Final report

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Optimising Avocado Yield with Region-Specific Canopy Management: Insights from Light Interception and Canopy Modelling

Project leader:

Gerhard Rossouw

Delivery partner:

Queensland Department of Primary Industries (lead agency) and Wilkie Horticulture (sub-contracted support agency)

Report author/s:

Gerhard Rossouw, Neil White, John Wilkie

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Level 15
141 Walker Street
North Sydney NSW 2060

Telephone: (02) 8295 2300

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Public summary

AV24011 was undertaken to help the Australian avocado industry better understand how canopy structure and light environment influence productivity, and to identify the research and technology development needed to support more regionally tailored canopy management in future. Pruning and canopy management are major decisions for avocado growers, but the effects of pruning on future flowering, fruit set, fruit retention and yield are still difficult to predict. A key challenge is that avocado orchards are grown across diverse Australian environments, and a canopy strategy that works in one region may not work in another. This project addressed the need for clearer knowledge about how light moves through avocado canopies, how this relates to productivity, and how future tools could help growers make more informed canopy management decisions.

The project reviewed national and international information on avocado physiology, orchard light environments, canopy management, light measurement tools, sensing technologies and modelling approaches. It also involved input from a Project Reference Group, growers, industry representatives, modellers, researchers and technology providers. These activities were used to identify the main knowledge gaps that currently limit light-informed canopy management in avocado. The project found that while light environment is widely recognised as relevant to avocado productivity, the industry does not yet have clear, quantified light targets that describe how much usable light is needed in different parts of the canopy to support leaf retention, shoot growth, flowering, fruit set, fruit retention and fruit growth. The project also found that technologies such as LiDAR, imaging, light sensors and digital canopy models have strong potential, but they need to be linked with real orchard measurements of light, canopy structure and crop response before they can support reliable grower decision-making.

The project produced a literature and technology review, a modeller and technology engagement report, a grower feedback webinar summary, an industry article for Talking Avocados, and an R&D investment options analysis. The investment options describe a pathway for future work, including defining practical canopy light targets, quantifying how canopy leaf area and density influence usable light distribution, developing sensing tools, testing pruning strategies in commercial orchards, and building modelling or digital twin approaches that could allow pruning options to be assessed before they are applied in the orchard. These recommendations are described by target region, expected grower benefit and Technology Readiness Level, so they can help guide future industry investment.

The main benefit of AV24011 is that it provides a clearer pathway from current knowledge gaps to practical future tools for growers. Future R&D should focus on developing evidence-based, regionally relevant canopy management guidance that helps growers identify low-productivity canopy zones, reduce pruning guesswork, manage light more deliberately, and improve yield consistency over time. The project highlights that grower-ready tools will require staged development, but that the foundations now exist for more targeted investment in canopy sensing, light modelling and practical pruning decision support for Australian avocado orchards.

Keywords

avocado; canopy management; light interception; photosynthetically active radiation; pruning; light use efficiency; LiDAR; canopy modelling; digital twins.

Introduction

The Australian avocado industry has expanded substantially over the past decade, creating both opportunities and challenges for growers. As production expands and competitive pressures increase, improving orchard productivity, yield consistency and production efficiency becomes increasingly important. Canopy management is central to this challenge because avocado trees can develop large, dense canopies that limit light penetration, reduce productive canopy volume, increase management complexity and make pruning decisions difficult (Whiley et al., 2024). While growers use a range of canopy management strategies, these decisions are often based on experience, local practice and visual assessment rather than quantified information on how canopy structure, light distribution and tree physiology interact to influence yield.

Light interception and light distribution are likely to influence orchard productivity (Wilkie et al., 2019; Schaffer et al., 2024), but their specific relationships with avocado flowering, fruit set, fruit retention, fruit growth and yield remain insufficiently quantified. At the whole-orchard scale, the amount of photosynthetically active radiation (PAR) intercepted by the canopy influences the energy available for photosynthesis. However, productivity is unlikely to be explained by total light capture alone. The distribution of usable light within the canopy is also likely to be important, because leaves, shoots, flowers and developing fruit need to be supported in positions where light availability is sufficient for sustained function. As canopies become dense, a greater proportion of

intercepted light is likely to be absorbed by the outer canopy, reducing the light available to internal canopy zones. These shaded internal zones are likely to become less functional and less able to contribute to crop load and productivity. Conversely, excessive canopy opening can remove productive wood, expose fruit and branches to damaging conditions, and stimulate vigorous regrowth that rapidly closes the canopy again. Effective canopy management therefore requires a balance between light capture, light distribution, canopy renewal, fruiting wood retention and regional production constraints.

These issues are especially important in Australia because avocado production occurs across diverse growing regions, including warm tropical and subtropical environments, cooler temperate regions and Mediterranean-type production areas. These regions differ in climate, radiation environment, phenology, cultivar mix, crop timing, canopy vigour and management windows. As a result, a canopy management strategy that is appropriate in one region may not be directly transferable to another. The timing and severity of pruning, the risk of excessive vegetative regrowth, the need to maintain bearing wood, and the potential effects on flowering and fruit retention all need to be considered within a regional and orchard-specific context.

AV24011 was established as a one-year study to provide a stronger foundation for future research and development on avocado canopy management, light interception and canopy modelling. The project did not aim to conduct field trials, collect new experimental datasets or develop a commercial decision-support tool within the current investment. Instead, it aimed to synthesise current knowledge, identify the most important knowledge gaps, engage with growers and technical experts, and recommend future R&D pathways that could support region-specific canopy management tools. In this context, the project served as a strategic step between existing knowledge and future applied research, helping to clarify what must be understood, measured and validated before more objective pruning guidance or light-based decision-support tools can be developed.

The project built on earlier avocado canopy management research and related work in perennial tree crops. It also considered relevant developments in orchard sensing, LiDAR, light modelling, functional-structural plant modelling, digital twins, mechanisation and decision-support approaches from avocado and other tree crops. This broader perspective was important because many of the technologies that could support future avocado canopy management are developing rapidly, but their application to dense, evergreen avocado canopies remains constrained by gaps in biological understanding and model validation.

The project is aligned with the Avocado Strategic Investment Plan through its focus on improved orchard management, productivity, yield consistency, fruit quality and the identification and adaptation of technologies that may improve production efficiency. It contributes to the industry objective of developing improved orchard management practices based on better knowledge of tree physiology, while also identifying technology pathways that could support more efficient and objective canopy assessment. The intended users of the project outputs include Hort Innovation, the Strategic Investment Advisory Panel, avocado growers, consultants, agronomists, researchers, technology providers and future project teams developing R&D proposals in this area.

The significance of AV24011 lies in clarifying the pathway from current canopy management challenges to future practical tools. The project identified that the major limitation is not simply a lack of pruning techniques or sensing technologies, but the absence of quantified relationships linking canopy light environment, canopy structure, avocado physiological responses and yield outcomes. Without these relationships, technologies such as LiDAR, imaging systems, light sensors and digital canopy models can describe aspects of the canopy, but cannot yet predict which pruning decisions will improve productivity under specific regional conditions. By integrating the literature review, stakeholder engagement, modeller and technology provider input, grower feedback and Technology Readiness Level (TRL) assessment, AV24011 proposes a staged R&D investment pathway for developing more evidence-based, regionally relevant canopy management strategies for the Australian avocado industry.

