Final Report

National tree crop intensification in horticulture (citrus)

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National tree crop intensification in horticulture (citrus) (AS18000)

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Public summary

The Australian citrus industry continues to deliver excellent fresh fruit and juice to domestic and export markets, growing to more than $1billion in farmgate value in recent years. To continue to meet markets' needs and manage rising costs, it is important to look to the future of production systems. This project aimed to contribute to increased productivity and profitability of Australian citrus through new cropping system intensification knowledge and extending our findings on advanced production systems in ways that can be deployed by growers. The New South Wales Department of Primary Industries and Regional Development (NSW DPIRD) has developed outputs that can be deployed by growers: those currently struggling to recover over-crowded orchard blocks, or thinking about planting a new block today, or looking to understand systems that may have relevance in 15 years' time.

We conducted seven replicated experiments on pruning strategies to recover over-crowded orange blocks. This work was conducted on both NSW DPRID's and growers' properties. In each case we included a 'local best practice' treatment. To further describe technology to control tree vigour during the planting and establishment phase, we developed two replicated experiments using the citrus dwarfing viroid – a way of controlling tree vigour by inoculating young planted trees with a viroid known to slow growth. We measured tree growth and architectural features to describe the breadth within a large arboretum. We also laid down two replicated advanced production systems experiments – stumping an existing block of trees and training them in different ways on a trellis.

Our team has published papers and case studies in reputable journals and industry magazines, providing valuable insights into orchard intensification, viroid management, and pruning techniques. We also produced a literature review. Beyond immediately applicable material for growers to use today, our work provides a solid foundation for future experimentation and practical insights for improving citrus production.

Tailored workshops and field days have been conducted to meet growers' needs, focusing on practical applications of our research. These events have been well-received, with participants reporting high satisfaction.

Factsheets and videos were developed to extend project findings nationally and show growers and their advisors specific methods they can use on their farms. We have produced case studies and 'plain language' videos to demonstrate a clear path between difficult orchard blocks and more advanced production systems on farm. Many of these outputs were shared through the Australian Citrus News industry magazine and through the NSW DPIRD citrus website.

We have actively engaged with the citrus community through regional forums, annual meetings, and webinars, fostering collaboration between researchers, growers, and industry stakeholders. The new knowledge and outputs developed in this project will help growers increase their knowledge and understanding of tree intensification and give them the confidence to adopt these advanced systems. Exposure to this information was valued by industry members, surveyed independently by RMCG for the mid-term review, and in survey- and written-feedback in the project's final year.

Keywords

High density, vigour, growth rate, canopy efficiency, tri-state, productivity.

Introduction

Increasing productivity and canopy efficiency in citrus orchards is crucial for growers aiming to maximise their yield and profitability. By intensifying citrus orchards, growers can enhance the fruit-bearing portion of the canopy without compromising fruit quality or tree health. The volume of fruit-bearing foliage, rather than the number of trees, is key to per hectare yield. High-density orchard blocks are more efficient to manage and harvest, and they are better suited to automated management practices. Additionally, these systems are less susceptible to damage from cold temperatures and high winds.

Producing more citrus fruit per hectare helps meet the growing demand for fruits and vegetables, driven by their proven health benefits. Planting at high density generates more fruit without requiring additional land, which is essential for sustainable production. The benefits of intensifying citrus orchards can be realised by understanding tree growth and behaviour, improving orchard design, and controlling tree vigour using dwarfing rootstocks, viroids, or tree training techniques.

Both under- and over-exposure to light can decrease the efficiency of photosynthesis in an orchard canopy. Under-exposure limits the energy available for photosynthesis, while over-exposure indicates inefficiency in tree structure, where some leaves intercept more light than needed, depriving other leaves. Most light interception and fruiting occur in the outer 1 meter of the canopy. Computer models show that increasing leaf area beyond a certain point does not enhance the well-illuminated bearing volume, leading to reduced fruit size and colour due to intra-canopy shading.

To push production systems beyond this plateau, a combination of technologies is required. There is unlikely a future for commercial orchard production without hand pruning, but with an underlying vigour control technology each pruning-dollar spent becomes more efficient, promoting more refined pruning methods to maximise the number of fruiting sites. Understanding and implementing these technologies, considering establishment and maintenance costs, is essential for their mainstream adoption.

The NSW DPIRD project team was Dave Monks, Mahmud Kare, Steven Falivene, Andrew Creek and Nerida Donovan.

Methodology

This project was established to generate new information to address citrus growers' needs. The research program considered three different situations our growers find themselves in:

Those with an existing, high density orchard that has become overcrowded, decreasing yield and increasing costs. For this group, we established a range of both replicated experiments and demonstration blocks across the **Sunraysia** and **Riverina** regions comparing both mechanical hedging and hand pruning, and an extreme option – converting a 12-year old block to trellis. We also wrote a review of the literature describing ways of intensifying citrus tree crops and modifying tree canopies. The review, presented at the 2022 International Horticultural Congress in France, was published in 2024.

1. At the Dareton Primary Industries Institute, **Sunraysia**, four replicated experiments were established comparing different strategies to revive orchard blocks to productivity.
    a. Different mechanical hedging and hand pruning treatments were chosen to represent common industry practice as well as more severe hedging and more detailed hand pruning treatments. This work was conducted in both Atwood and Hockney mid-season navel oranges and ran for the whole life of the project.
    b. Different training systems were compared on navel orange trees with the canopy and branches completely removed by stumping with chainsaws to approximately 1200mm. This work compared espalier, cordon and palmate-style training, tying growing branches to a trellis structure to encourage flower and fruit formation over vegetative growth. This work was conducted in both Atwood and Hockney mid-season navel oranges and ran for the whole life of the project.
2. Three demonstration blocks were established on a grower collaborator's property in **Sunraysia**. Each involved five treatments, selected from different styles of hand pruning, with and without summer regrowth management, and hedging intensities. The three blocks on Brett Hullah's property chosen were:

    a. Chislett late-season navel orange
    b. Cara Cara mid-season navel orange
    c. And Barnfield late-season navel oranges inoculated with the citrus dwarfing viroid

3. In the **Riverina** we established a range of both replicated experiments and demonstration blocks to compare different pruning and hedging strategies to recover over-crowded orange orchard blocks to productivity. All of these studies were conducted on grower collaborators' blocks.
    a. In Justin Davidson's Salustiana common oranges we compared two hand pruning and three hedging strategies, incorporating the grower's own best practice as a control in a replicated experiment.
    b. In Tony Naimo's Powell late-season navel oranges we compared two hand pruning and two hedging strategies, incorporating the grower's own best practice as a control in a replicated experiment.
    c. In Peter Ceccato of Superseasons' Valencia oranges we compared two hand pruning and three hedging strategies, incorporating the grower's own best practice as a control and a novel hedge 'slot' cut in the shoulder of the canopy in a replicated experiment.
    d. In Frank Madaffari's Valencia oranges we demonstrated four hedging and two hand pruning strategies.

For **those wanting to plant a new orchard tomorrow** we aimed to provide new information about citrus dwarfing viroids, available for use in establishing smaller-stature citrus orchards.

At Dareton Primary Industries Institute, two new experiments were established and another, 35-year old, block to measured anew to understand the longevity of this dwarfing technology.

1. A newly planted block of Neilson mid-season navels was inoculated with a range of citrus viroids, included some known to be dwarfing, individually or in various combinations, to investigate the impact multiple, different, viroids have on the rate of canopy expansion.
2. Additionally, a newly planted block of Neilson mid-season navels was inoculated with a similar combination of viroids, but the application of each individual viroid was separated within an individual treatment by six months. That is, each tree was allocated a treatment where one viroid was inoculated after 12 months and a second 6 months later.
3. A 35-year-old viroid-inoculated Bellamy late-season navel block was also revisited, with new data collected to compare the performance of the treatments in a mature block.

Plate 1. Two Bellamy navel oranges, inoculated with different viroids during their establishment, showing the different rates of canopy expansion 35 years after planting at Dareton Primary Industries Institute, NSW.

For **those wanting to plant in 15-years' time**, we aimed to generate new information on the range of phenological responses in a large pool of citrus genetics. We observed canopy growth rates to describe upper and lower bounds in our environment, that could be used by breeders or researchers in their own work. This work could lead to outcomes for industry in new work, possibly generating new hybrids or selections for a breeding program or informing the direction of future research efforts.

1. To do this, we hedged citrus trees and recorded their regrowth over time – both length from the cut surface and proportion of that cut surface that showed evidence of regrowth. The work was conducted in our arboretum collection at the Dareton Primary Industries Institute **with 396 citrus varieties** and selections, giving us a broad range of citrus, including 1 citron, 88 common oranges, 24 grapefruits, 2 kumquats, 17 lemons, 10 limes, 117 mandarins and mandarin hybrids, 47 miscellaneous citrus, 44 navel oranges, 21 pummelos (AKA shaddocks), 18 rootstocks, and 7 Seville oranges.
2. From the early results of that work, we focused on 12 varieties with highly contrasting growth habits to aloe more detailed measurements at the growth unit level.

Results and discussion

This section discusses the results from each of the major areas of research: **pruning, hedging and trellis** strategies to recover an overcrowded orchard block to productivity, **viroids** to control the rate of canopy expansion, and the breadth of **phenological responses** in an arboretum collection.

Pruning, hedging

It is challenging to manage high vigour citrus trees in high-density plantings. The pruning work conducted at DPII and on grower collaborator properties showed no improvement in yield with any hand pruning strategy over the standard grower hedging practice. This work showed how important it is to choose a suitable plant spacing to accommodate the expected vigour of the tree. The hand pruning strategies in high-density plantings triggered vigorous canopy regrowth responses, which had to be removed in summer to allow light into the tree, maintain row access and tree height. Pruning can take time to take effect because the benefit of pruning arises from new shoot growth replacing old canopy. In conventional planting densities, the trees would have had enough space to accommodate this regrowth; the regrowth from the hand pruning would be managed successfully in the next season's pruning, maintaining bearing wood between seasons.

Our work showed clearly however, that trying to reduce canopy size further using heavier hedging was very damaging to yield – be it a once-off 'hair cut' or maintaining a heavy hedging program for multiple seasons. In an attempt to bring the canopy in by 50cm on top and 15cm on the sides after the first recorded harvest, trees dropped yield in the following year to 200kg/ha only, on 1111 trees/ha. This treatment completely removed the layer of bearing wood that had been established through constant light hedging. This additional hedging led to an extremely low yield in Year 2 as the narrower side cut and lower tree top cut removed a disproportionate amount of fruiting wood. Similarly, a heavy hedge (0.95cm more removed from the western side) at the end of the 1st and 4th harvests has struggled to recover productive canopy and had reduced annual yields. All trees had been maintained at 2.7 m wide prior to out treatments

Information from a 2023 Spain and 2024 South Africa study tour on managing vigorous mandarins suggested managing regrowth a few times during the season can cause a compact canopy that does not require excessive pruning and will bear more fruit. Briefly, their findings were to remove water shoots that were greater than 1.5 m, or in areas of congested regrowth. The first regrowth management would occur when shoots were about 20-30 cm long, thinning out shoots to a hand-span apart and breaking the top one third of the remaining shoots (tipping), to retain about 4 - 5 buds. The tipped regrowth will then produce 3 new shoots and these shoots can be tipped again during summer. This results in a branch with 6 - 9 shoots that is complex, could bear fruit and is much shorter than unmanaged shoots. The complex branch will remain in the tree whilst a long water-shoot branch will probably be removed.

This work has been presented to growers through a number of field days, workshops, videos and written outputs. A summary of the treatments and a more in depth discussion of the findings can be found in a video produced for the project, focusing on Salustiana common orange: https://www.youtube.com/watch?v=d94F0wuVzOU, and an invaluable guide to hand pruning for profit https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/1503246/Hand-pruning-citrus-for-profit.pdf. Additional results, including fruit quality an economic analysis, were presented at the 2024 International Citrus Congress in Korea, and again in person to growers at field days in Dareton, Leeton, Griffith and Yoogali.

A paper is in preparation for submission to *Acta Horticulturae*, and was presented at the 2024 International Citrus Congress in Korea. The abstract attached as Appendix 1: *Five Different Pruning Strategies Were Not Able to Improve Productivity a Densely Planted Salustiana Common Orange Block in Short Term*. Learning from our results in this area, the shoot tipping regrowth management concept will be integrated into new and ongoing work.

Trellis

In addition to the pruning treatments described above, we also stumped 105 trees in the adjacent rows and converted them to a trellis system. These trees were trained to the wire as palmate, espalier and cordon beginning in July 2021. We aimed to improve light use efficiency, fruit quality and yield. In 2024, yield within the pruning experiment was ~10 t ha^{-1}, with an average canopy volume of ~12,000 m^3 ha^{-1}. Trees in this experiment intercepted an average of 53% of incident solar radiation. By comparison, in 2024 the trellis system yielded ~20 t ha^{-1} with an average canopy volume of only ~4,000 m^3 ha^{-1} . The trellised trees intercepted an average of only 39% of incident solar radiation. This means the trellised system showed a much higher canopy efficiency compared with the pruning experiment. The trellis trees increased canopy efficiency from 0.80 kg m-3 to 5.0 kg m-3; over conventional trees. With a 300 g fruit, that is a difference of 14 more fruits m-3 resulting in double the number of fruit from 31,200 to 66,600 ha^{-1}. If, hypothetically, our trellis rows were 0.9 m narrower (4 × 3.5 m), the trellis trees' yield and canopy volume would increase from 20 to 24.6 t ha^{-1} and 4,000 to 4,900 m3 ha^{-1}, with the same tractor access. The trees have not yet filled their allotted space, so these numbers should only increase until canopy closure. Each season, however, we are moving into unknown territory, and the relationship between costs and yield, canopy volume and yield, and vegetative vs floral growth is unknown. In the 1960s and 1970's, California researchers shown the system breaking down, as the vigour of the tree could not be contained by pruning. We wait to see how the massive increase in knowledge about trellis training systems since then will impact the success of this system in citrus in Australia.

Costing tool

There are various citrus production systems each with different costs and yields. Some intensive systems have a high initial costs and higher yields in the early years. The high early yields are very attractive, however it's easy to forget the extra costs involved with intensive practices and to mentally calculate the costs, returns and profit over a 20-year cropping cycle. It's also difficult to mentally calculate interest payments on borrowings which can be considerable if high initial input costs occur.

An economic citrus development analysis tool has been developed to assist growers to assess the comparative long-term profitability of different production systems. The tool comprises a report that presents the production scenarios and a downloadable excel spreadsheet and will be available via the NSW DPIRD citrus website. The tool presents orchard development budgets for various 20-year production cycle scenarios of high-density planting, tree dwarfing trellis production and robotic future orchard. Detailed budgets for each stage of the cropping cycle are presented in the report along with a 20-year summary budget to quickly assess long-term profitability. More information, including discussing converting an underperforming block to trellis, was presented at the International Citrus Congress, 2024. The abstract for which is attached as Appendix 2 and was published in *Acta Horticulturae*.

Viroids

Controlling vegetative growth and canopy size while maintaining productivity is important for high-density citrus plantings. This can be achieved by inoculating trees with dwarfing viroids, but understanding viroid interactions in mixed infections is crucial. A field trial started in 1989 to study the impact of citrus viroids on canopy volume, height, and fruit production of Bellamy navel orange on trifoliate orange rootstock. Trees were inoculated with hop stunt viroid, citrus dwarfing viroid, and two strains of citrus exocortis viroid, both singly and in combination. LiDAR was used to measure tree canopy volume, height, light interception, and fruit production, size, and quality from 2022. Results showed that, 35 years after inoculation, some viroid combinations significantly reduced canopy volume and tree height compared to the uninoculated control. However, there was no significant effect on total canopy light interception, and most viroid treatments did not affect yield per tree, fruit size, or quality. This long-term experiment demonstrated that viroids can impact tree size throughout the life of an orchard. Knowing which viroids are present in field trees is essential before inoculating with commercial dwarfing viroids to plan proper tree spacing and maximize yield per hectare. Some of this work was describe in a publication in *Acta Horticulturae* and presented at the International Citrus Congress, 2024 and is attached as Appendix 3.

Phenological responses

Future work in citrus intensification will rely on new genetics to increase canopy efficiency. To that end, we aimed to quantify the way citrus trees grow in a large arboretum collection – and to provide phenological data and genetic material to a global effort to develop a multi-variate genomic prediction model to improve understanding of the G×E relationship and predict performance of citrus in different environments. Currently there are 396 selections within the Dareton arboretum.

For all trees in the arboretum, the average rate of growth for the 217 days from hedging was 5.20 mm/day. Our large arboretum collection, drawn together from multiple sources over many years, has both very fast and very slow growing citrus trees. From this data, a sustained rate of growth exceeding 7 mm/day from early winter to mid-summer appears to be a reasonable description of a very vigorous citrus tree. This compares with 3.0 mm/day new shoot growth in sweet orange, as modelled by Brazilian researchers in 2021. Similarly, our data shows healthy trees growing at below 2 mm/day for the same period could be considered very low vigour. This work was presented to international colleagues at the XIII International Symposium on Integrating Canopy, Rootstock and Environmental Physiology in Orchard Systems in New Zealand, 2025, and will be published in *Acta Horticulturae*. The abstract is attached as Appendix 4.

<u>Contributions toward global genomic prediction in citrus</u>

Through the program, we also had a chance to contribute in a small way to a large piece of work defining genotype-by-environment interaction (G×E) in citrus. Craig Hardner, Centre for Horticultural Science, Queensland Alliance for Agriculture and Food Innovation, is working within a large USDA project "Enabling Genomics-Assisted Specialty Crop Breeding and Research through Advanced Database Resources" to accumulate citrus data sets from USA, Brazil, Australia and Japan. The description here is from our recent paper presented at the International Citrus Congress, 2024. The abstract of which is attached as Appendix 5.

“This phenomenon is not well understood in horticultural crops. Knowledge on the stability of cultivar performance across environments is important to optimise cultivar breeding and deployment through improved genotype-by-environment matching. Conventionally, G×E is studied using multi-environment trials of clonally replicated genetic material. However, establishment and assessment of these type of trials can be economically and logistically challenging in tree crops. Recently, multi-variate genomic prediction models (which track replication of alleles across individuals) have been used in sweet cherry, peach, apple, and strawberry to aggregate datasets from multiple environments to improve understanding of G×E and predict performance of individuals in environments in which they have not been tested.

As part of a large USDA project “Enabling Genomics-Assisted Specialty Crop Breeding and Research through Advanced Database Resources” we have started accumulating citrus data sets from USA, Brazil, Australia and Japan using the Breeding Information Management System in the Citrus Genome Database and are developing pipelines and workflows for standardisation and curation of these datasets.”

Coupled with the data collected in our arboretum, we also collected leaf samples for genetic analysis which will be used to build out the model. Our contribution will be used, in the first instance, as a test population to validate a model trained on international data. A description of this work was published in the upcoming proceedings of the International Citrus Congress with co-authors from USA, Brazil and Japan.

<u>A citrus ideotype</u>

The idea of a citrus ideotype, a theoretical ‘best’ tree, is born and lives as a discussion topic. It is not a realistic expectation and often compromises on much of the practical realities of growing citrus trees profitably. What it does do, however, is describe a platform that would allow increased productivity driven by the tree’s natural habit – rather than the system we are forced to wrap around it. That is, a tree that establishes and fills its allocated space quickly, has no juvenile phase, carries the bare minimum leaf area on the least amount of scaffold wood, sets every flower and holds a first grade piece of fruit to maturity at a marketable size, would be most desirable. Digging within this ‘simple’ sentence reveals a number of areas that could underpin years of research and development – but, taken as a whole, highlights every element of orcharding we have to manipulate with cultural interventions to produce a profitable crop.

The concept of an ideotype is not new for citrus. In the 1960s and 1970s, Californian citrus researchers were describing a tree using a ‘dwarfing rootstock with a slow-growing, highly fruitful, old-line bud’. Being more specific, key architectural components would include reduced internode length and a more compact branching habit, similar to that seen when using the dwarfing Flying Dragon trifoliate orange rootstock. The ideotype should maintain a branching angle of approximately 45°, to optimise light penetration while providing structural support. A target height of ~2.5 m would improve harvest efficiency.

Leaves could increase chlorophyll content to maximize photosynthetic efficiency within a smaller canopy volume, and those leaves should be smaller to allow better light penetration through the canopy. Reproductive efficiency would be enhanced by promoting shorter flowering period, a low- to no- juvenile phase. Even fruit distribution throughout the smaller canopy would improve picker access and speed and minimise sun damage.

Root architecture should drive efficient nutrient uptake while maintaining drought tolerance and stability through a more fibrous system with increased lateral branching, similar to that seen in some semi-dwarfing citrus rootstocks.

Literature review

One of the highest impact outputs from the project will be our review of the way to modify citrus canopies. The paper, presented at the International Citrus Congress, 2024, and published in *Acta Horticulturae* the same year, reviews the literature on high density planting of citrus to understand the motivation for crop intensification and the different strategies for manipulating tree size such as dwarfing rootstocks, dwarfing viroids, pruning and trellis training. The abstract is attached as Appendix 6.

The paper explains in detail that “Citrus vigour can be manipulated during orchard block establishment and/or during the production phase. Prior to orchard establishment, the scion and rootstock combination is selected and the decision to use the dwarfing viroid is made, given there influence on tree spacing. If a trellis system is to be used, this needs to be decided prior to planting, too. Planting density is chosen to optimise the capture of incoming solar radiation based on expected tree size – that is, smaller trees will be planted closer together than larger trees. In the production phase, canopy- or root-pruning, girdling, and plant growth regulators can be used to control vigour. Both water and/or nutrient restrictions can also influence growth." The paper goes on to describe each of these methods of citrus intensification, drawing on scientific principles driving whole-of-orchard productivity.

Outputs

Table 1. Output summary

Output	Description	Detail
Milestone reports	Annual reports were prepared to report on the project progress.	MS102, MS103, MS104, MS105, MS106 and MS107 were submitted to Hort Innovation as per contract agreement. These reports aligned with the project monitoring and evaluation plan.
Fact sheets	NSW DPIRD released factsheets giving detailed coverage to an issue	"Hand pruning for profit" – Primefact. This is provided as an attachment in Appendix 7 and is available online, here: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/1503246/Hand-pruning-citrus-for-profit.pdf
Presentations to industry	Invited presentations given at the behest of Citrus Australia, to inform and update members on progress and results.	Conferences, congress, forums etc. "Citrus varieties and tree intensification project" - Citrus Australia's Murray Valley Regional Forum. 2021. "AS18000 project and citrus orchard intensification" – Citrus R&D Roadshows, Sunraysia and Riverland. 2022. Tree Intensification – Citrus Australia's Technical Forum. 2023. This is provided as an attachment in Appendix 7.
Presentations to the science community	Papers accepted for oral presentation.	Conferences, congresses, symposia etc. International Horticulture Congress, France, 2022 "Estimating tree canopy growth and light interception using LiDAR-based methods in viroid-dwarfed oranges" "Intensifying citrus tree crops and modifying tree canopies: a brief review" International Citrus Congress, 2024 "W.Murcott mandarin canopy management: 3 year trials, grower experiences in Australia, South Africa and Spain" Falivene *et al.* "Five Different Pruning Strategies Were Not Able to Improve Productivity a Densely Planted Salustiana Common Orange Block in Short Term" Mahmud *et al.* "Trellis and high-density navel pruning; first three seasons of results" – Falivene *et al.* "Effect of Dwarfing Viroids on Canopy Volume and Height, and Fruit Production of Bellamy Navel Oranges 35 Years After Inoculation" Mahmud *et al.* International Symposium on Integrating Canopy, Rootstock and Environmental Physiology in Orchard Systems, New Zealand, 2025 "Canopy regrowth following mechanical hedging in a large arboretum collection" Monks and Mahmud. This is provided as an attachment in Appendix 7.

