dry matter accumulation and the early stages of floral initiation.

<u>Orchard 2 (Victoria)</u>

A second trunk girdling project was established at Orchard 2, also at Lindsay Point, in December 2014 to young 'Nonpareil' trees planted in 2013, with 10 girdled and 10 non-girdled "control" trees in a systematic design with girdled and control trees alternating along the same row. Trees were budded on 'Nemaguard' seedling rootstock at 6.85 x 4 m spacing (365 trees per ha). Trunk girdles involved complete removal of a 5.0 mm wide strip of bark around the trunk of each tree. Trees had been planted for just 1 year and did not produce a crop in 2014. The objective of our treatment was to increase flowering in spring 2015 on the girdled trees and thus increase commercial yield in 2016. Application of trunk girdles in December was timed to coincide with the early stages of floral initiation.

<u>Orchard 3 (South Australia)</u>

A third trunk girdling project was established at Orchard 3 in January 2016, using 'Nonpareil' trees 2- and 3-years from planting in 2014 and 2013, respectively. Trees were budded on 'Nemaguard' seedling rootstock and planted at 7 x 5.5 m spacing (260 trees per ha), with the 2- and 3-year-old trees planted in separate rows, at an orchard near Paringa in the Riverland region of South Australia. Two girdling methods were evaluated. The first method involved using a Stanley knife to make a single cut completely around the trunk; the second technique involved using a VACA girdling knife to remove a 2.0 mm wide strip of bark around the trunk. Two sets of 2.0 mm girdle trees were included so that one set could be repeat girdled in the second year; this repeat girdling treatment was applied in March 2017 following harvest of the current crop. Treatments were compared with non-girdled control trees, to make a total of four treatments with 10 replicates. The 2-year-old trees were non-cropping when girdling treatments were applied; the 3-year-old trees had already produced their first significant crop. Application of trunk girdling treatments in January was timed to coincide with floral initiation.

Following up on a possible link between rate of callus development and genotype, we also applied a 5.0 mm wide girdle to two ‘Price’ and two ‘Carmel’ trees in December 2015 at Orchard 3. These are polleniser varieties, planted in 2013 on ‘Nemaguard’ seedling rootstock as alternating rows with the ‘Nonpareil’ trees used in the main trial.

Orchard 4 (California)

A trunk girdling project was also established on a private grower site near Fowler in California, in collaboration with the Almond Board of California and Burchell Nursery. The variety was BA2 (Shasta®), a new self-fertile variety, spring budded on ‘Nemaguard’ rootstock and planted in January 2015 at 6.5 x 4.5 m spacing (342 trees per ha) in a solid block of Shasta® trees.

A complete trunk girdle was applied to 10 trees using a 3 mm VACA girdling knife in October 2017, and 10 trees were left ungirdled as a control, in a systematic design with girdled and control trees alternating along the same row.

Data collection

Flowering

At each orchard in Australia, 2-year-old shoots were tagged on each tree, when dormant in winter, for assessment of flowering in spring and final nut count at harvest in the following summer. Flowering assessments were made after budbreak (green tip) and before flower opening, when it was possible to distinguish between dormant, vegetative and floral buds. At Orchard 1, one 2-year-old shoot was selected from central, northern and southern positions on each tree. Note that rows were oriented east-west at this orchard. At Orchards 2 and 3, shoots were selected from the eastern and western side of each tree, as rows had been planted in a north–south direction.

Total yield and kernel quality

In Australia, the crops were machine harvested in February or March of each year and the total fresh weight (hull, shell and kernel) per tree recorded. Yield data were collected from Orchard 1 in 2015, 2016 and 2018; from Orchard 2 in 2015; and from Orchard 3 in 2017 and 2018. In California, trees were hand harvested in August 2018.

In each case a 2.0 kg subsample was taken from the harvested crop for hulling and shelling to provide an approximately 100 g subsample of kernels. The moisture content of this subsample was determined using a Burrows DMC-750 moisture meter and this information used to adjust the total kernel yield data to kg of kernel at 5.0% moisture content. In California, moisture content of the kernel subsample was measured using a Dickey-John GAC 2100 Moisture Meter located at Hughson Nut Co. in Modesto CA.

Additional kernel quality data were collected from each orchard in Australia in 2016. This involved taking the 100 g kernel subsample, counting the number of kernels to determine average kernel weight, then grading the kernels into three categories: sound, pinched and shrivelled. The pinched category is when the kernels are normal size but have formed a crease across the kernel. The shrivel category is when the kernel is significantly smaller than normal because of severe dehydration.

Tree dimensions

Tree height and canopy width were recorded annually on each tree and used to estimate canopy volume based on the equation for a truncated inverted cone with circular base and top (https://rechneronline.de/pi/truncated-cone.php). Trunk diameter or circumference data were used to calculate trunk cross-sectional area (TCA).

In California, tree canopy volume was determined from digital images taken at right angles to each tree along the row. ImageJ Fiji software (http://imagej.nih.gov/ij) was used to trace the perimeter of the tree canopy from which to calculate cross-sectional canopy area. This cross-sectional area was then converted to a circle from which it was possible to calculate radius. Canopy volume (V) was calculated as $V = 4/3*\pi*radius^3$. All trees were isolated and not growing into each other so it was valid to assume a uniform canopy cross-section regardless of the angle at which the digital image was taken.

Statistical analyses

Tree dimensions, yield and kernel quality data were collected from each data tree (n=10). Analyses were completed using analysis of variance with Minitab® v18.1 with mean separation by Tukey's pairwise comparison method. Percentage data were arcsin transformed for analysis and then back-transformed for presentation. Paired T-Tests were used to analyse trunk cross-sectional area data above and below the trunk girdles.

Results and discussion

Orchard 1

There was no effect of trunk girdling at Orchard 1 in December 2014 on either nut moisture content or tree yields in the following March (Table 1).

Flowering data collected on 13 August 2015 showed that at that time, 96% of flowers on the girdled trees were at full bloom or beyond compared with 60% of flowers on control trees (data not presented). So there was some indication that girdling had advanced the time of flowering. There was some indication (not statistically significant) that girdling had decreased the number of flowers on shoots on the shaded side of trees ($p = 0.115$), but not on the more exposed shoots on these trees (Table 2).

In 2016, kernel yield was reduced ($p<0.10$) and kernels were smaller ($p<0.10$) in response to the 2014 girdling treatments, although not statistically significant (Tables 1 and 3). There was no effect on kernel moisture content or kernel quality at this stage, in terms of the number of pinched or shrivelled kernels at harvest.

Table 1. Effect of trunk girdling in December 2014 on yield of 'Nonpareil' almond trees at Orchard 1 in Victoria, harvested in March 2015 and 2016. Trees were planted in 2012. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; (*) = *p*<0.10.

Year	Treatment	Fresh weight[a] (kg/tree)	Kernel moisture (%)	Kernel weight (kg/tree)[b]	Kernel weight (t/ha)[b,c]
2015	Control - no girdle	11.4 ± 0.7	5.9 ± 0.4	1.618 ± 0.15	0.900 ± 0.08
	Girdled	11.0 ± 0.4	5.4 ± 0.2	1.473 ± 0.17	0.819 ± 0.09
	Significance	*NS*	*NS*	*NS*	*NS*
	p-value	0.619	0.305	0.527	0.527
2016	Control - no girdle	18.5 ± 0.7	4.5 ± 0.4	5.583 ± 0.23	3.104 ± 0.13
	Girdled	16.7 ± 0.8	4.8 ± 0.4	4.883 ± 0.31	2.715 ± 0.17
	Significance	*NS*	*NS*	*(*)*	*(*)*
	p-value	*0.113*	*0.678*	*0.080*	*0.080*

[a] Fresh weight of whole fruit (hull, shell and kernel)

[b] Adjusted to 5.0% moisture content

[c] Based on 556 trees/ha (6 x 3 m spacing)

Table 2. Effect of trunk girdling in December 2014 on the number of flowers produced in August 2015 on selected 2-year-old branches of 'Nonpareil' almond trees at Orchard 1 in Victoria. Trees were planted in 2012. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are branch averages ± SE (n = 10 trees). Significance: NS = not significant.

		No. of flowers per branch		
Treatment	Branch position[a]	Centre	North	South
Control (no girdle)		260 ± 39	170 ± 54	155 ± 21
Girdled		260 ± 34	130 ± 23	117 ± 12
	Significance	*NS*	*NS*	*NS*
	p-value	*0.997*	*0.476*	*0.115*

[a] One 2-year-old branch was selected from central, northern and southern positions on each tree, rows were oriented east-west

Table 3. Effect of trunk girdling 'Nonpareil' almond trees at Orchard 1 in Victoria in December 2014 on kernel quality at harvest in March 2016. Trees were planted in 2012. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; (*) = *p*<0.10.

Treatment	Kernel moisture (%)	Kernel weight (g/kernel)	Kernel quality (% of fruit in each category)		
			Sound	Pinched	Shrivelled
Control - no girdle	5.18 ± 0.2	1.25 ± 0.03	98.1 ± 0.5	1.4 ± 0.4	0.5 ± 0.2
Girdled	5.10 ± 0.1	1.15 ± 0.04	98.5 ± 0.4	1.2 ± 0.5	0.3 ± 0.2
Significance	*NS*	*(*)*	*NS*	*NS*	*NS*
p-value	*0.713*	*0.054*	*0.800*	*0.791*	*0.438*

Girdling in December 2014 resulted in a slight reduction in tree height by July 2015, but there was no indication that girdling had affected tree width, canopy volume or TCA above the girdle (Table 4).

However, the trunk girdle did restrict growth of the trunk below the girdle. Indeed, girdling appeared to cause the death of two trees which did not resume growth in spring 2015.

Table 4. Effect of trunk girdling in December 2014 on tree size, canopy volume and trunk cross-sectional area (TCA) of 'Nonpareil' almond trees at Orchard 1 in Victoria in July 2015. Trees were planted in 2012. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; * = *p*<0.05; * = *p*<0.001.**

Treatment:	Height (m)	Canopy width (m)		Canopy volume[a] (m^3)	TCA (cm^2)			
		along row	across row		above girdle	below girdle		
Control - no girdle	4.4 ± 0.06	2.8 ± 0.10	3.3 ± 0.12	11.8 ± 0.8	108 ± 5.4		*Significance*	*p-value*
Girdled	4.2 ± 0.07	2.8 ± 0.05	3.4 ± 0.07	11.1 ± 0.4	98 ± 2.6	89 ± 3.3	***	*<0.000*
Significance	*	*NS*	*NS*	*NS*	*NS*			
p-value	*0.031*	*0.824*	*0.342*	*0.882*	*0.116*			

[a] Canopy volume estimate based on truncated inverted cone with circular base and top

Callus development was very slow on all girdled trees so that even after 12 months many of the girdles had still not completely healed (Figure 1). By this stage, average trunk circumference was 38.5 cm on the girdled trees and of this only 14.3 cm had callus bridging the girdle, 22.6 cm had callus development but this had not joined across the girdle, and 1.6 cm of total trunk circumference had no callus development. It was expected that girdles would heal within 4–6 weeks for optimum benefit.

Figure 1. Trunk girdling treatments applied to 'Nonpareil' almond trees at Orchard 1 in Victoria in January 2015. Trees were planted in 2012. Image on left was taken immediately after 5.0 mm wide girdles were applied; image on right was taken 1 year later, in January 2016, still showing incomplete callus development across the girdle.

No data were collected in 2017; however, when reviewing the trees again in 2018, it was obvious that the girdled trees were visibly smaller than the non-girdled control trees. Although trees were a similar overall height, the canopy on girdled trees was 4.6 m across compared with 5.36 m on the control trees, and canopy volume was 17% less on the girdled trees (Table 5). Trunk diameter was also reduced by 23% on the girdled compared with control trees.

Table 5. Effect of trunk girdling at Orchard 1 in Victoria in December 2014 on tree size, canopy volume and trunk cross-sectional area (TCA) of 'Nonpareil' almond trees in April 2018. Trees were planted in 2012. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are tree averages ± SE (n = 5 trees). Significance: NS = not significant; ** = *p*<0.01; * = *p*<0.001.**

Treatment	Tree height (m)	Tree width (across row, m)	Canopy volume (m^3)[a]	TCA (cm^2)
Control – no girdle	5.98 ± 0.1	5.36 ± 0.1	30.5 ± 0.8	323 ± 30
Girdled	5.88 ± 0.1	4.60 ± 0.1	24.7 ± 0.5	188 ± 8
Significance	*NS*	**	***	**
p-value	*0.525*	*0.001*	*<0.001*	*0.002*

[a] Based on truncated inverted cone with circular base and top.

Despite the smaller tree size, kernel yields in March 2018 were similar on the control and girdled trees, producing the equivalent of 4.03 and 3.79 t/ha, respectively (Table 6). Cropping efficiencies (yield of kernel vs canopy volume) were also similar between treatments (Tables 5 and 6).

Table 6. Effect of trunk girdling at Orchard 1 in Victoria in December 2014 on fresh weight of whole fruit (hull + shell + kernel) at harvest, kernel moisture and yield per tree and per hectare and cropping efficiency (yield of kernel vs canopy volume) of 'Nonpareil' almond trees in April 2018. Trees were planted in 2012. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are tree averages ± SE (n = 5 trees). Significance: NS = not significant.

Treatment	Fresh weight (kg/tree)[a]	Kernel moisture (%)	Kernel weight (kg/tree)[b]	Kernel weight (t/ha)[b,c]	Kernel weight (g/m^3 canopy)[b]
Control – no girdle	24.3 ± 1.3	8.8 ± 1.5	7.26 ± 0.9	4.03 ± 0.5	238 ± 29
Girdled	22.9 ± 1.8	9.4 ± 1.1	6.83 ± 0.6	3.79 ± 0.3	278 ± 27
Significance	*NS*	*NS*	*NS*	*NS*	*NS*
p-value	*0.563*	*0.775*	*0.697*	*0.697*	*0.344*

[a] Fresh weight of whole fruit (hull, shell and kernel)

[b] Adjusted to 5.0% moisture content

[c] Based on 556 trees/ha (6 x 3 m spacing)

Orchard 2

There was some evidence that girdling treatments applied to trees at Orchard 2 in Victoria in December 2014 advanced time of flowering in the following spring. On 13 August 2015, 47% of flowers were at full bloom or beyond compared with 1.2% of flowers on control trees (data not presented). The girdling treatment also increased the number of flowers, from 93 to 125 flowers per branch on control and girdled trees, respectively (Table 7). However, by harvest in 2015 there was no difference in kernel yield between the girdled and non-girdled trees. While kernels were on average slightly smaller (by 7%) on the girdled than non-girdled trees, the percentage of sound kernels was similar (Table 8). Thus it appears that the difference in number of flowers in spring between the girdled and control treatments did not translate into differences in kernel yield at harvest, which was likely caused by lower fruit set or greater in-season fruit drop in the girdled trees.

Table 7. Effect of trunk girdling 'Nonpareil' almond trees at Orchard 2 in Victoria in December 2014 on the number of flowers on selected 2-year-old branches in August 2015 compared with whole tree kernel yield and quality data collected at harvest in February 2016. Trees were planted in 2013. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are branch or tree averages ± SE (n = 10 trees). Significance: NS = not significant; * = *p*<0.05.

Treatment	No. of flowers (spring 2015)	Fresh weight[a] (kg/tree)	Kernel moisture (%)	Kernel weight (kg/tree)[b]
Control – no girdle	93 ± 9	4.25 ± 0.4	4.61 ± 0.1	1.22 ± 0.12
Girdled	131 ± 14	4.90 ± 0.5	4.49 ± 0.1	1.24 ± 0.13
Significance	*	*NS*	*NS*	*NS*
p-value	*0.027*	*0.327*	*0.428*	*0.921*

[a] Fresh weight of whole fruit (hull, shell and kernel)
[b] Adjusted to 5.0% moisture content
[c] Based on 365 trees/ha (6.85 x 4.0 m spacing)

Table 8. Effect of trunk girdling 'Nonpareil' almond trees at Orchard 2 in Victoria in December 2014 on kernel quality at harvest in February 2016. Trees were planted in 2013. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; (*) = *p*<0.10; ** = *p*<0.01.

Treatment	Kernel moisture (%)	Kernel weight (g/kernel)	Kernel quality (% of fruit in each category)		
			Sound	Pinched	Shrivelled
Control – no girdle	5.35 ± 0.1	1.24 ± 0.01	95.8 ± 1.0	2.9 ± 0.8	1.3 ± 0.5
Girdled	5.40 ± 0.1	1.15 ± 0.04	98.1 ± 0.8	0.9 ± 0.5	1.0 ± 0.5
Significance	*NS*	**	*NS*	*(*)*	*NS*
p-value	*0.714*	*0.009*	*0.102*	*0.072*	*0.619*

Tree height was slightly lower on the girdled compared with non-girdled control trees at Orchard 2 during the first year following treatment but there was no effect on canopy width or volume (Table 9). Girdling increased the TCA of trees above the girdle but had only a slight or no effect (p= 0.181) on TCA below the girdle. This swelling of the trunk above the girdle is expected and a good indicator of a positive response to the girdling treatment.

In this trial, girdling appeared to cause the death of one tree in the first year and another tree in the second year of growth when the trees were producing their first crop of fruit. Also, as with other girdling treatments reported here, callus development across the girdle was unusually slow. Trees girdled at Orchard 2 in December 2014 had poor callus development, with healing still incomplete by December 2015. Average trunk circumference was 24.2 cm on the girdled trees in December 2015; of this only 11.6 cm had callus bridging the girdle, 2.8 cm had callus development but had not joined across the girdle, and 8.4 cm of total trunk circumference had no callus development (data not presented). It was expected that girdles would heal within 4–6 weeks for optimum benefit. Trunk girdling at Orchard 2 also appeared to cause severe leaf spotting and earlier leaf drop compared with the non-girdled trees.

Table 9. Effect of trunk girdling 'Nonpareil' almond trees at Orchard 2 in Victoria in December 2014 on tree size, canopy volume and trunk cross-sectional area (TCA) in July 2015. Trees were planted in 2013. Trunk girdles were applied using a VACA girdling knife to remove a 5.0 mm wide strip of bark around the trunk of each tree. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; (*) = *p*<0.10; * = *p*<0.05; * = *p*<0.001.**

	Height (m)	Canopy width (m)		Canopy volume (m^3)[a]	TCA (cm^2)			
Treatment:		**along row**	**across row**		**above girdle**	**below girdle**		
Control - no girdle	2.6 ± 0.05	1.6 ± 0.04	1.7 ± 0.05	1.8 ± 0.11	45.2 ± 1.4		*Significance*	*p-value*
Girdled	2.6 ± 0.05	1.7 ± 0.04	1.7 ± 0.05	1.9 ± 0.12	35.8 ± 1.3	32.9 ± 1.6	*	*0.024*
Significance	*NS*	*(*)*	*NS*	*NS*	***			
p-value	*0.51*	*0.085*	*0.658*	*0.452*	*<0.001*			

Orchard 3

Our experience from trunk girdling treatments at Orchards 1 and 2 was that the 5.0 mm wide girdles did not heal as quickly as expected. Hence at Orchard 3 in South Australia we tested less invasive girdling treatments.

Based on results from previous trials, we were concerned that we might get more flowering/fruit set in response to girdling but then have higher fruit drop so that final yield was not affected by the girdling treatment. Hence at Orchard 3, we tagged one branch on the west and east side of each tree and counted fruit numbers on these branches shortly after fruit set, in October 2016. Unfortunately we missed the narrow window in which to complete flower counts. We found no difference in fruit numbers shortly after fruit set in October between any of the treatments on both sets of trees (Table 10). When counts were repeated prior to harvest in February 2017 the results were similar, with an average of 95% and 98% fruit set for the 3- and 4-year-old trees respectively and no difference between treatments (data not shown).

Table 10. Effect of trunk girdling treatments at Orchard 3 in South Australia on fruit numbers shortly after fruit set of 'Nonpareil' almond trees. Girdling treatments were applied in January 2016 to 2- and 3-year-old trees (planted in 2014 and 2013, respectively). Data were collected in October 2016 from one branch on the east and west side of each tree. Values are branch averages ± SE (n = 10 trees). Significance: NS = not significant.

	No. of fruit per branch			
	3-year-old trees (planted 2014)		4-year-old trees (planted 2013)	
Treatment	**East**	**West**	**East**	**West**
Control - no girdle	13 ± 5	8 ± 2	26 ± 3	18 ± 3
Girdle - single blade cut	20 ± 4	7 ± 1	27 ± 4	13 ± 2
Girdle - 2 mm cut	17 ± 4	9 ± 1	32 ± 4	16 ± 3
Significance	*NS*	*NS*	*NS*	*NS*
p-value	*0.533*	*0.456*	*0.519*	*0.394*

As with the trunk girdling projects at Orchards 1 and 2, kernel yields were similar on girdled and non-girdled control trees at Orchard 3 (Table 11). We also found no difference in kernel size or the number of pinched or shrivelled kernels between the 2.0 mm wide girdle and non-girdle control trees. Average kernel size was 1.38 g, and 98% of kernels were sound for both treatments (data not presented).

Table 11. Effect of trunk girdling treatments at Orchard 3 in South Australia on kernel yield and quality of 'Nonpareil' almond trees. Girdling treatments were applied in January 2016 to 2- and 3-year-old trees (planted in 2014 and 2013, respectively) with one of the treatments repeated in March 2017. Yield and kernel quality data were collected in March 2017 and 2018. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; (*) = p<0.10; * = p<0.05.