Methodology

AV24011 was delivered as a one-year scoping, synthesis and stakeholder engagement project. The project did not include field trials, new experimental sampling, technology development or commercial model development. Instead, the methodology was designed to consolidate current knowledge, identify priority gaps, assess the readiness of relevant sensing and modelling approaches, and develop recommendations for future R&D investment. This approach was considered appropriate because the project addressed an early-stage industry question: what knowledge, data and technologies are required before regionally adapted light-informed canopy management models or decision-support tools can be developed for avocado?

The project had national reach and focused on the Australian avocado industry across contrasting production regions. The target audience included avocado growers, consultants, agronomists, researchers, technology

providers, Hort Innovation, the Strategic Investment Advisory Panel and future R&D providers. Attention was given to regional variation in canopy behaviour, phenology, climate, cultivar mix, orchard system and management constraints. The project therefore considered how future canopy management R&D could be relevant across Australia's diverse avocado production regions.

The project was undertaken through a structured literature and technology review. The review examined scientific and technical information on avocado physiology, orchard light environment, canopy management practices, modelling approaches and light assessment tools. Relevant information from other perennial tree crops was also considered where avocado-specific information was limited or where technologies and modelling approaches had potential relevance to avocado production. The review focused on identifying what is currently known, what remains insufficiently quantified, and which knowledge gaps limit the development of practical light-informed canopy management tools. The literature review was developed iteratively. An initial review was prepared to establish the project's technical framework and guide stakeholder engagement. This initial review helped refine the project's guiding questions and identify key areas requiring input from growers, modellers, researchers and technology providers. The final review considered additional literature, stakeholder insights and technology engagement findings, and was used as an evidence base for the R&D investment options analysis.

Stakeholder engagement was undertaken through a Project Reference Group (PRG), targeted industry and technical engagement, and an invite-only grower feedback webinar. The PRG included growers and industry representatives with knowledge of different avocado production regions and systems. The group provided guidance on the project scope, regional relevance, knowledge gaps and draft recommendations. PRG feedback helped keep the project focused on orchard light environment, canopy structure, modelling, sensing technologies and practical canopy management outcomes.

Targeted engagement was also undertaken with modellers, researchers and technology providers to assess current capabilities and limitations in canopy sensing, light assessment, LiDAR, imaging, light and functional-structural modelling, ray tracing, digital twins and commercial orchard platforms. These discussions were used to understand which approaches are currently feasible and which require further validation before they can support grower-facing decision tools. The engagement also assessed practical constraints such as cost, scalability, data requirements, technical complexity and suitability for dense avocado canopies.

An invite-only grower feedback webinar was held near the end of the project to test whether the draft investment pathway was useful, realistic and relevant from an industry perspective. Participants included growers and industry representatives from multiple production regions. The webinar presented the project rationale, key knowledge gaps and proposed future R&D investment areas. Grower feedback was used to refine the recommendations, particularly around pruning timing, regional variation, cultivar and rootstock considerations, staged delivery of practical outputs, and the need for future tools to reduce uncertainty in pruning decisions.

Together, the PRG, targeted expert engagement and grower feedback webinar ensured that the final recommendations were informed not only by the scientific and modelling literature and technology scoping, but also by commercial grower perspectives on practicality, regional relevance, implementation constraints and the need for staged delivery of useful outputs.

The R&D investment options analysis was developed by integrating the literature review, PRG feedback, modeller and technology engagement, and grower input. Five linked investment areas were identified: defining productive canopy light targets; quantifying canopy leaf area, density and light distribution relationships; developing canopy sensing workflows; undertaking pruning field trials for high-productivity canopy systems; and developing modelling or digital twin approaches to support future decision-making. Each investment area was assessed in terms of target region, expected grower benefit and TRL. This provided a staged pathway from early knowledge gaps through to future validated tools, management packages or decision-support systems.

Project management was supported by a Monitoring and Evaluation Plan, Stakeholder Engagement Plan, Communications Plan and Risk Management Plan. These plans guided project delivery, stakeholder targeting, communication activities, risk controls and performance assessment. Communication activities included project announcements, industry presentations, PRG engagement, preparation of an article for Talking Avocados, and industry update and presentation materials. Detailed project outputs, engagement summaries and supporting documents are provided in the appendices as outlined in Table 1.

Results and discussion

The project outputs consisted of a consolidated literature and technology review, stakeholder and expert engagement findings, grower feedback, and a proposed R&D investment pathway. These outputs define current knowledge, the main barriers to practical light-informed canopy management, and the research and technology development required before decision-support tools can be developed for Australian avocado orchards. Detailed

technical information, engagement summaries and investment recommendations are provided in the appendices.

The central finding of AV24011 is that the relationship between avocado canopy light environment and productivity is conceptually well supported, but remains insufficiently quantified for practical decision-making. The literature review indicates that avocado productivity is likely to be influenced by the interaction of canopy structure, light capture and distribution, leaf function, carbohydrate supply, nutrient status, hormonal regulation, flowering, fruit set, fruit retention and fruit growth. However, the review also found that the industry lacks quantified relationships between within-canopy PAR and the key growth and reproductive processes that ultimately determine crop load and yield. In practical terms, this means that growers may recognise that dense, shaded canopies can reduce internal productivity, but the industry cannot yet define how much light is required at specific canopy positions or phenological stages to support productive leaves, shoots, flowers and fruit.

This gap is important because canopy management decisions are made every season, but the consequences of pruning are difficult to predict and may persist beyond the season. Removing too little canopy may maintain excessive shading and low-productivity internal zones, while removing too much canopy can reduce bearing wood, increase exposure risk and stimulate vigorous regrowth. The project found that the key challenge is not simply identifying pruning techniques, but linking a pruning decision to a change in canopy structure, a change in light distribution and a subsequent crop response. Without this pathway, pruning remains partly experience-based and difficult to tailor objectively to different orchards and regions. The review also identified that total light interception alone is likely not sufficient to guide future canopy management decisions. While the amount of light intercepted by the orchard canopy is relevant to photosynthetic capacity, productivity is likely to also depend on how effectively that light is distributed through the canopy and utilised towards vegetative and reproductive growth. Dense canopies can intercept substantial light at the outer canopy surface while maintaining shaded internal zones that may contribute less to fruit production. Conversely, overly open canopies may reduce fruiting surface area or increase exposure stress. This finding supports the need for future R&D to consider both total interception and internal light distribution, rather than treating improved total interception as the only target.

A second major finding was that the avocado industry currently lacks practical canopy metrics that can link structure, density, light and productivity. Leaf area index, leaf area density, leaf area distribution, canopy porosity and light use efficiency may be important, but are not yet sufficiently parameterised for avocado. This limits the ability to define practical canopy targets, compare pruning systems, evaluate canopy density objectively or provide growers with measurable thresholds. Future work will need to quantify these attributes across regional environments before they can be used in decision-support systems. Regional variation was reinforced as a critical consideration throughout the project. Australia’s avocado production regions differ in climate, radiation environment, phenology, cultivar mix, orchard vigour, harvest timing and pruning windows. Stakeholder feedback indicated that a single national canopy management prescription is unlikely to be appropriate. Instead, future R&D should determine which principles are broadly transferable and which management recommendations need to be modified for different regions and orchard designs. This is particularly relevant for pruning timing, because pruning responses are likely to interact with flush cycles, flowering, bud development, regrowth, crop load, sunburn risk and harvest windows.