Field days/workshops	Events specifically organised by NSW DPIRD or other industry group to give growers access to field sites.	Discussion on the citrus tree intensification research with AS1800 Program Team Forums, 2021, 2022, 2023, 2024, 2025. Tree Intensification update and field walk, Dareton, 2022. Davidson's pruning experiment update, Riverina, 2023, 2024. Pruning high density trees for profit – workshop – Riverina, 2024. Pruning workshop, Murrami, Riverina, 2024. "Managing high density orange trees" – a series of four field days, 2024. Two major field days held in Dareton and in Riverina covered results and applications from the project. The Dareton field day (2024) had a report written about it, summarizing the content and attendees' responses. "DPIRD Dareton citrus field day report: 15 October 2024". This is provided as an attachment in Appendix 7.
Industry articles/case studies	Articles accepted for publication in the Australian Citrus News magazine.	"High density plantings, intensive orchards to be tested" – Citrus Australia website. No longer accessible. 2021. "Trellis systems could pave way for robotic harvesting" – Australian Citrus News, 2021 & https://citrusaustralia.com.au/latest-news/2021/08/trellis-systems-could-pave-way-for-robotic-harvesting/ AS18000 project overview – Australian Tree Crop magazine, 2021. "Pioneering citrus dwarfing viroid use in the Riverina" – two case studies – Australian Cirtus News, Issue 2, 2023. Republished in the Australian Tree Crop magazine, 2023. "Unlocking high-density citrus orchards in Sunraysia" – two case studies – Australian Cirtus News, 2024. This is provided as an attachment in Appendix 7. "Combination or inoculation order of citrus dwarfing viroids: experiments on navels" – Australian Citrus News "Challenges with high density orchards" – Australian Citrus News, June/July 2024. "Citrus Intensification" – lead article in the Citrus plant protection guide 2023-24 – NSW DPIRD
Progress reports submitted to the Project Reference Group and AS18000 intra-project meetings.	Summaries of progress and specific points of discussion presented to the project's industry reference group.	AS18000 Project Leadership Group presentations throughout the project --- giving an overview of each component of the project and highlighting specific experiments of broad interest. An example is provided as an attachment in Appendix 7, where we challenged team members to see our projects through different lens, appreciating the different priorities stakeholders have in our work.
Videos	Video outputs edited to give project updates, results and application advice.	"NSW DPI Citrus Trellising Trial" - an introduction and overview. Industry produced: "Citrus tree intensification overview" – a video introducing the AS18000 project and the individual components – with a grower discussing their interest. I have used this video multiple times as a concise overview. https://twitter.com/CitrusAustralia/status/1407109399739437068?s=20 Industry produced: A broad overview of the Roadshows, including many Hort Innovation co-funded projects, can be seen in this short video produced by Citrus

		Australia. All shots in the field are from the Dareton field day. https://www.facebook.com/watch/?v=465710394662410 "Mandarin pruning practices" QLD mandarin pruning practices videos (nsw.gov.au) "Pruning experiments" – overview and updates, Sunraysia and Riverina. This series of videos describes the treatments and 'philosophy' behind their inclusion. Linked through NSW DPIRD website. Navel orange pruning methods and trial (nsw.gov.au) "Window layer pruning" – a technical guide to enacting the pruning method. https://www.youtube.com/watch?v=vsMXGVUdqi0&t=1s – this video has more than 6,000 views to date. Others in the series include technical demonstrations of Half-tree heavy hedging, light hedging and chunk pruning. https://www.youtube.com/watch?v=OAx7WUqqGTg https://www.youtube.com/watch?v=Wt8pXetLfgg https://www.youtube.com/watch?v=G-nlOVCD2CI and an introduction to the pruning experiments: https://www.youtube.com/watch?v=ZydzUDYjC2Q "Citrus tree architecture" – an introduction and overview. NSW DPIRD website. Linked through NSW DPIRD website and https://www.youtube.com/watch?v=j87D6azhdRI Overview of citrus pruning technics used in Spain and Morocco. A playlist of 18 videos developed under CT19002, Afourer best practice canopy management. https://www.youtube.com/playlist?list=PL4zlvcUKKUmXZ-tjKQzOp7D-NRnLasy2P "High density trellis and non-trellis canopy management" – Youtube.com "Pruning high density trees for profit – workshop – Riverina" Youtube.com "Afourer grower Dean Morris pruning case study" - https://www.youtube.com/watch?v=Xr5I_2HGCpU "Canopy management trial in high density oranges" – a comprehensive overview of findings in Salustiana oranges in https://www.youtube.com/watch?v=d94F0wuVzOU "High density dwarfing in navel oranges – a grower shares his experiences" - https://youtu.be/hI1xKJlhINE
Non-industry articles	Articles accepted for publication in publications un-aligned with the horticulture sector.	"Research for the future" – Sunraysia Daily newspaper.
Journal papers	Peer reviewed science published internationally	"High-density espalier trained mangoes make better use of light" – 2023. Mahmud et al. Agronomy, #13
Financial tool	Costing scenarios for growers to use to compare financial viability.	This work was presented at the October 2024 Dareton field day and before an international audience at the International Citrus Congress, 2024. A draft report has been provided directly to Hort Innovation, and will be made available more broadly, once it has been published to our website. There will be a corresponding, editable spreadsheet released at the same time, updating the currently available budget costing model with relevant high density, trellis and dwarf-tree data.

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Increase productivity and profitability of Australian horticulture through cropping system intensification and innovation programs targeting the whole of horticulture.	Hort Frontiers Fund	Our work created the tools, shared them with growers and discussed how to use them to increase productivity and profitability on their farms.	Our work created new, robust information and tools and presented them to growers to make improved decisions. This work was generated from a series of well run experiments, designed to address the specific industry needs expressed in the RFP. The industry has reported they have had access to a suite of outputs that will allow them to make a decision to adopt advanced production systems. When interviewed by RMCG during the mid-term review, released early 2023, growers valued our research – appreciating seeing these new systems in their region and through videos. When surveyed in 2024, industry members across the tri-state region indicated they would be able to apply our findings to their business (e.g. Yoogali, NSW post-field walk 'dart board' evaluation responses, Plate 5). The same was true of the Dareton 2024 field day, where 70% of attendees said the work was 'highly useful'. Peak industry body, Citrus Australia, continues to ask us to attend their outreach events to speak specifically about this work – indicating a desire to hear and be exposed to concepts and tools we have developed. Industry has seen such value in our work that they have contracted new work to take many of the ideas developed within this project on in a Citrus Levy Fund project (CT23006).
End of project outcomes: New, robust information and tools available to growers to make improved production decisions Adoptable advanced production system that can be deployed by growers Plant morphology descriptions most suitable for intensive and productive cropping and harvesting	Project KPIs: Measure the growth habit of a wide range of citrus varieties to identify architectural features Measure different pruning management strategies for high density to maximise profitability Measure different dwarfing viroids for their impact on canopy size and productivity.	These are the tangible outputs delivered that allowed us to meet the industry's need. These are the communication channels used to connect those outputs with growers. These are the underlying experimental methods used to develop new information.	The Australian citrus industry is empowered to make an informed decision about planting and pruning high density orchards by the new materials we produced through this project. The cohesive body of work, specifically with video and field day support, has delivered an adoptable package of information for growers. Growers with trees now will benefit from pruning advice. Growers planting tomorrow will benefit from costing scenarios and plant spacing discussions. Growers planting in 15 years' time will see new information about viroids in combinations and the viability of trellis to increase yield and quality. That viroid work, generating two new replicated experiments (and leveraging an existing one) has sparked considerable discussion at field days regarding planting systems. We have measured the growth habit of a range of contrasting citrus varieties and delivered key information to industry and the wider science community. Scientists are already seeing the advantage of this phenology work, using our data to validate international GxE models for

		Measure the growth habit of a wide range of citrus varieties to identify architectural features	citrus. Citrus physiologists and breeders will have a better understanding of the highest and lowest growth rates from our phenology work – helping design better experiments and drive better decisions.

Monitoring and evaluation

Table 3. Key Evaluation Questions

<table>
<tr><th>Key Evaluation Question</th><th>Project performance</th><th>Continuous improvement opportunities</th></tr>
<tr>
<td>To what extent has the project achieved its expected outcomes?

To what extent has the project given industry members the tools to increase productivity and profitability of their citrus operation through cropping system intensification?</td>
<td>Yes, the project delivered the tools to increase productivity and profitability through intensification. They have been brought together in an adoptable package, adding to the pre-existing materials developed, on the NSW DPIRD citrus website.

The NSW DPIRD website, https://www.dpi.nsw.gov.au/agriculture/horticulture/citrus, and youtube channel, https://www.youtube.com/@NSWAgriculture/videos are repositories of the tools delivered to increase productivity and profitability. More than 95,000 people have viewed the dwarfing viroid video produced under CT17007 and promoted throughout AS18000.

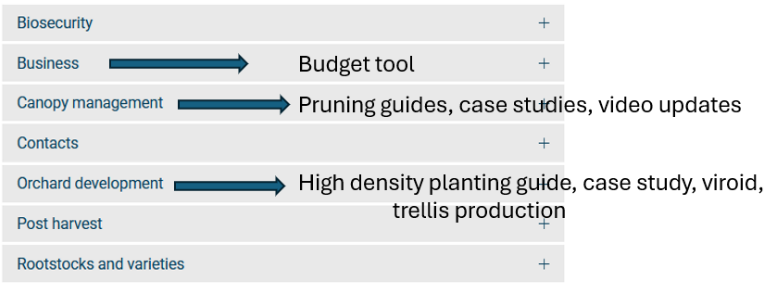


Plate 2. The outline of the NSW DPIRD citrus website, showing the major headings and the outputs within.

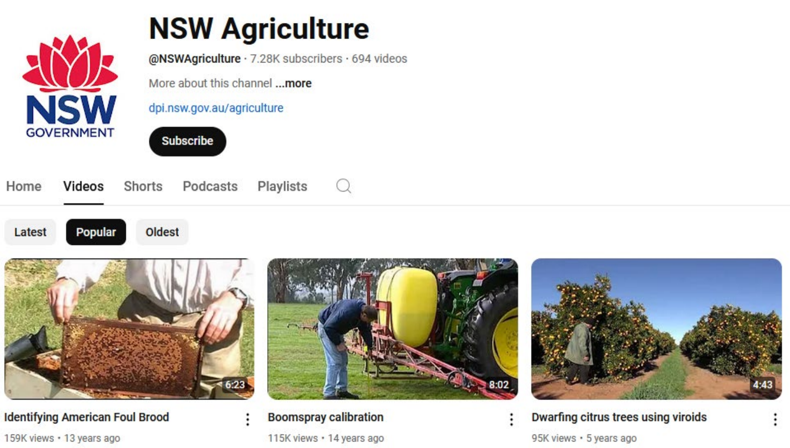
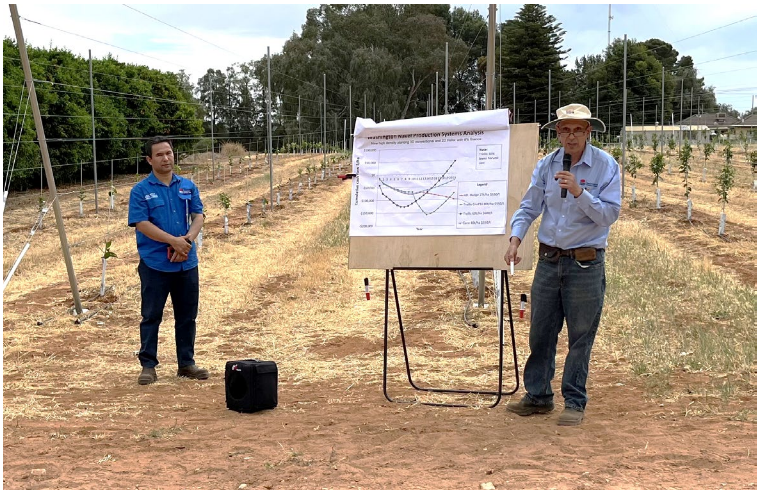
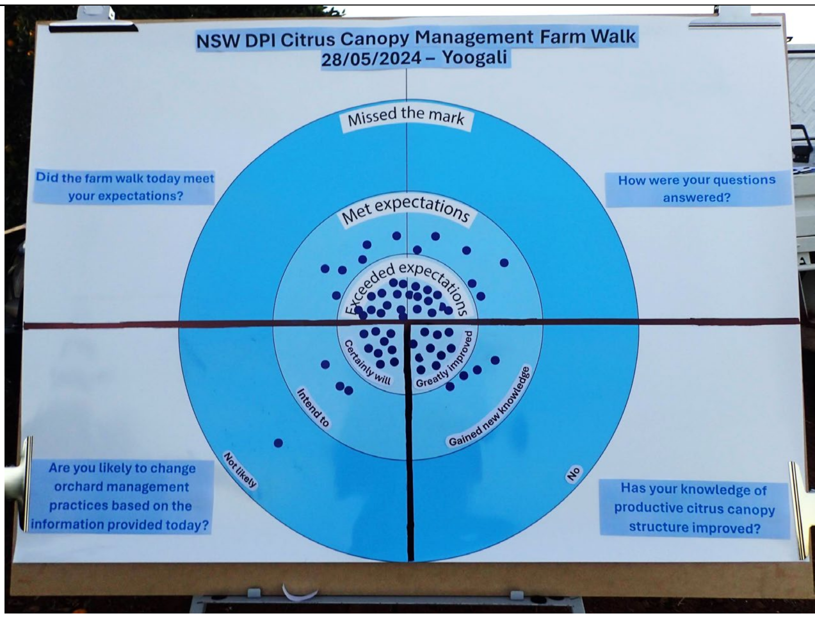


Plate 3. A screengrab of the NSWAgriculture Youtube channel.</td>
<td>We have pursued the best growers in the tri-state to contribute their thoughts on productive orchards. I think expanding the scope to include QLD and WA are key to understanding shared pain points and innovations used in different regions.

Navigating our NSW DPIRD Citrus portal is not intuitive. Created to be an open bucket of information, as our projects have focused more directly on specific areas on grower interest, our systems of displaying that information needs to be updated.</td>
</tr>
</table>

	The depth of knowledge available to growers to make on-farm decisions with confidence has increased through the life of AS18000. See Table 1., Outputs, for a comprehensive list – including scientific journals, industry magazines, field days, workshops, one-on-one discussions, forums, videos and conference presentations.	
How relevant was the project to the needs of intended beneficiaries? Has the project provided direction to current growers about the best way to manage blocks planted at high density? Has the project developed tools for growers considering planting high density orchards that give them a better chance at making a good decision?	The project has provided direction to growers about the best way to manage their blocks planted at high density, and has developed tools to help growers considering the same. For those with trees in the ground now, we delivered comprehensive information about pruning overcrowded blocks profitably, including in-person, hands-on workshops and field days, cases studies and a great series of videos – accessible to all growers. Costing models were presented to industry contrasting different scenarios. For those considering planting at high density, we presented, through field days, case studies and videos, information to base their decisions on. We held field days highlighting the interaction between scion, rootstock and soil type to help growers understand planting density and showed them what that looks like so they could make the best choice for their farm. For those planting in 15 years, we established new work understanding the interaction between citrus viroids and their impact on tree vigour, and growing citrus on trellis. This data has been shared through field days, case studies, videos and a costing model. Our work with phenotyping is already being used to understand how G x E impacts the expression of genotypes across the globe.  Plate 4. Dr. Mahmud Kare and Steven Falivene, of NSW DPIRD, presenting financial information on the ROI for trellis systems at a 15 October 2024 field day. Photographer: Dave Monks.	Managing input costs is a key part in remaining profitable. Having the foundation required to understand how changes to a production system will impact inputs and outputs is key to making an informed decision on farm. The messages developed within this project will underpin all our future communications with growers – including the synthesis of international experience to upskill Australian citrus growers.
How well have intended beneficiaries been engaged in the project? To what extent have target members of industry been engaged?	We aimed throughout the project to engage with citrus growers through the citrus peak industry body, Citrus Australia, and through established NSW DPIRD channels. We produced and published five articles for the Australian Citrus News magazine, with an estimated readership of 5,000/quarter, distributed across Australia. In the most recent ACN (#4, 2024), Dave Monks summarised their busy year highlighting the 190 people that came to the DPII site in to see and discuss advances in citrus productivity – 165 asking specifically about AS18000 content. In the last five years, 334 people attended field days at the site to see our outputs, and 242 came independently to see the work with AS18000.	I think we did a very good job with extending the message to those in the tri-state and those connected to the Citrus Australian communications channels. Delivery of

	AS18000 outputs have been presented at three Citrus Australia conferences, forums, field days and congresses. At the most recent congress in Queensland, Dave Monks spoke specifically on the tools developed within AS1800 available to growers to use when considering intensification ("Dave Monks, NSW DPI – Tree intensification – tools for making decisions" - https://citrusaustralia.com.au/uncategorized/2024/03/acc2024presenations/). We have also partnered with Citrus Australia to speak at 8 of their Regional Forums, reaching growers from Western Australia to Queensland, and are scheduled to speak at 3 more this year (2025). Using our own networks to extend the message, we have delivered face-to-face technical workshops on pruning, field days covering all of our work on intensification and multiple videos – engaging our intended beneficiaries from project establishment to project end, and in continuation through the Citrus Levy Fund (Competitive Citrus Orchards (CT23006). We have also reported through our CitrusConnect e-newsletter in the later stage of the project. Of the 65 people attending our October 2024 field day at DPII, 90% self-reported as growers, packers and industry service providers. This was advertised through our own curated networks targeting industry members.	materials in to WA and QLD have occurred on the back of other project – including speaking at conferences etc., but an occasional webinar may have value for growers to hear and see our work from outside the region.
To what extent were engagement processes appropriate to the target audience/s of the project? How accessible were extension events, and written and digital outputs to targeted members of industry? Where the intra-project interactions and activities beneficial to coordination and of mutual benefit to the program members?	We aimed to have our outputs reach our audience in multiple forms to ensure the maximum access to the materials. We were able to present in-person forums, discussions, one-on-ones, field days, workshops, and conference presentations to reach people in the broadest way. We also delivered videos that captures the same content, able to focus on specific points using supplementary still images, for an audience unable to attend in person – or who prefer to view the content in that way. We also wrote outputs: some able to bring more-data dense summaries and others the briefest of high-level concepts. It was very common to prepare 'field notes' when taking larger groups into the field, so the details could be described by presenters and viewed again by the audience. Attendees at four recent farm walks in the Riverina, in May, March and December 2024, were asked to provide feedback. They were asked to comment on the degree 1. to which the farm walk met their expectations 2. to which their questions were answered 3. how likely they would be to change orchard management practices based on the information provided on the day 4. and how their knowledge of productive citrus canopy structures improved. Feedback at all events was overwhelmingly positive, with most respondents indicating they would 'certainly' or 'intend to' change their on-farm practices based on what they learned on the day. A sample of the survey is presented here, from a Yoogali, NSW, field day in May 2024.	

	 Plate 5. Yoogali, NSW post-field walk 'dart board' evaluation responses describing growers' positive sentiment regarding the field walk, ability to have questions answered, knowledge of productive citrus system, and their likelihood to change orange management practices based on the information provided. Photographer: Andrew Creek, NSW DPIRD. The intra-project interactions helped me see the wider issues in moving to intensive production and drew my attention to the shared problems – most of which were not production related, but process related. How do people measure light interception? What is the right way to handle data being passed to a functional-structural modeler? How do you keep a small, remote, team connected at the national and international level so the industry gets the best results? I've established professional relationships with the other crop leaders, but my technical team has not to any great extent. We we're very pleased to host the first meeting and would happily do it again, if we were staying within the program. It was good to get our ducks in a row, preparing field notes and talking points – and with much greater detail and depth than is possible with industry events. Speaking personally, I found the intra-project get togethers worthwhile and of high value. I appreciated meeting with the Queensland and Plant and Food teams, only a few of whom I knew before this Frontiers program. I have enjoyed forming a new network of like-minded colleagues tackling many of the same higher-level issues we are. I think the networks created will bring advances to Australian horticulture well beyond this piece of work.	
What efforts did the project make to improve efficiency? Most of the activities within the citrus project are actively pushing towards developing	We radically changed out canopy volume method when Mahmud Kare came on board the program. Mahmud, ex-QDAF (now QDPI), brought considerable knowledge and skill in collecting, manipulating and interpreting data collected for LiDAR devices. The project quickly pivoted from "eyeballing long bits of wood leaning on a tree" to a hand-held LiDAR able to collect accurate 3D point clouds across orchard blocks rapidly. The device allowed us to collect considerably more data per tree, and more quickly – which allowed us to measure more trees. It also eliminated the operator bias inherent with physically measurements. This new data has become a cornerstone in our extension materials, delivering visually striking images to communicate canopy shapes and sizes. We were able to optimise our citrus research extension program because of the co-location of many projects at the DPII and Griffith Centre of Excellence.	Continue to challenge our own assumptions – asking for input from outside our usual channels – to see new or different ways of doing things. Both technical and outreach.

existing concepts, to leverage the work that has gone before in other crops and projects (e.g. apples). It is not in the scope of this project to further optimise those methods; although incidental efficiencies will likely be made through broader discussion with AS1800 program members.	Because of this, we were able to consolidate the number of outreach events and increasing the value to industry. The October 2024 field day are DPII covered material funded through AS18000 (Frontiers Fund), Citrus Variety Evaluation (Citrus Levy Fund, CT26000), Citrus IPDM (Citrus Levy Fund), Citrus Rootstock Evaluation (Citrus Levy Fund), Citrus regulated deficit (Citrus Levy Fund, CT17000), Competitive Citrus Orchards (Citrus Levy Fund, CT23006) and Afourer mandarin canopy management (Citrus Levy Fund, CT19002). We have been able to provide similar efficiencies when delivering outputs throughout the Riverina and at Citrus Australia Regional Forum, conference and congress events. This has not only increased value to attendees, but also maximised financial efficiency – often having staff deliver work across multiple projects for the same travel budget, venue hire, etc. In the same way, we have been able to develop multiple, overlapping, supporting, outputs that provide industry with a depth and breadth of knowledge when considering an on-farm business decision. Data generated within CT23006, the new Competitive Citrus Orchards project, will continue to leverage materials generated within AS18000 and other projects to maximise efficiency.	

Recommendations

The citrus industry is fortunate to have a new Citrus Fund project, CT23006 Competitive citrus orchard systems, with DPIRD as delivery partner, led by AS18000 alum Dr Mahmud Kare. This project picks up on elements of AS18000 Citrus and new priorities for industry. Many of the recommendations from AS18000 have been taken up by this new work.

The impact on the pest and disease presence within advanced production systems is not well understood and should be quantified. Smaller trees with higher canopy efficiency will have an impact on pests' and beneficials' habitats, spray penetration, air flow, localised humidity, and the portion of yield (and canopy) in proximity to the soil and soil borne pathogens, etc.

Right now it is assumed that smaller trees will provide a cost saving with picking (and other 'at the tree' activities) – but this isn't the case in our limited experience speaking with contractors and growers using these systems. Picking is still the same cost/bin and we don't have good data to quantify the cost of activities on a ladder vs. on the ground.

I think there is value is better describing the breadth of tree architecture/phenotypes in the current breeding pool, and those on the fringes of inclusion. It is my experience, as the leader of a major commercial and pre-commercial citrus variety evaluation program (CT22000), other than pathogen resistance, tree traits are very low on the priority list. I think this should include international breeding programmes and should start with a set of well thought out questions articulating the issues at hand.

Across all crops, I think there should be a better description of the data used to generate functional/structural model – so more of it can be collected within other projects. We're often standing beside a tree with a clip board and ruler and could add a couple of the most useful data to the list, if only we knew what was required. Internode length? How many? How do you number them? Originating from where? I think Hort Innovation could prescribe some of these standardised methods and release them in plain English for other research teams to consider.

Refereed scientific publications

Journal article

“High-density espalier trained mangoes make better use of light” – 2023. Mahmud et al. Agronomy, #13

Chapter in a book or paper in conference proceedings

“Intensifying citrus tree crops and modifying tree canopies: a brief review” – Acta Hortic 1399. ISHS 2024. DOI 10.17660/ActaHortic.2024.1399.24

“W.Murcott mandarin canopy management: 3 year trials, grower experiences in Australia, South Africa and Spain” Falivene et al. Accepted for publication – Acta Hortic.

“Five Different Pruning Strategies Were Not Able to Improve Productivity a Densely Planted Salustiana Common Orange Block in Short Term” Mahmud et al. Accepted for publication – Acta Hortic.

“Trellis and high-density navel pruning; first three seasons of results” – Falivene et al. Accepted for publication – Acta Hortic.

“Effect of Dwarfing Viroids on Canopy Volume and Height, and Fruit Production of Bellamy Navel Oranges 35 Years After Inoculation” Mahmud et al. Accepted for publication – Acta Hortic.

“Canopy regrowth following mechanical hedging in a large arboretum collection” Monks and Mahmud. Accepted for publication – Acta Hortic.

Intellectual property

No project IP or commercialisation to report.

Acknowledgements

We wish to acknowledge the generous contributions of time and resources by our grower-collaborators and their businesses: Brett Hullah, Justin Davidson, Tony Naimo, Peter Ceccato and Frank Madaffari.

Appendices

Appendix 1

Five Different Pruning Strategies Were Not Able to Improve Productivity a Densely Planted Salustiana Common Orange Block in Short Term

Kare Mahmud, Andrew Creek, Dave Monks

Salustiana, a prominent common orange variety in Australia, can suffer from a decline in yield brought on by overcrowding due to its vigorous growth habit; this is further exacerbated when planted at higher densities. To assess the efficacy of hand and mechanical pruning to bring an overcrowded Salustiana orange block back into optimum production, five pruning treatments were carried out across four years in a commercial high-density orchard (1111 trees/ha). A basal treatment was applied across the experiment by hedging the sides of trees (light hedge) to give a canopy width to 270 cm. To this were applied two levels of hedging intensity treatments and two hand pruning treatments. All hand pruning treatments increased light penetration which stimulated new flush growth within the canopy. In all instances, however, none were better than the control (basal light hedging) in terms of yield (t/ha), number of fruit or fruit size, or by dollar returns when accounting for costs (of which mulching pruned material was considerable). The long-term value of the intensive hand pruning may yet to be realised, as new structural limbs are grown and begin to bare fruiting wood throughout the canopy, and the opportunity cost is discussed when comparing an attempt to regenerate a block with pruning or removing and replanting.