Tree age/Treatment	Harvest date	Fresh weight (kg/tree)[a]	Kernel moisture (%)	Kernel weight (kg/tree)[b]	Kernel weight (t/ha)[b,c]
3-year-old trees (planted 2014)					
Control - no girdle	**March 2017**	9.3 ± 0.9	7.9 ± 0.6	2.2 ± 0.2	0.58 ± 0.06
Girdle - single blade cut		8.9 ± 1.0	10.3 ± 1.1	2.2 ± 0.2	0.57 ± 0.06
Girdle - 2 mm cut		9.3 ± 0.9	9.0 ± 0.9	2.4 ± 0.2	0.62 ± 0.06
	Significance	*NS*	*NS*	*NS*	*NS*
	p-value	*0.945*	*0.227*	*0.856*	*0.856*
Control - no girdle	**March 2018**	47 ± 5	9.5 ± 0.3	11.3 ± 1.5	2.92 ± 0.34
Girdle - single blade cut		50 ± 3	9.9 ± 0.2	12.0 ± 0.9	3.11 ± 0.22
Girdle - 2 mm cut		44 ± 3	9.5 ± 0.1	10.4 ± 0.9	2.71 ± 0.25
Girdle - 2 mm cut (repeated 2017)		37 ± 4	9.4 ± 0.2	8.3 ± 0.9	2.17 ± 0.24
	Significance	*(*)*	*NS*	*NS*	*NS*
	p-value	*0.087*	*0.380*	*0.119*	*0.119*
4-year-old trees (planted 2013)					
Control - no girdle	**March 2017**	17 ± 1.4	6.0 ± 0.1	4.6 ± 0.5	1.19 ± 0.12
Girdle - single blade cut		18 ± 1.4	6.3 ± 0.2	4.9 ± 0.5	1.27 ± 0.14
Girdle - 2 mm cut		17 ± 1.5	6.4 ± 0.2	4.8 ± 0.5	1.24 ± 0.14
	Significance	*NS*	*NS*	*NS*	*NS*
	p-value	*0.881*	*0.232*	*0.896*	*0.896*
Control - no girdle	**March 2018**	43 ± 4	7.3 ± 0.3 b	11.5 ± 1.2	2.98 ± 0.32
Girdle - single blade cut		49 ± 5	8.7 ± 0.5 a	12.9 ± 1.3	3.34 ± 0.34
Girdle - 2 mm cut		42 ± 2	7.4 ± 0.3 b	11.4 ± 0.8	2.95 ± 0.12
Girdle - 2 mm cut (repeated 2017)		46 ± 4	7.8 ± 0.2 ab	11.8 ± 1.2	3.06 ± 0.32
	Significance	*NS*	*	*NS*	*NS*
	p-value	*0.546*	*0.021*	*0.791*	*0.791*

[a] Fresh weight of whole fruit (hull, shell and kernel)
[b] Adjusted to 5.0% moisture content
[c] Based on 260 trees/ha (7.0 x 5.5 m spacing)

Our next step was to repeat the 2.0 mm girdle treatment in 2017 on one set of the 2016 girdled trees. This time the girdles were applied in March, after the current crop had been harvested. This timing is similar to what we have used successfully with macadamias, an evergreen tree. Although almonds are deciduous, the trees retain their leaves for at least another 2 months after the crop has been harvested. As in previous years, this 2017 repeat girdle and the other 2016 treatments did not affect harvested yield in March 2018 (Table 11).

Trees girdled with a 2.00 mm wide cut when 2 years old were smaller than non-girdled control trees in the first year after girdling; the single knife cut treatment gave an intermediate result (Table 12). Combined with the yield data in Table 11, the cropping efficiency of the 2.0 mm girdle treatment was higher than for the control trees (p = 0.035), with 138, 156 and 196 g of kernel per m^3 of canopy for the control, single knife cut and 2.0 mm wide girdle, respectively (data not presented). We did not record a similar effect when the girdling treatments were applied to 3-year-old trees.

Table 12. Effect of trunk girdling 'Nonpareil' almond trees at Orchard 3 in South Australia on tree size, canopy volume and trunk cross-sectional area (TCA). Girdling treatments were applied in January 2016 to 2- and 3-year-old trees (planted in 2014 and 2013, respectively) and data were collected in January 2017. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; * = *p*<0.05; ** = <0.10.

Tree age/Treatment	Tree height (m)	Canopy volume (m^3)[a]	Trunk cross-sectional area (cm^2)	
			(above girdle)	(below girdle)
Three-year-old trees (planted 2014)				
Control - no girdle	3.8 ± 0.07 a	16.0 ± 0.9 a	128 ± 6	-
Girdle - single blade cut	3.6 ± 0.04 ab	13.8 ± 1.0 ab	129 ± 7	112 ± 6
Girdle - 2 mm cut	3.5 ± 0.05 b	12.3 ± 0.6 b	134 ± 7	114 ± 4
Significance	**	*	*NS*	*NS*
p-value	*0.006*	*0.023*	*0.794*	*0.820*
Four-year-old trees (planted 2013)				
Control - no girdle	4.3 ± 0.13	23.7 ± 1.4	191 ± 8	-
Girdle - single blade cut	4.2 ± 0.07	19.4 ± 1.7	209 ± 8	190 ± 7
Girdle - 2 mm cut	4.3 ± 0.07	21.0 ± 1.0	208 ± 10	181 ± 7
Significance	*NS*	*NS*	*NS*	*NS*
p-value	*0.432*	*0.104*	*0.288*	*0.405*

[a] Canopy volume estimate based on truncated inverted cone with circular base and top

As with previous trunk girdling projects with 'Nonpareil' almonds, there was no or very little visible callus development across the girdle one month after treatment (data not presented). However, there was some activity apparent before winter, and full callus development was observed across all girdling treatments by January 2017. All girdling treatments caused swelling of the trunk above the girdle, with TCA consistently higher above than below girdle (p<0.001) in January 2017 (Table 12).

Following up on a possible link between rate of callus development and genotype, we also applied a 5.0 mm wide girdle to two 'Price' and two 'Carmel' trees on 15 December 2015 at Orchard 3. These are polleniser varieties, planted in 2013 as alternating rows with 'Nonpareil'. The girdles had already partly healed by January 2016 and had completely healed by early February 2016 (Figure 2). This rate of callus development is more typical of the response found when girdles have been applied to other tree and vine crops. This is a very important result, because, while girdling may not be practical with 'Nonpareil' trees, it could be an option for trees in the polleniser rows. Girdling polleniser trees could be worthwhile if it reduced tree size and thus provided more room for the main crop 'Nonpareil' trees. This option could be considered in future planting system designs and also with new cultivars.

Figure 2. Trunk girdling treatments applied to 'Monterey' (left) and 'Carmel' (right) almond trees at Orchard 3 in South Australia. Trees were planted in 2013 and 5.0 mm trunk girdles applied using a VACA girdling knife in December 2015. Images were taken in February 2016, showing complete callus development.

Orchard 4 (California)

Trunk girdles were applied to Shasta® trees in California in October 2017, immediately after harvest. There was rapid callus development such that girdles had mostly healed within 6 weeks by the end of November 2017.

The total fresh weight of the crop harvested in August 2018 was less on the girdled than non-girdled trees (Table 13). The crop from the girdled trees were slightly drier at harvest than control trees, which may have contributed to this result. Although moisture content was not significant between treatments (*p*=0.121), there was much greater variation in moisture content between the girdled than non-girdled trees (Figure 3). Nevertheless, when corrected for moisture content, the yield of kernel at 5% moisture content was still slightly less on girdled than non-girdled trees. These data need to be taken with some degree of caution, as moisture content values over 10% are not particularly reliable and could have exaggerated sample variability within treatments. To mitigate this, moisture readings were repeated three times for each sample and the average value used in these analyses.

Table 13. Total fresh weight per tree, kernel moisture content, kernel weight per tree and cropping efficiency (yield of kernel vs canopy volume) of Shasta® almond trees at Orchard 4 in California. Treated trees had been girdled in October 2017, when trees were 3-years-old, with a 3 mm wide girdle. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; (*) = *p*<0.10; * = *p*<0.05.

Treatment	Total fresh weight (kg/tree)[a]	Kernel moisture content (%)	Kernel weight (kg/tree)[b]	Kernel weight (t/ha)[b,c]	Kernel weight (g/m^3 canopy)[b]
Control – no girdle	18.6 ± 1.0	16 ± 0.4	3.2 ± 0.1	1.09 ± 0.05	185 ± 14
Girdled	15.4 ± 0.7	14 ± 0.9	2.9 ± 0.1	0.96 ± 0.05	209 ± 22
Significance	*	*NS*	(*)	(*)	*NS*
p-value	*0.016*	*0.121*	*0.056*	*0.056*	*0.363*

[a] *Fresh weight of whole fruit (hull, shell and kernel)*

[b] *Adjusted to 5.0% moisture content*

[c] *Based on 342 trees/ha (6.5 x 4.5 m spacing)*

Figure 3. Box plot showing the moisture content (%) of almond kernel harvested from girdled and non-girdled Shasta® almond trees at Orchard 4 in California. Treated trees had been girdled in October 2017, when they were 3-years-old, with a 3 mm wide girdle and fruit harvested in August 2018. The median value is visible as a horizontal line within each box. The first quartile marks one end of the box and the third quartile marks the other end of the box. The "whiskers" extend from the ends of the box to the smallest and largest data values.

Tree height and canopy volume were similar for the girdled and not-girdled trees at the start of the project in October 2017 (Table 14). Tree height did not increase as much as expected during the period from application of the girdling treatment in October 2017 until harvest in August 2018. This was because the trees had been machine pruned in early summer 2018 to reduce tree height. However, tree canopy volume did increase substantially from one year to the next. By August 2018, control trees were larger, with greater canopy volume, than those receiving the trunk girdling treatment (Table 14). In terms of cropping efficiency, kernel yield per canopy volume was similar on the girdled and non-girdled control trees (Table 13).

Table 14. Tree height and canopy volume of 3-year-old Shasta® almond trees at Orchard 4 in California in October 2017 and August 2018. Treatment trees were girdled in October 2017 with a 3 mm wide girdle and nuts were harvested in August 2018. Values are tree averages ± SE (n = 10 trees). Significance: NS = not significant; * = *p*<0.05.

	Tree height (m)	Canopy volume (m^3)[a]	Tree height (m)	Canopy volume (m^3)
	October 2017		August 2018	
Control – no girdle	3.3 ± 0.09	9.9 ± 0.6	3.7 ± 0.2	17.6 ± 0.7
Girdled	3.2 ± 0.09	10.2 ± 0.9	3.5 ± 0.3	14.4 ± 1.3
Significance	*NS*	*NS*	*NS*	*
p-value	*0.856*	*0.796*	*0.229*	*0.043*

[a] *Canopy volume estimate based on truncated inverted cone with circular base and top*

Concluding comments:

Several attempts were made to promote precocity and increase yields on young 'Nonpareil' almond trees by trunk girdling. None were particularly successful in increasing yields per tree but there were long term effects on trunk cross sectional area and canopy volume, similar to the effect one might expect from a growth controlling rootstock. This growth control might lead to a reduction in management costs as trees become older and overcrowded; it might also provide growers with the opportunity to plant more trees per ha and thus increase potential orchard yields over the life of the orchard. However, there is a warning here. The 5.0 mm trunk girdles on young 'Nonpareil trees took an unusually long time to heal, with some girdles still only partly healed 12 months after treatment. It is not clear why this happened, but the delayed healing definitely would have contributed to the death of four trees across the 20 girdled trees at Orchards 1 and 2. There were suspicions that the girdling wounds could have been sprayed with herbicide, as the trunk spray guards had been removed from the girdled trees when girdling treatments were applied, and not replaced. It is possible that there was herbicide spray drift entering the open girdles soon after the girdles were applied.

An interesting feature at Orchard 2 was that there were several more flowers on the girdled than non-girdled trees, in the year following treatment. However, this difference did not persist and yields at commercial harvest were similar from both the girdled and non-girdled trees. We found no evidence that this was a consequence of smaller and shrivelled kernels at harvest. It is possible that the stress from girdling arrested kernel development and induced premature fruit drop.

Regardless of what happened at orchards 1 and 2, it was important that we assessed further, less severe girdling treatments, applying smaller cuts. This was carried out at Orchard 3. Callus development was more successful following these treatments, however, kernel yields were similar for the girdled and non-girdled trees and the degree of growth control was much less than that observed with the 5.0 mm girdles. The girdles were placed higher up on the trunks of these trees than in the earlier projects and so were not likely to have suffered any herbicide damage. There were no tree deaths at this site.

Another factor considered a possible explanation for the slow callus development on the 'Nonpareil' trees is that callus development is normally slow with this genotype. With the girdles applied to a different set of cultivars, the 5.0 mm girdles applied to 'Price' and 'Carmel' trees healed within a few weeks, as did the 3.0 mm girdle applied to 'Shasta' trees in California. No yield or tree size data were collected from the 'Price' trees, but 2 years after treatment, the girdled Shasta® trees in California were smaller than the non-girdled trees. Kernel yield was less on the girdled than non-girdled trees, but with the smaller tree volume, yield efficiency (weight of kernels per m^3 of canopy) was similar.

Although we were not able to produce the desired increase in yields from trunk girdles that have been achieved with other crops, the growth controlling response was of interest. With more refinement in terms of timing and severity, trunk girdling might be a useful option for growers unable to source growth controlling rootstocks, or who already have young trees in the ground.

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APPENDIX IV. Pruning responses of almond cultivars budded on medium- and high-vigour rootstocks

Introduction

Scion and rootstock cultivar choices are important considerations for growers establishing new orchards, particularly when trees are going to be planted at higher than traditional densities. In traditional almond orchards, growers plant trees that have been either spring- or winter-budded in the nursery and then planted in the orchard with a single trunk. This single trunk is headed back at planting to a strong lateral bud at approximately 90 cm above the bud union. Several strong scaffold branches develop in response to this heading cut. With no or minimal pruning, these branches quickly produce trees with large and spreading fruiting canopies. Trees are generally planted at wide spacing between and within rows, for example 7 x 4.25 m spacing, respectively (336 trees/ha), to allow room for the establishment of these large trees.

More recently, growers have experimented with closer planting distances, for example 6 x 3 m spacing (556 trees/ha), to obtain higher yields from young orchards. The risk with these higher density plantings is that the trees become crowded sooner than with traditional planting designs. Options to mitigate this risk include pruning trees to produce a narrower canopy, as well as planting “unpruned” trees to initiate a strong central leader growth habit. Rootstock choice is also important. Trees on high-vigour rootstocks can be useful to obtain high yields from young trees but they compound crowding issues as trees become older. In contrast, trees on lower vigour rootstocks can be slower to reach their full cropping potential but be easier to manage in the longer term.

In this project, we evaluated four scion varieties, ‘Nonpareil’, ‘Carmel’, ‘Monterey’ and ‘Price’, chosen because of their distinctively different growth habits, budded on to four rootstock varieties, ‘Nemaguard’, ‘Bright’s Hybrid’, ‘Cornerstone’ and ‘Garnem’, chosen for their vigour rating from medium to high vigour (Table 1). Low-vigour rootstocks were not available for this project.

Table 1. The range of almond scion cultivars and rootstocks compared in a pruning trial established at Orchard 2 in 2017.

Scion cultivar:	‘Nonpareil’	Diffuse branching, moderately upright
	‘Carmel’	Zonal branching, wide spreading canopy
	‘Monterey’	Zonal branching, wide spreading canopy
	‘Price’	Diffuse branching, upright, narrow branch angle
Rootstock:	‘Nemaguard’	Control, medium vigour
	‘Bright’s Hybrid’	High vigour
	‘Cornerstone’	Medium vigour
	‘Garnem’	High vigour
Tree types:[1]	Control	Traditional tree management regime adopted by nursery/orchard to produce trees with multiple trunks growing from a single heading cut applied at 90 cm, and all side shoots on the trunk trimmed to 2 cm when planted in the orchard.
	Central leader (narrow pruned)	Dormant-budded trees selected in winter to have a single dominant trunk with multiple side branches, which were left unpruned when the trees were planted in the orchard, followed by pruning in winter and spring 2018 to produce a narrow palmette-style canopy.

[1] All trees were pruned to remove any shoots forming on the trunks of the trees up to 60 cm. This was done at planting and during subsequent growth phases to create and maintain a clean trunk for access by tree shakers during harvest.

Materials and methods

'Nonpareil', 'Carmel', 'Monterey' and 'Price' trees budded on 'Nemaguard', 'Bright's Hybrid', 'Cornerstone' and 'Garnem' rootstocks were propagated and field planted at Orchard 2 in Lindsay Point in the Riverland region of Victoria, Australia (Table 1). All rootstocks were supplied by Ausbuds Pty Ltd in Sommerville, Victoria. The clonal rootstocks 'Bright's Hybrid', 'Garnem' and 'Cornerstone' were propagated as own-rooted cuttings; 'Nemaguard' rootstock were propagated from seed. All rootstocks were delivered to Lindsay Point in October 2014 and dormant budded in March 2015. They remained in the nursery until July 2016 when they were field planted in the orchard with tree spacing 6.85 x 3 m between and within rows, respectively (487 trees per ha). Rows were planted in a north-south direction.

Two tree types (treatments) were planted (Table 1). Control trees, the traditional tree type planted by growers, received heading cuts at 90 cm and trimmed side branches in the nursery. Central leader trees, left unpruned in the nursery, were planted with a single trunk (central leader) and multiple side shoots.

Note that for all trees, including control and central leader trees, any shoots forming directly on the trunks of the trees up to 60 cm were removed to maintain a clean trunk with no branching, to provide access for the tree shakers during harvest.

The central leader trees were leader-release pruned in August 2017, to remove competing shoot growth near the terminal shoot and promote rapid extension of the central leader. The central leader trees were then dormant-pruned in winter, in July 2018, by selectively cutting back any strong branches growing out towards the centre of the rows. This dormant, narrow prune was followed by an in-season prune in late-November 2018, to thin out strong regrowth shoots from the previous pruning. The overall objective of this was to produce a narrow ellipsoid or informal palmette-style tree shape, compared with the traditional more spherical shape of the control trees.

Treatments were replicated in four blocks of three trees each per cultivar/rootstock combination, in a systematic design with pruned central leader and control unpruned tree replicates alternating along each row. Unless otherwise indicated, data were taken from the centre tree in each three-tree plot. It was possible to have just one cultivar per row to meet the requirements of the collaborating grower. With only limited trees available, it was also decided to group the rootstocks according to expected vigour so that in the longer term the trees on the vigorous rootstocks did not dominate the growth of the trees on the less vigorous rootstocks. With this design it was possible to make statistical comparisons of pruning treatment effects within each cultivar/rootstock combination, which is the main objective of the trial. Comparisons between cultivars and rootstocks will be less reliable but still informative.

Tree dimensions

The number of shoots growing from the trunk of central leader trees was counted soon after planting in July 2016; note that all shoots on the control trees had been removed before planting. The branches that had survived and/or were new potential scaffold branches on the trunk were counted in the following year (May 2017) on both the central leader and control trees. Potential scaffold branches were those shoots growing directly from the trunk, with a minimum 7.0 mm basal diameter.

Tree height and trunk cross-sectional area (TCA) were recorded each year from 2016 until 2019. Canopy diameter was measured in an east-west direction, across the rows, in November 2019.

Flowering and kernel yield

The total number of flowers per tree was counted in August 2017, 1 year after planting, on a subset of 12 trees per treatment, with data combined from the 'Bright's Hybrid', 'Cornerstone', 'Garnem' and 'Nemaguard' rootstock treatments. Assessments were made after budbreak (green tip) and before flower opening, when it was possible to distinguish between dormant, vegetative and floral buds.

Trees were harvested by hand in 2017 and by machine in 2018 and 2019. The total fresh weight of fruit per tree was recorded and then a 2.0 kg subsample taken for hulling and shelling to provide an approximately 100 g subsample of kernels. The average moisture content of the kernels was determined using a Burrows DMC-750 moisture meter and this information used to adjust the total kernel yield data to kg of kernel at 5.0% moisture content.

Yields per hectare were calculated at the planting density for the orchard (6.85 x 3 m spacing, 487 trees per ha). Yields from the narrow-pruned central leader tree were also calculated with 556 trees/ha (6 x 3 m) and 667 trees/ha (5 x 3 m) and compared with the yield of unpruned control trees at the standard planting density. This was done on the assumption that the narrow-pruned trees planted with central leaders could be planted at the closer spacing.

Statistical analyses

The first year tree size data were collected from each tree and analysed by rootstock (n = 96). In subsequent years, tree dimensions and yield data were collected from the centre tree in each group of three trees. Analyses were completed using analysis of variance with Minitab® v18 and Genstat version 17 (2014, VSNi Ltd, Hemel Hempstead, UK). Mean separation was by Tukey's pairwise comparison method with $p \leq 0.05$.

Results and discussion

Tree dimensions

All trees established well and did not require staking (Figure 1). When planted, the central leader trees averaged 1.63 m tall and had 18 branches remaining on the trunks above 60 cm; after all branches below 60 cm on the trunk were removed (Table 2). Control trees were 90 cm tall with no side branches. The 'Carmel' central leader trees were among the smallest with the least number of branches. There was a trend for trees on 'Bright's Hybrid' and 'Garnem' to have bigger trunks (larger TCA) and to be taller than trees on 'Nemaguard' or 'Cornerstone' (Table 3).

Early season shoot growth was earlier and more vigorous on the control trees than the central leader trees (field observations). These differences most likely related to the number of growing points on each tree when planted, there being fewer buds competing to grow on the pruned control than the unpruned central leader trees. By the second year, however, the strong basitonic growth habit of the current almond cultivars had taken over and it became difficult to distinguish between the control and central leader trees. This was despite all central leader trees being leader-release pruned in winter. Basitonic growth habit is when the lower, structural branches on a tree become more dominant than branches further up in the tree, creating a wider, rather than narrower, tree canopy.

One year after planting, all trees had developed scaffold branches that would become the main fruiting framework for the trees. At this stage we identified potential scaffold branches as those with a minimum of 7 mm basal diameter. In winter 2017, the control trees had produced from 8.1 to 10.5

scaffold branches for ‘Nonpareil’ and ‘Price’, respectively (Table 2). Central leader ‘Monterey’ and ‘Nonpareil’ trees had more scaffold branches than the control trees with 16.2 and 12.8 branches, respectively. Variation in the number of scaffold branches and tree height due to the influence of rootstock was inconsistent (data not presented). However, in 2017, there were large differences in TCA between the rootstock treatments, with the trunks of trees on ‘Bright’s Hybrid’ and ‘Garnem’ being greater than those on ‘Cornerstone’ or ‘Nemaguard’ (Table 3). These differences were still apparent in 2018 and 2019. However, there were never strong effects of rootstock on tree height. In 2018, average tree heights between rootstock treatments ranged from 3.36 to 3.55 m for ‘Nemaguard’ and ‘Garnem’ rootstocks, respectively, a difference of 19 cm or 5%.”In 2019, when trees were in their fourth leaf, the range was 4.19 to 4.50 m, respectively, a difference of 31 cm or 7%. These differences may increase as trees get older, with growth slowing earlier for scions on the less vigorous rootstocks ‘Cornerstone’ and ‘Nemaguard’ than for scions on ‘Bright’s Hybrid’ or ‘Garnem’ rootstock.