Technology and modeller engagement identified several sensing and modelling approaches with potential for future avocado canopy management research. Existing technologies can already measure canopy size, volume, outer structure and some light interception attributes. LiDAR, RGB imaging, spectral sensing, robotics platforms and related digital tools can help characterise canopy structure, map orchard variability and assess structural changes before and after pruning. These technologies could improve the objectivity and efficiency of canopy measurement, particularly in future research trials and commercial demonstrations. However, the engagement also confirmed that important measurement challenges remain. Internal canopy structure is often difficult to capture in dense avocado canopies because of occlusion, canopy complexity and the difficulty of separating leaves, branches, fruit and open space. Accurately describing within-canopy light distribution is also challenging because light varies spatially and temporally, and point-in-time measurements may not represent the seasonal light environment experienced by leaves, shoots and developing fruit. High-resolution LiDAR and advanced modelling can provide detailed structural information, but these approaches are currently more suited to research, calibration and model development than routine commercial use. More scalable sensing systems may be practical at orchard scale, but often provide less detailed information.

The project therefore found that no single technology currently provides a complete solution. The most realistic pathway is to combine complementary tools. For example, LiDAR or other three-dimensional sensing approaches could be used to capture canopy structure, while light sensors or ray-tracing models could estimate

light interception and distribution. Imaging and machine learning may add information on canopy condition, fruit position or crop load. Over time, these data streams could support modelling and digital twin approaches that allow pruning scenarios, canopy structures or orchard designs to be tested virtually. However, these tools will be useful for decision support only if they are linked to validated biological relationships between canopy light environment, canopy structure, crop load development and yield. The PRG supported this interpretation and emphasised that the project outputs should clearly explain the grower relevance of the findings. PRG discussions reinforced that modelling and digital twins may provide a useful long-term pathway, but that the immediate R&D need is to build and validate the underlying sensing, modelling and yield-response relationships. The PRG also supported the use of TRL concepts to show that the current project has helped define early-stage concepts and knowledge gaps, while future investments should progressively move these concepts toward validated orchard-scale tools and management packages. The invite-only grower feedback webinar provided an industry check on the proposed direction. Growers and industry representatives considered the focus on canopy light environment, pruning decision-making, sensing technologies, modelling and commercial orchard validation to be relevant and worthwhile. Feedback highlighted that future tools need to address practical questions such as what to prune, how much to prune and when to prune under different regional and orchard conditions. Growers also emphasised the importance of staged delivery, with useful interim outputs developed before more advanced decision-support tools become available.

The R&D investment options analysis translated these findings into five linked areas for future work. These were: (1) defining productive canopy light targets for avocado, (2) quantifying canopy leaf area, canopy density and light distribution relationships, (3) developing and validating canopy sensing workflows, (4) undertaking pruning field trials for high-productivity canopy systems, and (5) developing modelling or digital twin approaches to support future canopy management decision-making. These areas should not be viewed as isolated projects, but as a staged pathway. The biological relationships and canopy metrics generated through the first two areas would provide the foundation for sensing workflows, pruning trials and future modelling tools. The TRL assessment indicated that the overall pathway from canopy light measurement to grower-ready decision support is still at an early stage. Most biological relationships, canopy metrics, pruning response datasets and modelling inputs remain at concept or early proof-of-concept stages. Canopy sensing tools are relatively more advanced because LiDAR and related technologies already exist, but avocado-specific validation and integration remain limited. The recommended next phase should therefore focus on progressing selected components toward orchard-scale validation, rather than expecting immediate commercial decision-support systems. Higher-readiness outcomes, such as sensing-guided pruning, commercial decision-support tools or autonomous canopy management, should be viewed as longer-term translation opportunities.

For industry, the immediate value of AV24011 is that it provides a clearer and more realistic pathway for future investment. It shows that practical canopy management improvements are unlikely to come from technology alone, or from pruning trials alone. Instead, progress will require integration of avocado physiology, canopy structure measurement, light modelling, commercial orchard validation and grower feedback. Future projects should be designed to generate both foundational knowledge and practical outputs, so that growers receive progressive guidance while longer-term modelling and decision-support tools are developed. Growers are more likely to engage with canopy management tools when they reduce uncertainty and provide practical, timely and economically relevant information for real pruning decisions. Future work should therefore avoid presenting sensing or modelling as ends in themselves. These technologies should be positioned as tools that help answer practical orchard questions, such as where the low-productivity canopy zones are, whether a canopy is too dense, how pruning changes light distribution, how quickly the canopy closes again, and whether different regional conditions require different canopy structures or pruning windows. The project’s main contribution is the identification of the knowledge gaps, enabling technologies, stakeholder priorities and investment sequence needed to move from current experience-based canopy management toward more objective, regionally relevant and evidence-based canopy decision support for Australian avocado orchards.

Outputs

Table 1. Output summary

Output	Description	Detail
Industry awareness, project updates and presentation activities	Project commencement, aims, planned activities, progress updates and emerging outcomes were communicated to avocado industry stakeholders through industry publications, broader regional forum presentations, the Avocados Australia Production R&D Summit and SIAP engagement. The intended audience included growers, consultants, researchers, extension personnel, industry representatives, Hort Innovation and R&D investment decision-makers.	The project was announced through the Avocados Australia Guacamole newsletter and in Talking Avocados magazine (Winter 2025 edition). Elements of the project, including aims, activities and progress, were incorporated into broader presentations delivered at four regional avocado forums: Central NSW (Jul 2025); North Qld (Aug 2025); South Qld (Mar 2026); and Tri-State (Apr 2026). The project purpose and expected outputs were presented at the Avocados Australia Production R&D Summit in Brisbane (Sep 2025), as well as to The Avocado Industry Development and Extension Project (AV23010) (Apr 2026). Project outcomes were also presented to the avocado SIAP (Jun 2026). Relevant communication materials, presentation slides and article copies are provided in Appendices [1-5].
PRG engagement and meeting records	A PRG was established to provide regional and technical guidance, refine project scope, review emerging findings and test draft recommendations. PRG engagement helped ensure the project remained focused on orchard light environment, canopy structure, sensing technologies, modelling and practical grower outcomes.	Three PRG meetings were held during the project, with minutes or meeting summaries prepared as project records. PRG outputs are provided in Appendix [6]. PRG guidance contributed to refinement of the literature review, stakeholder engagement approach, knowledge gap analysis and investment recommendations.
Literature review	A literature review was produced to synthesise current knowledge on avocado canopy physiology and light use, orchard light environment, canopy management practices, light modelling approaches, and sensing or measurement technologies. The review identified key knowledge gaps limiting development of practical light-informed canopy decision tools and regionally relevant decision-support approaches. The intended audience included Hort Innovation, SIAP, growers, consultants, agronomists, researchers and R&D providers.	The review was developed iteratively, with an initial version submitted at Milestone 102 to guide PRG discussion, stakeholder engagement and expert consultation. The final version incorporated additional literature, modeller and technology engagement considerations, PRG input and grower feedback. The final literature and technology review is provided in Appendix [7].
Modeller and technology engagement report	Targeted engagement was undertaken with modelling, remote sensing, LiDAR, imaging and orchard technology specialists to assess current capability, practical limitations and future relevance for avocado canopy management R&D.	Findings were consolidated into a modeller and technology engagement report, provided in Appendix [8]. The report helped inform the final literature review and investment recommendations by identifying which technologies are feasible, remain research-grade, and what validation is needed before grower-facing tools can be developed.