Appendix 2

Trellis and high-density navel pruning; first three seasons of results

Steven Falivene, Kare Mahmud, Dave Monks

A block of high-density Attwood navel oranges was planted in 2008 at 3.5 m x 4.9 m in Sunraysia, NSW, Australia. It has a mature tree average yield of 25 t/ha/year. Typical yields of mid-season navel oranges in this region are about 40-50 t/ha/year. The low yield was speculated to be caused by vigorous dense canopies resulting in over-shading and intense annual hedging to maintain row access removing viable fruiting sites. To quantify options to overcome this, two experiments were implemented in 2020 within the same block of trees: one comparing pruning treatments and one comparing trellis training systems. The pruning experiment included mechanical hedging, hand “chunk” pruning, hand “centre limb” pruning, hand “intensive” pruning, and hand “intensive” pruning with subsequent regrowth management. Each of these treatments decreased over-shading. Three contiguous years’ pruning treatments have not shown any differences in yield between treatments. It is possible that more time is needed for trees to adjust to their pruning regime, or the intensive vigour response of the trees is causing shading by mid-season. A trellis training systems experiment was implemented on trees adjacent to the pruning experiment three years ago. Regardless of training system, the trellised trees this season have set a significantly higher crop load than any of the pruning treatment trees (both yield/ha and yield/canopy m^3). More data is needed to conclude if trellis production is a practical and economically viable option. A preliminary cost-benefit analysis indicates an increase of at least 10 tons per hectare is required for the trellis to account for increased capital and annual maintenance costs.

Appendix 3

Effect of Dwarfing Viroids on Canopy Volume and Height, and Fruit Production of Bellamy Navel Oranges 35 Years After Inoculation

Kare Mahmud, Nerida Donovan, Tahir Khurshid, Dave Monks, Steven Harden

Controlling vegetative growth and canopy size while maintaining productivity is of interest for high density citrus plantings. This may be achieved by inoculating trees with dwarfing viroids, although it is important to understand viroid interactions in case of mixed infections. A field trial was established in 1989 to investigate the impact of citrus viroids on canopy volume and height, and fruit production of Bellamy navel orange (Citrus aurantium var. sinensis (L.) on trifoliate orange (Citrus trifoliata L.) rootstock. Trees were inoculated with hop stunt viroid (CVd-IIa), citrus dwarfing viroid and two strains of citrus exocortis viroid, singly and in combination. LiDAR (light detection and ranging) was used to estimate tree canopy volume, height, and light interception, and fruit production, size and fruit quality for three seasons from 2022. The results showed that, 35 years after inoculation, some viroid combinations led to a significant reduction in both canopy volume and tree height compared with the uninoculated control but there was no significant effect on total canopy light interception (%) and most viroid treatments did not influence yield per tree, fruit size or quality. This long-term experiment showed that the impact of viroids on tree size can remain over the life of an orchard, and knowing which viroids are present in field trees is critical prior to inoculation with commercial dwarfing viroids in order to plan correct tree spacing and maximise yield per hectare.

Appendix 4

The influence of rootstock, scion type, and northern or southern side of the canopy on the rate and proportion of individual citrus tree regrowth following mechanical hedging in a large arboretum collection

Dave Monks, Kare Mahmud

The rate of canopy regrowth and proportion of canopy regrowing was measured four times in the six months following heavy mechanical hedging in an arboretum collection containing 410 citrus species, varieties and selections in 2020 in Sunraysia, Australia. Data are presented on the impact of rootstock on scion regrowth, for example, within 70 navel varieties and selections, those planted on Poncirus trifoliata rootstock had regrown 57.7cm six weeks after winter hedging, compared with 65.5 cm for citrange (Citrus sinensis × P. trifoliata) and 64.1 cm for Rough lemon (C. jambhiri). Data are provided for each variety 'type' (common oranges, grapefruit, lemons, limes, mandarins, pummelo, rootstocks, and Seville oranges), the northern and southern sides of the tree and by species.

Appendix 5

Development of databases for Global Genomic prediction in Citrus

Hardner, C, F Gmitter, D Main, S Jung, M Cristofani Yal, T Shimizu, M Minamikawa, D Monks

Genotype-by-environment interaction (G×E) is a common in genetic improvement; however, this phenomenon is not well understood in horticultural crops. Knowledge on the stability of cultivar performance across environments is important to optimise cultivar breeding and deployment through improved genotype-by-environment matching. Conventionally, G×E is studied using multi-environment trials of clonally replicated genetic material. However, establishment and assessment of these type of trials can be economically and logistically challenging in tree crops and can lead to breeding efforts focussing on local environments. Recently, multi-variate genomic prediction models (which track replication of alleles across individuals) have been used in sweet cherry, peach, apple and strawberry to aggregate datasets from multi-environments to improve understanding of G×E and predict performance of individuals in environments in which they have not been tested. Here, we propose evaluating this approach in citrus with a focus on fruit size and sweetness. As part of a large USDA project "Enabling Genomics-Assisted Specialty Crop Breeding and Research through Advanced Database Resources" we have started accumulating citrus data sets from USA, Brazil, Australia and Japan using the Breeding Information Management System in the Citrus Genome Database and are developing pipelines and workflows for standardisation and curation of multiple datasets. We also have made initial evaluation of opportunities for prediction of performance of untested material in new environments using models developed in Minamikawa et al (2017) validated against performance in Australia environments. These models also offer opportunities for improved accuracy of GWAS and genomic prediction studies using these large data sets. We welcome further collaborations.

Appendix 6

Intensifying citrus tree crops and modifying tree canopies: a brief review

K. Mahmud, D. Monks, N. Donovan, A. Warren-Smith

High-density citrus orchards have proven benefits for productivity but canopy management using conventional practices becomes problematic after trees reach their allocated space. This paper reviews the literature on high-density planting of citrus to understand the motivation for crop intensification and the different strategies for manipulating tree size such as dwarfing rootstocks, dwarfing viroids, pruning and trellis training.

Appendix 7.

A list of attachments to this document. These attachments are representatives of the various categories of output described in Table 1. Outputs.

1. A fact sheet. Hand-pruning citrus for profit.

2. A presentation delivered at the 2024 Citrus Congress. Tree Intensification making decisions.

3. A presentation delivered to the science community at the NZ Orchard Systems, 2025. AS18000 overview and growth rate of a range of citrus following hedging in a large arboretum collection.

4. A field day report, including attendee feedback. DPIRD Dareton citrus field day report: 15 October 2024.

5. A case study published in the citrus industry magazine, Australian Citrus News. Unlocking high-density citrus orchards in Sunraysia: Part II.

6. A presentation delivered to the AS18000 cross-crop team forum in Mareeba, 2024. 240912 MONKS Citrus FORUM Mareeba. Considering stakeholder priorities.

A draft copy of the Density Dwarfing Trellis economic analysis has been provided to Hort Innovation separately and will be made available, along with the corresponding spreadsheet, once published to the NSW DPIRD citrus website.

Department of Primary Industries
Department of Regional NSW

DPI Primefact

Hand pruning citrus for profit

October 2023, Primefact PUB23/1049, first edition

Steven Falivene, NSW DPI Citrus Development Officer, Southern Horticulture, Dareton, NSW
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Contents

Why prune?

Pruning can give cleaner and bigger fruit, resulting in higher returns. However, it also has many other benefits, including:

- Harvest staff is used efficiently in pruned citrus trees as ladder work is reduced in trees with a lower height
- Harvest staff prefer picking smaller trees loaded with larger-sized fruit.
- Better spray penetration and air circulation improve pest, disease, and albedo breakdown management.

Identify the aims

Before starting pruning, identify the aims and priorities because these will require different types of cuts and the amount of canopy to remove. Some aims include:

- Reducing tree height – ease of harvest and crop management practices.
- Crop regulation – light branch pruning in early summer can reduce an excessive crop load.
- Skirting – pest and disease control.
- Row spacing – access.
- More internal fruiting – quality and larger fruit.
- Reduction of dead wood – reduced fruit blemish and disease control.

Types of pruning

The type of pruning will depend on the aim and the current canopy shape and condition of the tree. In most cases, pruning will done for all the aims listed above, but some might have a greater level of importance than others depending on the characteristics of the tree (vigour, size, yield), management (cash flow, time availability) and market conditions (price of fruit).

There are 2 main phases of pruning: structural pruning (limbs; those that emerge from the trunk and are larger than 40 mm in diameter) and canopy pruning (branches; groups of shoots older than one year). Structural pruning is changing the tree limb structure to give maximum opportunity for optimum fruit growth. If a tree has not been pruned for many years, this will be the main focus in the first 2–4 years. Removing excess limbs will probably remove enough canopy and let enough light into the tree. A structural prune can take 5 minutes per tree on a previously unpruned tree, depending on the size of the tree and the pruning intensity. It is advisable to structurally prune about 30% of the canopy each year to achieve a good limb structure in 2–3 years.

When all the excess limbs and large branches have been cut out of the tree, maintenance pruning is done to manage the fruit-bearing shoots (up to one year old growth) and branches. Maintenance pruning often only needs about 1–2 minutes per navel orange tree annually. The aim is to remove about 30% of the canopy each year in multiple cuts around the canopy so branches are no older than 4–5 years.

Structural pruning

Step 1: identify the desired shape

A desired framework has evenly spaced limbs extending to all directions of the canopy (Figure 1). Tree canopies are variable. Limbs might not be in the preferred position (Figure 1), and compromises are made while pruning. If a tree is missing lower limbs due to poor pruning practices (Figure 2, right), then drastic measures might be required to encourage lower limb growth. Cut an upright limb down to about waist to chest height, which will remove a large portion of the canopy (e.g. 50 %).

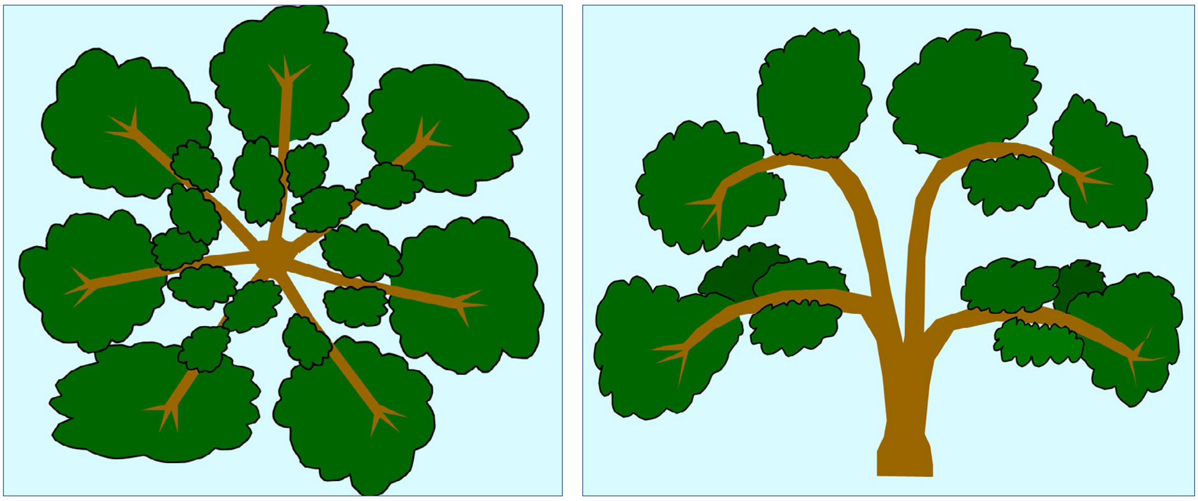


Figure 1. Top view and side view of a desired limb framework.

Figure 2. Left, good structure with lower limbs that are adequately spaced with young branches and shoots. Right, poor structure, there are no lower limbs, and the upright limb might have to be cut at waist height to regrow lower limbs and rejuvenate the tree structure. While this cut will cause a major reduction in short-term canopy volume, it will grow a better-structured tree for long-term yield benefits.

Caution

When structural pruning, avoid removing the lower limbs (Figure 2). Lower limbs are convenient and easy to remove, but they are very important to service the lower part of the canopy. Limbs that are too low, and will later become a skirting problem, must be removed. Trees with too many lower limbs removed tend to take on an undesirable palm tree or weeping willow shape.

Step 2: remove damaged or broken limbs

Limbs that are cracked or broken (Figure 3) are unproductive. If the limb is in a good structural position, then cut the limb back just behind the damage. If the limb is incorrectly positioned, remove the whole limb at its point of origin.

Step 3: remove central upright limbs

Limbs extending to the top of the canopy are undesirable because they shade the lower parts of the canopy (Figure 4). Tall limbs also mean the fruit will be too high in the canopy, making it difficult to manage and harvest. Sometimes the limb can be completely removed, or it might need to be gradually removed in successive stages over several years. Do not remove all upright limbs at once as this opens the tree too much, prompting excess vigour.

Figure 3. Remove any cracked or broken limbs.

Figure 4. Remove upright limbs and branches.

Note: it is best to remove about 30% of the canopy each year when structurally pruning an unpruned tree so its transformation can be gradual, e.g. over 3–4 years. Do not remove more than 20% of the top of the canopy at one pruning as this can induce an over-vigorous response, reducing crop yields. Occasionally a tree with very poor structure might need undesirable limbs removed, reducing the canopy by more than 40%, but this is rare.

Step 4: remove limbs that cross over

Limbs that cross over other limbs (Figure 5) cause access, rubbing and shading problems.

Step 5: remove water shoots

Water shoots can use tree nutrients and resources that would otherwise be used for growing bigger fruit (Figure 6). Thorns are often present on water shoots and can damage the fruit. It is much easier to remove water shoots while they are small. Water shoots grow to mature and cause access, picking and shading problems.

Note: in some instances, if a water shoot arises from a position where a new limb might be desired, topping and/or bending the water shoot can transform it into a limb.

Figure 5. Remove limbs that cross over branches.

Figure 6. Remove water shoots.

Step 6: remove side-by-side limbs

Two limbs very close together, servicing the same parts of the canopy (Figure 7) cause overcrowding, leading to shading, dead wood, and access problems.

Note: once a tree has been structurally pruned into a desired shape, there is usually no need to remove limbs unless they are diseased, sunburned or broken, or another limb in a better position has grown in its place. Continuing to structurally prune a tree (i.e. heavy chainsaw pruning) after the optimum tree shape has been achieved is undesirable and will reduce productivity. If a good, productive, well-spaced limb is accidentally removed, especially a lower limb, extra time is required to regrow the limb and its branches. Lower limbs are important, easy access, fruit producing limbs; think twice before removing a lower limb.

Figure 7. Remove limbs or branches that are too close together.

Maintenance pruning

Maintenance pruning is removing unproductive branches and shoots that produce small, poor quality fruit. Maintenance pruning aims to remove the oldest branches in the shortest time (e.g. 1–2 min) and removes about 30% of the canopy so branches are no older than 5 years.

Productive branches are young and vigorous, close to a main limb or secondary limb, directionally upright, and contain many leaves (Figure 8, left). Unproductive branches are older and predominately have spindly, downward-pointing shoots. These branches will also have dead wood and not many leaves (Figure 8, right).

Figure 8. Left, a pruned canopy with a young branch growing in an opening made from previous pruning. Right, an old canopy with long, downward-cascading branches and dead wood.

The whole branch is removed from where it forks or emerges from the limb. Usually, a branch will have a mix of good, young canopy and older canopy. The key to strategic pruning is having a quick look and removing branches with the most old wood (dead wood and thin, downward shoot growth, Figure 9). Two to four branches are removed from around the tree to spread the effect of pruning and to allow more light penetration throughout the tree.

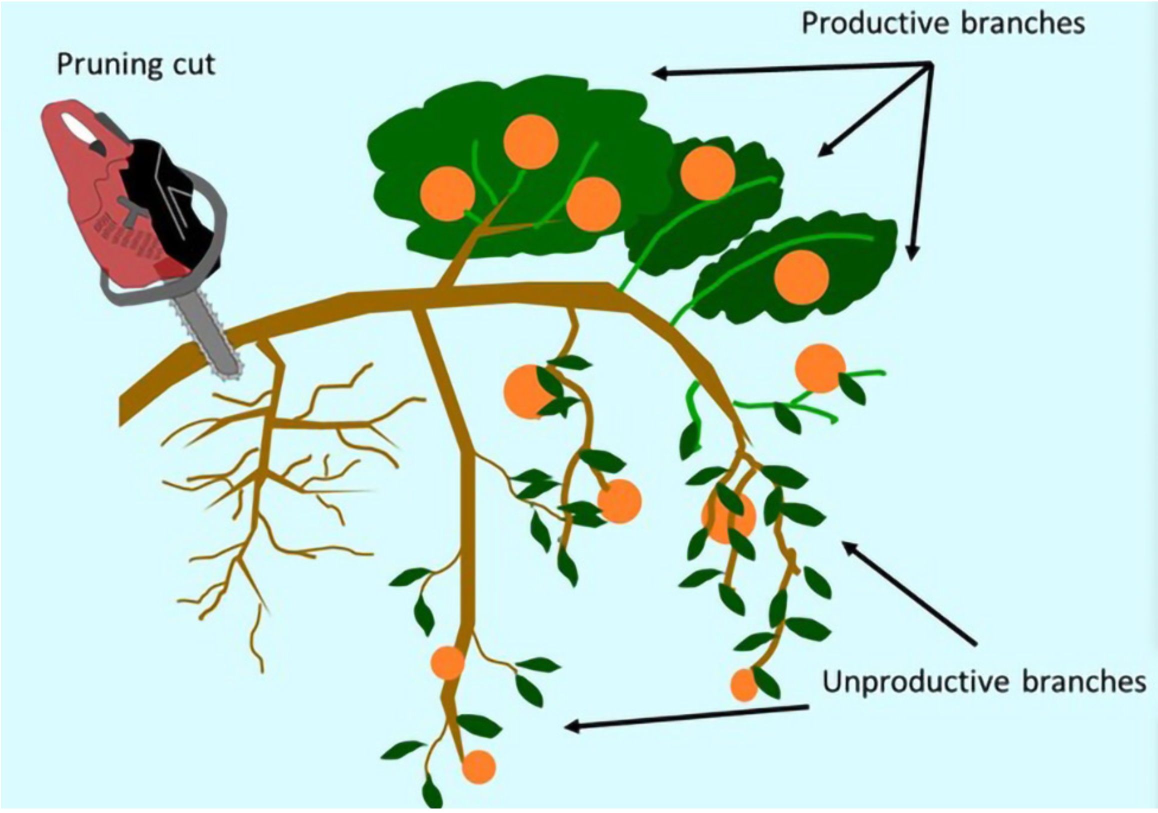


Figure 9. Remove the oldest branches on the tree.

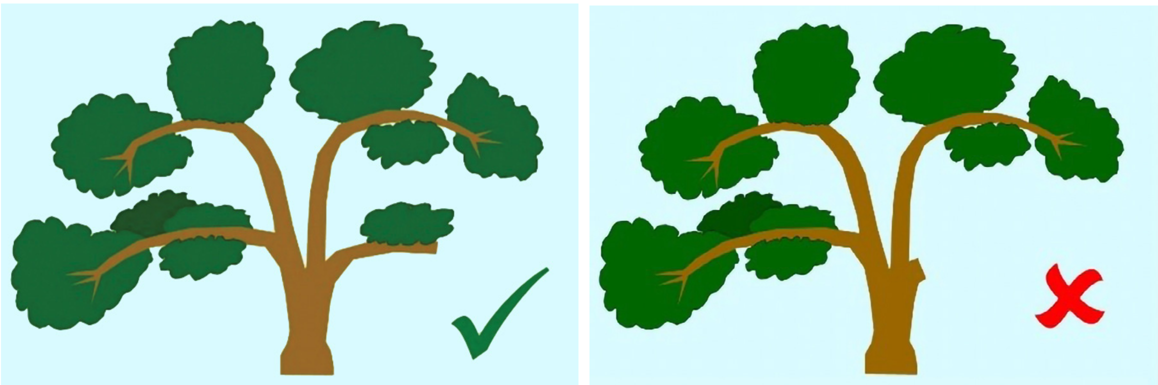


Figure 10. Only prune enough of the limb or branch to remove the old wood and allow enough room for the new branch to grow.

Caution

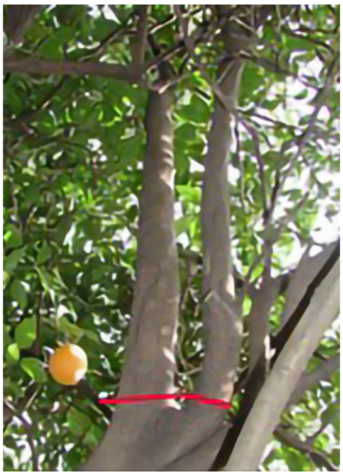
Do not remove the entire limb when branch pruning because a limb or branch pruned back to the trunk might not re-shoot. Prune enough of the limb or branch to remove the old wood and allow enough room for the new branch to grow (Figure 10).

Step 1: remove and thin out unproductive branches and shoots

Figure 11. Left: a branch with unproductive wood can be removed where it begins to fork or is attached to a limb (red). Right: a young branch (2–3 years old) with vigorous shoots and no dead wood should not be pruned. After another 2–3 years, this branch will be older and need to be removed.

Step 2: remove water shoots and other undesirable branches

Remove water shoots annually. Removing a one-year-old water shoot is easier (Figure 12, left) than waiting several years and removing a large unwanted limb that has shaded the lower canopy (Figure 12, middle). Continue to remove other undesirable branches and limbs as they appear, e.g. those that are too tall or broken (Figure 12, right).



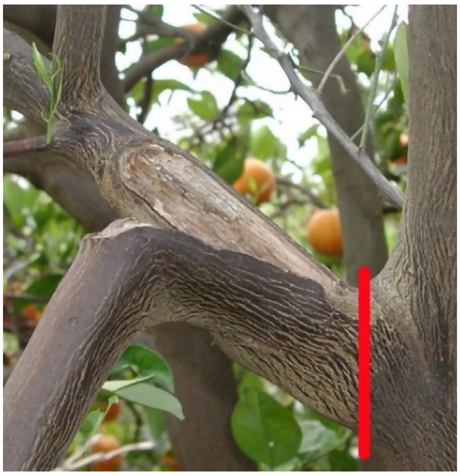


Figure 12. Remove water shoots (left), uprights (middle), and broken limbs and branches (right).

Note: trees should be pruned annually to remove unproductive branches, allowing younger, more productive branches to grow. Always target the oldest branches, removing about 25% of the canopy each year, resulting in a tree with branches no older than 4–5 years old.

Final result

A well-pruned tree should have well-spaced limbs with a thinned-out canopy so that branches are not overcrowded. Enough light should reach the inner parts of the tree to maintain shoots within the canopy. In the middle of the day, filtered light should reach the ground (Figure 13, left) and not completely shade below the canopy (Figure 13, right). There should be gaps in the canopy throughout the tree to let light in and allow access for picking and pruning.

Figure 13. Left: a well-pruned tree with good spacing between branches and predominantly young growth; some dappled light reaches the orchard floor. Right: a dense, over-crowded canopy with no light reaching the orchard floor.

References and further reading

A companion video for this factsheet is available from the NSW DPI citrus website (https://www.dpi.nsw.gov.au/agriculture/horticulture/citrus/content/canopy-management). More detailed videos also show the different pruning styles for navels and mandarins.