Pruning responses

The first round of pruning for the central leader ‘Nonpareil’, ‘Monterey’ and ‘Price’ trees was completed in August 2017. This involved a leader-release pruning, designed to maintain rapid extension of the central leader so that the tree reached maximum height as soon as possible. Pruning involved making four to five cuts per tree. The first target was to thin clusters (congestion) of shoots/branches at the first whorl below the terminal shoot to retain a single dominant growing point to continue extension of the central leader. If there was strong branching at the second whorl below the terminal shoot then the strongest shoots were removed leaving only the weaker shoots that would not likely compete with or restrict growth of the central leader. Pruning also involved removal of any aberrant branches that were growing vertically/upright on the main trunk, as these would interfere with branch development along the main trunk. No pruning was completed on the ‘Carmel’ central leader trees, as heavy flowering on the terminal shoot forming the central leader had stunted its growth and the dominance of the central leader had been lost.

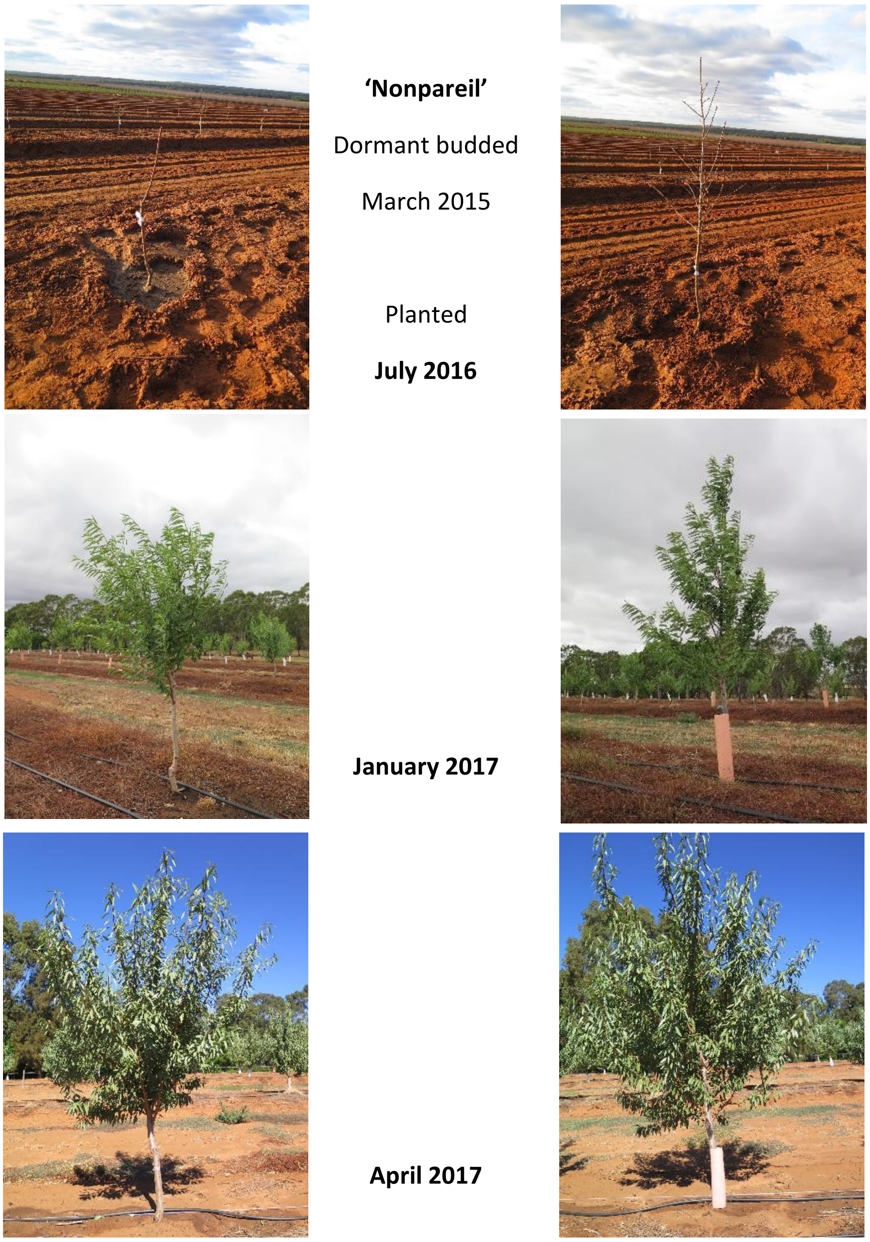

Figure 1. One year's growth of control (left) and central leader (right) 'Nonpareil' almond trees on 'Nemaguard' rootstocks at Orchard 2: at planting (top), mid-summer of first season (middle) and late in first season (bottom). Control trees were pruned to 90 cm and all branches removed before planting, while central leader trees were left with no pruning (refer text for details). Trees were planted in 2016 and left without additional pruning during the first year of growth.

Table 2. Tree height and branching of control and central leader 'Carmel', 'Monterey', 'Nonpareil' and 'Price' almond trees planted at Orchard 2 in July 2016. Control trees were pruned to 90 cm and all branches removed before planting, while central leader trees were left with no pruning (refer text for details). Tree height and branching data were collected immediately after the trees were planted in the orchard; counts of large scaffold branches formed during the 2016/17 growing season were made in winter 2017. Data were combined from 'Bright's Hybrid', 'Cornerstone', 'Garnem' and 'Nemaguard' rootstocks. Values are tree averages ± SE (n = 16). Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; (*) = *p*<0.10; * = *p*<0.05; ** = *p*<0.01; * = *p*<0.001.**

	Tree height (m) when planted in July 2016			
	Control	**Central Leader**		
'Carmel'	0.89 ± 0.01	1.42 ± 0.05 b		
'Monterey'	0.90 ± 0.01	1.70 ± 0.05 a		
'Nonpareil'	0.90 ± 0.01	1.66 ± 0.07 a		
'Price'	0.89 ± 0.01	1.75 ± 0.04 a		
Significance	*NS*	**		
p-value	*0.845*	*<0.001*		
	No. of branches when planted in July 2016			
	Control[1]	**Central Leader**		
'Carmel'	0	14.3 ± 1.4 b		
'Monterey'	0	17.9 ± 1.7 ab		
'Nonpareil'	0	21.6 ± 1.7 a		
'Price'	0	18.3 ± 1.3 ab		
Significance		*		
p-value		*0.012*		
	No. of scaffold branches in winter 2017[2]			
	Control	**Central Leader**	*Significance*	*p-value*
'Carmel'	10.1 ± 0.9 ab	11.3 ± 1.2 b	*NS*	*0.461*
'Monterey'	10.0 ± 0.7 ab	16.2 ± 0.8 b	***	*<0.001*
'Nonpareil'	8.1 ± 0.5 b	12.8 ± 0.8 ab	***	*<0.001*
'Price'	10.5 ± 0.5 a	11.6 ± 0.8 a	*NS*	*0.309*
Significance	*(*)*	***		
p-value	*0.053*	*0.001*		

[1] All side shoots had been pruned off the control trees
[2] Branches >7.0 mm diameter on primary growth axis (trunk)

Table 3. Trunk cross-sectional area (measured 60 cm above ground level) and tree height of almond trees budded on to four different rootstocks and field planted at Orchard 2 in July 2016. Data are combined from the scion cultivars 'Nonpareil', 'Monterey' and 'Price' for control and central leader trees. Control trees were pruned to 90 cm and all branches removed before planting, while central leader trees were left with no pruning (refer text for details). Values are tree averages ± SE (n = 24). Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; * = *p*<0.05; ** = *p* <0.01; * = *p*<0.001.**

	Trunk cross-sectional area (cm³)			
Rootstock	**2016**	**2017**	**2018**	**2019**
'Bright's Hybrid'	4.6 ± 0.3 ab	19.5 ± 0.9 a	62 ± 1.5 a	119 ± 3.0 a
'Cornerstone'	3.1 ± 0.2 c	15.8 ± 0.9 b	56 ± 1.2 b	107 ± 1.9 b
'Garnem'	5.0 ± 0.3 a	19.9 ± 0.8 a	64 ± 1.3 a	126 ± 3.6 a
'Nemaguard'	3.7 ± 0.3 bc	14.2 ± 1.1 b	51 ± 1.8 b	101 ± 2.6 b
Significance	***	***	***	***
p-value	*<0.001*	*<0.001*	*<0.001*	
	Tree height (m)[1]			
Rootstock	**2016**	**2017**	**2018**	**2019**
'Bright's Hybrid'	-	2.51 ± 0.05 ab	3.42 ± 0.05	4.50 ± 0.08 a
'Cornerstone'	-	2.47 ± 0.05 ab	3.45 ± 0.05	4.41 ± 0.09 ab
'Garnem'	-	2.62 ± 0.05 a	3.55 ± 0.06	4.50 ± 0.09 a
'Nemaguard'	-	2.27 ± 0.11 b	3.36 ± 0.05	4.19 ± 0.09 b
Significance		**	*NS*	*
p-value		*0.005*	*0.105*	*0.040*

[1] Control trees had been cut to 90 cm when planted in 2016 and central leader trees were left unpruned (refer text for details and Table 2 for central leader tree data), so the combined 2016 data are not included here. By 2017, control and central leader trees were a similar height and combined data are presented here.

In 2018, the central leader trees were dormant-pruned in winter to produce a narrow palmette-style of tree. This narrow prune involved use of heading cuts to cut back, by two-thirds, any strong branches growing out towards the centre of the rows and to stimulate the production of fruiting wood in the lower tree canopy (Figure 2). Pruning was done selectively, cutting back stronger shoots harder than less vigorous shoots. Additional "firming" cuts were needed on 'Monterey' and 'Price' trees, in particular, when there were too many long unbranched shoots. These were cut back to help strengthen them and to make them less prone to breakage and/or bending over under the weight of the fruit. Overall, pruning involved around 1 minute per side pruning time for each tree, depending on the number of cuts required, with more cuts needed on 'Monterey' trees and fewer cuts needed on the 'Nonpareil' and 'Price' trees. The 'Carmel' trees at this stage were expressing strong symptoms of non-infectious bud failure, causing blackening of stems and leaf death. We did not prune or harvest these trees during the 2018/19 season.

In-season pruning of the central leader trees was undertaken in late-November 2018. This involved cutting back or thinning re-growth from the dormant pruning cuts. This regrowth was vigorous on all scion/rootstock combinations so heavy cutting/side trimming was required. The procedure was to cut back approximately one-third of the length of shoots from the previous dormant cut and any vigorous new shoots developing from elsewhere in the canopy. The main targets of these firming cuts were the long unbranched shoots that needed to be strengthened for cropping next season. No, or very few, cuts were made to shoots growing along the rows between trees. Cuts were mainly made to shoots on the perimeter of the tree canopy facing the alley way. As in winter, this round of pruning involved approximately 1 minute per side of each tree.

Figure 2. Dormant pruning of young almond trees, planted in 2016 was completed in winter 2018. The overall objective was to produce a narrow ellipsoid or informal palmette-style tree shape, compared with the traditional more spherical shape of the control trees. This narrow prune involved use of heading cuts to cut back any strong branches growing out towards the centre of the rows (left) and to strengthen any long unbranched shoots that, during the season, would bend out into the rows under the weight of fruit (right). Arrows mark the location of pruning cuts.

Flowering and yield

The first flowering and yield data were recorded in the 2017/18 season. In spring 2017, there were substantial cultivar differences in the number of flowers per tree for the control trees, with 'Monterey' trees producing 620 flowers per tree compared with 142 flowers on the 'Price' trees (Table 4). However, this did not always translate into higher fruit yields. If each almond kernel weighs approximately 1 g, then while 'Nonpareil' trees had very low fruit set, with just 9% set (34 kernels cf. 369 flowers), 'Monterey' trees had around 47% fruit set (293 kernels cf. 620 flowers).

The number of flowers per tree was similar in spring 2017 on control and central leader trees, and in summer 2018 fruit yields were similar (Table 4). This was an interesting result as the trees were substantially different when planted. The central leader trees had been planted without pruning and thus had an older branching framework than the control trees, which were headed back to 90 cm high and had all side branches trimmed to two buds. This meant the control trees had to produce a totally new set of shoots to crop in the following year. We expected this might have delayed flowering and fewer flowers and fruit per tree. But this was not the case.

Crops harvested in summer 2018 from the 'Carmel', 'Nonpareil', 'Monterey' and 'Price' trees were still typical of young trees, with on average just 20 g of kernel per tree on 'Nonpareil' and 126 g per tree on 'Monterey' (Table 5). Scion variety had the biggest effect on fruit yield, with 'Monterey' producing more than twice the number of fruit than 'Carmel' and 'Price', which in turn produced more than twice the number of fruit than 'Nonpareil' trees. Rootstock did not appear to influence flowering in 2017 or fruit yield in 2018, irrespective of scion cultivar (data not presented).

Table 4. Number of flowers in spring 2017 and kernel yield in March 2018 for the first crop on control and central leader trees of ‘Carmel’, ‘Monterey’, ‘Nonpareil’ and ‘Price’ almond trees planted at Orchard 2 in July 2016. Control trees were pruned to 90 cm and all branches removed before planting, while central leader trees were left with no pruning (refer text for details). Data were combined from ‘Bright’s Hybrid’, ‘Cornerstone’, ‘Garnem’ and ‘Nemaguard’ rootstocks. Values are tree averages ± 1 SE. Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; * = *p*<0.001.**

		No. of flowers per tree (August 2017, n = 12)			
		Control	**Central Leader**	*Significance*	*p-value*
'Carmel'		312 ± 47 bc	386 ± 50 b	*NS*	*0.293*
'Monterey'		620 ± 74 a	779 ± 106 a	*NS*	*0.232*
'Nonpareil'		369 ± 43 b	391 ± 56 b	*NS*	*0.756*
'Price'		142 ± 29 c	207 ± 44 b	*NS*	*0.234*
Significance		***	***		
	p-value	*<0.001*	*<0.001*		

		Yield (g/tree) (March 2018, n = 16)			
		Control	**Central Leader**	*Significance*	*p-value*
'Carmel'		120 ± 20 b	142 ± 17 a	*NS*	*0.412*
'Monterey'		293 ± 46 a	203 ± 29 a	*NS*	*0.109*
'Nonpareil'		34 ± 9 b	53 ± 14 b	*NS*	*0.272*
'Price'		106 ± 17 b	138 ± 21 a	*NS*	*0.258*
Significance		***	***		
	p-value	*<0.001*	*<0.001*		

Table 5. Effect of rootstock on yield and moisture content of 'Carmel', 'Monterey', 'Nonpareil' and 'Price' almonds in February/March 2018. Trees were planted at Orchard 2 in July 2016. Data for control and central leader pruning treatments were combined. Control trees were pruned to 90 cm and all branches removed before planting, while central leader trees were left with no pruning (refer text for details). Values are tree averages ± SE (n=10). Values in each column followed by the same lower-case letters were not significantly different. Significance: NS = not significant; (*) = *p*<0.10; * = *p*<0.05.

Scion:	Rootstock:	Fresh weight (kg/tree)	Kernel moisture (%)	Kernel weight (kg/tree)[1]	Kernel weight (t/ha)[2]
'Carmel'	'Bright's Hybrid'	0.59 ± 0.11	5.8 ± 0.3	0.16 ± 0.03	0.078 ± 0.01
	'Cornerstone'	0.36 ± 0.05	5.5 ± 0.2	0.08 ± 0.01	0.040 ± 0.01
	'Garnem'	0.54 ± 0.14	5.4 ± 0.1	0.13 ± 0.03	0.065 ± 0.02
	'Nemaguard'	0.61 ± 0.11	5.4 ± 0.1	0.15 ± 0.03	0.074 ± 0.01
	Significance	*NS*	*NS*	*NS*	*NS*
	p-value	*0.247*	*0.319*	*0.148*	*0.148*
'Monterey'	'Bright's Hybrid'	1.14 ± 0.23	3.80 ± 0.03 a	0.32 ± 0.07	0.155 ± 0.03
	'Cornerstone'	0.70 ± 0.14	3.66 ± 0.04 b	0.16 ± 0.04	0.080 ± 0.02
	'Garnem'	1.03 ± 0.20	3.66 ± 0.03 b	0.28 ± 0.06	0.135 ± 0.03
	'Nemaguard'	0.88 ± 0.17	3.71 ± 0.04 ab	0.23 ± 0.05	0.133 ± 0.02
	Significance	*NS*	*	*NS*	*NS*
	p-value	*0.376*	*0.027*	*0.251*	*0.251*
'Nonpareil'	'Bright's Hybrid'	0.21 ± 0.08	7.7 ± 0.2	0.04 ± 0.22	0.019 ± 0.01
	'Cornerstone'	0.13 ± 0.03	7.5 ± 0.2	0.02 ± 0.01	0.011 ± 0.01
	'Garnem'	0.33 ± 0.13	7.8 ± 0.2	0.06 ± 0.02	0.029 ± 0.01
	'Nemaguard'	0.30 ± 0.07	7.7 ± 0.2	0.05 ± 0.01	0.025 ± 0.01
	Significance	*NS*	*NS*	*NS*	*NS*
	p-value	*0.334*	*0.717*	*0.426*	*0.426*
'Price'	'Bright's Hybrid'	0.87 ± 0.16	5.5 ± 0.2	0.17 ± 0.03 a	0.084 ± 0.02 a
	'Cornerstone'	0.45 ± 0.07	5.3 ± 0.1	0.07 ± 0.01 b	0.036 ± 0.01 b
	'Garnem'	0.75 ± 0.17	5.3 ± 0.1	0.13 ± 0.03 ab	0.064 ± 0.02 ab
	'Nemaguard'	0.63 ± 0.17	5.1 ± 0.1	0.11 ± 0.02 ab	0.052 ± 0.01 ab
	Significance	*NS*	*NS*	*(*)*	*(*)*
	p-value	*0.174*	*0.295*	*0.074*	*0.074*

[1] Adjusted to 5.0% moisture content

[2] Based on 470 trees/ha (3.0 x 6.85 m spacing)

The first commercial yields were harvested in summer 2019, from 'Nonpareil', Monterey' and 'Price' trees with an average of 1.6 kg of kernel per tree on 'Nonpareil' and 2.7 kg per tree on 'Monterey' (Table 6, Figure 3). As mentioned previously, several of the 'Carmel' trees had developed severe shoot dieback from non-infectious bud failure in autumn and spring 2018, so no further data were collected from these trees.

The fresh weight yield of whole fruit (hull + shell + kernel) at harvest from 'Monterey' trees was higher (p<0.001) than 'Nonpareil' or 'Price' (10.2, 7.2 and 6.3 kg/tree, respectively, Table 6). The fresh weight yield from the control trees was lower (p=0.010) than the central leader trees (8.5 vs 7.3 kg/tree, respectively). The moisture content from 'Price' trees was lower (p=0.001) than 'Monterey' or 'Nonpareil' trees (3.5%, 3.7% and 3.8%, respectively).

Figure 3. Narrow-pruned, central leader 'Monterey' trees (left) and unpruned control trees (right) at Orchard 2, immediately prior to harvest in March 2019. Trees were planted in 2016. Pruning treatments were applied to groups of three trees each. The branches in the unpruned control trees can be seen drooping down with the weight of the fruit.

Kernel weight per tree from 'Monterey' trees was higher ($p<0.001$) than 'Nonpareil', which was higher than 'Price' (2.7, 1.6 and 1.3 kg/tree, respectively). Kernel weight per tree was higher ($p=0.038$) from 'Bright's Hybrid' rootstock than 'Cornerstone' or 'Nemaguard' (2.1, 1.7 and 1.7 kg/tree, respectively); 'Garnem' at 2.0 kg/tree was not significantly different from any of the others. Kernel weight per tree was higher ($p=0.051$) from control than pruned trees (2.0 and1.8 kg/tree, respectively).

Yields per hectare in 2019 from the control and narrow-pruned, central leader trees were calculated at the standard planting density for the orchard (6.85 x 3 m, 487 trees/ha). Yields from control trees were also compared with theoretical yields from the narrow-pruned trees as if they were planted with 556 trees/ha (6 x 3 m) or 667 trees/ha (5 x 3 m). This assumes that the narrow pruning treatment would mean trees could be planted with rows closer together than possible for the unpruned control trees. Data were analysed using unbalanced analysis of variance since four data plots were missing. Significance tests were 'conditional', i.e. adjusted for the effects of other factors.

Table 6. Effect of rootstock and pruning treatment at Orchard 2, on fresh weight of whole fruit (hull + shell + kernel) and kernel moisture content and yield at harvest in February/March 2019 for 'Monterey', 'Nonpareil' and 'Price' almond trees. All trees were planted in winter 2016. Control trees were left unpruned while the central leader trees were narrow pruned during 2018 (refer text for details). Values are tree averages (n = 4).