Grower feedback webinar and summary report	An invite-only grower feedback webinar was held to present draft findings and proposed R&D investment recommendations. The webinar was designed to test whether the proposed pathway was useful, realistic and relevant from a grower and industry perspective.	Webinar held on 10 June 2026 with grower and industry representation from key regions (North Qld, Central Qld, Western Australia and Tri-State). The presentation slides and a summary of discussion and feedback are provided in Appendices [9-10]. Feedback supported the relevance of the proposed R&D pathway.
R&D investment options analysis	An R&D investment options paper was developed to identify and prioritise future work required to move from current knowledge gaps toward practical canopy management tools. The paper describes investment areas by target region, expected grower benefit and TRL.	Included in Appendix [11]. The analysis identifies five linked investment areas: productive canopy light targets, canopy leaf area and light distribution relationships, canopy sensing workflows, pruning field trials, and modelling or digital twin approaches. This output is intended to support future Hort Innovation, SIAP and industry R&D investment decisions.
Talking Avocados article	An industry-facing article was prepared to communicate the project rationale, key findings and future R&D pathway in accessible language for growers and industry stakeholders.	Article titled "Building a pathway to light-informed canopy management decisions" submitted to Talking Avocados. Copy provided in Appendix [12]. The article explains why canopy light matters, what knowledge gaps remain, and how future sensing, modelling and pruning research could reduce uncertainty in canopy management.

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Improved knowledge base and scientific foundation for avocado canopy management and light optimisation R&D (intermediate outcome)	Outcome 2: Strategy 2; KPI(s): New knowledge for growers on canopy management in low and high-density production systems; new knowledge to support orchard yield consistency and quality management.	The project consolidated current knowledge on avocado canopy physiology, orchard light environment, canopy management practices, modelling approaches and sensing technologies. This strengthened the scientific and technical foundation available to Hort Innovation, SIAP, growers, consultants, agronomists, researchers and future R&D providers. At the fund level, this contributes to improved orchard management by clarifying what is currently known, where evidence remains limited, and what needs to be quantified before more evidence-based canopy management guidance can be developed.	Literature and technology review. The review synthesised information across five key areas: physiological drivers of productivity, orchard light environment, canopy management practices, modelling approaches, and sensing and measurement technologies. The review identified major knowledge gaps related to canopy light environment, canopy structure, physiological responses, sensing technologies and modelling approaches.
Knowledge gaps and future R&D needs	Outcome 2: Strategies 2 and 3;	The project identified that the main barrier to light-informed canopy	Literature and technology review; PRG meeting

identified from the literature and project synthesis (intermediate outcome)	KPI(s): New knowledge to support orchard yield consistency and quality management; technologies and approaches to improve cost efficiencies are identified and shared with growers.	management is not simply a lack of pruning techniques or sensing technologies, but the absence of quantified relationships linking canopy light environment, canopy structure, avocado physiological responses and yield outcomes. Priority gaps included productive canopy light targets, within-canopy light-response relationships, leaf area index, leaf area density, light use efficiency and pruning responses across contrasting regions and orchard systems. At the fund level, this provides clearer direction for future investments aimed at improving productivity, yield consistency and practical canopy management.	records; R&D investment options and TRL analysis. Evidence includes the identification of priority knowledge gaps and the translation of those gaps into staged future R&D investment areas.
Stakeholder, regional, modeller and technology provider input was integrated into project findings and recommendations (intermediate outcome)	Outcome 2: Strategies 2 and 3; Outcome 3: Strategy 2; KPI(s): New knowledge for growers; technologies and approaches identified and shared with growers; cooperation and engagement supporting innovation	The project incorporated input from the PRG, growers, modellers, researchers and technology providers to ensure that findings and recommendations reflected industry needs, regional production differences and technical feasibility. Stakeholder input reinforced the importance of regional variation in climate, phenology, cultivar mix, orchard vigour, pruning windows and production systems. At the fund level, this supports development of future R&D that is technically grounded, regionally relevant and aligned with practical grower needs.	PRG meeting records; modeller and technology engagement report; grower feedback webinar summary. Evidence includes PRG guidance on regional considerations and project scope, targeted engagement with modellers and technology specialists, and grower feedback on the relevance and practicality of the proposed R&D pathway.
Current sensing and modelling capability for future avocado canopy management R&D was assessed (intermediate outcome)	Outcome 2: Strategy 3; KPI(s): Technologies and approaches to improve cost efficiencies are identified and shared with growers	The project assessed the potential relevance of LiDAR, imaging, light sensing, ray tracing, modelling approaches, digital twins and commercial orchard technology platforms for future avocado canopy management R&D. It clarified that several technologies can measure canopy size, volume, outer structure and light interception attributes, but that internal canopy structure, component separation and within-canopy light distribution remain technically more challenging. At the fund level, this helps reduce the risk of premature technology investment by distinguishing technologies that are promising, require validation, or remain more suited to research than immediate decision support.	Modeller and technology engagement report; literature and technology review. Evidence includes assessment of current sensing and modelling capabilities, limitations, data requirements, practical constraints and potential future use in avocado canopy management research.

R&D investment pathway developed for regionally relevant canopy management tools (end-of-project outcome)	Outcome 2: Strategies 2 and 3; KPI(s): New knowledge for growers on canopy management; new knowledge to support orchard yield consistency and quality management; technologies and approaches to improve cost efficiencies are identified and shared with growers	The project translated the literature review, PRG input, grower feedback and technology assessment into a staged R&D investment pathway. Five linked future investment areas were identified: defining productive canopy light targets; quantifying canopy leaf area, density and light distribution relationships; developing canopy sensing workflows; undertaking pruning field trials for high-productivity canopy systems; and developing modelling or digital twin approaches. At the fund level, this provides Hort Innovation, SIAP and future R&D providers with a clearer basis for designing future investments that move from early knowledge gaps toward validated orchard-scale tools and grower-relevant canopy management recommendations.	R&D investment options. The investment options were described by target region, expected grower benefit and TRL. PRG feedback supported an outcome-focused and TRL-based pathway, and grower feedback supported staged delivery of practical outputs before more advanced decision-support tools are developed. The project outcomes and future R&D recommendations were also presented to the avocado SIAP in June 2026.
Improved industry awareness of the opportunity, limitations and future pathway for light-informed canopy management (intermediate to end-of-project outcome)	Outcome 3: Strategies 1 and 2; Supporting alignment: Outcome 2: Strategies 2 and 3; KPI(s): Positive change in knowledge, attitudes, skills and aspirations; cooperation and engagement supporting innovation; new knowledge and technologies shared with growers	The project improved awareness among industry stakeholders that future canopy management tools need to link pruning decisions, canopy structure, light distribution and crop response. It also clarified that sensing and modelling technologies have potential, but must be validated against real avocado canopy and productivity responses before they can reliably guide grower decisions. At the fund level, this supports more informed discussion about future R&D priorities and helps position sensing and modelling as tools for answering practical orchard questions, rather than as standalone technologies.	Industry awareness activities, regional forum presentations, Production R&D Summit presentation, grower feedback webinar, SIAP presentation and Talking Avocados article. These activities communicated the project aims, emerging findings, future R&D pathway and practical relevance to growers, consultants, researchers, industry representatives and R&D investment decision-makers.