Acknowledgements

This is a project of the National Tree Crop Intensification in Horticulture Program (AS18000), funded by the Hort Frontiers Advanced strategic partnership initiative developed by Hort Innovation, with co-investment from NSW Department of Primary Industries and contributions from the Australian Government.

hort frontiers

NSW GOVERNMENT | Department of Primary Industries

Citrus Congress 2024:
Tree intensification

Dave Monks

hort frontiers Strategic partnership initiative | ADVANCED PRODUCTION SYSTEMS FUND

Queensland Government | Plant & Food Research Rangahau Ahumāra Kai | NSW GOVERNMENT Department of Primary Industries

The University of Queensland Australia | QAAFI | Government of Western Australia Department of Primary Industries and Regional Development | Government of South Australia Department of Primary Industries and Regions | SARDI

THE MAGAZINE OF THE CITRUS INDUSTRY
Citrograph
$3.00 a Year, 30c a Copy
Vol. 56, No. 9, July, 1971

Effects of training, hedging on young Valencia (1971)

Introduction

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Citrus Australia Output

Pruning

Videos


Winter...
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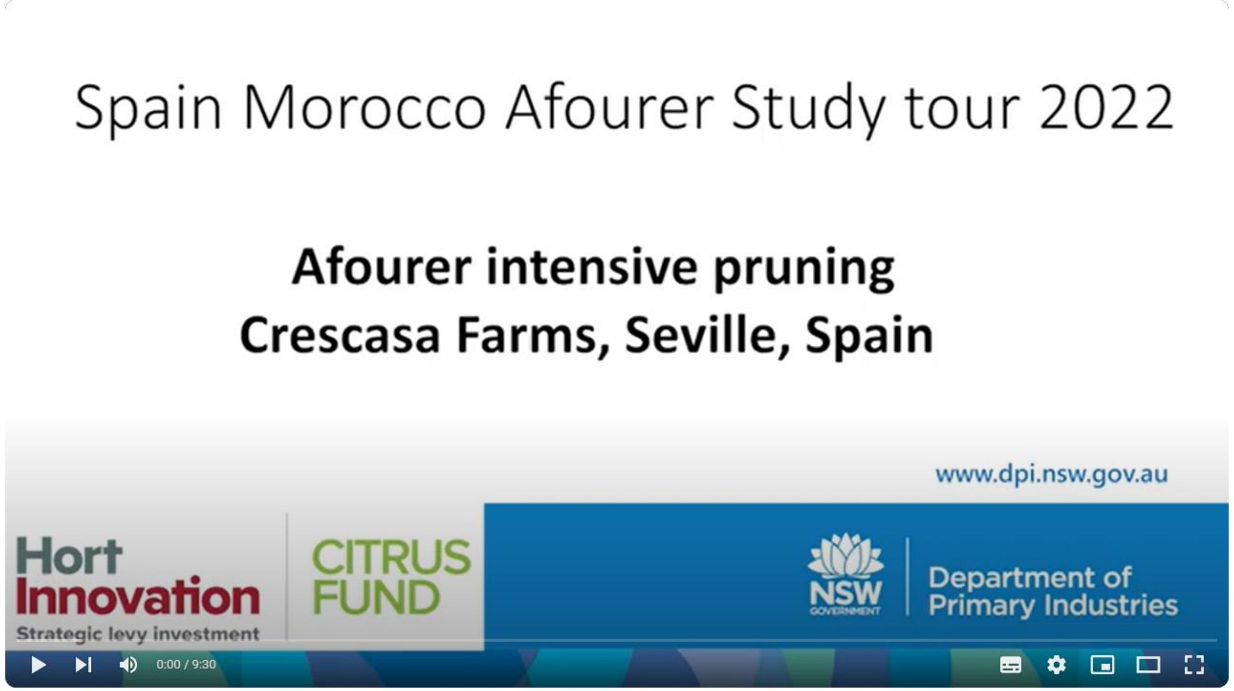
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Afourer intensive pruning
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Videos
Other videos:
1. Light hedging
2. Heavy hedging
3. Chunk pruning
4. Window pruning
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Field days, workshops

Pruning for $$

First grade navels get DOUBLE the price than second grade. Annual pruning is one of the best ways to improve packouts and its not as expensive as you think

"train you and your labourers on basics of pruning"

Hillston, Griffith and Leeton
30 min workshops
All invited

- Mon 26 Jul 2:30 pm: Super Seasons Talinga, Hillston
- Wed 26 Jul 1 pm: Mario's Packhouse, Research Stn Rd, Yoogali
- Thu 27 Jul 1 pm: Villa Rosa, Farm 1986, Davies Rd, Leeton

Limited to 5 participants per session

Register by SMS to Steven 0427 208 611 : your name and district
You will receive a reply to confirm
(if you do not get a reply please call)

This pruning demonstration is part of the 60+ Riverina project initiative (Riverina 60% 1st grade packout target) supported by Griffith and District Citrus Growers, Leeton Citrus Growers, Mario's Packhouse, Golden Grove Citrus, Joe's Citrus, Clear Lake Citrus, Lakes View Citrus and Pacific Fresh. This initiative is also a linked activity to the AS18000 Hort Innovation Tree Intensification project.

For more details contact Steven Falivene 0427 208 611 or Andrew Creek 0428 934 952

NSW Government Department of Primary Industries

Factsheets, financial tools are coming

High-density planting and pruning case study:

Sunmar Orchards, Sunraysia

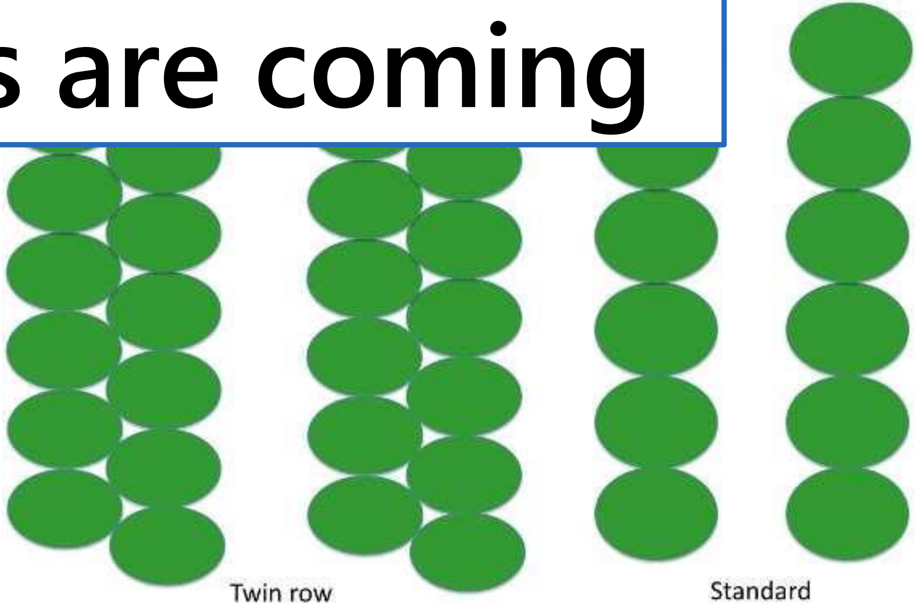
Key points

High-density plantings boost returns

Different layout, different management

Cashflow break even reached sooner

High-density plantings are delivering very good long-term returns to Sunmar Orchards in the Sunraysia region, the results of which are backed up by an economic analysis by the NSW Department of Primary Industries (NSW DPI).



Viroids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Healthy, true to type and scientifically sound
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Dwarfing citrus trees using viroids

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NSW DPI, Gosford Horticultural Institute

Graeme Sanderson

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These symptoms were attributed to a number of strains of citrus exocortis viroids (CEV). The various strains were classified as mild, moderate or severe, depending on the extent of tree stunting, decline

Case studies

Pioneering citrus dwarfing viroid use in the Riverina

BY DR MAHMUD KARE AND STEVEN FALIVENE

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"The mature dwarfed trees enable a person to pick 13 bins from the ground daily compared to ten bins when using ladders," Alan explained. "Furthermore, the dwarfed Salustiana, Hamlin, and Parson Brown (Figure 2) common orange varieties on Tri22 rootstock consistently yield between 50-60 tonnes per hectare annually."

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"In the first four seasons, GTD-inoculated trees grow at the same rate as non-infected trees. In the fifth season, the size-controlling effect becomes quite obvious."

Researchers from the New South Wales Department of Primary Industries (NSW DPI) have been working on the use of viroids for several years. They are extending this research as part of the citrus project in the National Tree Crop Intensification in Horticulture Program (AS18000).

The researchers have found that promoting rapid canopy expansion in the establishing years is important, as the available space within the canopy can be filled in before the slow-down effect occurs.

To maximise the dwarfing effect, trees with moderate-to-high vigour can be inoculated 12 months after planting (Figure 3). In comparison, moderate-to-slow varieties can be inoculated 18 months after planting, reducing the intensity of the dwarfing effect.

In Alan's experience, he does not recommend using dwarfing viroids in replant situations or on heavy clay soils because they slow the initial growth rate and compound the dwarfing viroid effect.

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(Figure 1) The mature, dwarfed Salustiana trees attained a height of 2.6 metres, whereas a tree that missed inoculation is 5 metres tall.

(Figure 2) Alan Harrison checks the 2022 season crop on Parson Brown.

Videos

Dwarfing citrus trees using viroids

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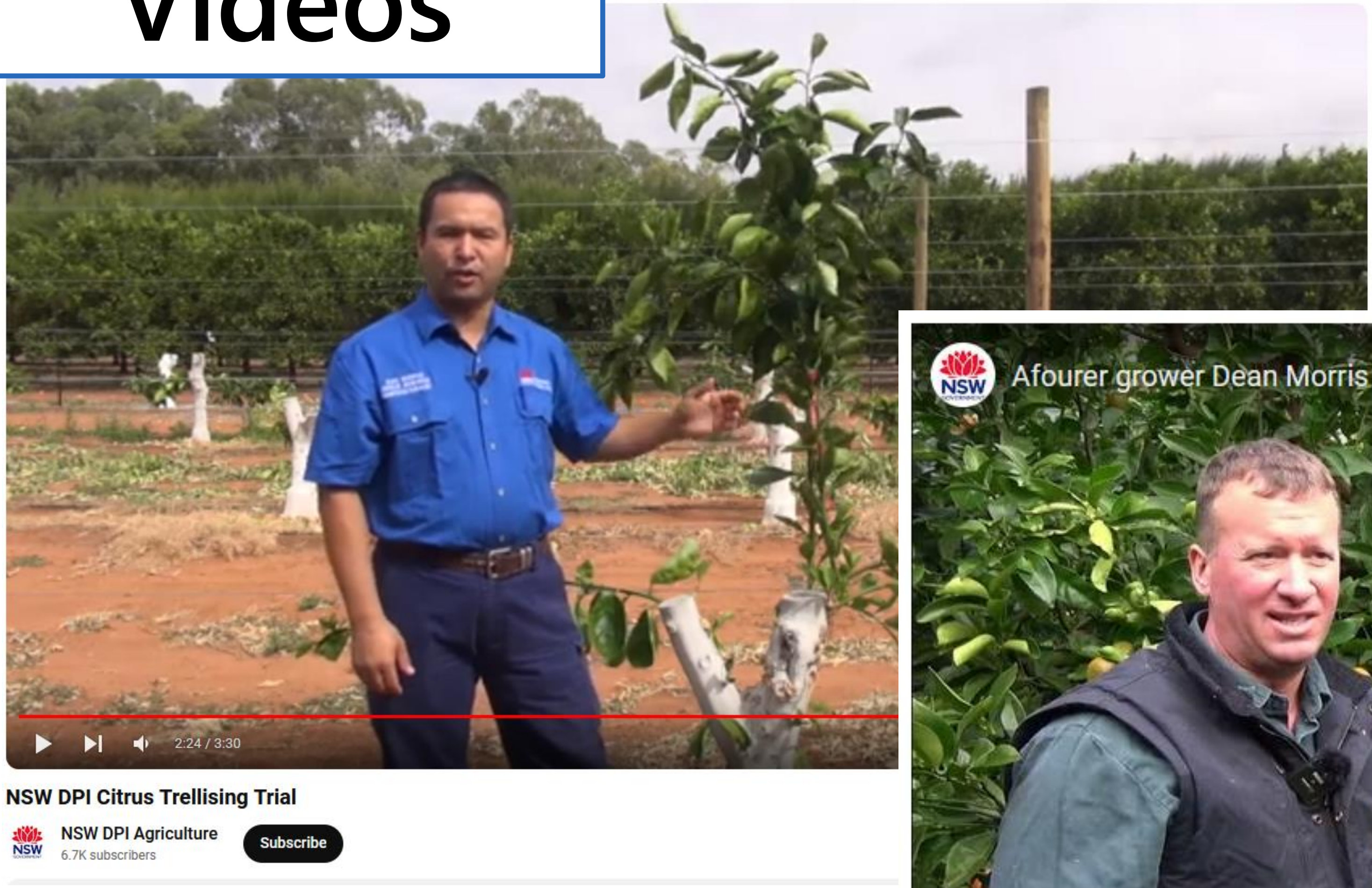
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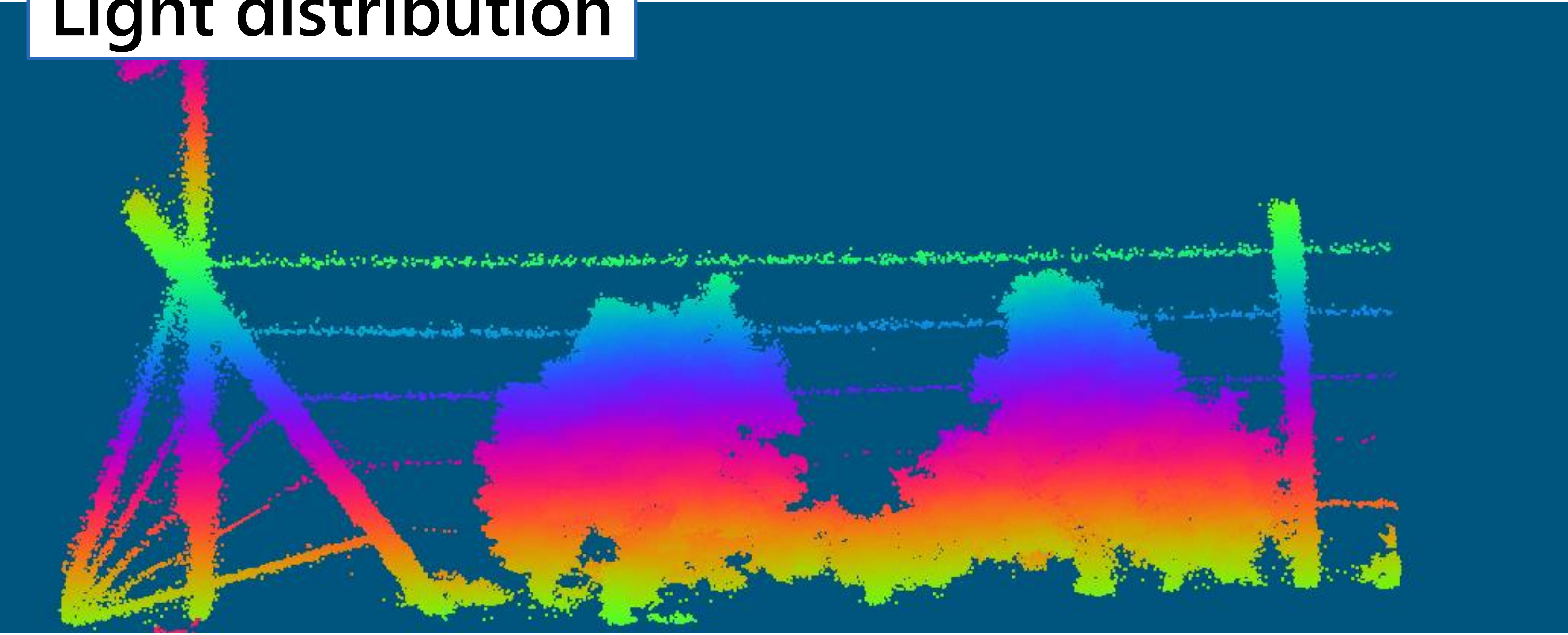
Light distribution



Articles

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Growing high density citrus for profit

Dave Monks
New South Wales DPI

The citrus industry will benefit from new insights into what it takes to establish and manage more intensified orchard systems as a result of a five-year program of research underway by the New South Wales Department of Primary Industries (NSWDPI). The project is funded by the Hort Frontiers Advanced Production Systems Fund and is being conducted as a component of the *National Tree Crop Intensification in Horticulture Program* (AS18000), a collaborative research program between Almond, Avocado, Citrus, Macadamia and Mango.

Costing tools are coming

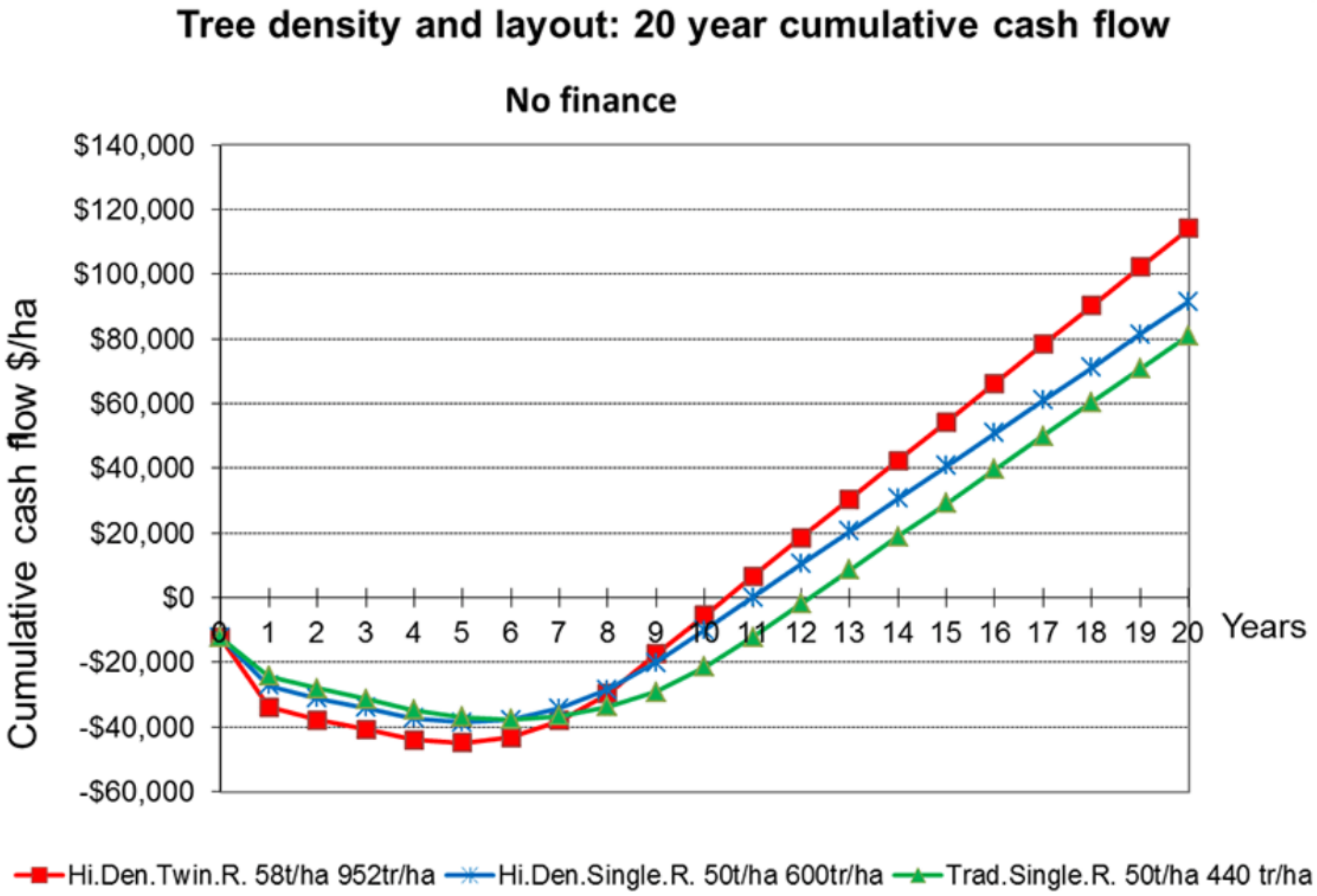

FIGURE 3: The cumulative cash flow of navel oranges at: high-density twin row layout (Hi.Den.Twin.R); high-density single row layout (Hi.Den.Single.R. 600 trees/ha); and traditional density single row layout (Trad.Single.R. 400 trees/ha).



Videos, articles to follow

Journal review

Intensifying citrus tree crops and modifying tree canopies: a brief review

K. Mahmud[1], D. Monks[1], N. Donovan[2], A. Warren-Smith[3]
[1]NSW Department of Primary Industries, Dareton, NSW, Australia
[2]NSW Department of Primary Industries, Menangle, NSW, Australia
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Abstract

High-density citrus orchards have proven benefits for productivity but canopy management using conventional practices becomes problematic after trees reach their allocated space. This paper reviews the literature on high-density planting of citrus to understand the motivation for crop intensification and the different strategies for manipulating tree size such as dwarfing rootstocks, dwarfing viroids, pruning and trellis training.

Keywords: citrus, high-density, canopy management, dwarfing, productivity, viroid

INTRODUCTION

Citrus is an important horticultural crop, contributing significantly to the global economy. Food and Agricultural Organization (FAO) (2020) showed that there were 2,850,000 hectares planted to citrus and 40,600,000 tonnes of fruit harvested from approximately 140 countries, of which Australia contributed 550,000 tonnes (1.35%) from 27,000 productive hectares (0.96%) .

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NATIONAL TREE CROP

Intensification In Horticulture Program

(AS18000)

The *National Tree Crop Intensification in Horticulture Program* is funded by the Hort Frontiers Advanced Production Systems Fund, part of the Hort Frontiers strategic partnership initiative developed by Hort Innovation, with co-investment from Queensland's Department of Agriculture and Fisheries, Plant & Food Research, NSW Department of Primary Industries, Queensland Alliance for Agriculture and Food Innovation- The University of Queensland, Western Australian Department of Primary Industries and Regional Development and the South Australian Research and Development Institute, and contributions from the Australian Government.

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Dave Monks
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Department of Primary Industries
and Regional Development

NSW GOVERNMENT

Citrus Tree Intensification

Orchard Systems
January 2025

Dave Monks
Research Horticulturist

Funding statement

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Hort Innovation
Frontiers





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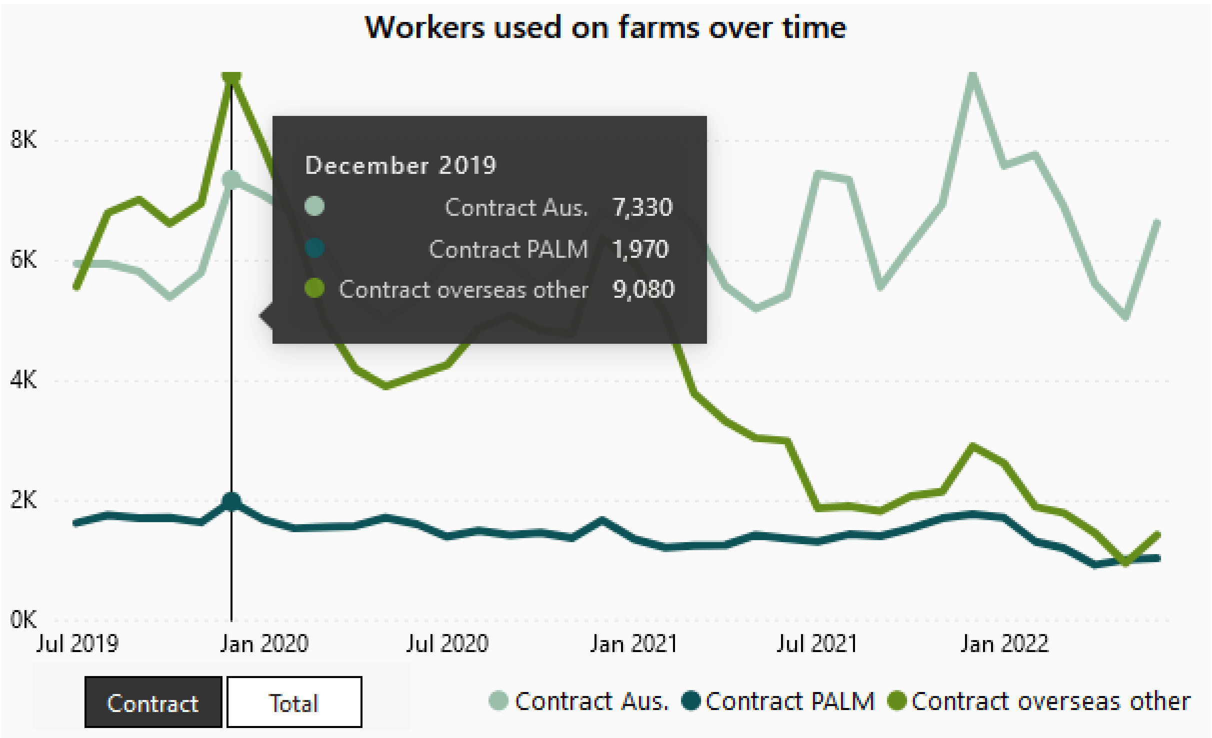
Canopy efficiency

Labour efficiency



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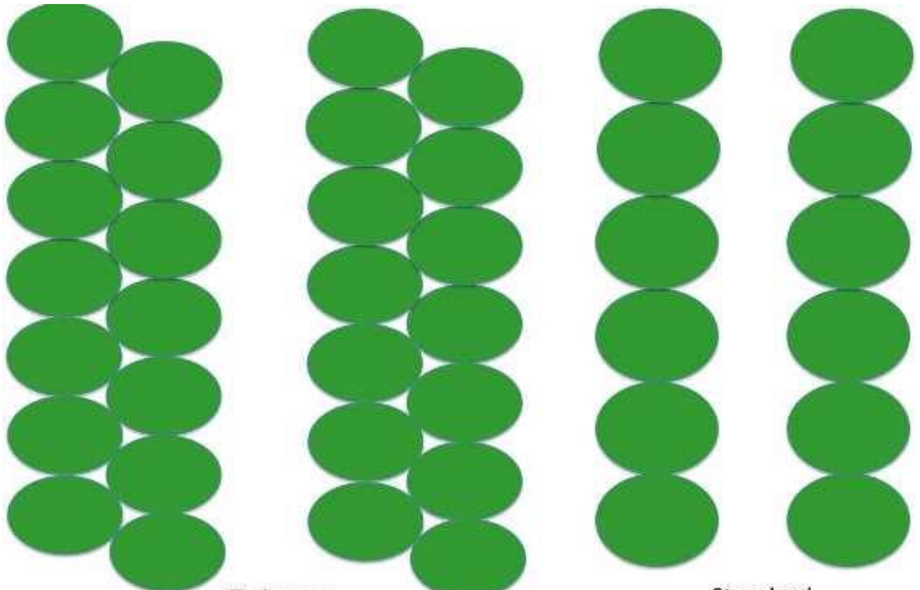
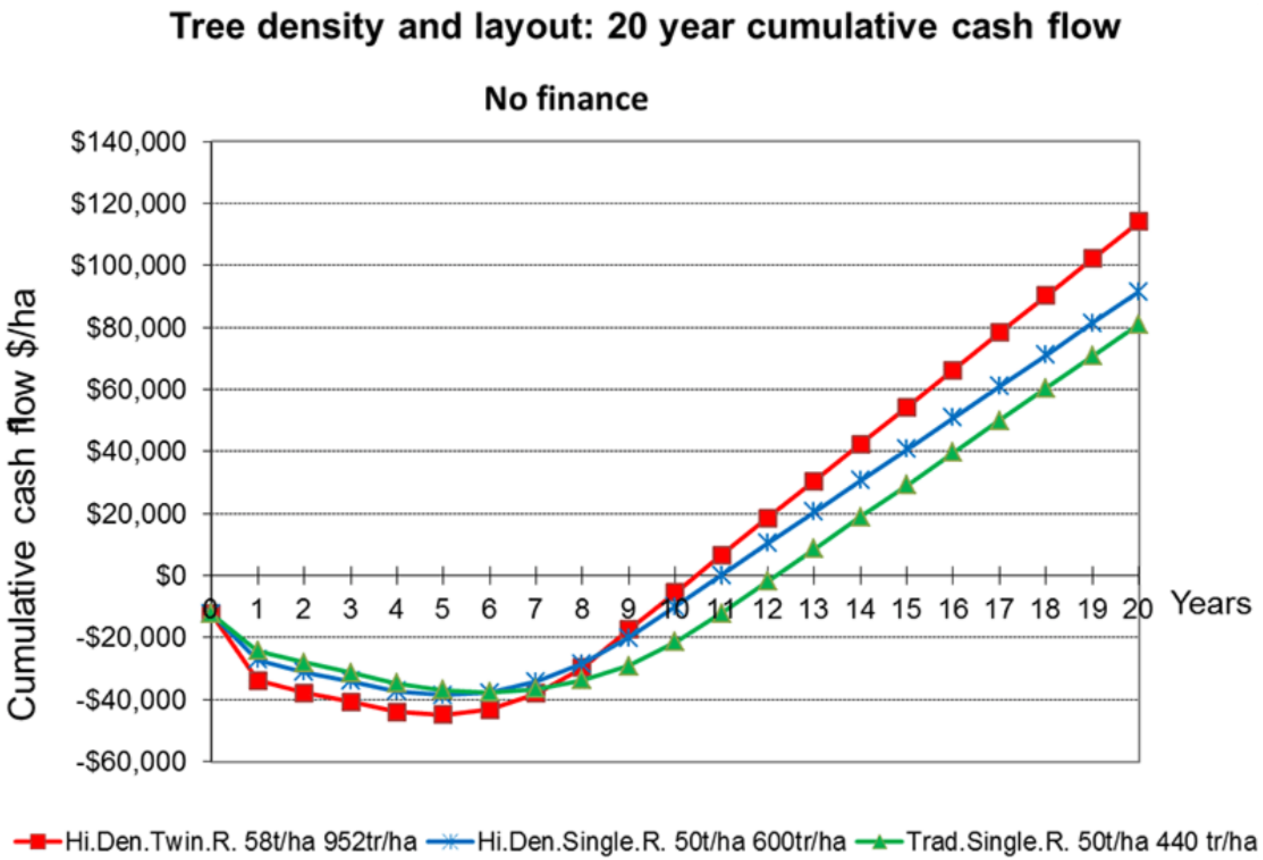
Educate and upskill

Pruning – Horizon 1

Costing tools



Case studies



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Viroids – Horizon 2

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... Brown.