Rootstock	Treatment	Total fresh weight (kg/tree)			Moisture content (%)			Kernel weight (kg/tree)[1]		
		'Monterey'	'Nonpareil'	'Price'	'Monterey'	'Nonpareil'	'Price'	'Monterey'	'Nonpareil'	'Price'
'Bright's Hybrid'	Control – no pruning	10.4	7.6	8.4	3.7	3.7	3.6	2.7	1.8	1.9
	Central leader - narrow pruned	11.5	6.9	7.1	3.9	3.9	3.4	3.2	1.5	1.5
'Cornerstone'	Control – no pruning	10.2	7.8	7.3	3.5	3.5	3.5	2.5	1.4	1.4
	Central leader - narrow pruned	9.0	7.9	5.3	3.5	3.9	3.5	2.3	1.8	1.0
'Garnem'	Control – no pruning	12.2	8.5	6.8	3.7	3.7	3.6	3.4	1.9	1.4
	Central leader - narrow pruned	10.6	5.4	4.6	3.5	3.7	3.5	3.0	1.2	0.9
'Nemaguard'	Control – no pruning	9.4	7.9	5.6	3.8	3.9	3.5	2.7	1.6	1.1
	Central leader - narrow pruned	8.4	5.8	5.5	3.8	3.9	3.2	2.1	1.5	1.1
	Least significant difference		*3.0*			*0.4*			*0.8*	

[1] Adjusted to 5.0% moisture content

Table 7. Effect of rootstock and pruning treatment at Orchard 2, on kernel yield per hectare of 'Monterey', 'Nonpareil' and 'Price' almond trees at harvest in February/March 2019. Control trees were left unpruned while the central leader trees were narrow pruned during 2018 (refer text for details). All trees were planted in winter 2016. Yields for control trees were calculated at the planting density for the orchard (6.85 x 3 m, 487 trees/ha) and compared with yields of central leader – narrow pruned trees also at 487 trees/ha and assuming either 556 trees/ha (6 x 3 m) or 667 trees/ha (5 x 3 m). Values are tree averages (n = 4).

		Kernel weight (t/ha)[1] 487 trees/ha			Kernel weight (t/ha) 556 trees/ha			Kernel weight (t/ha) 667 trees/ha		
Rootstock:	**Pruning treatment:**	**'Monterey'**	**'Nonpareil'**	**'Price'**	**'Monterey'**	**'Nonpareil'**	**'Price'**	**'Monterey'**	**'Nonpareil'**	**'Price'**
'Bright's Hybrid'	**Control – no pruning**	1.3	0.9	0.9						
	Central leader - narrow pruned	1.6	0.7	0.7	1.8	0.8	0.8	2.1	1.0	1.0
'Cornerstone'	**Control – no pruning**	1.2	0.7	0.7						
	Central leader - narrow pruned	1.1	0.9	0.5	1.3	1.0	0.6	1.5	1.2	0.7
'Garnem'	**Control – no pruning**	1.6	0.9	0.7						
	Central leader - narrow pruned	1.5	0.6	0.4	1.7	0.6	0.5	2.0	0.8	0.6
'Nemaguard'	**Control – no pruning**	1.0	0.8	0.5						
	Central leader - narrow pruned	0.8	0.7	0.5	1.2	0.8	0.6	1.4	1.0	0.7
	Least significant difference	*0.4*			*0.4*			*0.5*		

[1] Adjusted to 5.0 % moisture content

Using 487 or 556 trees per hectare for the narrow-pruned, central leader trees, there were significant cultivar and rootstock effects, and a significant cultivar x rootstock interaction. 'Nonpareil' trees performed similarly on all rootstocks, whereas 'Monterey' gave higher (p=0.033) yields on 'Bright's Hybrid' and 'Garnem' rootstocks than on 'Cornerstone' or 'Nemaguard', and 'Price' gave higher yields on 'Bright's Hybrid' than on 'Garnem' or 'Nemaguard' (Table 7). There was no significant pruning treatment effect, suggesting the potential higher density of narrow-pruned trees would balance the lower per-tree yield.

At 667 trees per hectare for the narrow-pruned, central leader trees, there were significant cultivar, rootstock and pruning effects, and significant cultivar x rootstock and cultivar x pruning interactions. As before, 'Nonpareil' performed similarly on all rootstocks, whereas 'Monterey' gave higher (p=0.043) yields on 'Bright's Hybrid' and 'Garnem' rootstocks than on 'Cornerstone' or 'Nemaguard', and 'Price' gave higher yields on 'Bright's Hybrid' than 'Garnem' or 'Nemaguard' (Table 7). At the higher planting density, the pruned trees gave higher (p=0.049) yields per ha than the controls on 'Monterey', while yields were similar between pruned and unpruned control trees for 'Nonpareil' and 'Price'.

Tree canopy diameters were measured across the rows in January 2020, when branches would have been bearing the full weight of the crop. These data showed that the narrow-pruned, central leader trees were on average narrower than the control trees, by 0.32, 0.52 and 0.34 m for 'Monterey', 'Nemaguard' and 'Price', respectively (Table 8, Figure 4). These data support the option of planting narrow-pruned trees at 6 x 3 m or even 5 x 3 m spacing. Note that these data were taken from the edges of the leaf canopy and do not take into account the location of large branches that impede orchard machinery. The narrow prune would have removed these large branches growing towards the centre of the rows and so enabled the closer row spacing.

Table 8. Tree canopy diameter measured east-west (across rows) of control and central leader 'Monterey', 'Nonpareil' and 'Price' almond trees planted at Orchard 2 in July 2016. Control trees were pruned to 90 cm and all branches removed before planting, while central leader trees were left with no pruning in the first 2 years, then narrow pruned during 2018 (refer text for details). Data were combined from 'Bright's Hybrid', 'Cornerstone', 'Garnem' and 'Nemaguard' rootstocks. Data were collected in January 2020. Values are tree averages ± SE (n = 16). Values in each column followed by the same lower-case letters were not significantly different. Significance: * = p<0.05; ** = p<0.01; *** = p<0.001.

	Tree canopy diameter (m) across rows (2020)			
	Control	**Central Leader (narrow pruned)**	*Significance*	*p-value*
'Monterey'	4.01 ± 0.06 ab	3.69 ± 0.09 ab	**	*0.002*
'Nonpareil'	4.47 ± 0.11 b	3.95 ± 0.09 b	***	*0.001*
'Price'	3.83 ± 0.12 a	3.49 ± 0.11 a	*	*0.039*
Significance	***	**		
p-value	*<0.000*	*0.006*		

Figure 4. 'Monterey' (left) and 'Nonpareil' (right) trees on 'Garnem' rootstock at Orchard 2 in January 2020. Trees were planted in 2016. Pruning treatments were applied to groups of three trees each. The first three trees along the row are the unpruned control trees, the second set of three trees are the narrow-pruned central leader trees. The branches in the unpruned control trees can be seen drooping down with the weight of the fruit.

Concluding comments

This project provided the opportunity to work with a number of scion cultivars with differing growth habits in the nursery and in the orchard. Compared with 'Nonpareil', the industry standard cultivar, 'Monterey' trees produced a more spreading canopy associated with the numerous long unbranched shoots formed in the early years. Several of these shoots needed to be pruned to create a narrower canopy suitable for high density plantings. On the other hand, 'Price', a very upright cultivar with acute branching angles, required minimal pruning to create a canopy suitable for high density plantings.

We were also interested in the propensity of different cultivars to develop and maintain a strong central leader tree structure, as we believed this to be an important step in producing a narrower tree canopy suitable for high density orchards. Growing central leader trees in the nursery proved to be no problem at all, apart from when trees produced too many axillary shoots, as these needed to be removed to produce a clean trunk up to 60 cm, to provide access for tree shakers during harvest. Once planted in the orchard, the central leader trees maintained their shape for the first 3 months of growth. However, by the end of the season the basitonic growth habit, characteristic of the current almond cultivars, came into play and it became difficult to distinguish between central leader and control trees. The benefits of having the structural limbs spread over a longer section of trunk, as with the central leader trees, were still apparent.

We anticipated that the central leader trees, with their existing component of branching, might produce more flowers than the control trees in spring following planting and in subsequent seasons. This was not the case. Of more concern, however, was that the 'Carmel' trees produced too many flowers near the top of the central leader trees, which inhibited any extension growth of the leader. This was not an issue with the other three cultivars that were examined in this project.

The different rootstocks expressed their expected influence over tree vigour, with trees on 'Garnem' and 'Bright's Hybrid' rootstocks being more vigorous than trees on the medium-vigour rootstocks 'Nemaguard' and 'Cornerstone'. These differences were not substantial, although they may not fully express themselves until much later in the life of the orchard. We also noted that it was easier to maintain a central leader growth habit with the higher vigour rootstocks than with the less vigorous rootstocks. This effect may be even more pronounced with low-vigour rootstocks, making it difficult to establish a central leader structure with trees on these rootstocks.

An unexpected feature from this research was the effect that the clone of ‘Bright’s Hybrid’ rootstock used in this study had on the branching patterns of the scion cultivars. No data were collected, but it was obvious that across all scion cultivars, those trees on this clone of ‘Bright’s Hybrid’ rootstock produced several relatively short shoots, in addition to the normal component of medium to long shoots (Figure 5). Our data did not indicate that this increased yield, as yields were similar for trees on ‘Garnem’ rootstock; however, it will be interesting to follow these shoots to evaluate their cropping potential over the longer term.

‘Monterey’ budded on ‘Nemaguard’

‘Monterey’ budded on ‘Bright’s Hybrid’

‘Nonpareil’ budded on ‘Nemaguard’

‘Nonpareil’ budded on ‘Bright’s Hybrid’

Figure 5. Shoot structure within trees of ‘Monterey’ (top) and ‘Nonpareil’ (bottom) almond scion cultivars on ‘Nemaguard’ (left) and ‘Bright’s Hybrid’ (right) rootstocks. Scion cultivars budded on ‘Bright’s Hybrid’ rootstock stimulated numerous relatively short axillary shoots, in addition to the normal component of medium to long shoots. This effect was consistent across all scion cultivars tested.

It is important to note here that the 'Bright's Hybrid' rootstocks used in this study were supplied by Mark Ryland as small, own-rooted cuttings propagated from clonal stock plants at the AUSBUDS nursery in Victoria. These stock plants were grown from tissue cultured material originally produced by ForBio Research (now RAMM Botanicals) in New South Wales. The exact origin of the 'Bright's Hybrid' clone propagated by ForBio Research is unclear.

'Bright's Hybrid' is an almond/peach hybrid rootstock (*Prunus dulcis* cv. Titan × *P. persica* cv. Nemaguard) first developed by the Bright's Nursery in California. The original plants sold as 'Bright's Hybrid' were selected seedling trees emanating from crosses between 'Titan' and 'Nemaguard'. Material of one or more of these seedling trees were subsequently propagated as clonal rootstocks and also sold as 'Bright's Hybrid'. In June 2006, the Bright's family gained a patent for one of these clones which they commercialised as Bright's Hybrid® #5. Meanwhile, in Australia, 'Bright's Hybrid' had become an industry standard rootstock, first propagated as selected seedlings and more recently as clonal plants. While more than one clone may have been sold in Australia under the name 'Bright's Hybrid', it is most unlikely that the Bright's Hybrid® #5 clone was included among them. Further research is required to confirm if any of these clones, including Bright's Hybrid® #5, produce the same branching effect on the scion variety as described here using the AUSBUDS clone of 'Bright's Hybrid'.

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APPENDIX V. Yield potential of narrow-pruned almond trees

Introduction

In traditional almond orchards, growers promote the growth of several strong scaffold branches on their trees which, without further pruning, quickly produce large and spreading fruiting canopies. Trees are generally planted at wide spacing between and within rows, for example 7 x 4.25 m (336 trees/ha), to allow room for the establishment of these large trees. Precocity, or the cropping potential of young almond trees, can have a negative effect on tree structure, as high yields can cause the collapse of young fruiting canopies.

'Nonpareil' has been the almond industry standard cultivar in California and Australia for several decades; in 2018, 46% of almond plantings in Australia were 'Nonpareil' (www.australianalmonds.com.au). 'Nonpareil' is not self-fertile and so requires polleniser varieties, such as 'Carmel', 'Monterey' and/or 'Price' trees, to be planted in alternating rows. 'Nonpareil' is the preferred variety in the market and the standard by which the market value is determined for kernels produced by polleniser varieties.

'Nonpareil' is not a high yielding cultivar when young, compared with the polleniser varieties, and generally forms a strong fruiting canopy with little pruning intervention required. However, with the high-yielding polleniser varieties, growers have learnt to adapt their management protocols to use more intervention pruning to prevent young trees from collapsing under the weight of fruit.

Once almond trees mature and have established a strong framework of scaffold branches, new issues arise as a result of trees becoming crowded. Of particular concern is when large scaffold branches grow out into the centre of the rows and restrict machinery access for normal orchard operations. These are the large branches that will "tear the windscreens out of tractor cabs". The standard remedy is that once trees become crowded, growers start a program of mechanical hedging to cut back the trees in winter to enable easier access for machinery. This pruning can reduce the productive potential of trees and orchards as it removes a lot of potential fruiting wood, which on older heavily shaded trees does not generate new shoot growth.

More recently growers have experimented with closer planting distances, for example 6 x 3 m spacing (556 trees/ha), to obtain higher yields from young orchards. The risk with these higher density plantings is that the trees become crowded sooner than with traditional planting designs.

In this project, we compared the pruning responses of 'Nonpareil' and 'Monterey' trees with two new, highly productive, self-fertile cultivars 'Carina' and BA2 (Shasta®). We investigated the option of early intervention pruning to create narrower canopies on young trees, before crowding becomes an issue, which would be compatible with trees planted in 5 m wide rows, resulting in more trees per ha and thus even higher potential orchard yields.

Materials and methods

Planting material

Two projects were planted in 2016 with 'Carina', 'Monterey', 'Nonpareil' and Shasta® trees spring-budded in December 2015 on 'Nemaguard' rootstock. At each site, trees were planted with one scion cultivar per row, in adjacent rows, in the same orchard block.

Three tree types were planted in these trials:

1. **Control** Traditional tree management regime adopted by nursery/orchard to produce trees with a single trunk, headed back to 90 cm and all side shoots trimmed to two buds. This pruning stimulates growth of several large scaffold branches.
2. **Central Leader – unpruned** Spring-budded trees selected in the nursery to have a single dominant trunk with multiple side branches and planted with no pruning of lateral shoots.
3. **Central Leader – bare pole** Spring-budded trees selected in the nursery to have a single dominant trunk with multiple side branches, with all lateral shoots/branches trimmed to two buds after planting.

Pruning regimes followed at each orchard included a combination of leader-release, dormant and in-season pruning:

1. Leader-release pruning

The main purpose of leader-release pruning was to maintain rapid extension of the central leader so that the tree reached maximum height as soon as possible. Generally applied in early summer, this pruning involved four to five cuts per tree to thin clusters (congestion) of shoots at the first section of branching below the terminal shoot. Pruning also involved removal of any aberrant branches that were growing vertically/upright on the main trunk as these would interfere with branch development along the main trunk.

2. Dormant, narrow-prune

Dormant, narrow-pruning in winter, aimed to produce a narrow palmette-style of tree suitable for closer row spacing. It involved use of heading cuts to cut back, by two thirds, any strong branches growing out towards the centre of the rows and to stimulate the production of fruiting wood in the lower tree canopy. Pruning cuts were selective, cutting back stronger shoots harder than less vigorous shoots. With some trees (especially 'Monterey'), additional heading cuts were made higher up on the tree and on the outside of the tree canopies, targeting the long/thin unbranched shoots and cutting these back by one third. The objective here was to help strengthen these shoots so that when they cropped in the following season there would be less tendency for the branches to break out or bend under the weight of the fruit.

3. In-season, narrow-prune

In-season, narrow-pruning, in early summer, involved thinning out or cutting back any vigorous re-growth from the dormant pruning cuts. The procedure was to cut back approximately one third of the length of shoots from the previous dormant cut and any vigorous new shoots developing from elsewhere in the canopy that needed to be strengthened for cropping in the next season. No, or very few, cuts were made to shoots growing along the row between trees; cuts were mainly made to shoots on the perimeter of the tree canopy facing the alley way. This pruning was targeted so as not to remove significant numbers of fruit.

Trial design and data collection

<u>Orchard 3</u>

Orchard 3 was located near Paringa in the Riverland region of South Australia. Trees were planted at 7 x 4.25 m spacing (336 trees per ha). All trees arrived from the nursery as traditional (control) unbranched trees headed back to 90 cm. Trees were planted in two blocks, with two treatments, control (unpruned) and narrow-pruned. The trees were planted in adjacent blocks with the same cultivar and rootstock combinations, propagated by the same nursery, and planted on the same date. For each block, the two treatments were applied to groups of six trees each, replicated four times (24 trees per treatment) in a systematic design with treatments alternating along the same row.

In the first block, narrow-pruned trees had the narrow-pruning treatment applied when dormant in August 2017; this involved the complete removal of shoots/branches growing out into the rows by cutting flush with the parent branch. In the second block, narrow-pruned trees had narrow-pruning treatment applied when dormant in 2018, when the trees were two-years-old. In this case, selected branches were cut back by two thirds using a heading cut, followed by an in-season prune in December 2018, after fruit set.

Tree height, trunk cross-sectional area (TCA) and canopy diameter across the rows (north–south) and along the rows (east–west) were measured in February 2019, before harvest. Calculations for canopy volume were based on a truncated inverted cone with an elliptic base (https://keisan.casio.com/exec/system/15374075528834).

Crops were machine harvested and the total fresh weight (hull, shell and kernel) per tree recorded. A 2.0 kg subsample was taken from the harvested crop for hulling and shelling to provide an approximately 100 g subsample of kernels. The moisture content of this subsample was determined using a Burrows DMC-750 moisture meter and this information used to adjust the total kernel yield data to kg of kernel at 5.0% moisture content.

Yields per hectare were calculated at the planting density for the orchard (7 x 4.25 m, 336 trees/ha), but for the pruned trees, yields were also calculated with either 556 trees/ha (6 x 3 m) or 667 trees/ha (5 x 3 m) and compared with the yield of unpruned trees at the standard planting density. This was done on the assumption that the narrow-pruned trees could be planted with rows closer together. Data were pooled from the six trees per replicate (n = 4) and analyses completed using analysis of variance with Minitab® v18.1.

Orchard 4

Orchard 4 was located near Darlington Point in the Riverina region of New South Wales. Trees were planted at 7 x 3 m spacing (474 trees/ha). All trees arrived from the nursery as central leader trees that had not been pruned in the nursery, other than to remove any shoots growing directly on the trunk below 60 cm. The intention was to apply three different pruning regimes to produce trees suitable for high-density orchards. Unfortunately, due to a misunderstanding at the orchard, we were not able to apply all three treatments to all cultivars and levels of replication were not ideal. Ultimately, we had control trees available for all cultivars, but only central leader – unpruned trees available for 'Carina' and 'Nonpareil' and central leader – bare pole trees available for 'Monterey' and Shasta®.

The pruning program for the control trees, as adopted at this orchard, included reducing the number of scaffold branches in winter 2017, leaving five scaffold branches, but making no more than four cuts per tree, plus cutting out the centre of each tree to create an "open vase".

The central leader trees were pruned in August 2017 using leader-release pruning. All trees were then narrow-pruned when dormant in May 2018, followed by an in-season prune in late-November 2018. Control trees were also narrow-pruned to emulate mechanical hedging which was standard orchard practice at this site. In late-December 2018, the orchard staff also used a hedge-trimming machine to apply a slight topping cut across all trees, cutting back 5 to 10 cm of shoot growth, as per their standard orchard practice.

Crops were machine harvested and yields determined, as described above for Orchard 3. Yields per hectare were calculated at the planting density for the orchard (7 x 4.25 m, 336 trees/ha). Data were pooled from the four trees per replicate and analyses completed using analysis of variance with Minitab® v18.1.

Results and discussion

Orchard 3

Pruning responses

Trees in the first block at Orchard 3 were narrow-pruned in August 2017, at the end of their first season's growth. By the end of the second year (winter 2018), there were no obvious effects of the narrow pruning treatment on tree size or growth habit, as the trees had easily outgrown the effects of the pruning cuts. No further pruning was applied to these trees and no further data were collected.

In the second block, trees were narrow-pruned when they were 2-years-old as we had carried out in a previous trial (Appendix II). Two rounds of pruning, a dormant and in-season prune, were completed. Branches on the 'Carina' and Shasta® trees were bearing substantial numbers of fruit at the time of the in-season prune; hence this pruning was targeted to minimise fruit losses. Some fruit losses were unavoidable, as several branches had already bent down under the weight of fruit and were already touching the ground (Figure 1).

Typically, pruning involved around 30 s per side for each round of dormant and in-season pruning.

Tree dimensions and yield

The narrow pruning treatment had no or little effect on trunk cross-sectional area, tree height or canopy width along rows (north–south direction) compared with the unpruned control trees (Table 1). However, the narrow-pruned trees were narrower, with canopy width across rows (east–west direction) being 0.8 to 1.0 m less than that for unpruned control trees. Corresponding to this result, canopy volume was consistently less on the pruned than unpruned control trees.

Fresh weight yields per tree were similar for 'Carina' and Shasta®, and were higher than 'Monterey' and 'Nonpareil' (Table 2). Kernel moisture content tended to be higher for 'Monterey', a late-maturing cultivar, than for the other cultivars.

At 336 trees/ha, the fresh weight yields per tree, kernel moisture content and kernel yield per ha were similar for unpruned control and narrow-pruned treatment trees. Because the narrow-pruned trees were consistently narrower than the unpruned-control trees, it is possible rows could be planted closer together. Thus assuming this allows for higher planting density (556 vs 667 trees/ha) with closer row spacing, then the kernel yield per ha for the pruned trees at 556 or 667 trees/ha would be consistently higher than for the unpruned trees at the standard 336 trees/ha (Table 2).

Shasta® unpruned control

Shasta® narrow-pruned

'Carina' unpruned control

'Carina' narrow-pruned

Figure 1. Shasta® and 'Carina' almond trees at Orchard 3, immediately prior to harvest in February 2019. Trees were planted in 2016. Trees on the left were unpruned control trees and trees on the right had been narrow-pruned (refer text for details). Both Shasta® and 'Carina' are precocious high-yielding cultivars. With these cultivars, the weight of the maturing crop causes the fruiting branches to bend out and downwards, creating issues for machinery access and limiting the trees' potential to be grown at high density with closer row spacing. The narrow-pruning treatment was employed to minimise this.