Monitoring and evaluation

Table 3. Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
Effectiveness: To what extent has the project consolidated and synthesised current knowledge on light interception, distribution, and their impacts on avocado productivity to	The literature and technology review consolidated current knowledge on avocado physiological drivers of productivity, orchard light environment, canopy management practices, modelling approaches, and sensing and measurement technologies. The project identified that the major limitation for light-informed canopy management is the lack of quantified relationships linking	Future R&D should move from synthesis to validation by quantifying canopy light targets, leaf area and light distribution relationships, pruning responses and yield outcomes under commercial orchard conditions. Future projects should also

identify key knowledge gaps and inform feasible, regionally relevant R&D pathways toward best-practice light-interception models and decision-support tools?	canopy light environment, canopy structure, avocado physiological responses and yield outcomes. These findings were translated into a staged R&D investment pathway covering productive canopy light targets, canopy leaf area and light distribution relationships, canopy sensing workflows, pruning field trials, and modelling or digital twin approaches.	include structured field data collection across contrasting regions, canopy systems and management windows to support model parameterisation and decision-support development.
Relevance: To what extent are the project's findings and recommendations on light interception, canopy management, and regional variability relevant and useful to avocado growers, researchers, and industry stakeholders in guiding future R&D and management strategies?	The project was relevant to intended beneficiaries because it addressed a recognised industry need for clearer, more objective canopy management guidance. PRG discussions, modeller and technology provider engagement, and the grower feedback webinar supported the finding that the project's focus on canopy light environment, pruning decision-making, sensing technologies, modelling and regional variability was useful and timely. Grower feedback reinforced the need for practical outputs that help address what to prune, how much to prune and when to prune under different regional and orchard conditions.	Future work should include broader grower and adviser participation once field-based or demonstration activities are underway. Larger grower surveys, regional workshops or on-farm validation sites could be used to test the usefulness of proposed canopy metrics, light benchmarks and pruning guidance across different production systems.
Process appropriateness: How effectively did the project's PRG-driven engagement model capture stakeholder and regional insights to inform the literature review and recommendations?	The PRG-driven engagement model was effective for the project's scoping and synthesis purpose. The PRG provided regional and technical guidance, helped refine the project scope, strengthened consideration of regional differences, and supported the adapted approach from broad regional travel toward deeper PRG input, targeted expert engagement and an invite-only grower feedback webinar. This approach allowed regional perspectives to be incorporated efficiently while keeping the project focused on orchard light environment, canopy structure, sensing technologies, modelling and practical R&D priorities.	Future projects should move from regional consultation to field validation across key production regions. Trials or demonstration sites in contrasting regions would allow regional canopy responses, pruning windows, light environments and production constraints to be assessed under real orchard conditions, including seasonal and emerging regional challenges. This would strengthen the ability to develop recommendations that are not only regionally informed, but regionally tested.
Process appropriateness: To what extent were the engagement activities, including the PRG-led provision of regional context, targeted workshops, webinars, and consultations with modellers and technology providers, appropriate for the project's objectives and target audiences within the avocado industry?	The engagement activities were appropriate for an early-stage project focused on synthesis, feasibility assessment and future R&D planning. Targeted engagement with modellers and technology providers helped assess the current capability and limitations of LiDAR, imaging, light sensing, modelling and digital twin approaches. The grower feedback webinar provided a practical industry check on the proposed investment pathway, while industry presentations and communication activities helped raise awareness of the project and its emerging findings.	Future engagement should be matched to the next stage of R&D. If future projects include field validation or technology testing, engagement should expand beyond targeted consultation to include on-farm demonstrations, regional workshops, adviser involvement and structured post-event feedback to measure changes in knowledge, attitudes, skills and aspirations.
Efficiency: To what extent has the project delivered its planned outputs	The project was delivered efficiently by using a targeted engagement model suited to its scoping purpose. The adaptation from broader regional	Future projects should define the engagement and validation pathway as early as possible,

efficiently and provided evidence-based recommendations that could improve the long-term efficiency of canopy management and R&D investment for the Australian avocado industry?	travel to deeper PRG involvement, targeted expert engagement and an invite-only grower feedback webinar reduced duplication and allowed resources to focus on synthesis, feasibility assessment and investment planning. Planned outputs were delivered, including the literature review, modeller and technology engagement report, grower feedback webinar summary, Talking Avocados article and R&D investment options analysis. The TRL-based investment pathway provides a clearer basis for prioritising future work and reducing the risk of premature investment.	including which activities are intended for consultation, which are intended for field validation, and which are intended for extension. Future R&D should also incorporate simple economic and adoption-readiness filters earlier in project design so that technical feasibility, commercial relevance and grower value are assessed together.

Recommendations

The following recommendations should be read in conjunction with the detailed R&D investment options and Technology Readiness Level analysis provided in Appendix [11]. Where possible, future investment should consider experimental designs that allow related activities to be progressed in parallel within the same orchard-scale trials, generating early practical outputs while also building the validated datasets required for longer-term modelling and decision-support development.

- Use the AV24011 outputs to guide future canopy management R&D investment. Future investment should build on the literature and technology review, stakeholder feedback, modeller and technology engagement, and R&D options analysis. The project identified that a key limitation preventing development of canopy decision-support tools is the lack of quantified relationships linking canopy structure, light distribution, tree physiology and yield outcomes.
- Prioritise field validation of canopy light, structure and productivity relationships. Future R&D should quantify productive canopy light targets, canopy density indicators, leaf area relationships and crop responses across different avocado regions.
- Develop and validate practical canopy sensing workflows. LiDAR, imaging, light sensing and related technologies should be tested under avocado orchard conditions to determine which approaches can reliably measure canopy structure (including quantity and distribution of leaf area and the separation of leaves from shoots and limbs), light distribution and pruning responses at research and commercial scales, and how these data could inform future decision-support tools.
- Conduct pruning and canopy management trials in key production regions. The next phase should move from synthesis to orchard-scale validation, with trials or demonstration sites that test how pruning timing, severity and canopy architecture affect light distribution, regrowth, flowering, fruit retention, yield and fruit quality.
- Treat modelling and digital twins as longer-term decision-support pathways that can be developed alongside field validation. Modelling approaches and eventual digital twin systems should be developed in conjunction with the generation of the required biological relationships, canopy measurements and pruning response datasets. Their initial role should be to integrate data and test canopy scenarios before commercial decision-support tools are developed.

Refereed scientific publications

Nil

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Intellectual property

No project IP or commercialisation to report

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Grower webinar participants – David De Paoli (Aust Chilli), Duncan Wells and Phil Johnson (Alterra), Henk van Niekerk (DBC Farming), Helen Bensilum (Kureen Farming), Camilo Fillippo (Avodon), Sarah Tucker-Boehm (Parkes Lane Produce).