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Acta Hortic. 2024

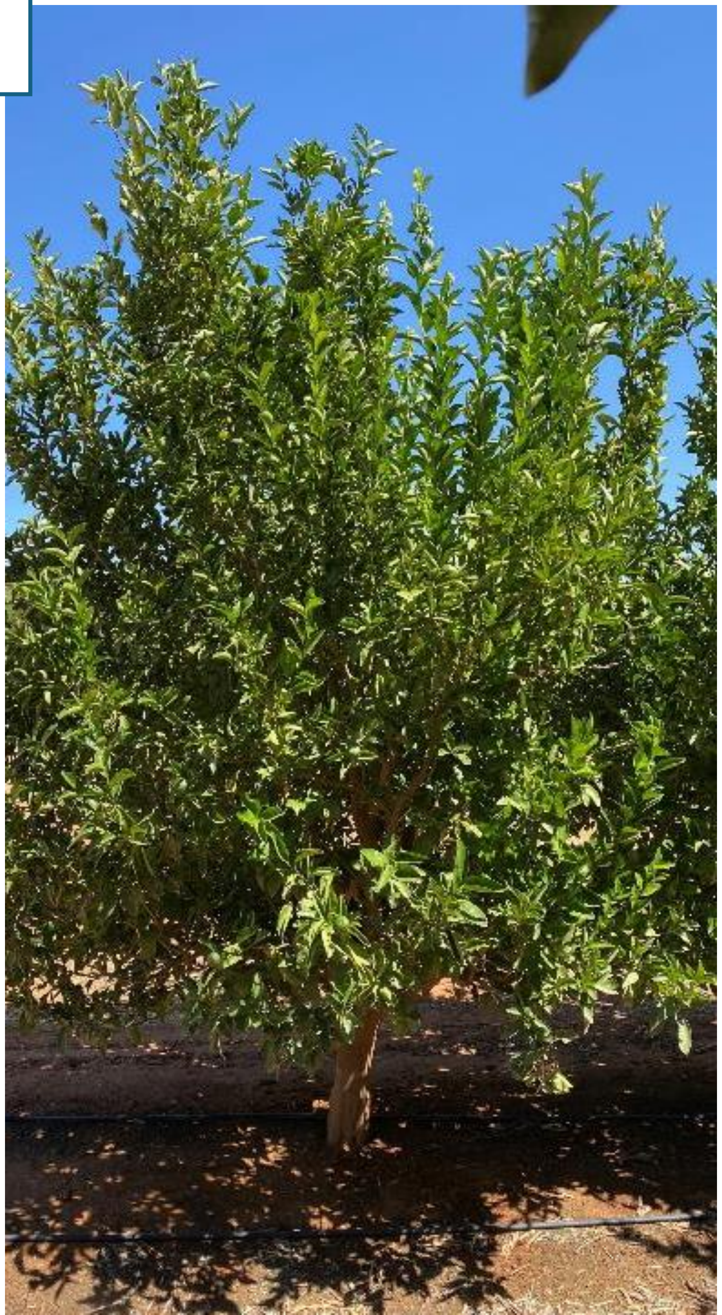
Trellis – Horizon 3

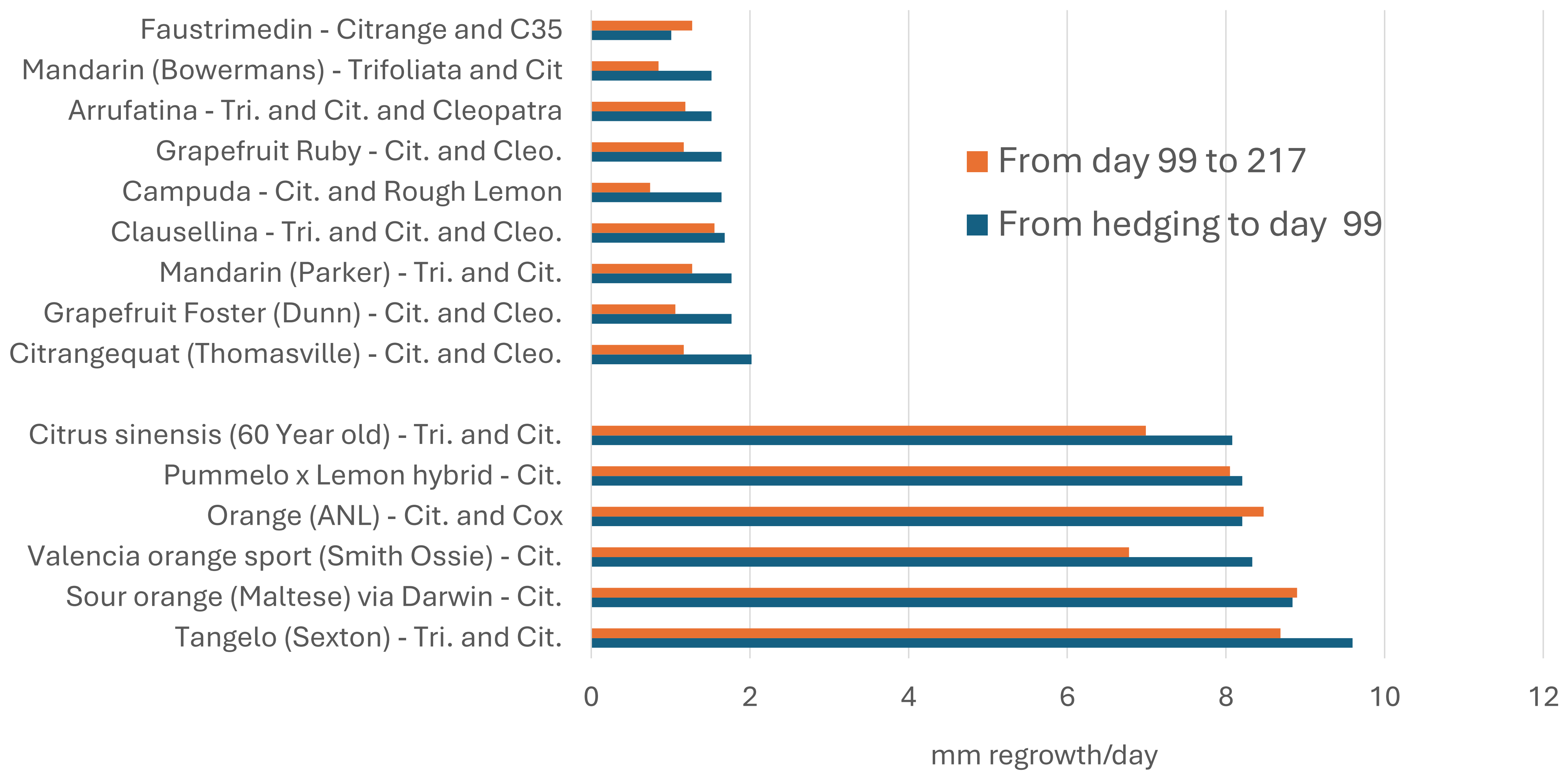
Espalier

Palmate

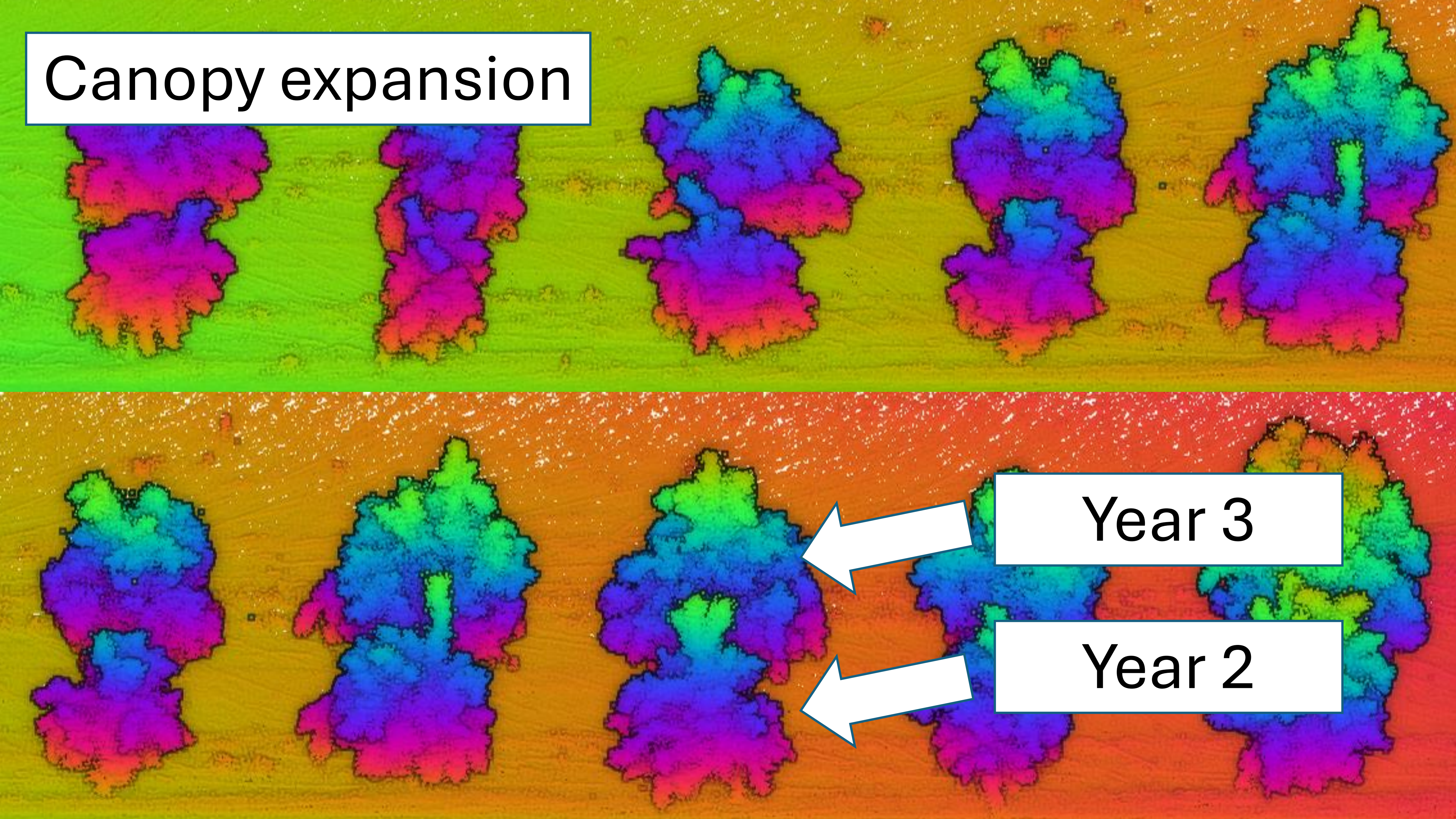
Cordon

Phenotypes

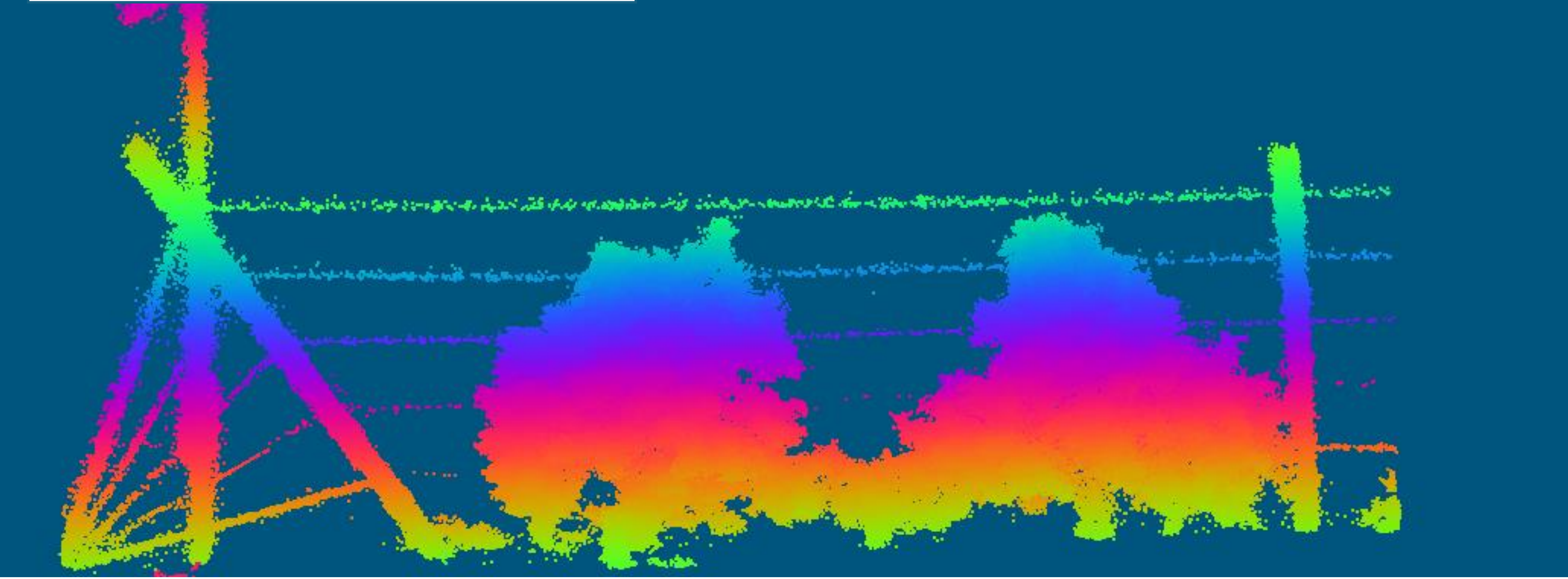




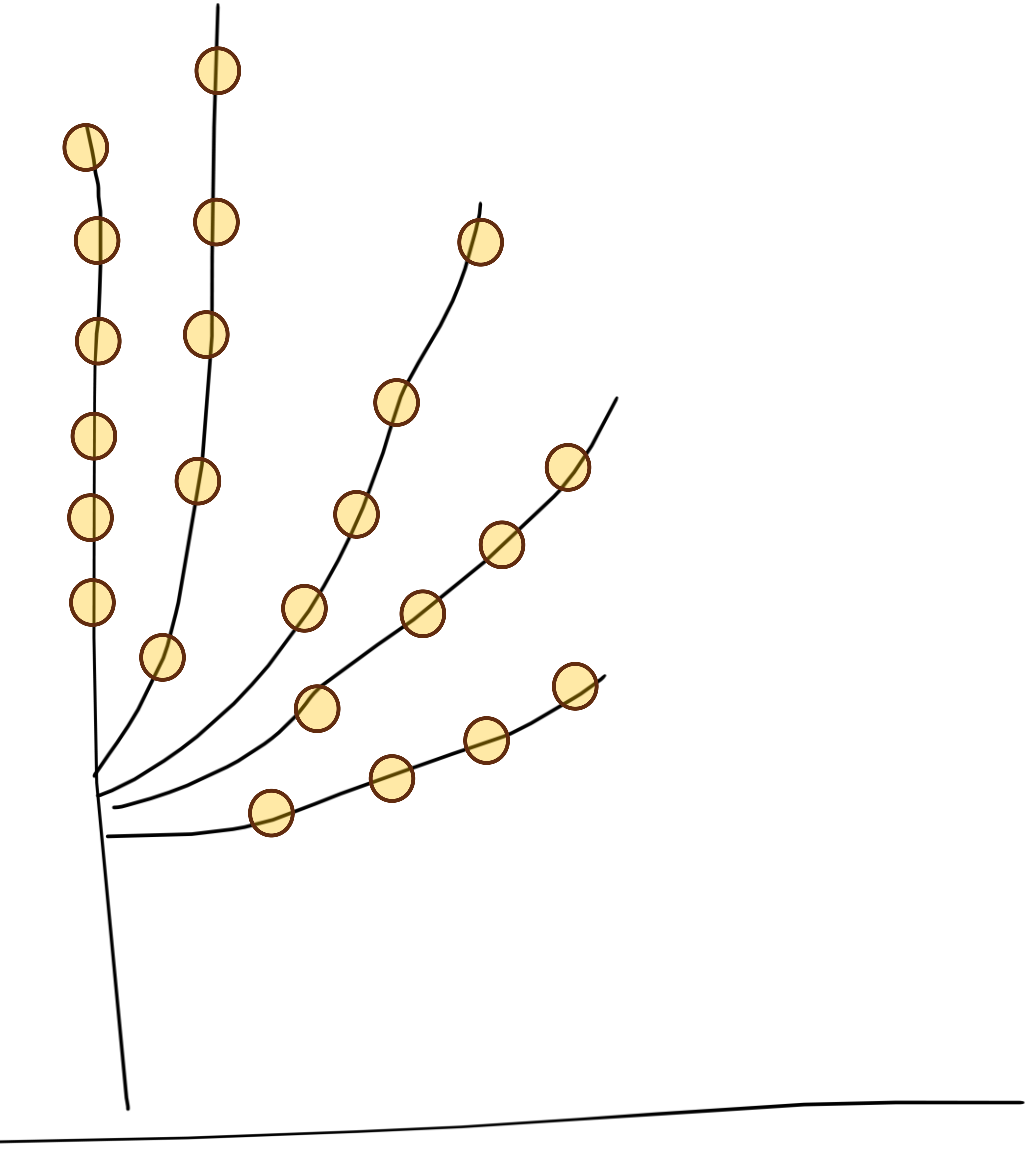
Faustrimedin - Citrange and C35
Mandarin (Bowermans) - Trifoliata and Cit
Arrufatina - Tri. and Cit. and Cleopatra
Grapefruit Ruby - Cit. and Cleo.
Campuda - Cit. and Rough Lemon
Clausellina - Tri. and Cit. and Cleo.
Mandarin (Parker) - Tri. and Cit.
Grapefruit Foster (Dunn) - Cit. and Cleo.
Citrangequat (Thomasville) - Cit. and Cleo.
Citrus sinensis (60 Year old) - Tri. and Cit.
Pummelo x Lemon hybrid - Cit.
Orange (ANL) - Cit. and Cox
Valencia orange sport (Smith Ossie) - Cit.
Sour orange (Maltese) via Darwin - Cit.
Tangelo (Sexton) - Tri. and Cit.
From day 99 to 217
From hedging to day 99
0
2
4
6
8
10
12
mm regrowth/day