Table 1. Dimensions of 'Carina', 'Monterey', 'Nonpareil' and Shasta® almond trees in response to narrow pruning at Orchard 3 in 2018 (refer text for details). Trees were spring-budded on 'Nemaguard' rootstock and planted in 2016 at 7 x 4.25 m spacing with rows running in a north–south (N-S) direction. Data were collected in February 2019, before harvest, and pooled from four replicates with six trees per replicate. Values are replicate averages ± SE (n = 4). Significance: NS = not significant; (*) = *p*<0.10; * = *p*<0.05; ** = *p*<0.01; * = *p*<0.001.**

Cultivar:	Treatment:	Trunk cross-sectional area (cm^3)	Tree height (m)	Canopy diameter (m)		Canopy volume (m^3)[1]
				N-S	E-W	
'Carina'	**Control**	108.7 ± 4.8	3.6 ± 0.08	3.8 ± 0.08	3.9 ± 0.09	17.2 ± 1.7
	Narrow-pruned	110.7 ± 4.0	3.7 ± 0.10	3.7 ± 0.04	2.9 ± 0.06	13.9 ± 0.7
	Significance	*NS*	*NS*	*NS*	***	*NS*
	p-value	*0.755*	*0.443*	*0.404*	*<0.001*	*0.127*
'Monterey'	**Control**	102.9 ± 1.1	3.8 ± 0.08	3.7 ± 0.09	3.9 ± 0.09	19.1 ± 0.1
	Narrow-pruned	107.8 ± 2.0	3.9 ± 0.09	3.9 ± 0.09	3.0 ± 0.10	15.7 ± 0.8
	Significance	*(*)*	*NS*	*NS*	***	**
	p-value	*0.078*	*0.800*	*0.192*	*<0.001*	*0.006*
'Nonpareil'	**Control**	101.5 ± 2.5	4.1 ± 0.04	3.6 ± 0.06	3.5 ± 0.07	18.3 ± 0.8
	Narrow-pruned	100.2 ± 2.7	4.1 ± 0.04	3.6 ± 0.10	2.7 ± 0.07	14.2 ± 0.7
	Significance	*NS*	*NS*	*NS*	***	**
	p-value	*0.743*	*0.999*	*0.833*	*<0.001*	*0.009*
Shasta®	**Control**	108.7 ± 2.9	3.7 ± 0.07	3.7 ± 0.06	4.0 ± 0.08	18.5 ± 0.4
	Narrow-pruned	107.8 ± 1.5	3.8 ± 0.04	3.8 ± 0.07	3.1 ± 0.02	15.6 ± 0.3
	Significance	*NS*	*	*NS*	***	**
	p-value	*0.796*	*0.045*	*0.505*	*<0.001*	*0.006*

[1] Based on a truncated inverted cone with an elliptic base

Table 2. Fresh weight of whole fruit (hull + shell + kernel) at harvest, kernel moisture content and yield per tree and per hectare of 'Carina', 'Monterey', 'Nonpareil' and Shasta® almond trees in response to narrow pruning at Orchard 3 in 2018 (refer text for details). Trees were spring-budded on 'Nemaguard' rootstock and planted in 2016. Data were pooled from four replicates with six trees per replicate. Values are replicate averages ± SE (n = 4). Significance: NS = not significant; * = *p*<0.05; ** = *p*<0.01. Yields per hectare for the control trees were calculated at the planting density for the orchard (7 x 4.25m, 336 trees/ha) and compared with yields from pruned trees at 336 trees/ha and assuming either 556 trees/ha (6 x 3 m) or 667 trees/ha (5 x 3 m).

Cultivar	Treatment	Fresh weight (kg/tree)	Kernel moisture (%)	Kernel weight (t/ha)[1]		
				336 trees/ha	556 trees/ha	667 trees/ha
'Carina'	Control	30 ± 1.5	5.5 ± 0.4	1.49 ± 0.03		
	Narrow-pruned	32 ± 2.0	6.0 ± 0.1	1.37 ± 0.10	2.26 ± 0.17	2.72 ± 0.20
	Significance	*NS*	*NS*	*NS*	**	**
	p-value	*0.599*	*0.217*	*0.289*	*0.004*	*0.001*
'Monterey'	Control	19 ± 0.7	7.2 ± 0.6	1.40 ± 0.08		
	Narrow-pruned	21 ± 0.8	10.3 ± 1.7	1.26 ± 0.12	2.09 ± 0.19	2.50 ± 0.23
	Significance[2]	*NS*	*NS*	*NS*	**	**
	p-value	*0.313*	*0.135*	*0.386*	*0.016*	*0.004*
'Nonpareil'	Control	14 ± 0.8	4.4 ± 0.2	0.76 ± 0.08		
	Narrow-pruned	13 ± 0.8	5.0 ± 0.4	0.63 ± 0.08	1.04 ± 0.13	1.25 ± 0.16
	Significance[2]	*NS*	*NS*	*NS*	*NS*	*
	p-value	*0.259*	*0.220*	*0.295*	*0.115*	*0.033*
Shasta®	Control	33 ± 4.0	5.6 ± 0.5	1.90 ± 0.09		
	Narrow-pruned	34 ± 3.2	5.7 ± 0.6	1.72 ± 0.11	2.85 ± 0.19	3.42 ± 0.22
	Significance[2]	*NS*	*NS*	*NS*	**	**
	p-value	*0.945*	*0.928*	*0.255*	*0.004*	*0.001*

[1] Adjusted to 5.0% moisture content

Orchard 4

Pruning responses

All trees were staked and established very well, with clear differences appearing between the growth habit of trees planted as control and central leader trees during the first year of growth (Figure 2). Field observations were that early season shoot growth was earlier and more vigorous on the control trees than the central leader – unpruned trees, and was earlier and more vigorous on the central leader – bare pole trees than the central leader – unpruned trees. These differences most likely related to the number of growing points (buds) remaining after pruning on each tree, ranging from low to medium to high on the control, central leader – bare pole and central leader – unpruned trees, respectively. The delayed growth on the central leader – unpruned trees was possibly not detrimental, as these trees formed a smaller, narrower canopy that was more stable during the extremely high winds typically experienced during spring and summer in this growing region.

An interesting feature of the central leader – bare pole trees was that the new shoot growth generally formed from the basal buds on the pruned axillary shoot; the growth from these basal buds tended to be more horizontal, with a less acute branching angle, than shoots arising directly from the trunk. In other temperate tree fruit industries this feature has been associated with less vigour and higher productivity.

By the second year, however, the strong basitonic growth habit of the current almond cultivars had taken over and it became difficult to distinguish between the control and central leader trees. This was despite all central leader trees being leader release pruned in winter. Basitonic growth habit is when the lower, structural branches on a tree become more dominant than branches further up in the tree, creating a much wider rather than narrower tree canopy.

In-season pruning of all trees at Orchard 4, in Year 3, was undertaken in late-November 2018. More cuts were required with 'Monterey' as there was strong regrowth from the dormant pruning in May than with the other cultivars. Shasta® trees required less pruning as there were fewer cuts made during dormant pruning than with 'Monterey' and less regrowth. At the time of the in-season prune, long shoots on Shasta® that were left unpruned during winter were now bending down under the weight of the fruit and required cutting back. A moderate number of cuts were required on 'Nonpareil' trees during in-season pruning, mainly cutting regrowth from the dormant pruning in May. Few to moderate cuts were required on 'Carina' as relatively few cuts were made during winter and many of these cuts had failed to generate new shoot growth. Typically, pruning involved around 1 minute per side for each round of dormant and in-season pruning, with more cuts needed on 'Monterey' trees and less cuts needed on the 'Carina', 'Nonpareil' and Shasta® trees.

Spring frosts during flowering in 2018 reduced the crop harvested from these trees in February/March 2019. Without heavy crops on the trees at this site there were no issues with limb breakage or branches bending under the weight of the fruit. Hence, the trees were still upright and very uniform at harvest (Figure 3).

'Carina' control | **'Carina' central leader – unpruned** | **Shasta® control** | **Shasta® central leader – bare pole**

Figure 2. Shasta® and 'Carina' almond trees at Orchard 4 in February 2017 (upper row) and August 2018 (lower row). All trees were spring-budded on 'Nemaguard' rootstock and planted in 2016, as unpruned control, central leader – unpruned and/or central leader – bare pole (refer text for details).

Shasta® **'Nonpareil'**

'Carina' **'Monterey'**

Figure 3. Narrow-pruned Shasta®, 'Nonpareil', 'Carina' and 'Monterey' almond trees at Orchard 4 in February 2019. All trees were planted in 2016 and dormant pruned by hand in May 2018 to produce a narrow palmette-style of tree suitable for closer row spacing. Pruning involved use of heading cuts to cut back any strong branches growing out towards the centre of the rows. Trees were then hand pruned in November 2018 to stimulate the production of fruiting wood for next season's crop in the lower tree canopy. In late-December 2018, all trees also received a light topping using a hedge trimmer, cutting back 5 to 10 cm of growth, as per standard orchard practice at this site.

Kernel yields

'Nonpareil' trees had the lowest fresh weight yield at harvest and 'Carina' had the highest (Table 3). Although not always significant, fresh weight yields were consistently higher on the central leader – unpruned and central leader – bare pole trees than the control trees. Kernel moisture contents were similar on 'Carina', 'Nonpareil' and Shasta® and were less than that on 'Monterey', a later-maturing cultivar. At 476 trees/ha, kernel yields per ha were similar on 'Carina', 'Monterey' and Shasta®, and were higher than on 'Nonpareil'. There was a similar trend for kernel yields per ha as that seen for fresh weight yields, with the standard 476 trees/ha being consistently higher on the central leader than control trees.

Table 3. Fresh weight of whole fruit (hull + shell + kernel) at harvest, kernel moisture content and yield per hectare of 'Carina', 'Monterey', 'Nonpareil' and Shasta® almond trees at Orchard 4. Trees were spring-budded on 'Nemaguard' rootstock and planted in 2016, as unpruned controls, central leader – unpruned and central leader – bare pole (refer text for details). Trees were planted at 7 x 3 m spacing (476 trees/ha). All trees were narrow-pruned in winter and early summer 2018. Data were pooled from replicates with four trees per replicate. Values are replicate averages ± SE. Significance: NS = not significant; (*) = *p*<0.10; * = *p*<0.05.

Cultivar:	Treatment:	Fresh weight (kg/tree)	Kernel moisture (%)	Kernel weight (t/ha)[1]
'Carina' (n=3)[2]	Control	3.1 ± 0.2	3.8 ± 0.1	0.21 ± 0.02
	Central Leader – unpruned	3.9 ± 0.6	3.6 ± 0.1	0.30 ± 0.04
	Significance	*NS*	*NS*	*NS*
	p-value	*0.255*	*0.346*	*0.133*
'Monterey' (n=3)	Control	2.3 ± 0.3	9.5 ± 1.0	0.13 ± 0.01
	Central Leader – bare pole	3.2 ± 0.2	10.3 ± 0.4	0.18 ± 0.01
	Significance	*	*NS*	*
	p-value	*0.047*	*0.476*	*0.036*
'Nonpareil' (n=1)	Control	0.31	4.1	0.028
	Central Leader – unpruned	0.25	4.5	0.023
	Significance	-	-	-
	p-value			
Shasta® (n=2)	Control	2.1 ± 0.3	3.4 ± 0.1	0.22 ± 0.04
	Central Leader – bare pole	3.1 ± 0.3	3.3 ± 0.1	0.31 ± 0.01
	Significance	*NS*	*NS*	*NS*
	p-value	*0.112*	*0.423*	*0.168*

[1] Adjusted to 5.0% moisture content
[2] n = number of 4-tree plots

Concluding comments

Two projects were planted in 2016 to explore a range of cultivars, tree types and pruning options for the establishment of almond orchards planted at higher density than is traditional. The trials were planted on private commercial orchards and because of restrictions around machinery access, it was not possible to have the trees planted at closer row spacing. However, the information and experience gained has provided important insights into the issues and opportunities with the implementation of high density almond orchards.

The obvious example from these projects is the low yield potential of young 'Nonpareil' trees compared with the polleniser cultivar 'Monterey' and in particular compared with the new self-fertile cultivars 'Carina' and Shasta®. While some management systems will work with the industry standard 'Nonpareil', adjustments are needed for other higher yielding cultivars.

The high yields recorded at Orchard 3, in particular, demonstrated the pressures on young trees to support large crops and the need for pruning interventions to develop a stronger fruiting framework. We believe this situation is made worse when trees are planted in the traditional form, with trees headed back to 90 cm to promote the rapid development of several large scaffold branches, all emanating from a similar position on the trunk. Narrow pruning, with a combination of dormant and in-season pruning starting in Year 2, helped mitigate some of the problems but not all.

The option we were interested to consider in these projects was to start with unpruned, central leader trees, direct from the nursery. In most nurseries this is the tree type that naturally grows, with a single trunk and with multiple side branches evenly distributed along the trunk. Depending on growing season and time of budding, these trees can be up to 1.8 m tall when planted.

The central leader trees planted at Orchard 4 developed good structure with scaffold branches well-spaced along the central leader. This was possible with both the central leader – unpruned and central leader – bare pole trees. Unfortunately we were not able to fully test this tree structure with a full load of fruit as, following successive frosts in both 2017 and 2018, these trees never had the opportunity to carry substantial crops. However, there was some indication in the data that yields were higher on the central leader trees than the control trees.

The important questions from these two projects then were: 1) should growers/nurseries stop heading their trees to 90 cm and aim for 1.5 m to promote more even scaffold development along the trunk; and 2) should growers be encouraged to carry fewer fruit on young trees, especially the new highly precocious cultivars?

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APPENDIX VI. Almond tree architecture – assisting breeders to redesign almond trees for future orchards

Introduction

Perennial tree growth is modular in construction; architectural tree models describe the form and arrangement of these modules. They are rules-based developmental models that describe tree growth according to variations in axis differentiation, including patterns of branching and flowering. Extension of these models to finer categories can be used to define architectural ideotypes and to distinguish differences between scion cultivars of the same species.

Understanding tree architecture and how trees respond to manipulation, is fundamental to orchard system design and developing new management systems, specific for each crop and cultivar. With a knowledge of tree architecture, we are better able to describe physiological mechanisms and to identify/quantify architectural traits associated with high productivity.

Architectural traits that form the unique branching and fruiting pattern of trees within the same genera and/or species include whether trees form monoaxial (single) or polyaxial (multiple) trunks; acrotonic (terminal) or basitonic (basal) branching dominance; plagiotropic (horizontal) or orthotropic (vertical) shoot orientation; and terminal or axillary location of flowers. Within species, branching patterns of different genotypes/cultivars can be described as either proleptic (delayed) if from a resting bud, or sylleptic (immediate) if growth is contemporaneous with extension of the parent shoot. In many temperate tree crops, such as almond and apple, shoot types can also be classified as short (spurs), medium (brindilles/dards) or long (vegetative). Tree growth can also be described as decurrent, growing downwards, or excurrent, growing in a more vertical orientation (Figure 1). It is the combination of these features that give a cultivar its characteristic form.

In commercial tree fruit production, the above architectural features are typically modified by pruning and training to suit a particular growing system or orchard design. These modifications can commence in the nursery or when the young tree is first planted in the orchard. For example, almond trees generally exhibit a strong basitonic growth habit, producing a set of very large scaffold branches near the base of the trees. Growers promote this natural growth tendency by cutting the trunks of young trees back to 90 cm to stimulate the formation of these scaffold branches. The trees inevitably develop wide canopies with poor light transmission to lower canopy zones, resulting in a large barren area in the centre of each tree. Experience from other tree fruit crops is that orchards with narrow, slender pyramid-shaped trees, have much improved light interception and are more productive and profitable than traditional orchards. If we want to redesign almond orchards to fit these new growing systems, then we need to redesign almond trees with new cultivars with architectural traits better suited to more intensive growing systems (Figure 1).

Current planting regimes and management systems in Australia are based on Californian cultivars and practices. ‘Nonpareil’ is the industry standard cultivar but it requires cross pollination. For this reason, blocks are planted with rows of ‘Nonpareil’ trees alternating with rows of polleniser cultivars. New highly productive, self-fertile cultivars from breeding programs in Australia and California are now available to Australian growers. The objective of this current project has been to evaluate a range of these standard and new cultivars, along with a range of novel genotypes from international breeding programs, to identify those with architectural features better suited to high density growing systems. An expected outcome from the research will be a set of architectural traits that breeders can use, at an early stage in the breeding cycle, to select/screen for or against in their breeding populations.

Figure 1. A compact, upright tree like R52 T202 with excurrent branching (left) will be easier to manage in high density blocks than trees with wide, spreading canopies and long, decurrent branching like R19a T166 (right). These differences are obvious within the first 2 years of growth.

Materials and methods

Our objective was to help almond breeders develop methods to accelerate breeding and selection of almond cultivars with architectural features associated with high productivity and that are suitable for planting in high density orchards. In a series of short-term studies we developed methods to characterise desirable architectural traits in current and future almond cultivars, starting with trees in their first leaf.

In each project described here, the trees were budded with a single bud to form the trunk. All axillary shoots were removed from the trunks up to 60–70 cm high, after which trees were left with no pruning to grow as central leader trees. Trees were budded in the nursery in summer and transferred to the orchard in the following winter where they were left to develop for a further 2 years, with no pruning, so that the true natural growth habit of each genotype, including flowering and fruiting patterns, could be observed/recorded.

Branching patterns on 1-year-old trees - California

In this project in California we collected data on the branching patterns of 1-year-old, unpruned almond trees from a range of cultivars with distinctive growth habits (ideotypes) and used the L-studio modelling platform to provide 3D simulations of the growth attributes of each cultivar (www.algorithmicbotany.org).

The first round of data collection was completed in October 2016 at the Burchell Nursery in Oakdale, California using 1-year-old, unpruned almond trees of eight commercial cultivars (10 trees of each cultivar) budded in May 2016 onto seedling 'Nemaguard' rootstock. The cultivars included were 'Nonpareil', 'Aldrich', 'Carmel', 'Fritz', 'Monterey', BA2 (Shasta®), 'Winters' and 'Wood Colony'. Data collected included tree height and diameter at the base, mid-point and apex of the parent growth axis (trunk). The total number of nodes and position of axillary shoots along the trunk, and the basal diameter and length of each axillary shoot, were also recorded. Average branch angle was determined from a subset of the axillary shoots. These data were used by Dr Neil White from The University of Queensland to create 3D simulations of each genotype using the L-studio modelling platform.

Commercial cultivars and advanced genotypes - Australia

In Australia, we worked with the new Australian-bred almond cultivars 'Carina', 'Capella', 'Maxima', 'Mira', 'Rhea', 'Vela' and eight advanced selections from The University of Adelaide almond breeding program, with 'Nonpareil' as a control. All trees of the 15 genotypes were budded on 'Garnem' rootstock in mid-December 2017. In July 2018, the trees were transferred and planted at the Almond Board of Australia (ABA) Almond Centre of Excellence experimental orchard at Loxton North in the Riverland region of South Australia. The trees were planted in blocks spaced at 4.5 x 3.0 m (741 trees per ha). There were five experimental blocks for each genotype extending across five rows with 60 trees per row (300 trees) in a randomised complete block design. Each genotype was planted in groups of four trees each, with data taken from the centre two trees.

In May 2018, while trees were still in the nursery, we recorded tree height, trunk diameter above the bud union, and the total number of shoots. Flexural rigidity of the trunk of each tree was also measured, using a three-point fulcrum device described in a subsequent section. In this project, the trees were held in place at the lower two points (35 and 45 cm above ground) and pressure applied at the upper point (65 cm above ground).

For two of the genotypes (R20a T101 and R19a T166) we collected additional data to describe the fate of each node along the trunks of the trees between autumn in Year 1 and summer in Year 2. In June 2018, we recorded the growth stage at each node on current season's wood as either: 0 = dormant bud; 1 = shoot; or 2 = insipient shoot (leafy bud) (Figure 2). Then on the same trees, in October 2018, we recorded the growth stage on the now 2-year-old wood as either 3 = dormant bud; 4 = leafy spur; or 5 = new shoot. Data are presented as the total number and percentage of nodes at each growth stage.

Figure 2. Stages of bud and shoot development on current season almond shoots, showing from left to right: dormant, undifferentiated bud; insipient shoot (leafy bud) with no internode extension; and new shoot with

internode extension.

In August 2019, data from all 15 genotypes were recorded in two sections, the first related to the central leader trunk as planted, and the second related to the extension of the central leader during the 2018/19 growing season, delineated by a transition zone between the two sections. Data collected included height to first branch and number of scaffold branches (>8 mm diameter) below the transition zone, total number of new shoots directly on the trunk above the transition zone, length of central leader extension beyond the transition zone, and trunk diameter above and below the transition zone (Figure 3). Tree height and trunk diameter at 50 cm were recorded again in November 2019.

Figure 3. Uniform extension of the central leader is desired at the transition zone between one growth flush and the next (left); compared with poor central leader development caused by dominant axillary branching (centre) or weak terminal bud development (right).

A prototype rating system based on these quantitative data was also developed to provide a qualitative description of the propensity for each genotype to produce a strong central leader. Key attributes included: dominance of the trunk; number, length, diameter and orientation of scaffold branches; and number, length and diameter of mainly sylleptic dard shoots and proleptic subterminal shoots (Figure 4). Dards are mainly sylleptic axillary shoots that develop at the same time as the parent shoot; they are generally located along the lower to mid-section of the parent shoot. Subterminal shoots are mainly proleptic axillary shoots that develop after a period of rest; they are generally clustered near the terminal bud on the parent shoot. These data were collected in August 2019, as observational data, with a single value obtained from observations of five pairs of trees per genotype.

Figure 4. Dards (left) are mainly sylleptic axillary shoots that develop at the same time as the parent shoot. Subterminal shoots (right) are mainly proleptic and develop after a period of rest; they are generally clustered around the terminal bud on the parent shoot. Note the high number of insipient shoots (leafy buds) on the trunk below the subterminal shoots.

Advanced genotypes - California

In a second project in California we worked with five commercial cultivars ('Nonpareil', 'Winters', 'Monterey', Shasta® and BA3 (Pyrenees®), seven advanced genotypes from the University of California (UC Davis) breeding program led by Dr Tom Gradziel, and two advanced genotypes from the Burchell Nursery almond breeding program led by John Slaughter and Kaylan Roberts. All trees of the 14 genotypes were budded on container-grown, 'Cornerstone' rootstock in June 2017 and planted in February 2018, with 4.6 x 2.3 m spacing (945 trees/ha), at the Burchell Nursery in Fowler, California. There were five experimental blocks of two trees each per genotype extending across five rows with 30 trees per row (150 trees) in a randomised complete block design with each genotype represented once in each row.