Appendices

Appendix 1: Talking Avocados magazine project announcement article

Appendix 2: Slide extracts from regional avocado forum presentations

Appendix 3: Avocados Australia R&D summit presentation slides

Appendix 4: Project overview presentation to AV23010 extension team

Appendix 5: Presentation to Avocado Strategic Investment Advisory Panel

Appendix 6: Project Reference Group (PRG) meetings summaries

Appendix 7: Final literature review

Appendix 8: Modeller and technology engagement report

Appendix 9: Grower feedback webinar presentation

Appendix 10: Grower feedback webinar outcomes summary

Appendix 11: R&D Investment Options Recommendations Paper

Appendix 12: Talking Avocados article on project findings

New Avocado Canopy Management Project Launched

AV24011 – Optimising avocado yield with region-specific canopy management: insights from light interception and canopy modelling

By Gerhard Rossouw, QDPI

Photo courtesy of David Bin (Queensland DPI).

Hort Innovation has launched project AV24011, led by the Queensland Department of Primary Industries and Wilkie Horticulture, to guide future R&D in region-specific avocado canopy management. Rather than conducting trials, the team, Gerhard Rossouw, John Wilkie and Neil White, will develop strategic recommendations for future major initiatives.

Over the next 12 months, the project will:

- Review literature, grower input, and expert insights
- Assess how canopy manipulation, tree physiology, and light-optimisation technologies can be applied commercially
- Consult growers in key regions to identify challenges and opportunities, understanding how regional conditions and current management practices influence canopy performance

Findings will inform future investment and development of best-practice canopy strategies tailored to local conditions.

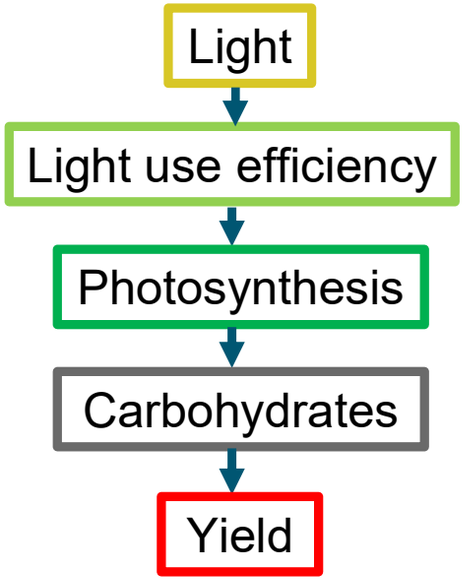
For details, contact Gerhard Rossouw: *gerhard.rossouw@dpi.qld.gov.au*.

AV24011 - Optimising avocado yield with region specific canopy management: insights from light interception and canopy modelling

- **Objective:** To develop recommendations for next phase avocado canopy management R&D.
- **Focus:** Integrating light optimisation with canopy management and technologies, with a regional perspective.

Hort Innovation AVOCADO FUND Wilkie Horticulture Queensland Government

It starts with the light environment

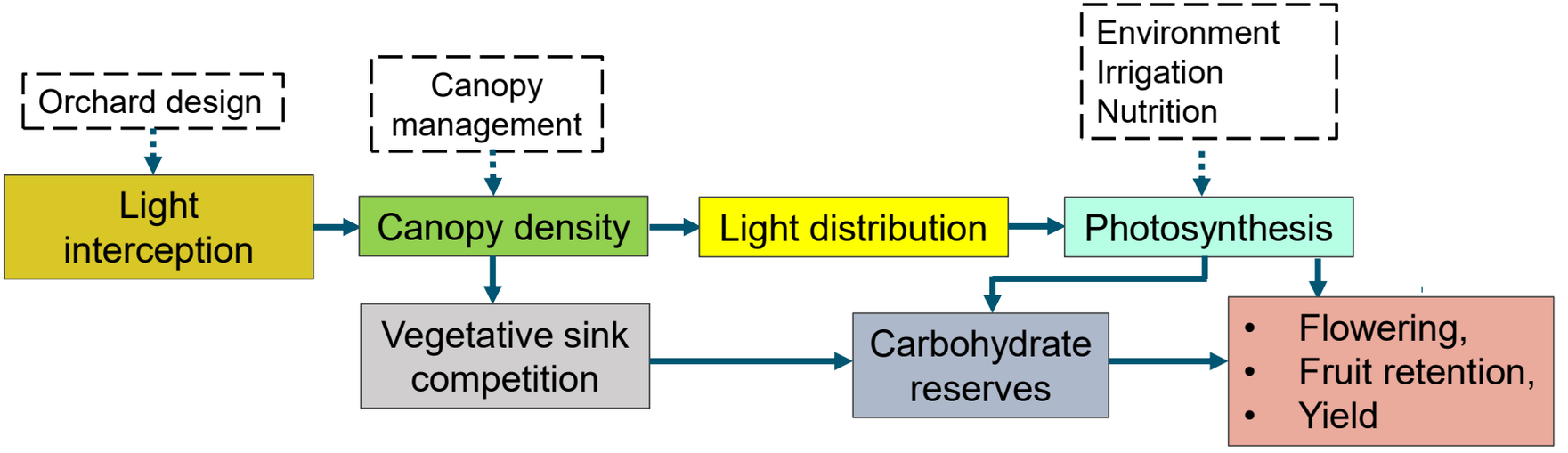


- Light interception, distribution and use efficiency determine carbon supply
  - Note: practical light targets for yield not yet well defined for avocado
  - Canopy management is our main lever to optimise light
  - **AV24011** project: Identifying light-related knowledge gaps to inform next-phase canopy management R&D
    - Linking canopy management with light optimisation, sensing and modelling approaches

Slide extract from Tri-state Avocado forum (April 2026)
(from "Carbohydrates and productivity in avocado" by Gerhard Rossouw)

Managing light environment

- Canopy management is our main lever to optimise light
- **AV24011**: Identifying light-related knowledge gaps to inform next-phase canopy management R&D
  - Linking canopy management with light optimisation, **sensing and modelling approaches**
  - It's not just how much light trees capture, but how it is distributed and used in the canopy



Smarter canopy management: identifying knowledge gaps in avocado light environment and related technologies

Gerhard Rossouw, John Wilkie, Neil White

Queensland Department of Primary Industries

Hort Innovation AVOCADO FUND Wilkie Horticulture Queensland Government

Queensland Government

What is this project about?

- ‘AV24011 - Optimising avocado yield with region specific canopy management: insights from light interception and canopy modelling’
- **Tackling a key yield factor –** canopy structure and the orchard light environment
- **No one-size-fits-all –** regional conditions and challenges require tailored canopy strategies for stable, high yields
- AV24011 is **identifying** knowledge gaps, with light interception highlighted as a priority area
  - *Considering modelling, sensing, and management approaches*
- **Designed to inform future R&D, not prescribe fixed solutions**

Optimising canopy strategies

- **Why this matters**?