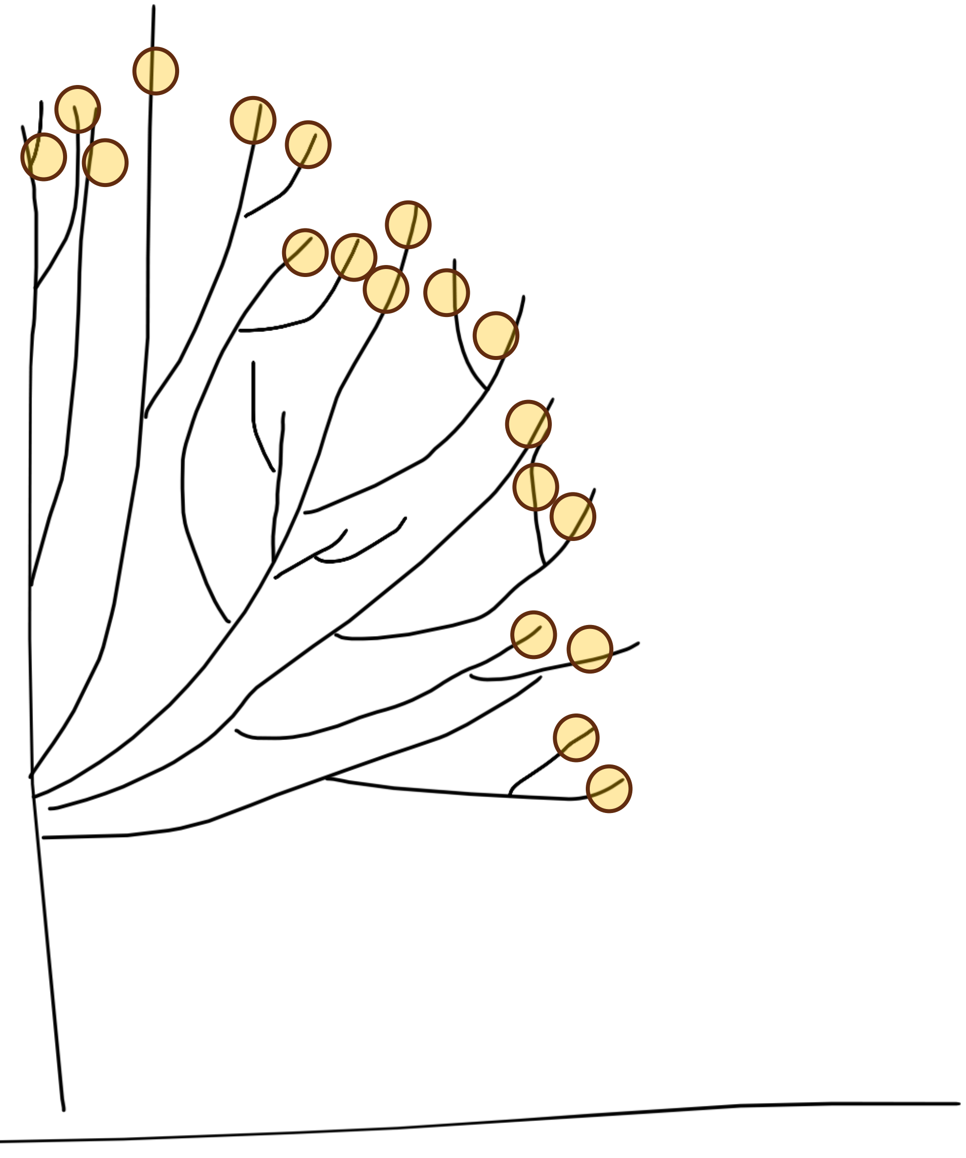

Canopy expansion
Year 3
Year 2

Light distribution



Architecture





Modelling

QAAFI

GxE validation: background

Hardner, Campbell, Shimizu, Minamikawa, Iwata, Monks

SCIENTIFIC REPORTS

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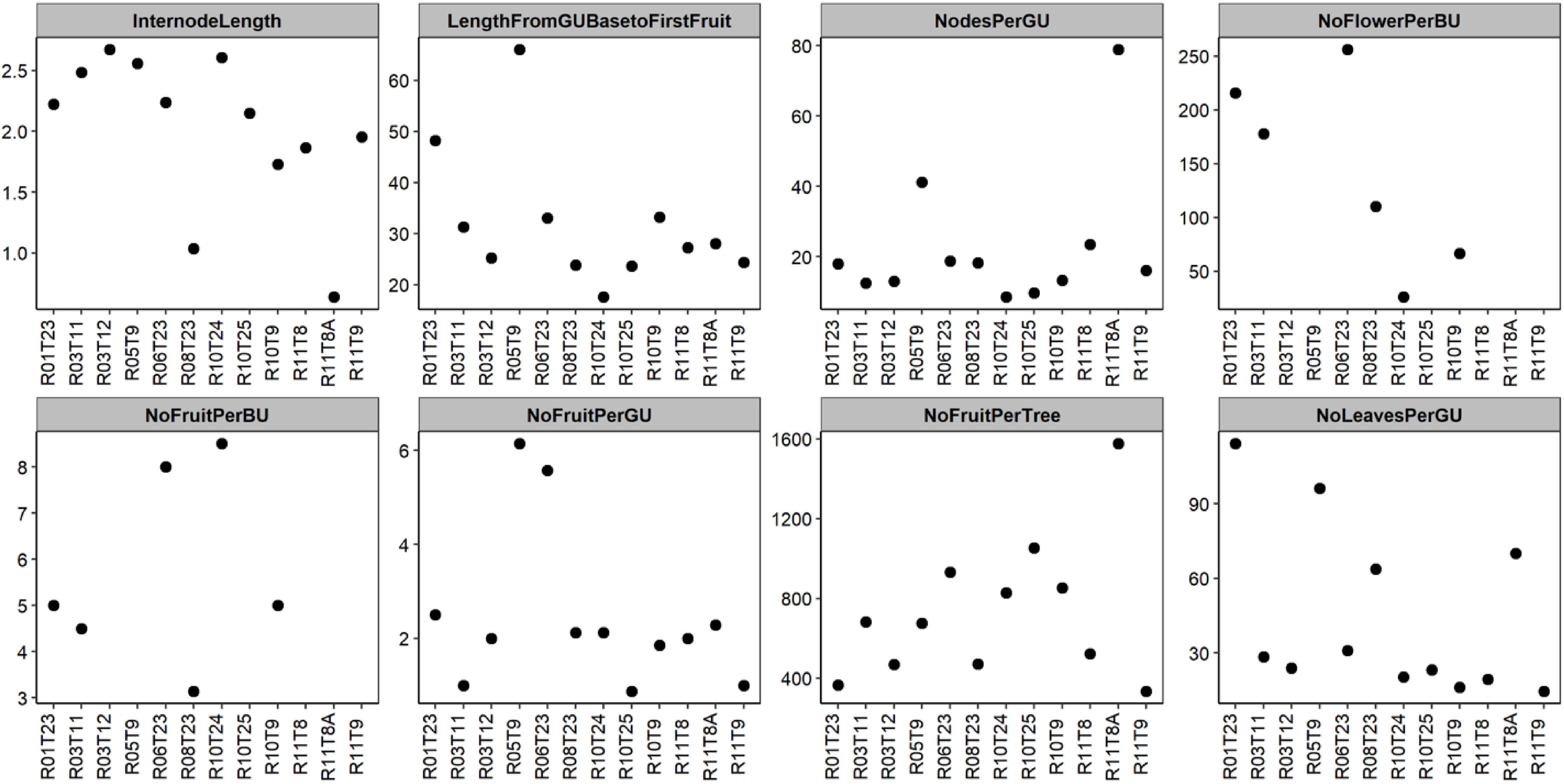
Genome-wide association study and genomic prediction in citrus: Potential of genomics-assisted breeding for fruit quality traits

Int. Citrus Congress 2024



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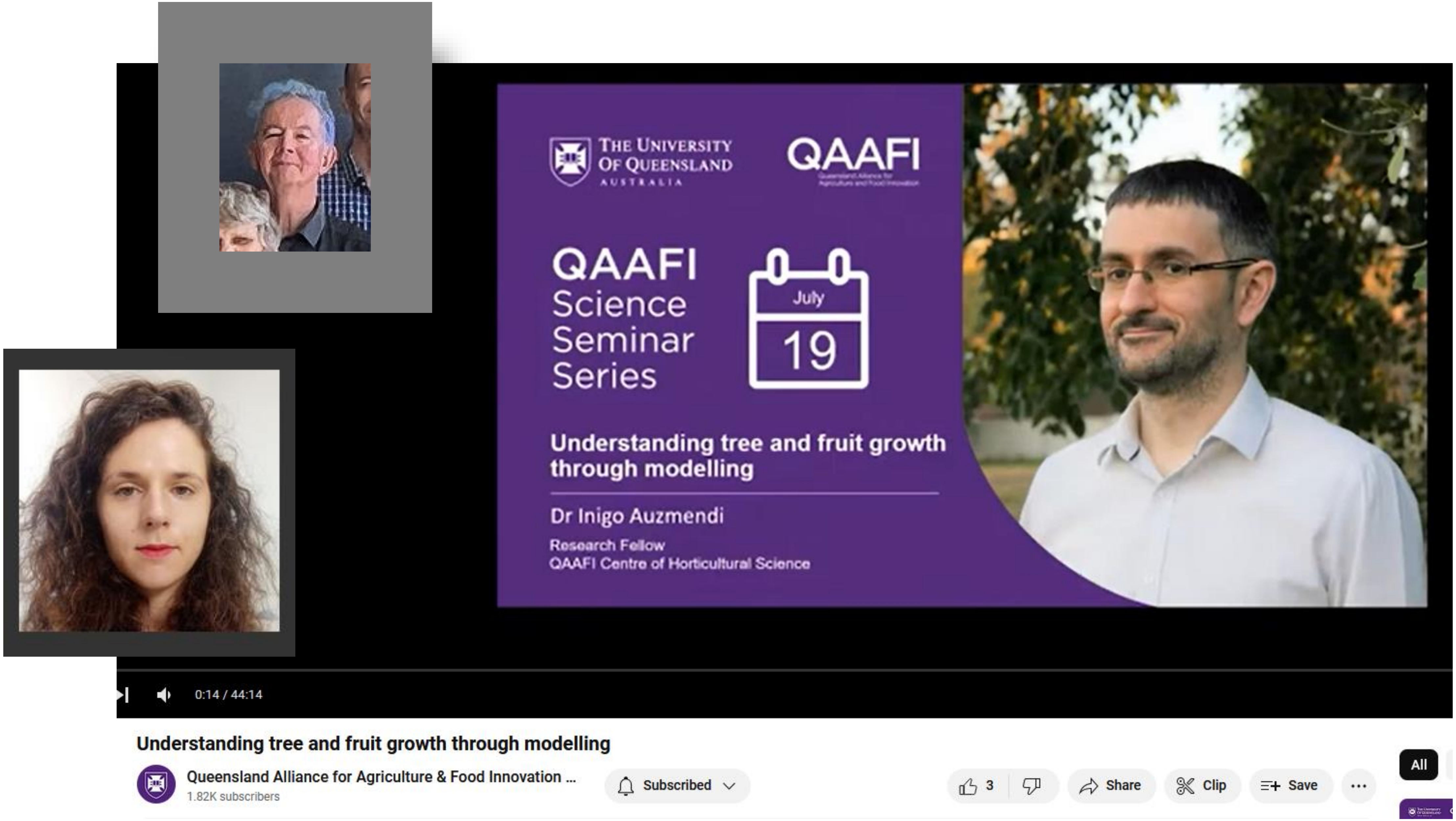
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Canopy Parameter Estimation of *Citrus grandis* var. *Longanyou* Based on LiDAR 3D Point Clouds

by Xiangyang Liu [1], Yaxiong Wang [1,*], Feng Kang [1], Yang Yue [1] and Yongjun Zheng [2]

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Functional–structural plant modelling: a new versatile tool in crop science

J. Vos, J. B. Evers, G. H. Buck-Sorlin, B. Andrieu, M. Chelle, P. H. B. de Visser

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, Issue 8, May 2010, Pages 2101–2115,

history ▾

Modeling seasonal flushing and shoot growth on different citrus scion-rootstock combinations

Everton V. Carvalho [a], Juan C. Cifuentes-Arenas [b], Laudecir L. Raiol-Junior [c], Eduardo S. Stuchi [c], Eduardo A. Girardi [c], Silvio A. Lopes [a b]

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Modelling the architecture of hazelnut (*Corylus avellana*) Tonda di Giffoni over two successive years

Francesca Grisafi, Sergio Tombesi, Daniela Farinelli, Evelyne Costes, Jean-Baptiste Durand, Frédéric Boudon Author Notes

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Optimization of a Citrus Canopy Shaker Harvesting System: Properties and Modeling of Tree Limbs

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Developing perennial fruit crop models in APSIM Next Generation using grapevine as an example

Junqi Zhu, Amber Parker, Fang Gou, Rob Agnew, Linlin Yang, Marc Greven, ...hael C T Trought ... Show more

Junqi Zhu

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b021, https://doi.org/10.1093/insilicoplants/

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Department of Primary Industries
and Regional Development

DPIRD Dareton Citrus Field Day Report: 15 October 2024

Prepared By Steven Falivene

20 October 2024

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Introduction

The field day at Dareton Citrus Research Institute on 15 October (appendix 1) was an opportunity to showcase the research and development activities conducted at the Dareton Citrus Research Institute and to also communicate to industry key technical information and outputs of various projects and initiatives conducted by the DPIRD citrus team. 65 participants attended the field day with over 90% of participants being directly related the production of citrus (growers, packers and industry service providers). The presenters of the field day were Dr Tahir Khurshid, Dr Dave monks, Dr Mahmud Kare, Steven Falivene and Andrew Creek. The field day commenced at 10 AM on October 15 and concluded at about 1 PM. A barbecue lunch was provided by Muirs, a service provider and product reseller.

The following document summarises the content of the field day. The results of feedback sheets completed on the day highlight the value of the field day and describes production topics of interest for future projects.

Key messages

- Citrus variety information is available from the DPIRD website and by direct communication with Dr Dave Monks.
- Planting high-density orchards with vigorous trees is not advised because the trees eventually overcrowd the allocated space that results in a decline in production. Intensive annual pruning may not deliver the desired results because new fruiting wood is continually removed. It's best to plant an orchard at a spacing that accounts for the size of the mature tree. A new regrowth management technique from South Africa (Afourer canopy management project) might assist in improving yields.
- Dwarfing viroids and rootstocks are important technologies for productive high-density orchards to prevent trees growing too big in their allocated space.
- Growing trees on a trellis has significant advantages in harvest efficiency and light inception, however the system demonstrated on site require an extra ~20 tons per hectare in yield to pay for the cost of infrastructure and ongoing management (intensive pruning and training).
- Water deficit irrigation in autumn can improve fruit Brix by 1° and decrease fruit size by 1 to 2 mm. Improving fruit quality is an important way for Australia to maintain and expand an competitive edge in the future.
- The effect of over irrigation and water logging reducing fruit size and grower returns might be underestimated in the citrus industry. There is opportunity to improve irrigation efficiency and orchard productivity with improved understanding, education and use of using modern water management and sensing equipment and tools. SAP flow sensors show that tree water use dramatically decreases during cloudy periods; growers should reassess irrigation schedules on cloudy days.
- Afourer grown on vigorous rootstocks need adequate plant spacing for a long productive life. In narrower spacings, intensive pruning and regrowth management is required to maintain yields. Recent information from South Africa outlines a successful regrowth management technique to maintain vigorous trees in a narrow row spacing.
- New pest management resources are available: fact sheets, posters, videos and field guides. The information will be on the DPIRD website and hardcopies will be available at regional agricultural government offices.
- Feedback indicated that participants: were very satisfied with the field day and that Dareton DPIRD provides value for money to industry, would value on-farm adoption project that engaged with growers, the top three useful topics presented were rootstocks, precision irrigation and pest management and the top 3 production topic that participants would like more research and development are new varieties, 1st grade pack-out and nutrition. Opportunity exists to conduct on farm adoption projects that includes irrigation management.

Presentation summaries

Rootstock and water deficit irrigation (Dr Tahir Khurshid)

New Chinese rootstocks are showing promise in their dwarfing effect and production efficiency capabilities. All the rootstocks mentioned have higher Brix levels than the current industry standard counterparts. This is very important to improve the internal quality and taste of Australian citrus. These less vigorous rootstocks shall provide opportunities for high density planting to improve productivity and harvest efficiency. It will also reduce or eliminate the need for picking ladders, making harvest more efficient. C54 is a hybrid (Sunki mandarin x *Poncirus trifoliata* - Swingle) from USDA and it also called Carpenter. This hybrid grows at about 80% of the rate of the Australian standard citrange (Troyer *Citrange*). Zao Yang is another *Poncirus trifoliata* type rootstock from China that is similar in growth to the industry standard (Tri22) or slightly reduced but has higher Brix levels. The dwarfing rootstock 85-24 (*Poncirus trifoliata*) grows at 65% of the rate of Tri22 and rootstock No. 24 grows at about 50% of the rate of Tri22. The Chinese *Poncirus trifoliata* rootstocks have shown greater resilience in the sandy soils at Dareton compared with the Tri22 rootstocks. During this trial, some Tri22 trees died during the early stages of the trial. The rootstock work has been funded through various projects over numerous years with Hort Innovation and ACIAR.

Tahir discussed the results of a Hort innovation citrus co-levy funded regulated deficit irrigation project that was conducted at the research station with team members Steven Falivene and Robert Hoogers (Irrigation officer). The trial showed that the Brix levels of fruit can be increased by about 1°, however it can cause 10% reduction in large fruit (85-87 mm) in diameter. Water stressing in February is not recommended because of the active fruit growth, however, fruit trees can be stressed in mid-march once the average fruit size has achieved 72 mm. During the project life, trees stressed in early or late February was able to increase Brix levels and caused significant reduction in fruit size. On other hand when trees were stressed in mid-March, the effect on fruit size reduction was minimal. Further detailed information is available from the final report published on the Hort Innovation website.

Figure 1. Dr Tahir Khurshid shows participants the different size of navel trees using various root stocks.

New Varieties, dwarfing viroid and PGRs (Dr Dave Monks)

Dave is leading a Hort innovation citrus co-levy funded citrus variety assessment project. Most new varieties that enter Australia are provided to Dave so he can rework trees and conduct fruit assessments within 4 years. Information from the assessments is communicated through variety fact sheets available on the DPIRD website.

Dave is also available to answer grower questions and conduct viewings by appointment (pending approval of variety owners).

Dave is the leader of the Hort Innovation tree intensification project (AS1800 Frontiers funding) that is working on citrus growth habit, dwarfing viroid, high-density management and trellis production systems. The team on the project includes Dr Mahmud Kare, Steven Falivene, Andrew Creek and Dr Nerida Donovan. Dave discussed the dwarfing viroid and plant growth regulators (PGRs).

The current commercial dwarfing viroid was selected from several viroids to provide a moderate level of tree dwarfing. The experiment at the research station is looking at many of these viroids alone and in combination in navel trees. Inoculated trees grow at their normal rate for the first five years as the concentration of the viroid increases. This is an advantage over dwarfing rootstocks because rapid tree growth can be achieved in early years (high early productivity) and then the tree can slow down once it matures. However, the viroid might only reduce growth by 20%-30% whilst some dwarfing root stocks have greater growth reduction capabilities; viroids and dwarfing rootstocks have their advantages and disadvantages in certain situations.

PGRs are used in South Africa to suppress vigour and enhance fruit set and flowering. Dr Mahmud Kare will conduct investigative trials DPIRD Dareton to assess the performance of these chemicals in Australian conditions on navels and mandarins. A video from by Steven Falivene interviewing a key South African researcher, Paul Cronje, well explains PGR use in South Africa. The video will be posted on the DPIRD website by early next year and viewing the draft video is available upon request.

Figure 2. Dr Dave monks is showing participants viroid inoculated trees.

High-density pruning and trellis production systems (Dr M.Kare, S.Falivene and A.Creek)

Dr Mahmud Kare is leading a new Hort innovation citrus co-levy funded Competitive Citrus Orchards project (CT23006), that will continue the core work of the AS1800 project managed by Dr Dave Monks that will soon finish. The project team includes Steven Falivene and Andrew Creek that will continue working in collaboration with Mahmud in pruning and trellis production systems. Steven and Mahmud are working on a pruning trial with treatments from minimal pruning (mechanical hedging) to intensive 3D tree pruning and highly intensive 2D trellis pruning. Intensive pruning in the high-density trees have shown no yield advantage over the annual hedging treatment. It is suspected that the regrowth from the intensive pruning is highly vigorous and causes considerable congestion and shading within the season. To maintain row access and allow enough light into the tree, the new regrowth must be removed each season, eliminating productive wood that would otherwise produce fruit. This emphasises the importance of selecting a suitable plant spacing that matches the expected vigour of the tree (rootstock, variety, climate and soil etc); planting to close provides good early returns but then results in a decline in yield once the trees mature because of canopy crowding and excessive pruning. Dwarfing viroids and rootstocks are an important technology to the successful utilisation of high-density production systems. A new 3D pruning treatment will now include the management of regrowth as discussed in the Afourer canopy management project (discussed in the next sections).

The current trellis trial was established over existing trees four years ago by stumping them and training regrowth on the trellis. The trial was to gain a quick insight into potential production capabilities and ongoing management. Two seasons of yields on the trellis are showing good promise (7 t/ha and 19 t/ha). Last season, the conventional high-density trees only yielded 10 t/ha. Mahmud has recently installed a new trellis trial using nursery trees that will gain production and management insights for a new trellis experiment. Steven discussed the trellis agronomic and economic lessons to date; installing a wooden pole trellis is a little cheaper and easier than a steel structure, pruning a trellis the tree is easier than a conventional 3D tree but takes more time, the canopy of the trellis trees have good exposure to sunlight and are also producing shoots with medium vigour (not excessively vigorous), the trellis will need about an extra 20 tons per hectare of yield to pay for the initial investment of the trellis structure, higher density of trees, higher annual management costs and be a financially attractive investment. Steven also highlighted how improving fruit price and yield has the greatest effect on increasing grower returns; improving 1st grade price and pack-out is important for industry to increase grower returns (improving quantity and quality [taste] of 1st grade packouts). Steven will publish a report outlining the economic risk assessment of 2D and 3D production systems early next year.

Figure 3. Dr Mahmud Kare describes the treatments in the trellis trial.

Figure 4. Steven Falivene describes the agronomic and economic aspects of 3D and 2D (trellis) pruning production systems.

Afourer Canopy management project (Steven Falivene and Andrew Creek)

Steven has been leading a Hort innovation citrus co-levy funded Afourer canopy management project. Numerous trials have been conducted trying different pruning strategies on Afourer trees with various vigour. As discussed in the high-density pruning trial at DPIRD research station, there are problems of growing a vigorous tree in a restricted plant spacing. Most trials did not show a yield advantage of intensively pruning mature Afourer trees, however, a demonstration trial in South Australia that conducted intensive pruning and regrowth management did increase yields and improve management. The cost benefit of investing in extra regrowth management was about 3:1, however some farms may not have the availability of labour and must manage trees using mechanical pruning methods. Videos on a study tour to Spain showing intensive pruning are available on the DPIRD website and videos on a recent South African tour that describe the intensive regrowth management technique (2-3 shoot thinning and tipping events) will soon be available on the DPIRD website. Afourer grower case studies are also available on the DPIRD website. A final report and factsheets will be published in Autumn 2025

Precision Irrigation and on-farm water deficit trials (Steven Falivene)

Steven worked with DPIRD irrigation officer, Robert Hoogers, in various projects (Agri-Futures, Southern Drought Hub and DPIRD Climate Smart) over the past 4 years. The project developed and delivered several irrigation masterclass workshops throughout the southern regions. The work also explored modern irrigation monitoring equipment and conducted water deficit trials on growers' orchards. Telemetry monitored capacitance probes and tensiometers provided the greatest value in assisting real-time irrigation scheduling requirements. In the drip irrigated trial situation, the trunk and fruit dendrometers were helpful in providing data to help assess historical irrigation management, but did not contribute to real-time irrigation scheduling (Figure 5). Growers using sprinkler irrigation have reported real time benefits of using trunk dendrometers. SAP flow sensors provided valuable data in showing real-time movement of water up the trunk so a more accurate understanding of daily water use can be determined. The SAP flow sensors showed that water use dramatically decreased once clouds covered the sun. An important learning outcome is when cloud cover occurs, growers should carefully reassess irrigation needs (check soil moisture sensors) and not over water.

The project implemented water deficit trials on growers' properties (turning off the water from mid-March for a few weeks and then applying 50% application until a couple of weeks prior to harvest). Most orchards increased fruit Brix levels by 1° and decreased fruit size by 1 to 2 mm. However, a surprising result was that some orchards increased fruit size when deficit irrigation was applied. These blocks were noted to have very damp soils and were probably over-watering; the deficit irrigation helped to dry out the soil and improve tree health. The impact of over-watering in orchards might be overlooked and underestimated by growers and industry. Over the past few decades, increasing water application volume and frequency had been a trending theme. Orchards with drainage issues resulted in waterlogged parts of the orchard with declining and dying trees. The potential loss of fruit size in blocks throughout the regions from over-watering might be underestimated and substantially affecting on yield and fruit prices. There is opportunity to conduct more irrigation on-farm projects to help increase grower skill, understanding, and use of optimum precision irrigation practices.

Figure 5. SAP flow and trunk dendrometer installed on a navel tree.

Pest management (Andrew Creek)

Andrew Creek is leading the Hort innovation citrus ley co-funded national citrus Integrated Pest and Disease Management (IPDM) Extension Program. Andrew informed participants that many new pest management publications are currently available on the DPIRD website and regional agricultural government offices (paper copies). The publications include fact sheets, videos, posters, and pest guides. Andrew provided a discussion and engaged growers in a quiz of identifying beneficial insects in the orchard. Andrew collected insects from surrounding citrus trees using a vacuum / leaf blower with a gauze mesh on the suction end. Andrew explained the insect biodiversity caught in the sample with participants.

Figure 6. Field Day participants conducting the "circle the beneficial insects" pest management quiz.

Figure 7. Andrew Creek identifying pest and beneficial recently caught in surrounding citrus trees

Access to pest factsheets and information is available from the NSW DPIRD website. Click on the link below or scan the QR code (left) using your phone camera or QR reader app.

https://www.dpi.nsw.gov.au/agriculture/horticulture/citrus/content/ipdm-extension-program

Participant Feedback

A feedback sheet was provided to all participants (appendix 2). The results of the feedback exercise are as follows.

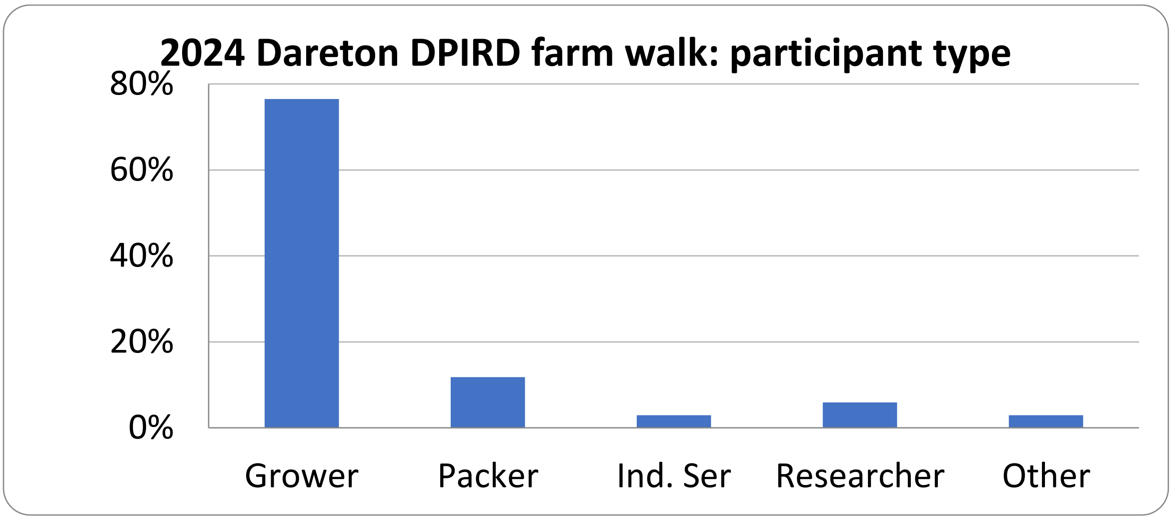

Figure 8. Industry work type

Over 90% of the participants of the field day were directly involved in the production of citrus (Figure 8). With over 75% grower participation.