In November 2017, while the plants were still in the nursery, we recorded a range of architectural traits of 10 trees each of five of the UC Davis advanced selections, one Burchell advanced selection, and 'Nonpareil' and 'Winters' as controls. Traits measured included tree height, number of axillary shoots, and trunk diameter of the rootstock below the graft and of the scion at the first extended internode above the graft, at the mid-point along the trunk and near the apex of the plant at the last extended internode. Flexural rigidity of the trunk of each tree was also measured, using a three-point fulcrum method, with the trees held at 35 and 45 cm above the ground and pressure applied at a point 65 cm above ground, as described in the previous section.

Tree height and trunk diameter (at 50 cm) from all 14 genotypes in California were recorded again in January 2019, when the trees had been in the orchard for 12 months. Tags were attached to the primary growth axis (trunk) and to a single axillary scaffold branch on each tree to mark the transition point at the base of the 2018 season's extension growth. Each tagged branch usually included two or three sections of new growth. Basal diameter and length of each tagged branch and the number of axillary shoots and flowers were recorded in February and March 2019, and the number of fruit per branch counted in May 2019 to give % fruit set. In May 2019, we also recorded data from the tagged scaffold branch, including the growth stage at each node recorded as either 2 = 2018 shoot; 3 = dormant bud; 4 = leafy spur; or 5 = new shoot.

A prototype rating system, described in the previous section, was also used to provide a qualitative description of the propensity of trees of each genotype to produce a strong central leader. Key attributes included the relative dominance of the trunk and scaffold branches, as well as axillary shoot types. These data were collected in February 2019, as observational data with a single value obtained from observations of ten trees per genotype.

In a separate experiment we measured tree height, trunk diameter and flexural rigidity of 'Nonpareil', 'Winters' and Shasta® trees that had been budded in May 2017 onto field grown 'Nemaguard' rootstock at the Burchell Nursery in Oakdale. Data were collected in November 2017. Flexural rigidity was measured as described below, but as these were relatively large trees the upper fulcrum was placed 80 cm above ground.

Flexural rigidity

A new device was constructed to record the flexural rigidity or bending stiffness of trees with the ambition that this might be useful to identify genotypes with branches that easily bend under the weight of the developing crop, especially on young trees. Flexural rigidity was measured as the kilograms force (kgf) required to achieve a 45° bend in the trunk. Pressure was measured using an Imada ZTA Digital Force Gauge (www.imada.com). A device was developed based on a three-point fulcrum with the tree being held in place at the lower two points and the Imada pressure gauge applied at the upper point with pressure applied at right angles to the stem until a 45° angle was obtained (Figure 5).

Figure 5. A device based on a three-point fulcrum was used to measure the flexural rigidity (kilograms force to achieve a 45° bend) of the trunks of young almond trees. The device was fixed in two places, with the tree being held in place at the lower two points and an Imada pressure gauge applied at the upper point. Pressure was applied at right angles to the stem until a 45° angle was obtained.

Obviously large diameter stems required more pressure to bend than small diameter stems so this was used as a co-variate to correct data according to trunk diameter. Initially, one-factor analysis of variance (ANOVA) was done. Several measurements on the trees' trunks were checked as possible covariates. Diameter above the base of the graft was a significant covariate in all three data sets. Plotting flexural rigidity against the possible covariates, there appeared to be a good overall relationship between diameter above base of graft and flex. Analysis was carried out using Genstat version 17 (2014, VSNi Ltd, Hemel Hempstead, UK). Data are presented as the original means and standard errors (SE), and as the covariate-adjusted means with an LSD (least significant difference).

When collecting these flex data it was important to adjust the location of the upper point according to the average trunk diameter of the group of individuals being compared. When measuring flexural rigidity on populations of relatively small trees with thin, more flexible trunks, the upper point needed to be relatively low on the trunk and closer to the lower fixed points. With populations of relatively large trees with thick trunks and thus less flex, the pressure needed to be measured higher up the trunk further away from the fixed points. As long as the same points were used for all individuals in the population then valid comparisons could be made. Average readings of about 2–4 kgf were sought, because any higher than this increased the risk of individual trees requiring too much force to achieve a reading, and possibly damaging or at worst breaking the trunk. Only the first reading was used, as a second successive reading from the same tree tended to require less pressure.

Statistical analyses

Unless otherwise indicated, analyses were completed using analysis of variance with Minitab® v18.1. Percentage data were arcsin transformed for analysis and then back-transformed for presentation.

Results and discussion:

Branching patterns on field-grown nursery trees - California

Axillary shoot production on field-grown trees budded in May 2015 were recorded in October 2015, while the trees were still in the nursery. All cultivars expressed zonal branching, with a sequence of nodes with high branching frequency followed by a section with low frequency (Figure 6). Zonal branching was less apparent with ‘Winters’ which produced the most shoots ($p<0.001$) and more apparent with ‘Wood Colony’ which produced the least shoots, with 55 and 16 shoots, respectively. ‘Nonpareil’ and Shasta® had more consistent, diffused branching zones with numerous, relatively small shoots, compared with ‘Monterey’ which had numerous, long shoots (Figure 7). ‘Wood Colony’ and ‘Monterey’ also had a very strong branching zone low down on the tree.

Both ‘Fritz’ and ‘Aldrich’ had relatively narrow branch angles compared with ‘Wood Colony’ and ‘Monterey’ (Figure 7). Narrow branch angles would be useful in high density plantings, but both ‘Fritz’ and ‘Aldrich’ produced relatively few axillary shoots which is not desirable. While ‘Monterey’ and ‘Wood Colony’ may be well suited to the “multiple-axis” growing system used by most almond growers, they may not be suitable for “single-axis” growing systems being evaluated for new, high-density growing systems. It is possible that a more consistent diffused pattern of shoot production is a desirable attribute for central leader trees to be grown for high density orchards; ‘Nonpareil’ and Shasta® are good examples.

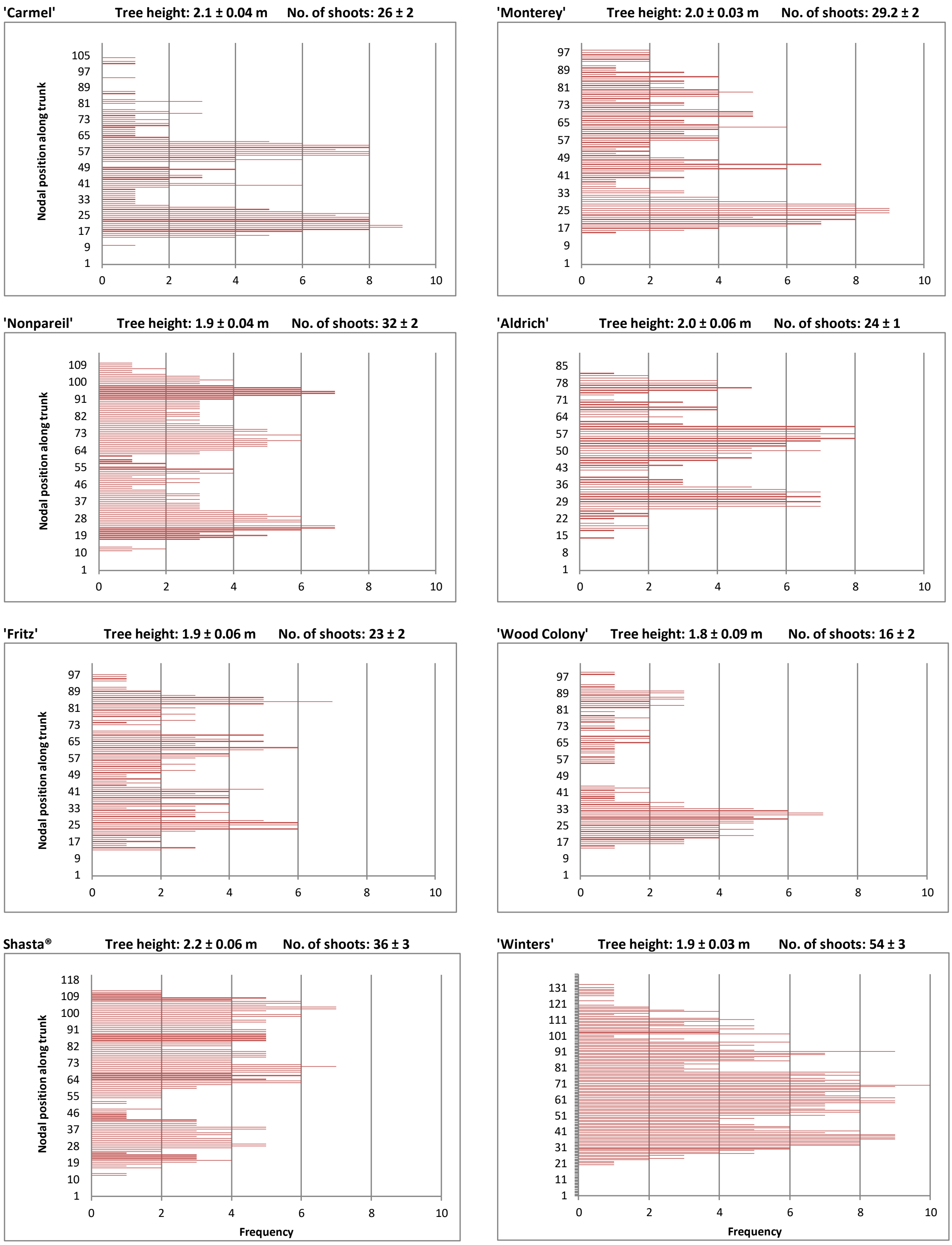

Figure 6. Frequency of branching at nodal positions along the trunks of ten, 1-year-old budded trees of eight almond cultivars. Trees were budded in May 2015 at Burchell Nursery in Oakdale, California. Data were collected in October 2015. Node 1 is at the base of the plant. Additional data are average tree height, measured from the bud union, and average number of axillary shoots per tree ± SE (n=10).

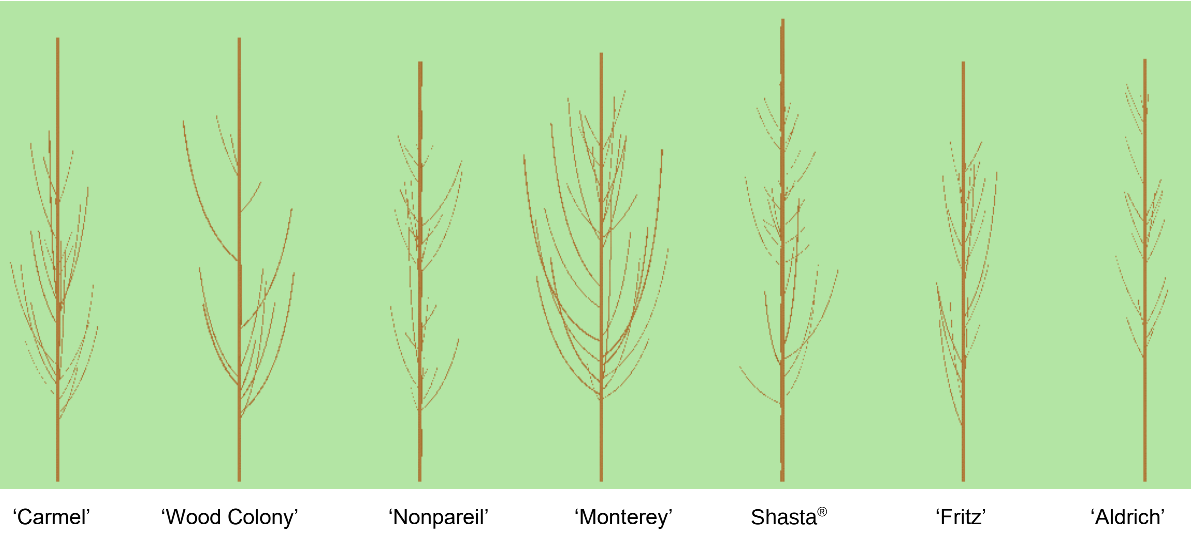

Figure 7. Growth simulations of 1-year-old almond trees still in the nursery, showed a range of branching habits typical for each cultivar. Desired attributes for central leader trees are uniform branching and even distribution of branches along the trunk, as tends to be seen on 'Nonpareil' and Shasta®. Simulation models were produced by Dr Neil White from The University of Queensland, using the L-studio modelling platform.

Commercial cultivars and advanced genotypes – Australia

In this project we worked with the new Australian almond cultivars 'Carina', 'Capella', 'Maxima', 'Mira', 'Rhea' and 'Vela', and eight advanced selections from The University of Adelaide almond breeding program led by Dr Michelle Wirthensohn, with 'Nonpareil' as a control. This combination of genotypes provided a range of tree types with substantial differences in tree stature and branching on trees while still in the nursery, just 6 months from budding. Tree height ranged from just 0.99 m on the compact growing R52 T202 genotype to 1.57 m on the R19a T166 and R20a T101 genotypes (Table 1). R20a T101 also had the largest average trunk diameter and R52 T202 had the smallest at 15.7 and 12.4 mm, respectively. The most substantial difference between the genotypes, however, was in the number of axillary shoots produced, ranging from 11.6 shoots on 'Rhea' trees to 39.1 shoots on genotype R36 T212 trees. Conversion of this value to number of shoots per m of trunk, from above 60 cm height, showed Rhea' trees produced 14 shoots per m, compared with R36 T212 trees which produced 60 shoots per m.

This group of trees also highlighted the issue of "nursery burn", where trees of some genotypes did not fully harden off in the nursery and still retained their leaves when planted in the field in winter. On some trees, this led to substantial shoot dieback and poor/delayed growth in spring.

A useful range of values for flexural rigidity was recorded among the different genotypes, ranging from 1.5 kgf for genotype R36 T212 to 3.6 kgf for R19a T166 (Table 2). Note that these values were adjusted using trunk thickness as a covariate. Whether this range proves to be sufficient to show up as a difference in stature of the mature cropping trees remains to be seen. Note that in this study the new cultivar 'Vela' had a relatively high flexural strength but the unpruned tree shows early development of a spreading tree shape. This is because this cultivar has a decurrent branching habit with axillary shoots that naturally extend downward, which is in contrast to cultivars such as 'Monterey' that produce long upright shoots that bend downwards in a cascading habit under the weight of fruit.

Table 1. Tree height, trunk diameter of the scion at the first extended internode above the bud union, and number of axillary shoots above 60 cm on the trunk of almond trees budded in December 2017 onto 'Garnem' rootstock and field grown at Mossmont Nursery in Griffith NSW. Data were collected in July 2018. Values are averages for each genotype ± SE (n = 10). Significance: *** = p<0.001.

Genotype	Tree height (m)	Trunk diameter (mm)	No. of axillary shoots	Axillary shoots per m[1]
'Capella'	1.29 ± 0.03	13.3 ± 0.6	24.0 ± 1.5	35 ± 2.9
'Carina'	1.42 ± 0.04	14.8 ± 0.6	19.7 ± 1.6	24 ± 2.3
'Maxima'	1.31 ± 0.03	14.0 ± 0.3	21.5 ± 1.9	30 ± 2.7
'Mira'	1.42 ± 0.05	14.3 ± 0.7	28.2 ± 1.6	35 ± 1.8
'Nonpareil'	1.42 ± 0.05	13.4 ± 0.5	24.2 ± 1.4	30 ± 1.4
R19a T166	1.57 ± 0.03	13.6 ± 0.6	18.5 ± 2.0	19 ± 1.9
R20a T101	1.57 ± 0.03	15.7 ± 0.5	22.4 ± 1.3	23 ± 1.0
R30a T25	1.38 ± 0.05	13.7 ± 0.7	15.6 ± 1.9	20 ± 2.4
R36 T195	1.30 ± 0.03	12.9 ± 0.4	22.2 ± 1.2	32 ± 2.2
R36 T212	1.25 ±0.03	14.3 ± 0.4	39.1 ± 2.6	60 ± 2.6
R52 T202	0.99 ± 0.04	12.4 ± 0.6	19.3 ± 1.5	53 ± 5.1
R52 T204	1.32 ± 0.01	15.5 ± 0.6	37.9 ± 1.9	53 ± 2.9
R8b T58	1.36 ± 0.04	14.1 ± 0.6	12.6 ± 0.9	17 ± 1.4
'Rhea'	1.39 ± 0.04	14.7 ± 0.8	11.6 ± 2.4	14 ± 2.8
'Vela'	1.43 ± 0.06	15.3 ± 0.6	18.6 ±1.5	23 ± 2.5
Significance	***	***	***	***
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*

[1] No. of axillary shoots per m of trunk above 60 cm height

Table 2. Flexural rigidity (kgf) of almond trees budded in December 2017 onto 'Garnem' rootstock and field grown at Mossmont Nursery in Griffith, NSW. Data were recorded in July 2018. Original values were also adjusted using trunk thickness of the scion at the first extended internode above the bud union as a covariate. Values are averages for each genotype ± SE (n = 10).

	Flexural rigidity (kgf)	
Genotype	**Original values**	**Adjusted values**
'Vela'	3.6 ± 0.5	3.1
'Mira'	3.4 ± 0.6	3.3
R19a T166	3.4 ± 0.5	3.6
R20a T101	3.0 ± 0.4	2.3
'Carina'	2.9 ± 0.4	2.6
R52 T204	2.6 ± 0.3	2.1
'Rhea'	2.5 ± 0.4	2.3
'Capella'	2.3 ± 0.3	2.7
R8b T58	2.1 ± 0.2	2.1
R30aT25	2.1 ± 0.2	2.3
'Maxima'	2.0 ± 0.2	2.0
'Nonpareil'	1.9 ± 0.2	2.2
R36 T195	1.9 ± 0.2	2.4
R36 T212	1.5 ± 0.2	1.5
R52 T202	1.0 ± 0.2	1.8
Least significant difference	*1.0*	*0.7*
p-value	*<0.001*	*<0.001*

With two of the genotypes, R20a T101 and R19a T166, we also recorded nodal development along the trunk of each tree in the nursery in May 2018, and again on the same trees once planted in the orchard in December 2018. All trees had been pruned in the nursery to remove all shoots below 60 cm, so data were collected from nodes beyond this point. Both genotypes exhibited high levels of bud break along their trunks in the nursery, producing either leafy buds (insipient shoots) or new shoots (Figure 2). R20a T101 and R19a T166 trees had 76.0 and 83.2% of nodes producing either a shoot or leafy bud in the nursery (Table 3). For leafy buds, 22.8 and 29.7% became a leafy spur in the second year and 10.7 and 16.9% became a new shoot, respectively. Overall, by December 2018, 56.1 and 59.5% of nodes had formed a shoot either in the nursery or in the orchard, and 29.8 and 32.6% of nodes had formed a leafy spur in the orchard, respectively. Further research is required to determine the potential productivity of each of these growth categories when the trees have produced their first crop.

Further data collected from the trees of all 15 genotypes related to the development of the central leader trunk, as planted in the orchard in winter 2018, and its extension during the 2018/19 growing season, delineated by a transition zone between the two sections. In August 2019, average tree height ranged from 2.46 to 3.25 m for R52 T204 and 'Mira', respectively (Table 4). Average trunk diameter ranged from 6.9 to 8.3 cm for R36 T212 and R52 T204, respectively. Central leader extension ranged from 0.89 m for R52 T204 to 1.48 m for 'Mira', which is consistent with tree height data.

Table 3. Description of axillary production (dormant bud, spurs and shoots) along the primary growth axis (trunk) of 1-year-old almond trees in the nursery in May 2018 and on the same trees in the orchard in December 2018. Ten trees each of two genotypes were budded on 'Garnem' rootstock in December 2017 and planted in August 2018 at Loxton North in the Riverland region of South Australia. Growth stages described in the nursery were: 0 = dormant bud; 1 = shoot; 2 = insipient shoot (leafy bud) and in the orchard the stages were: 3 = dormant bud; 4 = leafy spur; 5 = new shoot. Data are the number and percentage of each node at a particular growth stage. Values are averages for each genotype ± SE (n = 10).