1. **Lack of tailored guidance** – Canopy strategies that work in one region can be counterproductive in another. ☀️
2. **Evidence gaps remain** – We know light interception and distribution affect productivity, but the interactions with physiology and yield stability in avocado are not yet well defined. 🧬
3. **From research to tools** – Integrating modelling, sensing, and management approaches into practical decision-support options for growers. 📊

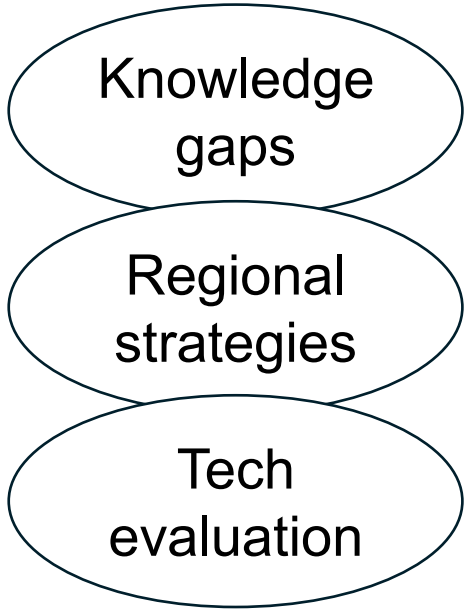
Goal:

Framework and recommendations for regionally adapted canopy strategies that highlight light interception as a priority area, while clarifying physiological knowledge gaps to reduce reliance on reactive interventions and costs.

Strategic alignments with industry priorities

1. **AAL Strategic Plan – Priority 3: Improve productivity and quality**

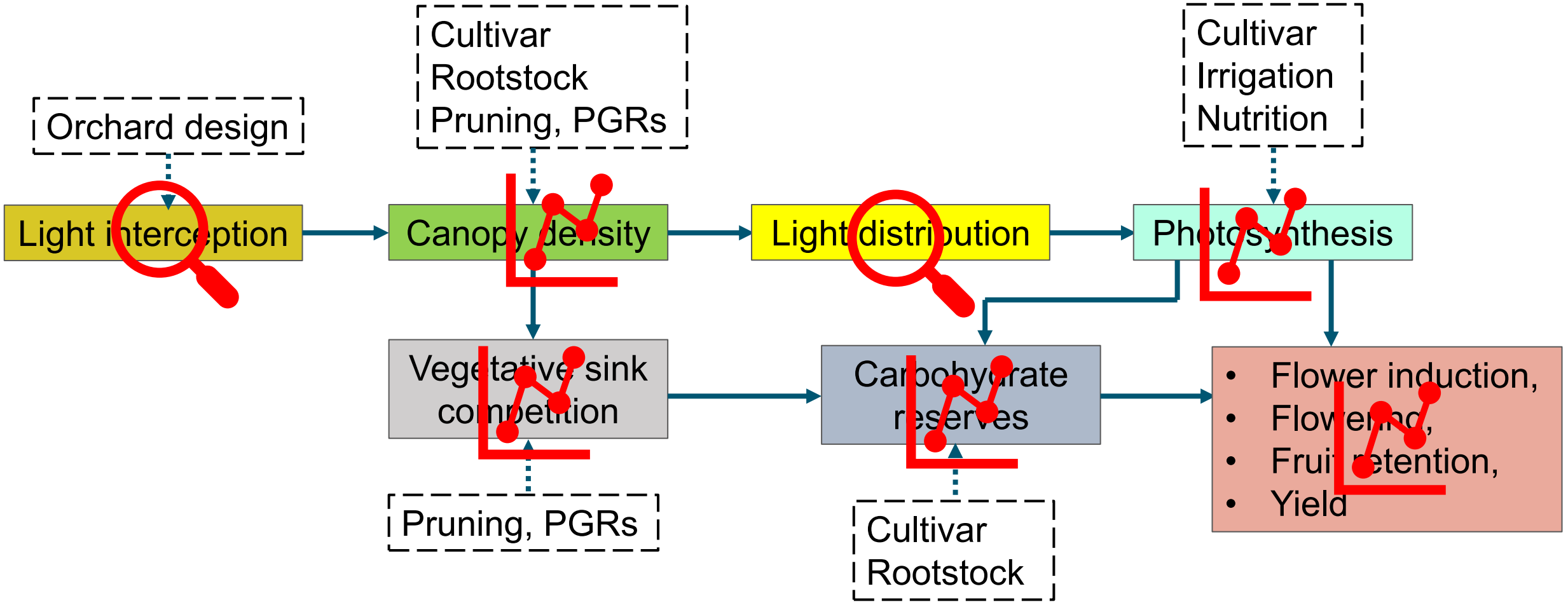
- **Supports strategy 3.2**: *Developing best practice guidelines through focused R&D*
  - *Strategic canopy management based on improved knowledge of tree physiology and technology options*



2. **Hort Innovation SIP – Outcome 2: Supply, productivity, sustainability**

- **Supports 2.2**: Improved orchard management practices through better understanding of light dynamics and yield drivers
- **Supports 2.3**: Identification and evaluation of cost-effective, scalable canopy management technologies

Linking light interception, canopy management, and yield drivers – the AV24011 scope



AV24011 – Evidence base and recommendations

1. Inputs
(evidence base)

- Light environment
- Canopy management
- Physiological drivers of productivity
- Tech review: sensing & modelling

2. Process
(synthesis and prioritisation)

- Review light interception alongside canopy structure and physiology
- Assess regional context
- Evaluate modelling/sensing approaches
- Identify knowledge gaps

3. Outputs
(recommendations)

- Matching tech solutions to canopy management & light priorities

Recommendations for future R&D: to develop regionally-adaptable canopy management tools

What we know about avocado canopy & light

- **Tree traits**: Evergreen (12–18-month leaves), multiple flushes, need for fruiting wood renewal; growth forms range from spreading to upright.
- **Key management challenges:** Vigour, shading, narrow intervention windows (pruning, PGRs), crop cycle overlaps, mechanisation trade-offs.
- **Physiology link:** Light drives sugars and starch reserves; carbohydrates buffer demand: supports flowering & fruit retention.
- **Knowledge gap:** Yield impact of light interception not well quantified; regionally adapted models/tools can help guide best practice.
- **Bottom line:** Evidence-based guidelines for timing and integration are lacking — tech and modelling can help fill the gap.

Technology Options – measuring canopy light

- **Light sensing and canopy monitoring tools:**

  1. **Direct light measurement**: e.g. ceptometers, smartphone PAR apps, drone mapping.

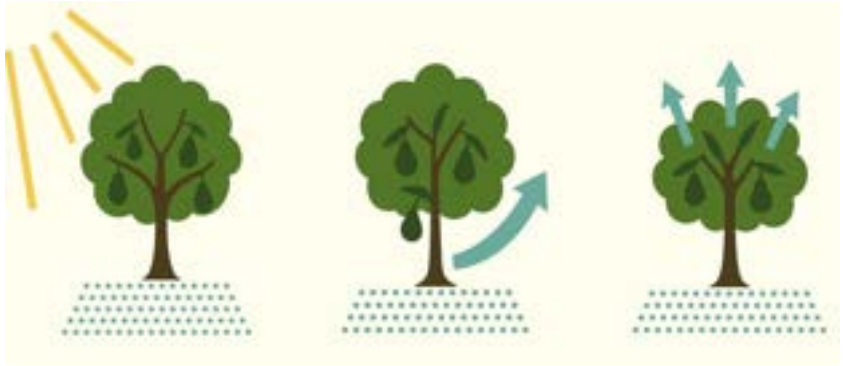
  2. **Canopy monitoring (indirect)**: e.g. imagery (RGB, multispectral), LiDAR scans, growth sensors → infer vigour, shading, and structure.