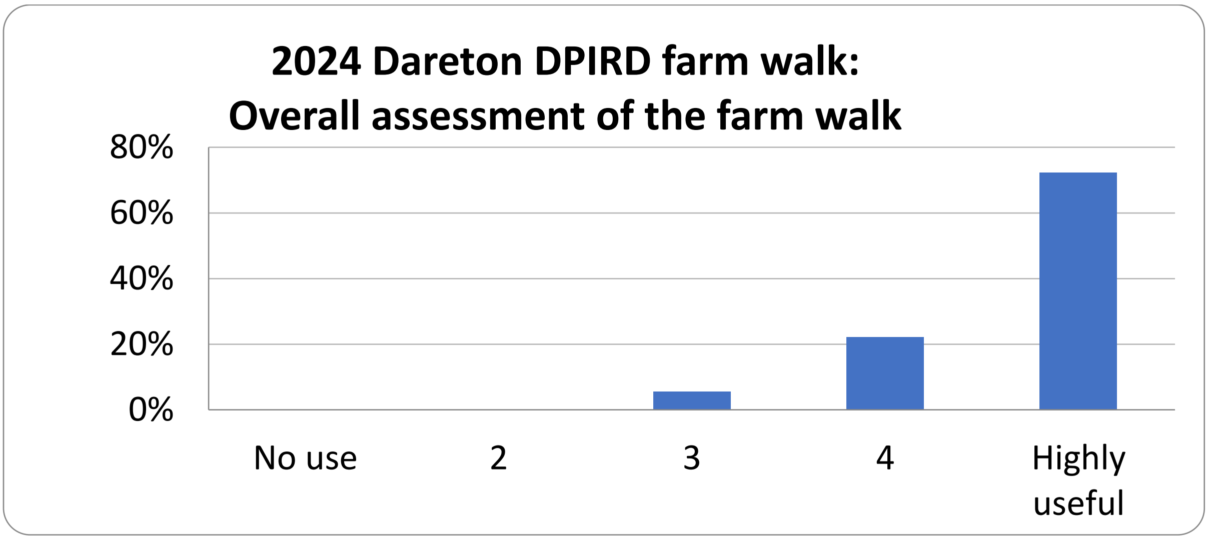

Figure 9. Participants overall assessment of the farm walk

Over 70% of participants responded that the farm walk was highly useful (Figure 9) with 100% indicating the farm walk had acceptable usefulness (response value equal to or greater than 3)

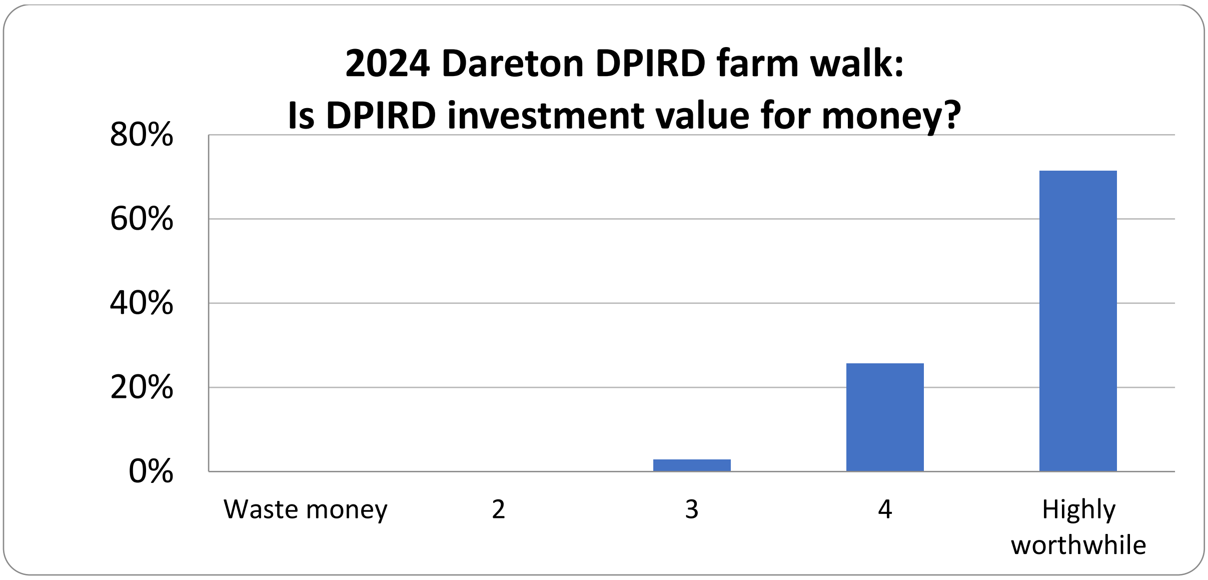

Figure 10. The value of investing in the work conducted at DPIRD Dareton.

Over 70% of participants believed that the work conducted at DPIRD was a highly worthwhile (Figure 10). 100% of participants indicated that the investment into the work conducted at DPIRD was worthwhile.

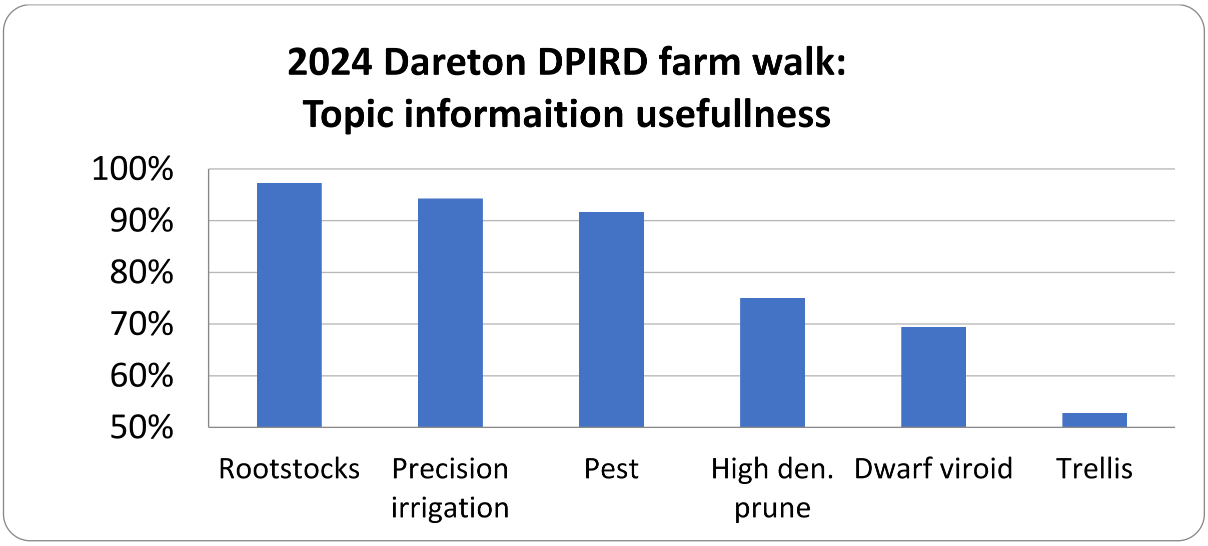

Figure 11. The practical and adoptable usefulness of each of the topic presented.

Rootstocks, precision irrigation and pest management were identified as three information topics that had similar immediate practical usefulness to participants (Figure 11). Growers are continually replanting their orchard and the knowledge of rootstocks that can provide better quality fruit and allows trees to be planted at a high density is very important to the longevity of the orchard. Irrigation is a key component of orchard production and is often regarded as 80% of the skill required to manage a successful orchard. Growers recognise that parts their orchard are less healthy and less productive and thus see any improvements in knowledge skill and understanding of irrigation can have significant impacts on productivity and profitability. Pests are an ongoing problem and understanding their control is key to maintaining a good quality crop during the season. The other topics were less relevant because if the growers did not have blocks of high density or other intensive systems then the information may not be as relevant, however their relevance was recognised because it is obviously a long-term consideration.

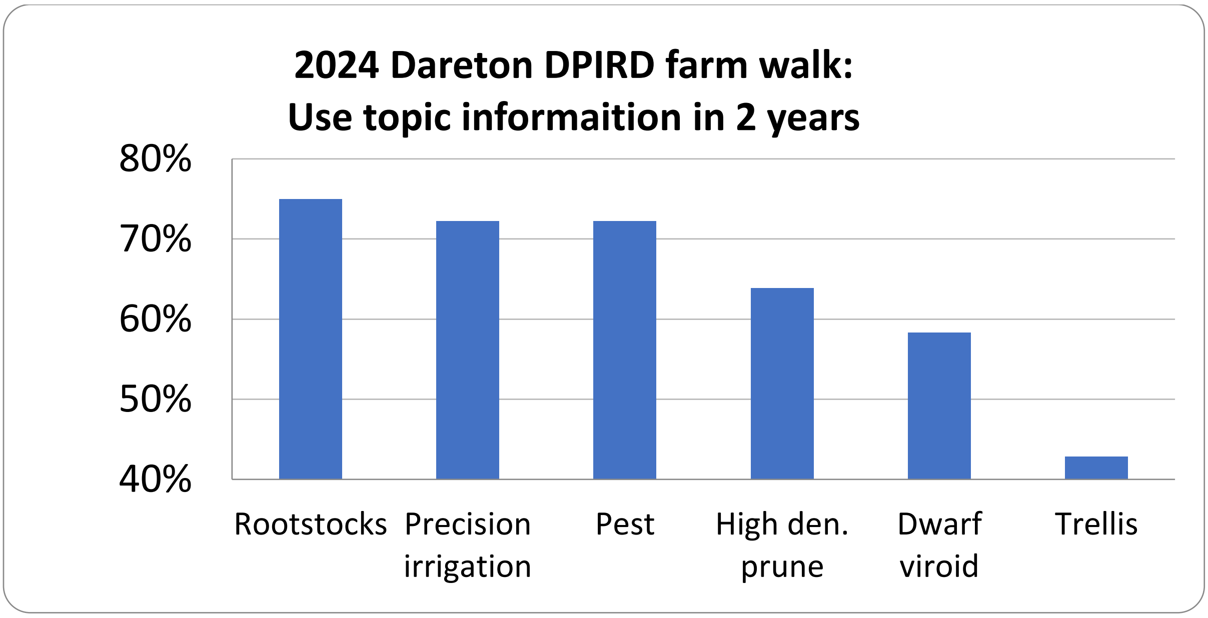

Figure 12. Usefulness of the information in the next 2 years.

The previous question was focused on immediate usefulness of the information and this question considered the longer-term view of 2 years (Figure 12). The survey provided similar results to the previous question and is recognised that the high-density systems presented at the field day have longer term implications (5-10 years) and perhaps the question should have asked the usefulness of information in the next 10 years.

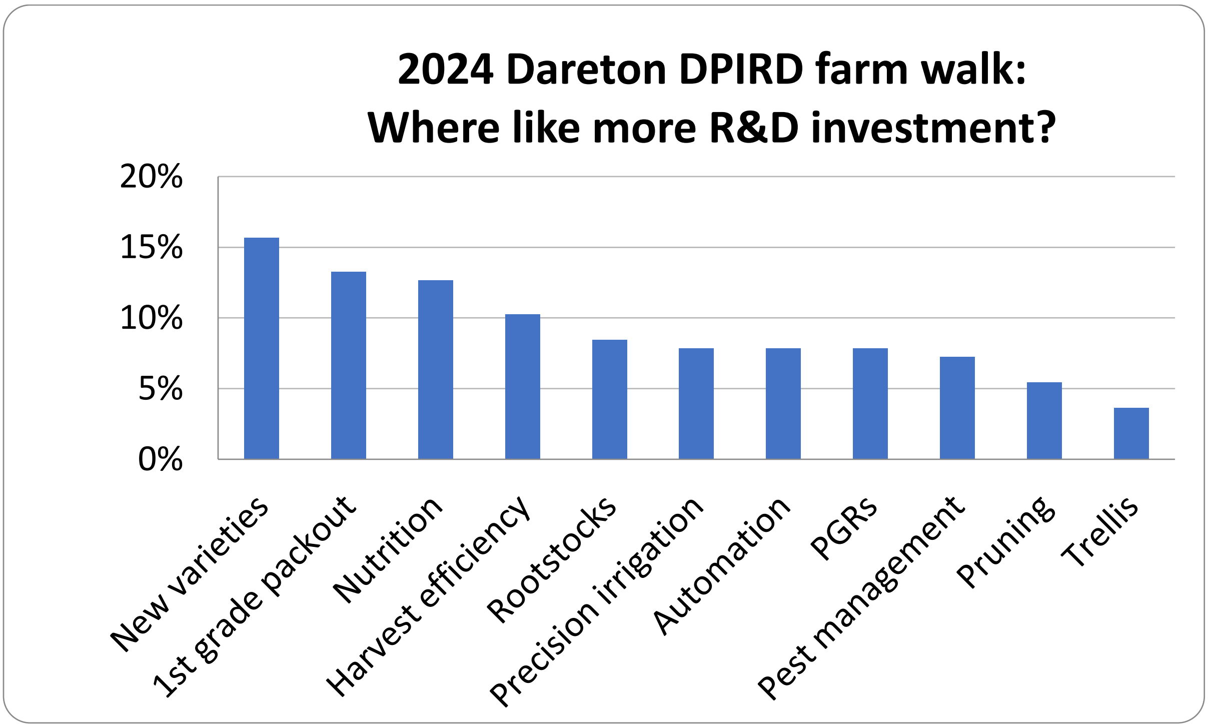

Figure 13. Topics that participants indicated they would like to see more R&D investment.

New varieties, 1st grade packout and nutrition were the three top topics where participants would like more Research and Development investment (Figure 13). New varieties are a key aspect of production as growers need to choose varieties that are productive and have market demand that provides acceptable prices. Choosing the wrong variety can quickly “make or break” a long-term investment. 1st grade packout in terms of fruit quality and quantity are the next most important factor to orchard profitability. Steven demonstrated to participants how prices and yield make the most dramatic differences to on-farm profitability. The other topics were not too far behind in interest for future project investment demonstrating that industry needs a diverse portfolio to meet the needs of a long-term profitable Australian citrus industry.

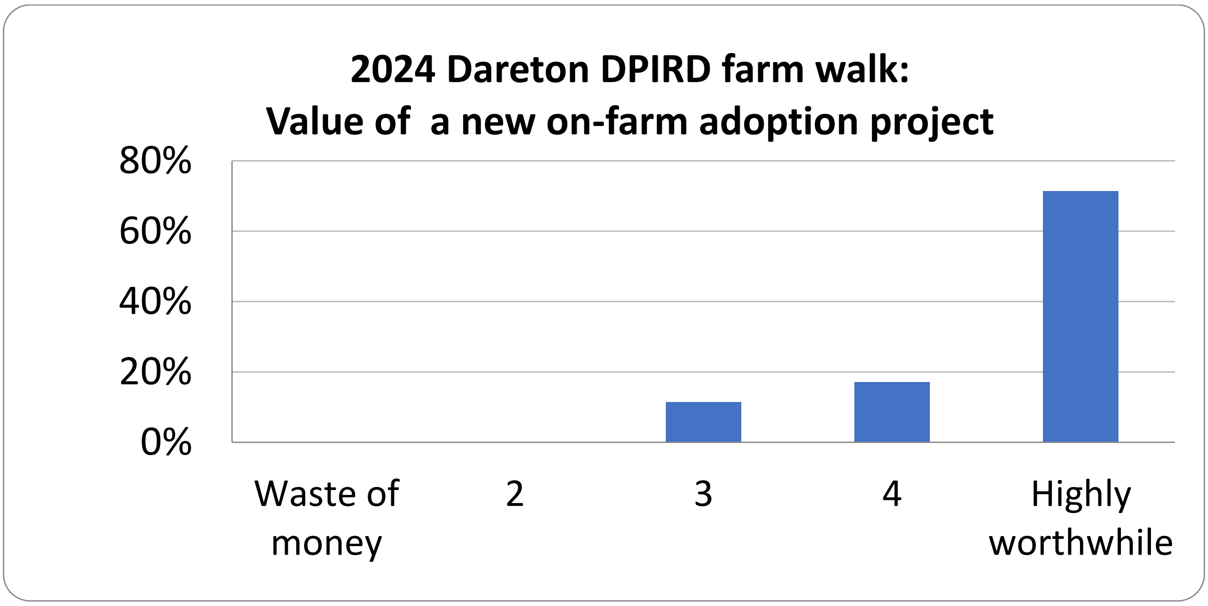

Figure 14. The value of investing in a new on-farm adoption project

Over 70% of participants indicated that it is highly worthwhile in conducting an on-farm adoption project and the other 30% indicated it was at least worthwhile (Figure 14). Research is about discovering and validating technical information and adoption is about on-farm engagement and activities that facilitates learning, practical adaptation and demonstrating how to implement improved practices in a commercial farming system so that others can be encouraged to follow. Adoption is also developing practical information and tips to assist in the adoption process. Other industries have extension and adoption projects, and there is great opportunity for the citrus industry to develop projects that work with growers in adoption. Adoption projects are about engaging with growers, conducting demonstration trials that can detect differences, and the grower teaching other growers of their success. Also, if a practice does not perform, understanding where not to invest time and money is just as important as understanding worthwhile investment of time and money. A project could cover the topics of interest highlighted in this survey including irrigation, pest, 1st grade packout and intensive orchard systems, and other topics such as automation, harvest efficiency, nutrition, crop regulation and foliar sprays. The project would also be a mechanism to encourage grower industry participation. The project would also provide sites for industry field days.

Appendix 1 – Field day promotional brochure

Appendix 2: Feedback sheet

Dareton NSW DPIRD farm walk

TUESDAY 15 Oct 2024

Please provide your answer by circling a number or word on the scale

1) Involvement: Grower Packer Industry services Researcher Other: Please indicate
2) Overall assessment of the farm walk

   1 2 3 4 5

   No use or relevance Highly useful and relevant (now or in future)

3) Is the work at DPIRD Dareton a worthwhile investment of your levy money?

   1 2 3 4 5

   Waste of money Highly worthwhile

4) Please circle the relevant number for each session on whether the information was useful to assist you to make better management decisions now and into the future.

	Not relevant	Minor usefulness	Useful	Useful and use in next 2 years
Rootstocks	1	2	3	Y
High density pruning	1	2	3	Y
Trellis	1	2	3	Y
Irrigation	1	2	3	Y
Dwarfing viroid	1	2	3	Y
Pest management	1	2	3	Y

5) Did you want any more information on any of these topics, and any other suggestions for field day improvements (please leave your name and number is you wish a follow up)?

6) Is it worthwhile using your levy money for an on-farm adoption and extension project that conducts studies, trials and field days on your farm (e.g. labour savings, sprays, thinning, pruning, irrigation, etc.)?

   1 2 3 4 5

   Waste of money Highly worthwhile

7) What other topics you would like more research, development and extension (please circle ones of interest)

Precision irrigation Nutrition Pest management Pruning Trellis New varieties

1st grade packout practices Harvest efficiency Rootstocks Farm automation PGRs

Unlocking high-density citrus orchards in Sunraysia: Part II

Sunraysia grower Trevor Radloff shares practical insights from his experience with high-density plantings.

Trevor Radloff within the Lane Late twin-row staggered planting

Trevor Radloff is a producer of both citrus and wine grapes at Palinyewah, New South Wales.

During the mid-2000s, Radloff planted seeded Daisy mandarin and Lane Late navel varieties in a staggered twin-row formation to optimise early production.

The twin-rows were 2.2m wide, with a tree spacing of 2.9m along the row. A tractor access row of 5.2m was established either side of each twin-row formation, resulting in a density of 940 trees per hectare.

DAISY MANDARINS

The Daisy mandarins were planted in 2005. Harvesting started three years later, with a yield of approximately 6 tonnes per hectare.

The alternate bearing nature of Daisy mandarins meant annual production volumes fluctuated from 6 tonnes to 80 tonnes per hectare until the ninth year. From year four to year six, average yield was approximately 25 tonnes per hectare.

This increased to an average 73 tonnes per hectare between years ten and eighteen, although the yield was again highly variable year-to-year over this period — ranging from 50 tonnes to 114 tonnes per hectare.

Mahmud Kare, a research horticulturist with the New South Wales Department of Primary Industries and Regional Development (NSW DPIRD), said the alternate bearing nature of these trees meant higher yields often resulted in smaller fruit sizes, thereby reducing the returns per tonne.

Radloff's canopy management technique involved a blend of mechanical hedging and hand pruning, which was adjusted according to the alternate bearing cycle.

"In years of heavy fruit set, the trees were lightly topped, while in years of low fruit set, the trees were not topped and were allowed to grow to bear fruit. So, the pruning schedule typically resulted in topping every alternate year," Radloff explained.

"Additionally, the trees were side-hedged for tractor access every two or three years."

Given the narrow row-spacings, Kare said a high-density planting can quickly become overgrown if it is not managed correctly.

With this in mind, Radloff's rigorous hand pruning technique involved removing selected central limbs, crossovers, and any excessively wide branches in the twin row plantings.

Radloff said this technique ensured sufficient light penetration into the middle of the staggered rows and provided pickers with better access to the fruit. However, it was a labour-intensive process that came with added costs.

"Our pruning expenses are typically around $1.50 per tree, however, on high-density plantings they were double that at around $3 per tree," Radloff explained.

Now that the trees have matured and their canopy is fully enclosed, Radloff said weed issues are minimal in the twin-row plantings, due to the well-shaded ground.

Radloff's weed control program involves highly effective early weed management, which also delivers greater herbicide and application rate efficiency, allowing the tractor to operate for fewer hours.

"Spraying weeds when they are young provides better results than when they are mature," Radloff explained.

Kare said skirting was a concern for twin-row staggered trees, although this fruit is not being sent to KCT (Korea, China and Thailand) protocol countries. Low skirts present a management issue, allowing more access points for pests and increasing the loss of fruit due to rots.

LANE LATE NAVELS

The Lane Late navel high-density orchard, grafted on citrange rootstock, was planted in 2006, a year later than the Daisy mandarins.

The initial harvest commenced in year four, with an average yield of approximately 40 tonnes per hectare until year nine. The average yield then declined to 30 tonnes per hectare from years ten to sixteen, attributed to the intensive pruning required to maintain the trees at an acceptable size.

"The more heavily you prune to eliminate the deadwood, the more it stimulates a vigorous response that necessitates further pruning," Radloff explained.

Radloff also has single-row Lane Late plantings that are achieving comparable mature tree yields to the high-density twin-row staggered plantings, with significantly less pruning and other management inputs.

"Although the yields were satisfactory in the initial years, I decided not to use twin-row staggered plantings for future orchard design," Radloff said.

"Firstly, pruning in the staggered rows is a more arduous task as it requires the limbs to be pulled out for access to the row for mulching.

"Secondly, the time spent on pruning for both standard and high-density trees is equivalent, thus leading to higher pruning costs.

"Finally, the inability to mechanically skirt the staggered intra-row side of the trees poses a challenge."

Radloff has chosen to plant more Daisy mandarins using a standard spacing of 3.5m x 6.7m. He said he would use a similar planting density for any upcoming navel plantings.

Kare said careful planning and informed decision-making, based upon long-term forecasting of management, production and profitability considerations, is needed when exploring high-density plantings.

The New South Wales Department of Primary Industries and Regional Development (NSW DPIRD) citrus crop intensification team thanks Trevor Radloff for sharing his high-density citrus planting experiences in this article.

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hort frontiers

This article was prepared by the New South Wales Department of Primary Industries and Regional Development's (NSW DPIRD) citrus crop intensification team and Citrus Australia.

It is the second article in a two-part series on high-density plantings in the Sunraysia region.

The first article was published in Issue 1 2024 of Australian Citrus News and can be viewed here: https://bit.ly/4coHZEM

More information on high-density planting and pruning is available on the NSW DPIRD website.