Genotype:	R20a T101		R19a T166		
Total nodes per tree	98.4 ± 2.7		103.8 ± 2.6		
Nodes above first shoot[1]	55.1 ± 2.2		59.5 ± 3.0		
Growth stage transition	**Frequency**	**(%)**	**Frequency**	**(%)**	**Description:**
0 - 3	2.4 ± 0.7	4.4	0.4 ± 0.2	0.6	Dormant bud in nursery and in orchard in summer
0 - 4	3.8 ± 1.0	6.8	1.4 ± 0.5	2.3	Dormant bud in nursery, became leafy spur in orchard in summer
0 - 5	1.7 ± 0.6	3.0	4.3 ± 0.7	7.0	Dormant bud in nursery, became new shoot in orchard in summer
1 - 1	23.1 ± 1.3	42.5	20.9 ± 2.1	36.6	Shoot present in nursery (still present in orchard in summer)
2 - 4	12.6 ± 1.6	22.8	18.0 ± 2.4	29.7	Insipient shoot in nursery, leafy spur in orchard in summer
2 - 5	6.0 ± 1.0	10.7	9.8 ± 1.7	16.9	Insipient shoot in nursery, became new shoot in orchard in summer
0	5.4 ± 0.7	9.9	4.3 ± 0.8	6.9	Dormant buds on terminal shoot in summer, beyond the last axillary shoot
Outcome in orchard[2]	56.1%		59.5%		Branching frequency in orchard (% of nodes that formed a shoot either in the nursery or in the orchard)
	29.8%		32.6%		Spur-type frequency in orchard (% of nodes that formed a leafy spur in the orchard)

[1] Trees had been pruned in the nursery to remove all shoots up to 60 cm on the trunk, so bud fate data were collected from beyond this point

[2] Occurrence relative to the number of nodes above the first shoot

Table 4. Description of central leader trunk development and branching on 2-year-old almond trees. Ten trees each of genotype were budded on 'Garnem' rootstock in December 2017 and planted in August 2018 at Loxton North in the Riverland region of South Australia. Data relates to the central leader trunk as planted in August 2018 and to the extension of the central leader during the 2018/19 growing season, delineated by a transition zone between the two growth sections. Data were collected in August 2019. Values are averages for each genotype ± SE (n = 10). Significance: * = *p*<0.05; * = *p*<0.001.**

Genotype	Tree height (m)	Trunk diameter (cm)	Central leader extension (m)	Scaffold[1] branches per m	New shoots above transition point	Trunk diameter above transition point (mm)	Trunk diameter below transition point (mm)	Ratio of trunk diameter above and below
'Capella'	3.19 ± 0.09	7.5 ± 0.10	1.46 ± 0.04	15 ± 1.2	9 ± 1.1	21 ± 0.9	31 ± 1.2	0.70 ± 0.03
'Carina'	2.70 ± 0.06	7.6 ± 0.12	1.25 ± 0.03	14 ± 1.2	6 ± 0.8	17 ± 0.7	27 ± 1.6	0.64 ± 0.03
'Maxima'	2.61 ± 0.06	7.7 ± 0.13	1.28 ± 0.07	21 ± 1.5	12 ± 1.3	20 ± 0.9	30 ± 1.8	0.67 ± 0.04
'Mira'	3.25 ± 0.08	7.8 ± 0.12	1.48 ±0.06	17 ± 0.8	8 ± 1.1	18 ± 0.6	28 ± 1.8	0.64 ± 0.03
'Nonpareil'	3.14 ± 0.07	7.2 ± 0.06	1.43 ±0.03	17 ± 1.5	5 ± 0.7	21 ± 1.0	31 ± 1.4	0.68 ± 0.02
R19a T166	2.63 ± 0.07	7.2 ± 0.11	0.90 ± 0.13	12 ± 1.1	9 ± 1.4	17 ± 0.9	23 ± 1.2	0.75 ± 0.04
R20a T101	2.86 ± 0.06	7.6 ± 0.13	1.18 ± 0.08	14 ± 0.5	6 ± 1.1	19 ± 1.0	26 ± 1.2	0.71 ± 0.03
R30a T25	3.09 ± 0.08	7.7 ± 0.11	1.27 ± 0.10	14 ± 1.7	11 ± 1.6	20 ± 1.5	29 ± 1.7	0.68 ± 0.04
R36 T195	3.11 ± 0.04	8.0 ± 0.14	1.49 ± 0.06	18 ± 1.1	7 ± 1.3	20 ± 0.8	31 ± 1.8	0.67 ± 0.04
R36 T212	2.69 ± 0.05	6.9 ± 0.08	1.18 ± 0.08	12 ± 1.3	17 ± 2.8	20 ± 0.9	31 ± 1.4	0.66 ± 0.03
R52 T202	2.49 ± 0.05	7.7 ± 0.14	0.98 ± 0.05	20 ± 1.6	16 ± 2.1	17 ± 0.8	29 ± 1.3	0.59 ± 0.02
R52 T204	2.46 ± 0.06	8.3 ± 0.09	0.89 ± 0.04	17 ± 0.7	21 ± 1.9	18 ± 0.7	24 ± 0.6	0.74 ± 0.03
R8b T58	2.74 ± 0.04	7.9 ± 0.12	1.29 ± 0.05	16 ± 2.1	4 ± 0.7	17 ± 1.1	26 ± 1.7	0.66 ± 0.04
'Rhea'	2.86 ± 0.05	7.0 ± 0.13	1.29 ± 0.05	18 ± 1.3	4 ± 0.6	15 ± 0.8	25 ± 1.2	0.59 ± 0.03
'Vela'	2.55 ± 0.06	7.6 ± 0.08	0.87 ± 0.14	15 ± 1.7	8 ± 1.7	17 ± 0.7	25 ± 1.8	0.71 ± 0.05
Significance	***	***	***	***	***	***	***	*
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.028*

[1] Potential scaffold branches were axillary shoots with >8.0 mm diameter.

Scaffold branching density on the original trunk, below the transition zone, ranged from 12 to 21 branches per m of trunk for R19a T166 and 'Maxima', respectively (Table 4). These data are consistent with values obtained in the nursery where there were 12 and 21 axillary shoots, respectively, for these two genotypes (Table 1). The lower value indicated that not all of the axillary shoots present on the trees in the nursery reached a minimum 8.0 mm basal diameter to be classified as a potential scaffold branch. R36 T212 trees had the most axillary shoots per m of trunk in the nursery but had one of the lowest number of scaffold branches in the orchard, with 60 shoots in the nursery and only 12 in the orchard (Tables 1 and 4). It is possible that the high number of shoots on the young R36 T212 trees in the nursery inhibited strong scaffold shoot growth in the orchard. R52 T202 and R52 T204 trees also showed a large drop in shoot number between the nursery and the orchard. In contrast, R8b T58 went from 17 shoots in the nursery to 16 scaffold branches in the orchard. Clearly there is an optimum level of axillary shoot production for young trees, which can be identified in the nursery, to ensure development of an adequate fruiting framework as trees become older.

Almond trees start off in the nursery with dominant central leaders, but soon lose this habit in subsequent years. An indicator of this is the difference in trunk diameter of the central leader at the transition zone between Year 1 and Year 2 extension growth; a 1:1 ratio between these two values would indicate no change in diameter across the transition zone. No trees approached a 1:1 ratio (Table 4). R19a T166 trees were the best in this respect with a ratio of 0.75. Trees of R52 T202 and 'Rhea' had the lowest ratio values indicating a greater difference across the transition zone, i.e. a greater loss of central leader dominance.

Another indicator of central leader trunk development was obtained via an informal rating protocol based on observational data, an approach more amenable than the quantitative data presented in Table 4, for screening large breeding populations. Attributes were rated under 3 categories (trunk, scaffold branching and axillary shoots) using a scale from 1 to 3, with 1 regarded as undesirable and 3 as desirable traits. A rating index was then determined by taking the sum of the rating values for the trunk, average of values for scaffold branches and average of values for axillary shoots, then dividing by three, to give an overall score for that genotype (Table 5). The general concept was that a desirable ideotype would have a strong central leader, with numerous, short and medium vigour scaffold branches, a medium number of medium vigour but strong dards and few, medium vigour but strong subterminal shoots (Figures 3 and 4).

With this overall rating, R36 T212 and R30 T25 rated highly, and 'Vela' and R8b T58 were among the lowest (Table 5). 'Vela' had poor central leader trunk development, with horizontal branching and long, decurrent axillary shoots. R19a T166 also had a horizontal branching structure, which was interesting as the trunks on both genotypes in the nursery were relatively firm/rigid (Table 2 and Figure 1). R52 T202 and R36 T212 scored highly on the rating scale (Table 5); both genotypes have compact/upright growth and both have very supple wood in the nursery with low flexural rigidity (Table 2, Figure 1).

Table 5. Rating protocol for qualitative descriptions of central leader trunk development and branching on 2-year-old almond trees in Australia. Ten trees of each genotype were budded on 'Garnem' rootstock in December 2017 and planted in August 2018 at Loxton North in the Riverland region of South Australia. Data were collected in August 2019: observational data, with a single value obtained from five pairs of trees per genotype. Attributes were rated from 1 to 3, with 1 regarded as undesirable and 3 as desirable. Values are averages for each genotype ± SE (n = 5). Significance: NS = not significant; * = *p*<0.05; ** = *p*<0.01; * = *p*<0.001.**

	Trunk	Scaffold branches				Axillary shoots (current year)						
	Central leader (dominance)	Vigour (length)	Strength (diameter)	Number (count)	Orientation (angle)	Dards[1] (count)	Dards[1] (length)	Dards[1] (diameter)	Subterminal shoots[2] (count)	Subterminal shoots[2] (length)	Subterminal shoots[2] (diameter)	
Rating scale: **Genotype**	1-weak 2-moderate 3-strong	1-long 2-medium 3-short	1-weak 2-strong 3-medium	1-few 2-medium 3-many	1-horizontal 2-upright 3-compact	1-few 2-many 3-medium	1-long 2-short 3-medium	1-weak 2-medium 3-strong	1-many 2-medium 3-few	1-long 2-short 3-medium	1-weak 2-medium 3-strong	**Rating index[3]**
'Capella'	1.4	1.5	2.6	1.8	2.2	2.7	2.8	1.7	2.8	2.5	1.8	1.94
'Carina'	1.9	1.5	2.6	1.8	1.7	1.8	2.5	1.8	2.6	1.7	1.8	1.94
'Maxima'	2.1	1.6	2.9	2.5	1.5	2.5	2.9	1.9	2.8	3.0	1.8	2.24
'Mira'	2.5	1.1	2.2	2.2	2.0	2.7	2.7	1.8	3.0	2.2	1.8	2.25
'Nonpareil'	2.3	1.5	3	2.5	1.6	1.4	2.9	1.7	2.7	2.2	1.5	2.17
R19a T166	1.8	1.1	1.5	2.2	1.0	1.0	1.4	1.9	2.8	2.6	1.8	1.72
R20a T101	2.6	1.2	2.8	2.2	1.6	2.5	2.6	2.0	3.0	2.0	2.0	2.30
R30a T25	2.5	1.8	2.4	1.7	3.0	1.8	2.8	1.8	2.8	2.3	2.2	2.34
R36 T195	1.7	1.2	2.4	1.9	1.5	1.4	3.0	2.2	2.8	2.5	2.0	1.92
R36 T212	2.5	1.8	2.6	1.9	2.5	2.2	2.6	2.3	3.0	1.8	2.0	2.34
R52 T202	1.6	2.3	1.4	2.2	3.0	2.4	2.7	2.1	3.0	2.5	1.7	2.08
R52 T204	1.7	1.6	2.8	2.3	1.5	2.6	2.7	1.8	2.7	3.0	1.7	2.06
R8b T58	1.3	1.0	2.7	2.0	1.8	1.0	1.6	2.3	2.8	1.0	2.4	1.68
'Rhea'	1.7	1.3	3	2.1	1.6	1.0	2.3	1.2	2.6	1.7	1.8	1.82
'Vela'	1.3	1.2	2.5	1.8	1.0	1.8	1.0	2.1	3.0	1.4	2.1	1.61
Significance	***	***	**	***	***	***	***	**	*NS*	*	*NS*	
p-value	*<0.001*	*<0.001*	*0.002*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.006*	*0.761*	*0.018*	*0.482*	

[1] Dards are mainly sylleptic axillary shoots that develop at the same time as the parent shoot; they are generally located along the lower section of the parent shoot

[2] Subterminal shoots are mainly proleptic axillary shoots that develop after a period of rest; they are generally clustered around the terminal bud on the parent shoot

[3] Rating index is sum of rating values for the trunk, average of values for scaffold branches and average of values for axillary shoots, then dividing by three, to give an overall score for that genotype

Commercial cultivars and advanced genotypes – California

In this project trees had been planted as central leader trees with a single trunk. They were generally 0.9 - 1.2 m tall, ranging from 0.7 m for genotype A04, 5-252 to 1.36 m for A05, 8-69 (Table 6). Trunk diameter at the first extended internode above the bud union ranged from 6.9 mm for genotype A04, 5-252 to 10.2 mm for 'Nonpareil'. The most obvious difference between the varieties was in the number of axillary dard-type shoots formed above 60 cm on the trunk (shoots below this point had been removed during the propagation process). While some genotypes had relatively few shoots per tree (<6), for example A04, 5-252 and Pyrenees®, others had several axillary shoots (up to 18), for example A06, 3-542, A05, 11-60 and 'Winters'.

Table 6. Tree height, trunk diameter of the scion at the first extended internode above the bud union, and number of axillary shoots above 60 cm on the trunk of almond trees. The trees were budded in June 2017 onto 'Cornerstone' rootstock and grown as central leader trees at Burchell Nursery in Fowler, California. Tree data were recorded in December 2017. Values are averages for each genotype ± SE (n = 10).

Genotype	Tree height (m)	Trunk diameter (mm)	No. of axillary shoots
A04, 5-252	0.70	6.9	4
A05, 11-60	1.07	8.9	17
A05, 8-69	1.36	8.6	10
A06, 3-542	1.19	9.9	18
A07, 2-292	1.19	8.6	12
'Nonpareil'	1.18	10.2	6
Pyrenees®	1.15	9.7	4
'Winters'	1.20	9.1	16
Least significant difference	*0.049*	*0.508*	*1.710*
p-value	*<0.001*	*<0.001*	*<0.001*

A useful range of values for flexural rigidity were recorded among the genotypes measured at Fowler, ranging from 1.2 kgf for 'Winters' to 4.9 kgf for genotype A05, 8-69 (Table 7). There were also clear differences in flexural rigidity between cultivars recorded at Oakdale, with Shasta® having the highest flex and 'Winters' the lowest (Table 8). However, there was no consistency between readings for cultivars tested at both sites, highlighting a difficulty in working with disparate groups of trees, one small, container grown and the other large, field grown trees.

Table 7. Flexural rigidity (kgf) of almond trees budded in June 2017 onto 'Cornerstone' rootstock and grown as central leader trees at Burchell Nursery in Fowler, California. Tree data were recorded in December 2017. Original values were also adjusted using stem thickness of the scion at the first extended internode above the bud union as a covariate. Values are averages for each genotype ± SE (n = 10).

	Flexural rigidity (kgf)	
Genotype	**Original values**	**Adjusted values**
A05, 8-69	4.7 ± 0.37	4.9
A05, 11-60	2.5 ± 0.19	2.6
'Nonpareil'	2.3 ± 0.23	1.9
Pyrenees®	2.0 ± 0.16	1.7
A06, 3-542	1.8 ± 0.12	1.4
A07, 2-292	1.5 ± 0.15	1.7
'Winters'	1.2 ± 0.09	1.2
Least significant difference	*0.6*	*0.6*
p-value	*<0.001*	*<0.001*

Table 8. Tree height and trunk diameter of the scion at the first extended internode above the bud union and flexural rigidity of almond trees budded in May 2017 onto field grown 'Nemaguard' rootstock and grown as central leader trees at Burchell Nursery in Oakdale, California. Tree data were recorded in November 2017. Original values for flexural rigidity were also adjusted using stem thickness of the scion as a covariate. Values are averages for each genotype ± SE (n = 10).

			Flexural rigidity (kgf)	
Cultivar	**Tree height (m)**	**Trunk diameter (cm)**	**Original values**	**Adjusted values**
'Nonpareil'	2.12	16.3	3.5 ± 0.4	3.5
'Winters'	1.93	14.7	2.6 ± 0.4	3.3
Shasta®	2.37	17.3	5.5 ± 0.5	4.9
Least significant difference	*0.158*	*1.27*	*0.08*	*1.0*
p-value	*<0.001*	*<0.001*	*<0.001*	*0.004*

Further data were collected from the 14 genotypes in California to record tree growth and branching in January 2019, flowering in February/March, and fruit set in May 2019. A05, 252 trees were among the smallest in height, trunk diameter, central leader extension and length of tagged axillary branches, and 'Nonpareil' trees were among the tallest, with the largest trunk diameter, longest central leader extension and longest axillary branches (Table 9). The number of flowers on the central leader extension ranged from 3 to 46 flowers per shoot on A05, 11-60 and A06, 3-542, respectively. A06, 3-542 also had the highest number of flowers on their axillary shoots, more than double the number recorded on the other genotypes. Fruit set % was variable, ranging from 9 to 95% set on the central leader extension and from 6 to 64% set on the axillary shoots. In many, but not all instances, fruit set was higher on the central leader extension than on the axillary branch.

Table 9. Tree and branch dimensions and flowering/fruit set on 2-year-old central leader almond trees in California. Ten trees of each genotype were budded on 'Cornerstone' rootstock in June 2017 and planted in January 2018 at the Burchell Nursery in Fowler, California. Tree and branch dimension data were collected in January 2019, with flowering recorded in March and fruit set in May 2019. Values are averages for each genotype ± SE (n = 10). Significance: ** = *p*<0.01; * = *p*<0.001.**

Genotype	Tree height (m)	Trunk diameter (cm)	Central leader[1] extension (m)	Axillary branch[1] length (cm)	No. of flowers on central leader extension	No. of flowers on axillary branch	Fruit set (%) on central leader extension	Fruit set (%) on axillary branch
A05, 11-60	1.98 ± 0.05	3.6 ± 0.16	1.01 ± 0.15	96 ± 6	3 ± 1	2 ± 1	19 ±16	17 ± 11
A06, 3-542	2.04 ± 0.09	3.5 ± 0.10	1.04 ± 0.15	71 ± 10	46 ± 8	34 ± 9	29 ± 5	27 ± 6
A07, 2-292	2.46 ± 0.13	3.6 ± 0.22	1.10 ± 0.11	101 ± 10	16 ± 6	5 ± 3	59 ± 12	53 ± 16
A05, 8-69	2.40 ± 0.14	2.9 ± 0.11	1.08 ± 0.12	85 ± 9	18 ± 6	5 ± 2	18 ± 7	22 ± 10
A04, 5-252	1.26 ± 0.06	2.5 ± 0.08	0.56 ± 0.11	43 ± 5	17 ± 4	2 ± 1	9 ± 2	25 ± 10
'Nonpareil'	2.54 ± 0.09	3.8 ± 0.09	1.51 ± 0.18	113 ± 11	14 ± 4	3 ± 2	31 ± 6	20 ± 12
Pyrenees®	2.17 ± 0.10	3.4 ± 0.14	1.27 ± 0.20	69 ± 12	27 ± 4	11 ± 3	82 ± 8	64 ± 7
'Winters'	1.56 ± 0.19	3.3 ± 0.14	0.87 ± 0.16	72 ± 8	8 ± 2	8 ± 4	38 ± 9	37 ± 9
Shasta®	2.34 ± 0.10	3.3 ± 0.13	1.04 ± 0.09	92 ± 9	19 ± 8	7 ± 3	59 ± 12	42 ± 16
'Monterey'	1.88 ± 0.10	3.2 ± 0.11	0.95 ± 0.20	67 ± 10	16 ± 4	5 ± 2	49 ± 8	66 ± 8
X4-5E	2.01 ± 0.07	3.8 ± 0.19	1.00 ± 0.15	72 ± 8	16 ± 4	12 ± 3	29 ± 12	6 ± 3
'Lassen™'	2.24 ± 0.11	3.6 ± 0.24	1.21 ± 0.16	87 ± 7	14 ± 4	3 ± 1	43 ± 10	48 ± 21
UCD 1-232	2.32 ± 0.10	3.8 ± 0.18	1.19 ± 0.25	93 ± 7	31 ± 5	8 ± 2	74 ± 10	71 ± 16
UCD 8-201	2.00 ± 0.08	3.8 ± 0.19	0.59 ± 0.09	63 ± 9	26 ± 4	16 ± 7	95 ± 3	44 ± 10
Significance	***	***	**	***	***	***	***	***
p-value	*<0.001*	*<0.001*	*0.004*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

[1] The 2018 extension of the central leader is the primary shoot; axillary branches had formed directly on the primary shoot during 2018.

Working again with the 14 genotypes, four of the these (A05, 11-60, A06, 3-542, A07, 2-292 and 'Winters') had relatively high numbers of 2018 axillary shoots on the tagged scaffold branches, compared with the other genotypes, which corresponds with counts made on the trunks of young trees in the nursery (Tables 6 and 10). However, the number of new axillary shoots produced on the tagged branches in 2019 were not consistent with the number of axillary shoots on these trees while still in the nursery, or with the number of 2018 shoots on the trees in the orchard. There was a better correlation between the number of shoots on trees in the nursery in Australia and the number of new shoots produced on these same trees in the orchard (Tables 1 and 4). It is possible that the inconsistencies found in California were because the trees were relatively small, container grown trees that started with few axillary shoots, whereas the trees in Australia were larger, field grown trees.

Overall, % budbreak on the tagged scaffold branches in California ranged from 59 to 91 % for A04, 5-252 and Shasta® trees, respectively. Shasta® had high % budbreak because it produced a high number of leafy buds and only a moderate number of new shoots (Tables 10). The tagged scaffold branch on the A04, 5-252 trees had low % budbreak, with unusually low numbers of leafy spurs, but the branches were relatively short with few nodes. 'Nonpareil' trees were among the tallest trees and had the most nodes in the orchard, 1 year after planting, but they had the highest number of buds that remained dormant which reduced the overall % budbreak for this cultivar.

Qualitative data collected using an informal rating protocol, from all genotypes in California, gave the highest ratings to UCD 8-201 and A04, 3-542 and the lowest to Pyrenees® (Table 11). UCD 8-201 and A04, 3-542 both had strong ratings for central leader development, with medium vigour upright scaffold branching, moderate numbers of short to medium dards and subterminal shoots that were relatively few in numbers and did not dominate the branch.

Pyrenees® trees were interesting because they are strong spur bearing trees and so have no or very few axillary shoots along the scaffold branches on young trees, which lowered their overall rating. A05, 8-69 trees were an aberrant tree type with distorted, malformed branching.

Table 10. Number of shoots, leafy spurs and dormant buds on axillary branches of 2-year-old central leader almond trees in California. Ten trees of each genotype were budded on 'Cornerstone' rootstock in June 2017 and planted in January 2018 at the Burchell Nursery in Fowler, California. Data were collected in May 2019 from one 2018-season branch per tree. Values are averages for each genotype ± SE (n = 10). Significance: ** = *p*<0.01; * = *p*<0.001.**

Genotype	2018 shoots	Dormant buds	Leafy spurs	New axillary shoots	Total nodes	Budbreak (%)[1]
A05, 11-60	14 ± 2	18 ± 2	22 ± 3	21 ± 3	76 ± 6	75 ± 2
A06, 3-542	16 ± 6	12 ± 5	27 ± 3	10 ± 2	65 ± 1	85 ± 3
A07, 2-292	13 ± 2	14 ± 1	46 ± 4	14 ± 2	87 ± 6	83 ± 1
A05, 8-69	3 ± 1	12 ± 3	34 ± 6	18 ± 3	67 ± 10	84 ± 3
A04, 5-252	2 ± 1	15 ± 3	6 ± 2	14 ± 2	37 ± 6	59 ± 5
'Nonpareil'	5 ± 2	35 ± 4	30 ± 3	27 ± 4	97 ± 7	63 ± 3
Pyrenees®	2 ± 1	10 ± 3	39 ± 3	10 ± 3	60 ± 9	85 ± 3
'Winters'	8 ± 2	14 ± 3	20 ± 2	13 ± 1	54 ± 6	76 ± 5
Shasta®	2 ± 1	9 ± 3	63 ± 5	13 ± 3	87 ± 8	91 ± 3
'Monterey'	2 ± 1	9 ± 2	31 ± 6	17 ± 4	60 ± 10	86 ± 2
X4-5E	2 ± 1	5 ± 1	31 ± 2	22 ± 5	60 ± 5	91 ± 3
'Lassen™'	1 ± 0	12 ± 2	39 ± 4	26 ± 4	78 ± 8	84 ± 3
UCD 1-232	1 ± 1	9 ± 3	34 ± 6	30 ± 7	74 ± 7	88 ± 4
UCD 8-201	5 ± 2	5 ± 1	21 ± 2	14 ± 3	45 ± 6	89 ± 1
Significance	***	***	***	**	***	***
p-value	*<0.001*	*<0.001*	*<0.001*	*0.002*	*<0.001*	*<0.001*

[1] % budbreak was determined as sum of leafy spurs and shoots produced per total number of nodes per branch

Table 11. Rating protocol for qualitative description of central leader trunk development and branching on 2-year-old almond trees in California. Ten trees of each genotype were budded on 'Cornerstone' rootstock in June 2017 and planted at the Burchell Nursery in Fowler, California. Data were collected in February 2019, as observational data with a single value obtained from observations of ten trees per genotype. Attributes were rated from 1 to 3 with 1 regarded as undesirable and 3 as desirable. Values are the single rating score for each genotype.

	Trunk	**Scaffold branches**				**Axillary shoots (current year)**						
	Central leader	Vigour	Strength	Number	Orientation	Dards[1]			Subterminal shoots[2]			
	(dominance)	(length)	(diameter)	(count)	(angle)	(count)	(length)	(diameter)	(count)	(length)	(diameter)	
Rating scale:	1-weak 2-moderate 3-strong	1-long 2-medium 3-short	1-weak 2-strong 3-medium	1-few 2-medium 3-many	1-horizontal 2-upright 3-compact	1-few 2-many 3-medium	1-long 2-short 3-medium	1-weak 2-medium 3-strong	1-many 2-medium 3-few	1-long 2-short 3-medium	1-weak 2-medium 3-strong	
Genotype												**Rating index[3]**
A05, 11-60	1	1	3	2.5	1.5	3	2.5	1	2	3	1	1.7
A06, 3-542	3	3	2	3	1	2	2.5	2	0	-	-	2.3
A07, 2-292	2	2	2	2	1	3	2.5	2	2.5	2.5	2	2.1
A05, 8-69	2	2.5	1	1	1	3	1.5	2	0	-	-	1.7
A04, 5-252	1	3	2	2	2	1	3	3	3	3	3	2.0
'Nonpareil'	2	1	3	2	1.5	1	2	1	3	3	1	1.9
'Pyrenees®'	1.5	2	3	2	1	0	-	-	0	-	-	1.2
'Winters'	1	2	3	2	2	2	3	1	3	3	2	1.9
Shasta®	2	1	3	2	1.5	1	3	2	3	1.5	2	2.0
'Monterey'	2	1	3	3	2	0	-	-	2	3	1	1.9
X4-5E	2	2	2	3	1	0	-	-	3	2.5	3	2.0
'Lassen™'	1.5	3	2	3	2	1	3	1	0	-	-	1.8
UCD 1-232	2	1	2	3	1.5	1	2	2	3	1.5	2	1.9
UCD 8-201	3	3	3	2	2	2.5	2.5	2	3	2.5	1	2.6

[1] Dards are mainly sylleptic axillary shoots that develop at the same time as the parent shoot; they are generally located along the lower section of the parent shoot
[2] Subterminal shoots are mainly proleptic axillary shoots that develop after a period of rest; they are generally clustered around the terminal bud on the parent shoot
[3] Rating index is sum of rating values for the trunk, average of values for scaffold branches and average of values for axillary shoots, then dividing by three, to give an overall score for that genotype

Concluding comments

A range of architectural traits were investigated for their suitability as selection criteria when breeding for high productivity in new almond cultivars for high density orchards. Potential methodologies to accelerate the breeding cycle for these new cultivars were also considered. The question was, is it possible, from the growth of 1-year-old trees in the nursery and the development of tree structure and bearing capacity of 2- and 3-year old trees in the orchard, to predict the growth habit and ultimate cropping potential of the mature tree? Our data indicated that, with some provisos, this is possible.

For example, the distinctive structure of 'Monterey' and 'Wood Colony' trees, with their very strong basitonic growth habit, was clearly evident in the newly budded, unpruned trees in the nursery. Key traits were the long axillary shoots produced in a compact branching zone, low down on the trunk of the trees. While this trait has been useful in traditional multi-axis growing systems, it would be a negative trait if selecting genotypes for central leader trees in new, high-density plantings. The suggestion is that extreme examples of this trait could be selected against, while trees were still in the nursery. A more consistent, diffused pattern of medium length shoots along the trunk, as found with 'Nonpareil' and Shasta®, would be a positive selection criterion.

Options for automated data collection were considered, especially with young trees in the nursery, to quantify plant height and the number, length and angle of branching. Field grown trees would be amenable to this as there was good correlation between branching patterns in the nursery and in the orchard. However, the relationship was not as promising with the container grown trees in California, as they were smaller and produced fewer branches than field grown trees. This would limit options for using automated data collection facilities such as at the Australian Plant Phenomics Facility in Adelaide (https://www.plantphenomics.org.au/).

Observations of tree growth and the predisposition of trees to produce and maintain a strong central leader once transferred to the orchard revealed that while some of the genotypes were very easy to train/grow as central leader trees with minimal pruning, others were difficult to grow in this way. An important issue was the strong competition from axillary shoots reducing the vigour of the terminal shoot forming the central leader, as with the Californian cultivar 'Winters'. In this case, the production of too many sylleptic axillary shoots (dards) could be regarded as a negative trait, especially as this shoot type can be very thin and sensitive to cold and dry conditions. This trait that can be observed in the nursery can also be expressed in the orchard. Genotypes that produce numerous dards can also have low fruiting potential and appear to struggle to survive in low light conditions, which would be a negative trait (Figure 8). Numerous, strong dards that remain productive in low light conditions would be a very positive trait in any new cultivar.

The alternative situation, where trees produce relatively few axillary shoots with growth dominated by long, vigorous subterminal shoots competing with the central leader, as with R8b T58 trees, would also be a negative trait. Another potential issue with strong subterminal branching is that they can often produce long barren sections of wood with no axillary growth which would be a negative trait (Figure 9). Shasta® can produce strong subterminal branching, but this cultivar also has a very high % budbreak producing numerous leafy buds and leafy spurs, a positive trait.

Figure 8. While strong axillary shoot production is important to increase the number of potential fruiting sites, these shoots (dards) need to be robust enough to survive in low light conditions and sustain high productivity. Images show poor (left) and strong (right) survival rate and productivity of dard shoots.

Figure 9. Strong branching from terminal and subterminal buds can produce long barren sections of wood; this undesirable habit can be observed in second-leaf trees.

It is possible that numerous axillary shoots could also delay development of perennial fruiting structures such as spurs (Figure 10). If the parent shoot produces a shoot at every node in Year 1, then will it take another year for these daughter shoots to become productive? In contrast, if the parent shoot produces buds or leafy buds at every node in Year 1, will these become fruit buds in Year 2? Many of the recent Spanish-bred cultivars with high productivity (e.g. 'Soleta', 'Guara' and 'Vairo') have strong spur bearing habits with relatively few axillary shoots produced on current season's growth. Branches on these cultivars generally develop as strong proleptic shoots from subterminal buds on previous season's growth. Observations of mature canopies of these cultivars suggests that it would be a more positive trait to have equal vigour among the subterminal and terminal shoots, as with 'Soleta', than to have a dominant terminal shoot and weak subterminals, as with 'Guara' and 'Vairo'. This trait should be apparent in Year 3 or 4.

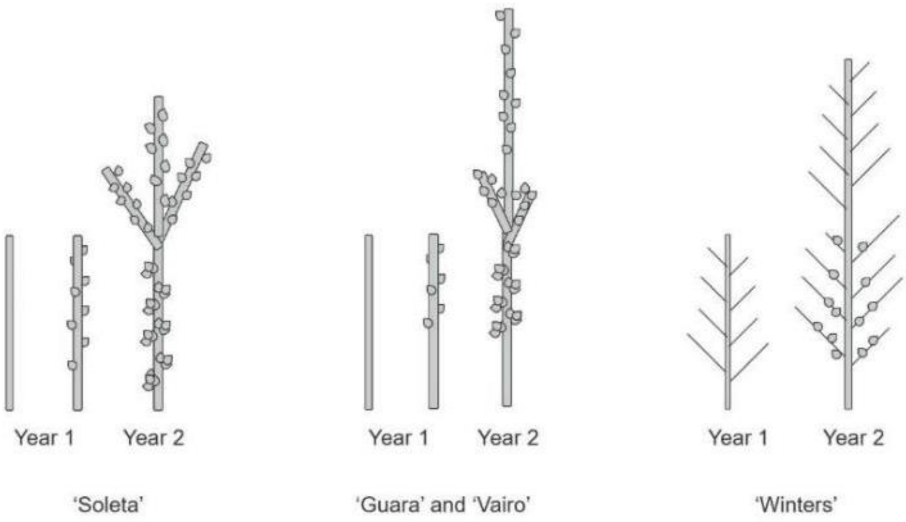

Figure 10. Bud and spur development on contrasting cultivars. Is strong axillary growth in Year 1 at the expense of strong bud and spur development in Years 1 and 2, respectively?

Investigating the long-term viability of spurs was outside the scope of this program (Figure 11). However, it is an important trait that requires further research to develop robust screening methods for young trees. A method based on artificial shading of fruiting spurs and shoots to reveal differing levels of light sensitivity could be considered as a screening protocol on young trees.

Figure 11. Long-term viability of spurs will be important for sustained high productivity, as will the generation of new fruiting wood. At what stage in the breeding cycle can we predict spur longevity?

Several almond cultivars develop a wide, spreading, horizontal tree structure, which is accentuated when trees begin cropping (e.g. 'Carina' and Shasta®, Appendix V). However, some genotypes (e.g. 'Vela') will produce decurrent shoots that grow downwards, even on young trees without the weight of fruit. Attempts were made to quantify this as a measure of the flexural rigidity (stiffness) of the trunks on young trees in the nursery. A useful range of values was recorded among the genotypes, but unexpectedly, the genotypes with high rigidity (e.g. 'Vela' and R19a T166) were the ones that had spreading canopies, and the ones with low rigidity (e.g. R52 T202 and R36 T212) were the more upright and/or compact genotypes. Flexible trunks with low flexural rigidity could be a positive trait, identifiable in the nursery.

Considerable variation in tree stature and structure was observed among seedling trees in almond breeding populations from Australia, California and Spain (Figures 12 and 13). This could be reduced, and breeding efficiency improved, by budding all seedling progeny onto clonal rootstocks (Figure 12). This would give the breeder more confidence to remove aberrant and undesirable growth types so the focus remained on progeny with the desired architectural traits.

Figure 12. Seedlings from breeding populations growing on their own roots typically show large variation in vigour (left), which is not seen with nursery trees on clonal rootstocks (right). Would it make the breeding process more efficient if all breeding progeny were budded and evaluated on clonal rootstocks?

Figure 13. Tree architecture among breeding populations can easily be observed in Years 1 and 2. Would it accelerate the breeding process if trees with negative architectural traits were eliminated before the trees produced their first crop?

Shell and kernel quality are important breeding targets for almonds, as are self-fertility and pest and disease tolerance. However, new cultivars are required for the almond industry to make a step change in productivity, ones that are stacked with architectural traits that enable high productivity. Methodologies described here should help achieve that ambition.

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APPENDIX VII Project related conferences and meetings

17 July 2014	Met with Ben Brown from the Almond Board of Australia (ABA) and Andrew Hobbs from CMV Farms at Lindsay Point to initiate the first of the almond productivity research projects
28-30 October 2014	Attended ABA Annual Conference in Adelaide
1-8 December 2014	Almond meetings with UC Davis, Burchell Nursery and Californian almond growers, California to discuss options for collaborative research on almonds
9-10 December 2014	Attended the Almond Board of California (ABC) Annual Conference, Sacramento CA
21 April 2015	Attended the Australian Nut Conference, Sydney
12-14 May 2015	Attended the XVI GREMPA Meeting of the Mediterranean Research Group for Almond and Pistachio Conference, in Meknes, Morocco
18-25 May 2015	Almond collaborative research meetings with IRTA, CSIC and University of Seville, Spain
7 July 2015	Met with Alan Saunders from Agromillora nurseries in Mildura VIC to discuss new almond project work
8 July 2015	Met with Ross Skinner (CEO) from ABA in Berri SA to discuss future almond project work and collaborations
1 September 2015	Met with Tom Burchell from Burchell Nursery in Oakdale California to view their nursery operation and discuss collaboration on future almond research
3 September 2015	Met with Steve Huffman form Agromillora Nursery in California to discuss potential collaboration on almond research
16 September 2015	Met with John Slaughter and Kaylan Roberts from Burchell Nursery in Fowler, California to discuss collaboration on almond high density growing systems research
16 December 2015	Met with Ian Moss from Mossmont Nursery in Griffith NSW to establish collaborative projects on almond new cultivar research
18 April 2016	Met with Ross Skinner from ABA in Adelaide SA to discuss potential strategic research alliance between ABA and PFR
19 May 2016	Attended ABA R&D Workshop in Adelaide
28 June 2016	Met with Rob Wheatley, General Manager - Almonds, OLAM International in Brisbane QLD to discuss future collaborations with OLAM on almonds
29 June 2016	Met with Daryl Winter, National Manager - Almonds, Rural Funds Management (RFM) Ltd in Griffith NSW to discuss future collaborations with RFM on almonds
4 July 2016	Met with Karen Lapsley from ABC in Adelaide to discuss potential almond research projects in California
8 July 2016	Met with Karen Lapsley from ABC, Ross Skinner from ABA and Dave Monks and Michael Treeby from Dept of Ag Victoria, at Lindsay Point to discuss almond research
29 Aug-2 Sept 2016	Attended ISHS Orchard Systems Symposium in Bologna
23 September 2016	Met with Michael Treeby and Dave Monks from Dept of Ag Victoria, in Mildura to discuss collaborative research projects on almond
25 October 2016	Attended ABA planning meeting for Loxton Research Centre, in Adelaide

15 November 2016	Met with OLAM staff at their Kerarbury orchard to present a summary of our almond research data
2 December 2016	Met with Dr Gurreet Brar at California State University Fresno (CSU Fresno), in Clovis CA to discuss future collaborative research on high density growing systems for almond
5 December 2016	Attended business meeting of the ABC, in Modesto CA, to discuss almond research collaboration
7-8 December 2016	Attended ABC Annual Conference, in Sacramento CA
11December 2016	Met with Tom Gradziel UC Davis at Wolfskill Research Centre to discuss collaborative research on almond tree architecture
19 December 2016	Met with Andrew Downs and Brett Rosenzweig (ABA staff), Darren Graetz (South Australian Research and Development Institute (SARDI)) and Michael Speedy (Dept of Ag Victoria) to discuss collaborative projects on almond tree architecture, at Dareton germplasm site
19 January 2017	Met with Zubi Shazad, Technical Manager at OLAM to review current almond projects and ways of collaboration, in Mildura.
20 January 2017	Met with John Kennedy, Lacton Farm, to review almond research data, in Lindsay Point.
1 February 2017	Met with OLAM staff at their Kerarbury orchard to review data from our almond research trials
15 February 2017	Met with Andrew Downs and Brett Rosenzweig (ABA staff) to review future trial blocks for Loxton Centre of Excellence.
28-29 March 2017	Attended Australian Nut Conference, in Melbourne.
23-24 April 2017	Attended Hort Innovation, ABA, ABC, PFR meetings in Modesto to discuss Hort Innovation co-investment funding model to support collaborative research projects between Australia and California.
25 April 2017	Met with Bob Curtis and Sebastien Saa from ABC to review PFR almond research trials at Burchell Nursery, CSU Fresno and UC Davis
28 April 2017	Met with Bob Curtis from ABA, Gureet Brar from CSU Fresno and Bruce Lampinen UC Davis in California to discuss collaborative research on almond growing systems
2 May 2017	Attended ABC workshop, in Modesto
5-7 May 2017	Attended PMA Hort Connections trade meeting in Adelaide
25 May 2017	Attended ABA Almond Rootstock Field day, at Lindsay Point VIC.
26 May 2017	Met with Allan Saunders (Agromillora) to discuss opportunities to collaborate with their high density growing systems trial with almonds, in Irymple VIC.
29 May 2017	Met with Kevin Saunders (apple grower) to review high density growing systems for apple, at Three Bridges VIC.
29 May 2017	Met with Rob Fleming (nurseryman) to review almond propagation, in Hoddles Creek, VIC.
11 July 2017	Met with Andrew Downs (ABA) in Loxton (SA) to discuss PFR projects at ABA Almond Centre of Excellence
10 August 2017	Met with Andrew Downs and Brett Rosenzweig (ABA) and Mark Skews and Darren Graetz (SARDI) to discuss collaborative research trials to be planted at ABA Almond Centre of Excellence at Loxton
10 August 2017	Met with Craig Simes in Lyrup SA, Grower Services Manager, Almondco, to discuss current and future trials including site visits

18 August 2017	Met with Alok Kumar (Hort Innovation) in Melbourne VIC to discuss Hort Frontiers funding model and call for concept proposals for the Advanced Production Fund
22 August 2017	Met with Karen Lapsley and Guangwei Huang at ABC in Modesto (CA) to discuss “shake and catch” harvesting options and arrange visits to manufacturers
24 August 2017	Met with Bob Curtis (ABC) and Michele Barefoot (PFR California) to discuss California almond research proposals
3 October 2017	Attended Almondco, Mossmont and ABA industry workshop at Renmark SA, then visit to field trials at Lindsay Point VIC
4 October 2017	Attended Almondco and Mossmont grower seminar at Virginia SA
24-25 October 2017	Attended ABA R&D Forum in Loxton SA
10 -11 November 2017	Hosted Xavier Miarnau from IRTA Spain, visiting almond growers and nurseries
6-9 November 2017	Attended ISHS International Symposium on almonds and pistachio in Adelaide
5-7 December 2017	Attended ABC Annual Conference, Sacramento CA
8-16 February 2018	Visited almond researchers in Spain to discuss potential collaborations with Maria Jose Rubio Cabatas at CITA in Zaragoza and with Ignasi Batlle and Xavier Miarnau at IRTA
12 February 2018	Met with Fernando Buros at Tenias Harvesting Company in Ejea de los Caballeros, Spain to discuss possible collaboration on development of their “shake and catch” harvesting and in-field hulling machines
7 March 2018	Meeting with Ross Skinner from ABA to discuss planting PFR research trials at the ABA Almond Centre of Excellence at Loxton
14 March 2018	Met with University of Queensland (UQ) and Department of Agriculture and Fisheries, Queensland (DAFQ) staff and Nick Gould to discuss collaborative research to be included in the Hort Innovation Hort Frontiers Advanced Production Systems Fund “Orchard Intensification” programme
23 March 2018	Attended the Hort Innovation Hort Frontiers Advanced Production Systems Fund Expert Advisory Panel meeting in Sydney
25 May 2018	Met with Jeremy Miatke, Orchard Manager at CMV Farms to discuss small tree pruning systems for almonds and possible commercial scale trials
1 June 2018	Met with Grant Zaiger from Zaiger’s Genetics in Modesto CA to discuss potential research collaboration using their advanced almond genotypes including the self-fertile variety ‘Independence’
1 June 2018	Met with Karen Lapsley, Sebastien Saa and Guangwei Huang (ABC) in Modesto to discuss collaborative research opportunities in California and Australia on advanced harvesting systems for almond.
19-21 June 2018	Attended PMA Hort Connections trade meeting in Brisbane
12 July 2018	Met with Ross Skinner ABA to discuss research programme in Australia and California and preparation of new funding proposals for Hort Innovation
6-14 August 2018	Travelled to California with Ross Skinner from ABA, and Alok Kumar and David Moore from Hort Innovation, to attend meetings with ABC and other potential research partners in California.
7 August 2018	Attended ABC Almond Biomass workshop in Modesto CA
29 August 2018	Met with ABA Production Research Committee in Mildura to present almond research
31 Oct-1 Nov 2018	Attended ABA Almond Conference in Melbourne

4-6 Dec 2018	Attended ABC Almond Conference in Sacramento CA
8 December 2018	Hosted Dr Michelle Wirthensohn, almond breeder from The University of Adelaide to view almond productivity and architecture projects in California
8 May 2019	Attended meeting on potential collaboration on almond research with University of Adelaide
23 May 2019	Attended meeting with ABC and UC Davis staff to review field trials at Fowler and Fresno
19 June 2019	Started discussions to form consortium with SARDI, AgVic, NSW Department of Primary Industries, UQ, Queensland Alliance for Agriculture and Food Innovation (QAAFI) and DAFQ to prepare proposal document in response to call from Hort Innovation for National Tree Crop Intensification Program
24-26 June 2019	Attended Hort Connections trade meeting in Melbourne
19-21 August 2019	Met with Maria Jose Rubio Cabatas and PhD student Álvaro Montesinos Joven at CITA in Zaragoza to discuss collaborative work on almond tree architecture
22 August 2019	Met with Ignasi Batlle and Xavier Miarnau at IRTA in Spain to discuss collaboration on almond tree architecture and high density growing systems
1 November 2019	Hosted John Slaughter and Kaylan Roberts from California to view almond productivity and tree architecture research trials in the Riverland and Sunraysia regions
6 November 2019	Met with Ben Brown and staff at Select Harvest's Carina West orchard to review high density research trial and future plans

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AL14007

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PUBLICATION DATA

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