Case study: https://bit.ly/4auAScW

Economic analysis: https://bit.ly/4asOOE2

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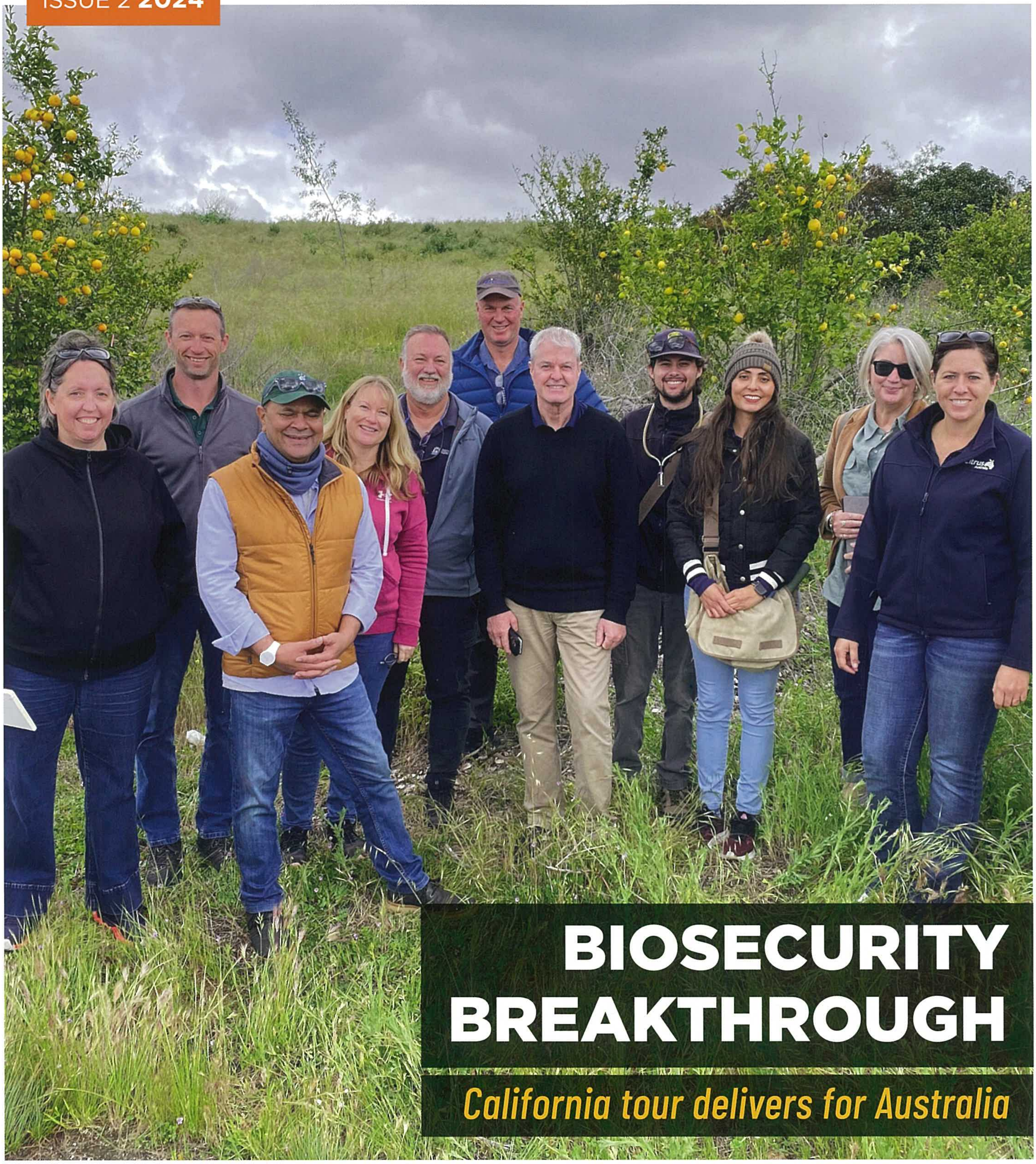

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Intensifying citrus tree crops and modifying tree canopies: a brief review

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Abstract

High-density citrus orchards have proven benefits for productivity but canopy management using conventional practices becomes problematic after trees reach their allocated space. This paper reviews the literature on high-density planting of citrus to understand the motivation for crop intensification and the different strategies for manipulating tree size such as dwarfing rootstocks, dwarfing viroids, pruning and trellis training.

Keywords: citrus, high-density, canopy management, dwarfing, productivity, viroid

INTRODUCTION

Citrus is an important horticultural crop, contributing significantly to the global economy. The Food and Agricultural Organization (FAO) (2020) showed that there were 2,850,000 ha planted to citrus and 40,600,000 t of fruit harvested from approximately 140 countries, of which Australia contributed 550,000 t (1.35%) from 27,000 productive ha (0.96%). In Australia, the rising costs of land and water have put pressure on the profitability of conventional tree crop production systems. The cost and availability of labour are also limiting factors. Citrus growers worldwide are facing similar pressures, including threats to their industry from devastating pests and diseases such as huanglongbing (HLB), a bacterial disease that is not known to occur in Australia. Orchard intensification can increase resource use efficiency as the industry strives to maintain the productivity and sustainability of citrus production systems.

Intensifying a citrus orchard can improve productivity ha^{-1} (Boswell et al., 1970; Wheaton et al., 1986; Castle et al., 2007; Bordas et al., 2012) by maximising the fruit-bearing portion of the canopy (Singh and Singh, 2018) without affecting fruit quality (Bordas et al., 2012; Mishra and Goswami, 2016; Singh et al., 2020) or tree health (Wheaton et al., 1995b; Hamido and Morgan, 2020). Intensifying a citrus planting can also increase profitability (Wheaton et al., 1995a, b; Castle et al., 2007; Dogar et al., 2017), economic growth (Ford et al., 1989; Skaria and Hanagriff, 2008; Tzul, 2016) and industry sustainability (Tilman et al., 2011; Garnett and Godfray, 2012). Higher density orchard blocks are more efficient to manage (Gallasch, 1983; Atkinson and Else, 2003; Singh and Singh, 2018) and harvest (Whitney et al., 1994; Whitney, 1995; Vidalakis et al., 2010b; Bordas et al., 2012) and are better suited to automated management practices (Mendel, 1968; Bordas et al., 2012; Liu et al., 2018; Singh and Singh, 2018). High-density systems are also less susceptible to damage from cold temperatures (Wheaton et al., 1986; Harrison et al., 2013) and high winds (Drinnan et al., 2018).

Producing more citrus fruit ha^{-1} contributes to meeting the demand created by increased fruit and vegetable consumption (Mason-D'Croz et al., 2019), especially given the proven health benefits of citrus (Iglesias et al., 2007; Legua et al., 2014). Planting at high-density also generates more fruit without increasing the land required (Castle, 1978; Pretty, 2008; Horlings and Marsden, 2011; Tilman et al., 2011; Firbank et al., 2013; Ahmed and Azmat, 2019); an important contributor to sustainable production (Pretty, 2008; Horlings and Marsden, 2011).

The many benefits to be gained from intensifying citrus orchards can be realised by understanding tree growth and behaviour, improving orchard design, and controlling tree vigour using dwarfing rootstocks, viroids, or tree training techniques.

IMPORTANT FACTORS IN HIGH-DENSITY CITRUS ORCHARD BLOCKS

Commercial high-density citrus orchards have been grown conventionally for decades, resulting in higher yield and profit in the early years (Bevington, 1989; Castle et al., 2007; Ladaniya et al., 2020, 2021). However, most of these higher density blocks managed using conventional practices become problematic at maturity because of overcrowding (Stuchi et al., 2007) and inter-tree competition (Wheaton et al., 1995a). This can be overcome by controlling tree size (Whitney et al., 1994), provided the trees are not so small they are no longer suitably productive (Castle, 1978). It is the volume of fruit-bearing foliage, not the number of trees, that contributes to the yield ha^{-1} (McCarty et al., 1969).

A significant challenge for tree crop growers is the time between establishing an orchard and the trees coming into production (Iglesias et al., 2007; Donadio et al., 2019), which can be more than six years for some citrus cultivars. To achieve early high yields of good quality fruit with lower labour and operating costs, appropriate scion and rootstock combinations, planting density and training systems are required.

Standard planting densities for citrus range from 370 to 889 trees ha^{-1} (Whitney et al., 1990), with an average of 400 to 600 trees ha^{-1} (Hutton et al., 2000). High-density plantings range from 1300 to 2020 trees ha^{-1} (Aubert, 1990; Wheaton et al., 1990, 1991; Skaria and Hanagriff, 2008; Ladaniya et al., 2020, 2021). In the late 1970s, a standard sized tree was considered to be approximately 6 m at maturity, and a sub-standard tree about 5 m (Castle, 1978; Wertheim, 1985). A semi-dwarfed tree is about 60% of the size of a standard tree, or 3.6 m tall at maturity and a dwarfed tree would not grow taller than 2.4 m when mature, with growth reduced by about 75% (Bitters et al., 1979). The current standard citrus tree size in Australia is approximately 3.5 to 4.0 m, a sub-standard tree around 3.0 m, a semi-dwarfed tree 2.5 m and a dwarfed tree about 2.0 m at maturity (Steven Falivene, Andrew Creek and Justin Lane, pers commun.). In New South Wales, Australia in the early 2020s, most citrus trees were pruned to allow picking from a 3.0 to 3.6 m ladder (10 to 12 step ladders are most popular), with resulting average standard mature tree heights of 4 m maximum. Use of 4.2 m ladders (14 step) has decreased over time, now constituting only 5% of sales (Andrew Creek, pers. commun.).

There are many benefits of growing smaller, dwarfed trees including:

- smaller canopies can produce greater volumes of fruit per unit area (Whitney et al., 1994) because they have a more favourable ratio of fruit-bearing foliage compared with the non-producing woody framework of larger trees (Castle, 1978);
- greater production ha^{-1}, especially in the early years (Long et al., 1972) because more of the total incoming light is captured by the canopy;
- dwarfed trees are comparatively better at capturing and converting light into fruit (Uddin et al., 2017) by achieving greater light interception and a greater proportion of well-illuminated leaf area than larger trees planted at low densities (Singh et al., 2020);
- dwarfed trees can be spaced closer together than vigorous trees without suffering from crowding or the need for frequent, severe pruning (Long et al., 1972; Castle, 1978);
- it is easier to perform management practices in orchards with smaller sized trees (Whitney et al., 1994);
- it is easier to apply chemical treatments to smaller trees and the effects of spray drift and environmental contamination can, therefore, be reduced (Atkinson and Else, 2003);
- more accurate canopy density measurements, using tools such as mobile LiDAR, leads to better pest and disease control in dwarfed trees through more precise and cost-effective spray application (Owen-Smith et al., 2019);
- smaller trees with lower vigour are cheaper to harvest (Castle, 1992) because little or no ladder work is needed (Long et al., 1972; Hutton et al., 2000).

Fruit quality must be maintained or improved in all citrus production systems

(Wheaton et al., 1995a; Bowman and McCollum, 2015; Singh et al., 2020) because quality is a component of productive yield and determines consumer acceptance in both the fresh and processing markets (Wheaton et al., 1995a). Light penetration, tree spacing, and location of the citrus fruit on the tree affect fruit rind colour and soluble solids (Monselise, 1951; Phillips, 1974). At least 30% of the light must pass to fruiting sites to ensure fruit colour, quality and flower bud differentiation (Grappadelli and Lakso, 2007). Light interception and distribution can be optimised by training trees on trellis systems and changing tree canopies from thick/dense three-dimensional shapes to two-dimensional shapes (Singh et al., 2020). Light interception can also be enhanced by bending inefficient vertical- or intermediate-limbs to become efficient horizontal limbs for more reproductive growth, using single-row planting systems, north-south row orientation, and dwarfed trees with canopies of low leaf area density that do not spread over adjacent trees (Wertheim, 1985; Jackson, 1989; Palmer, 1999).

CANOPY MANAGEMENT TECHNIQUES

Citrus vigour can be manipulated during orchard block establishment and the production phase. Before orchard establishment, decisions are made on the scion and rootstock combination and whether or not the trees will be inoculated with dwarfing viroids or if the trees will be grown on a trellis. Planting density is chosen to optimise the capture of incoming solar radiation based on expected tree size – that is, smaller trees will be planted closer together than larger trees. In the production phase, canopy or root pruning, girdling, and plant growth regulators can be used to control vigour. The restriction of both water and/or nutrients can also influence growth (water and nutrient manipulation is outside the scope of this review).

Scion cultivars

Citrus trees vary in their vigour and growth habits, both between and within each of the six true citrus genera (Saunt, 2000). Conventional production systems leverage rapid canopy expansion to drive per-tree fruit production, therefore favouring vigorous cultivars that grow into large trees, often with erect growth (Saunt, 2000). Contrary to this, cultivars to be planted at a higher density should expend the least amount of energy growing scaffold branches, instead producing a greater quantity of fruiting wood with a spreading habit to cast the least shadow on other branches. Those branches should bear fruit year-on-year, minimising the need for continual canopy expansion to maintain yield (Singh and Singh, 2018).

A scion cultivar suited to planting at high-density will have low juvenility (Iglesias et al., 2007; Donadio et al., 2019), early cropping, high yield, improved cropping efficiency (kg cm^{-2} of trunk cross sectional area) and fruit quality (Simon et al., 2006; Zhang et al., 2016; Tustin et al., 2022). It must also have suitable tree architecture at maturity – naturally, or in response to pruning – to enhance light interception and distribution through the canopy (Simon et al., 2006; Tustin et al., 2022) and not be prone to biennial bearing (Davis et al., 2004). Defining many of the contrasting characteristics that describe the components of yield within different cultivars is an ongoing research priority for the authors.

Rootstocks

Choosing the right rootstock cultivar is essential for high-density orchard blocks (Bordas et al., 2012). Rootstock choice influences tree health (Bowman et al., 2016a; Dubey and Sharma, 2016; Donadio et al., 2019) and survival (Bowman et al., 2016b), resistance to pests and diseases (Bitters, 1986; Iglesias et al., 2007; Albrecht and Bowman, 2012; Donadio et al., 2019), scion vigour (Lliso et al., 2004; Mademba-Sy et al., 2012; Bowman et al., 2016b), fruit production, yield and fruit quality (Wheaton et al., 1991; Bowman et al., 1997, 2016b; Castle et al., 2010), which each contribute to orchard profitability (Roose et al., 1989; Zekri, 2000). There can be more than a six-fold difference in yield between the best and worst rootstocks (Wutscher and Bowman, 1999). Importantly, rootstocks also influence tree size, vigour, leaf area and therefore light penetration into the canopy (Roose et al., 1989; Wheaton et al., 1990; Zekri, 2000). Citrus scion cultivars grafted to moderate vigour rootstocks perform better (induce the scion to be relatively early bearing and produce good quality fruit) than very vigorous or dwarfing rootstocks and are considered the most suitable for moderate density orchard systems (Wheaton et al., 1991).

Citrus (syn. *Poncirus*) *trifoliata* rootstocks have been used for many years in New South Wales citrus production because they are resistant to *Phytophthora citrophthora* (Benton et al., 1950), citrus tristeza virus and citrus nematode (*Tylenchulus semipenetrans*), and trees budded on it produce high-quality fruit (Cheng and Roose, 1995). *Citrus* (syn. *Poncirus*) *trifoliata* var. *monstrosa* (Flying Dragon, FD) is a size-controlling rootstock and is the only one to develop commercial interest among many that have been evaluated (Wheaton et al., 1991; Castle et al., 2007). The commercial dwarfing rootstock 'Flying Dragon' controls vigour by reducing the rate of canopy expansion for a range of *Citrus* species including Valencia orange, tangelo, grapefruit, tangor and navel orange when compared with Troyer citrange (*Citrus sinensis* × *C. trifoliata*) (Whitney et al., 1994; Castle et al., 2007; Mademba-Sy et al., 2012). This leads to trees of most mature varieties planted on Flying Dragon stock only attaining 75% of the size of trees grown on standard rootstocks and rarely exceeding 2.5 m in height (Bitters et al., 1979), making it a true dwarfing rootstock (Cantuarias-Avilés et al., 2011). This vigour control is driven by an increase in hydraulic resistance in the rootstock, leading to a reduction in stomatal conductance, decreasing net photosynthetic CO_2 assimilation (Martínez-Alcántara et al., 2013). There are some reports of incompatibility (Roose, 1986) but trifoliate rootstocks are still considered a useful rootstock for high-density orchard blocks (Ashkenazi et al., 1993).

Other dwarfing rootstocks have been released recently but have not yet attained the same level of renown as Flying Dragon. They include the Forner-Alcaide hybrid selections (FA-517 and FA-418) (Legua et al., 2013) and USDA-bred US-812 and USA-897 (Bowman et al., 2016a). It should be noted that the increased time it takes to produce nursery trees and continued slow growth in the field has, classically, detracted from the use of dwarfing rootstocks. A rootstock that grew at the pace of a citrange rootstock between germination in the nursery and, say, the fourth-year post-planting and then decreased vigour to the level of 'Flying Dragon' would give the very best of both rootstocks.

Dwarfing viroids

Viroids that induce mild to moderate dwarfing in infected citrus species can be used to intentionally reduce canopy volume by inhibiting shoot apical growth (Lavagi-Craddock et al., 2020). Citrus viroids are efficiently transmitted between infected plant tissues, as occurs during graft and bud propagation or mechanically via pruning shears (Flores et al., 2005; Di Serio et al., 2014).

Citrus exocortis viroid (CEVd) presents as peeling bark on susceptible rootstocks (known as scalybutt) with dwarfed and unthrifty growth (Duran-Vila et al., 1988). These symptoms were attributed to several variants of citrus exocortis viroid (Visvader and Symons, 1985). Since then, eight viroid species have been identified; citrus bent leaf viroid (CBLVd), hop stunt viroid (HSVd), citrus dwarfing viroid (CDVd), citrus bark cracking viroid (CBCVd), citrus viroid V (CVd-V), citrus viroid VI (CVd-VI) and the newly described citrus viroid VII (CVd-VII) (Duran-Vila et al., 1988; Ito et al., 2001; Chambers et al., 2018). There are variants of each viroid species that can differ in their effect on the host plant, from benign to severely damaging, and there are differences in how cultivars respond to infection. There can also be an increased or decreased effect when more than one viroid is present (Vernière et al., 2006). Studies have reported that co-infection of CVd-V with either CBLVd or CDVd enhanced symptom development (Serra et al., 2008), but co-infection of CEVd with CBCVd led to a suppression of symptoms (Vernière et al., 2006).

Viroids that induce mild to moderate dwarfing of citrus trees can be beneficial to production citriculture by controlling individual tree vigour without compromising canopy volume/unit area (coupled with increased planting density) (Van Vuuren and Da Graça, 1996; Vidalakis et al., 2011). Productivity increases early in the life of the orchard block planted at high-density arise from an increased rate of canopy closure and maximising solar radiation interception, compared with conventional planting densities (Hutton et al., 2000). That is, the canopies of trees infected with commercial dwarfing viroid grow at the same rate as uninfected trees for the first 4-5 years after planting, being able to fill available space rapidly, before inducing a reduction in the rate of canopy expansion (Bevington and Bacon, 1977; Hutton et al., 2000). Dwarfed trees should be well maintained as they can be less able to cope with stress, particularly drought or salinity (Hardy et al., 2007).

Many studies have shown viroid inoculation does not affect fruit yield, size or quality (Roistacher et al., 1991; Albanese et al., 1996; Vidalakis et al., 2011; Najar et al., 2017). In Australia, inoculation of trees with dwarfing viroids is recommended 6-18 months after field planting, to avoid contamination of other trees in the nursery environment (Hardy et al., 2007). Delaying inoculation of dwarfing viroids into trees even 3 years after planting decreased the dwarfing response, and application on mature trees had no effect (Vidalakis et al., 2004). Those authors speculated that the metabolic and developmental events that result in the dwarfing response must be initiated within this early period of tree maturation.

Viroids deliberately used to benefit a production system by reducing canopy volume are commonly referred to as either 'graft-transmissible dwarfing viroids' (GTD) (Hardy et al., 2007) or 'transmissible small nuclear ribonucleic acids' (TsnRNAs) (Semancik et al., 1997).

Pruning

Pruning is a canopy management strategy that influences fruit quality by allowing more light into the canopy (Verheij and Verwer, 1973) and increasing orchard productivity (Singh et al., 2020), making pruning one of the most important practices for citrus fruit production in conventional orchards. Regular pruning or hedging to control vigour involves removing branches that would otherwise lead to a greater rate of canopy expansion and result in a proportional reduction in yield (Tucker et al., 1994). This compromise is made to avoid overcrowding and excessively tall trees, which result in decreased light penetration (Krajewski and Krajewski, 2011), death of lower bearing branches (Smith, 2002) and reduced fruit quality (Fake, 2012).

Vigorous, closely spaced trees require frequent pruning to keep them within their allotted space (Fake, 2012; Mishra and Goswami, 2016) and manage overcrowding (Hampson et al., 2002; McFadyen et al., 2004), but this in turn perpetuates the problem by stimulating excessive vegetative growth at the expense of fruiting wood, ultimately reducing yield (Wheaton et al., 1995b). Untrained higher-density orchard blocks can take significantly longer to prune than low-density conventional orchards because of the dense canopy and greater number of trees to prune (Strik and Buller, 2002).

Pruning programs that are implemented earlier in the life of the orchard employing frequent (annual/biennial), less aggressive cuts are recommended over harsh, infrequent (4+ years) pruning to reduce the effect on year-to-year yield differences (Smith, 2002; Fake, 2012; Ghosh et al., 2016; Singh and Singh, 2018). The size of slow growing trees can be maintained more uniformly with pruning (Aubert, 1990), with fewer pruning cuts required, removing less of the canopy and, therefore, fewer fruiting sites (Krajewski and Pittaway, 2000; Singh and Singh, 2018) compared with more vigorous trees.

Tree training systems

Tree training systems, such as trellising, have been used to achieve maximum light interception and distribution, higher fruit yields and quality, and easier staff access in cherries (He and Schupp, 2018), apples (Ampatzidis and Whiting, 2013) and blueberries (Strik and Buller, 2002; Tustin et al., 2022), but evaluations in high-density citrus orchard blocks have not been published. Similarly, the effect of light distribution within the canopy on flowering, fruit-set and fruit-quality is not well understood for citrus. The authors know of several research and commercial blocks planted using trellis systems, both in Australia and internationally, and anticipate the results of this work will be of interest to many.

Plant growth regulators

Plant growth regulators (PGRs) used in agriculture are synthetic analogues of naturally occurring plant hormones and include abscisic acid, auxins, cytokinins, ethylene and gibberellins. Several other compounds also act similarly to the traditional PGRs and include brassino-steroids, jasmonates, oligosaccharins, polyamines, salicylic acids and strigolactones

(El-Otmani et al., 2000). PGRs affect physiological processes, modifying the rate or incidence of plant development and growth. PGRs act antagonistically on plant growth, functioning to decrease cell elongation and/or division. Within this retardant category, anti-gibberellins, such as paclobutrazol (PBZ) and chlormequat chloride (CCC, cycocel), can reduce the growth rate of shoots (Vu and Yelenosky, 1992; Jain et al., 2002) by inhibiting gibberellin biosynthesis (Rademacher, 2000). These chemicals, and other similar growth retardants, may form part of a vigour control package for citrus production (Rani et al., 2018), but care must be taken in their use as the rate, timing and method of application can affect other production factors such as flowering and fruit-set (Basra, 2000).

Root pruning

Most *Citrus* spp. have a single tap-root, with lateral roots forming a dense mat in the surface layers (Morgan et al., 2007). In mature citrus orchards, root pruning can be employed to control vigour (Sansavini et al., 2019) as the plant redirects assimilates to replace the removed parts (Gilman, 1990). In fully developed citrus trees, root pruning reduced tree height growth (Mullin, 1966). However, evidence suggests vegetative growth is accelerated in young orchards as the trees established more fibrous roots in response to root pruning (Budiarto et al., 2019).

Girdling

Girdling, sometimes referred to as ringing (Bitters, 1986) or scoring, is a technique used to increase citrus fruit set, yield and quality (Morgan et al., 2009) by blocking the downward translocation of photosynthates and metabolites through the phloem (Li et al., 2003; Poirier-Pocovi et al., 2018). This action, taken at anthesis (when 60% of the flowers were opened), has been shown to enhance fruit set by delaying fruitlet abscission (Rivas et al., 2007; Ibrahim et al., 2016).

Severe girdling, in which a ring of bark is removed, is seldom used in citrus. Instead, more transient disruption of phloem transport is produced by making a single-blade cut through the bark around all or part of the trunk or scaffold branches (Morgan et al., 2009) where promoting fruit-set is prioritised over vigour control. Noel (1986) described a practice in South-Central Africa where girdling was used intentionally to kill trees slowly for firewood – providing a steady supply of dry kindling and, eventually, large limbs. A middle ground between maintaining photosynthate in the upper canopy to promote fruit-set and killing the tree may offer a pathway to vigour control as has been seen in other crops such as avocado (Wolstenholme and Whiley, 1992), but application on a commercial scale must consider the cost and evident risks.

CONCLUSIONS

Both under- and over-exposure to solar radiation decrease the efficiency of photosynthesis in an orchard canopy. Under-exposure reduces the energy to drive the photosynthetic electron transport chain below its maximum rate. Over-exposure demonstrates an inefficiency in tree structure – a leaf is oriented such that it is intercepting more light than it requires and is, ipso facto, not making that light available to other leaves that could benefit from it. This is why most of a citrus canopy's light interception and fruiting occurs in the outer 1 m of the canopy ('bearing volume'). Computer models of light distribution within a tree of a given size show a point is reached where a further increase in leaf area does not increase the well-illuminated bearing volume, instead moving it to the periphery of the tree. Those fruit growing in a lower-than-optimal light environment, suffering intra-canopy shading, tend to have reduced fruit size and colour resulting in the quantity of large fruit of full colour plateauing, even as the tree canopy volume increases.

Pushing production systems through that plateau will come from a combination of the technologies described in this review. There is not likely to be a future for commercial orchard production without pruning, but with an underlying vigour control technology – be it choice of scion or rootstock combination, dwarfing viroids, trellis training, plant growth regulators, root pruning, or girdling – each pruning-dollar spent becomes more efficient, promoting more refined pruning methods to maximise the number of fruiting sites.

The citrus industry requires a better understanding of these technologies and how to implement them, accounting for the cost of establishment and maintenance in a farming system, before they can become mainstream. The apple industry has found that several vigour control systems can produce trees of approximately similar size and shape and the cost of establishing and maintaining these systems were the deciding factors in their uptake. In Australia, research is often only a step ahead of progressive growers and their interest and support encourages researchers to deliver actionable, adoptable outputs to grow their orcharding business.

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