- **Objective and challenge:** tools must balance accuracy, cost, and usability, while directly informing canopy management (e.g. pruning, spacing, hedging).

- **Spectrum:** from high-end LiDAR (ultra-precise, research-oriented, higher cost) to smartphone light sensors (low-cost, grower-friendly).

Technology Options – modelling approaches

- **From light → to light + physiology: a spectrum of modelling options, e.g.:**
  - **Simple radiation models** – estimate canopy light interception; guide hedging/spacing.
  - **Crop growth models** – connect light capture to vigour, growth, and yield.
  - **Functional–structural plant models –** could simulate canopy architecture, light distribution, carbohydrate flows, and effects of pruning/PGRs**.**
- **Potential trade-off:** detailed models = more insight; simpler tools = more practical for grower decisions.



Key knowledge gaps AV24011 will help clarify

1. **Light interception–yield link:** What evidence exists on how light interception translates into yield in avocado, and what are the gaps that future research needs to address?

2. **Canopy interventions:** How can canopy inputs be assessed for their effects on light capture and downstream physiology, and what are the likely yield implications?

3. **Technology & modelling:** Which tools and modelling approaches show most promise for guiding canopy–light decisions in practice?

4. **Integration challenge:** How can canopy and light management be better aligned with avocado **phenology** to support more consistent yields across regions?

5. **Future R&D priorities:** Where should effort be directed to close the most critical gaps?

Queensland Government

Thank you

Project Team: Gerhard Rossouw, John Wilkie, Neil White

Hort Innovation AVOCADO FUND Wilkie Horticulture Queensland Government

gerhard.rossouw@dpi.qld.gov.au

AV24011

Optimising Avocado Yield with Region-Specific Canopy Management: Insights from Light Interception and Canopy Modelling

Gerhard Rossouw, John Wilkie, Neil White

Hort Innovation AVOCADO FUND Wilkie Horticulture Queensland Government

Queensland Government

What is this project all about?

- **A key yield limiting factor –** canopy structure and the orchard light environment
- **No one-size-fits-all –** regional conditions and challenges require tailored canopy strategies for stable, high yields
- AV24011 is **identifying** knowledge gaps, with orchard light environment highlighted as priority area
  - *Considering use of technologies (modelling, sensing, and management approaches)*
- **Designed to inform future R&D, not prescribe fixed solutions**

Optimising canopy light strategies

- **Why this matters**?

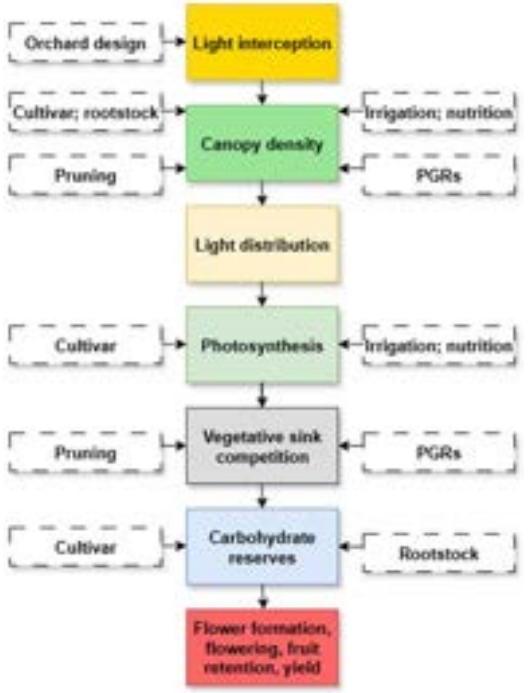
1. **Lack of tailored guidance** – Canopy strategies that work in one region can be counterproductive in another (or even within a region).
2. **Evidence gaps remain** – We know light affects yield, but how much, where, and when is not well defined.
3. **From research to tools** – Using modelling and sensing to support better canopy management decisions in the orchard.

Goal:

To guide the next phase of canopy management R&D by:

1. *Identifying key knowledge gaps in canopy light environment and related physiology determining yield*
2. *Recommending technologies to help close these gaps*

Literature review



1. **Physiological drivers of productivity need clarification**

   - Light use efficiency matters, not just light levels
   - Productivity, an integrated process:
     e.g. Light → Photosynthesis → Carbohydrates → Yield

2. **The avocado light environment**

   - Canopy characteristics affect light interception and distribution, and fruit production
   - But significant knowledge gaps remain in avocado systems, currently need to draw from other crops
   - Measuring light and canopy traits is often labour-intensive, but new technologies can help

Literature review

3. **Canopy management practices**
   - Main post-planting lever for modifying the light environment
   - Includes pruning, PGRs and indirect inputs (nutrition, irrigation, planting material)
   - Must be adapted to regional conditions (vigour, crop cycle duration, environmental stress)
4. **Modelling the light environment in orchards**
   - Current and emerging modelling approaches
   - Supporting tools and technologies also assessed
5. **Light environment assessment tools**
   - From basic to advanced (and anything in between)

Technology options scoping

1. **Modelling: canopy–light–yield simulations**

   - *Three modellers interviewed*
   - Multiple modelling approaches exist, with different levels of complexity and application, e.g.,
     - Simpler approaches: may use canopy size and shape to estimate total light interception
     - Functional-structural models: can simulate light interception + distribution; could incorporate other drivers of productivity (e.g., nutrient status, carbohydrates, plant hormones)
     - Digital twin frameworks (via LiDAR scans) with light simulation (ray tracing models) and potential to integrate fruit detection (using RGB imagery)
   - Key point: LiDAR-based approaches show strong potential for canopy mapping and simulating light and pruning effects

Technology options scoping

2. Sensing: Approaches for canopy and light

- *4 researchers (LiDAR use and sensing); 2 automation/orchard mapping companies; 1 LiDAR distributor interviewed*
- Multiple sensing approaches are being used and developed
- Based on LiDAR, RGB imaging, and other spectral or depth sensors
- Platforms: Ground based (terrestrial) – static or mobile, UAV (drone-based), Emerging autonomous systems
- What they measure: Canopy size and structure, light interception (easier); canopy density and leaf area (more complex); light distribution (challenging, require more sophisticated methods and higher-end instrumentation)

Technology options scoping

2. Sensing: Capabilities and limitations

- What works well:
  - Canopy size and outer structure,
  - Light interception estimation,
  - Fruit detection (RGB + machine learning; *needs development/validation for avocado)

- More challenging:
  - Internal canopy structure (segmentation of leaves vs branches/shoots vs flowers/fruit),
  - Light distribution in canopy,
  - Accurate canopy density and leaf area distribution

- Key point: Higher detail require higher resolution, cost and expertise

Technology options scoping

2. Sensing: Technologies and future direction

- LiDAR systems: Suitable for canopy mapping and structure; Can support light modelling and to simulate pruning effects
- Integration opportunities: LiDAR + RGB + spectral sensing; Digital reconstruction of trees/orchards; Linking canopy characteristics (e.g. density) to light and yield
- Automation and scaling: Robotics for autonomous scanning; UAV and possibly satellite for larger-scale monitoring
- Takeaway: Technology is advancing quickly, but trade-offs exist between cost, complexity and usefulness; expertise requirement is a possible bottleneck to commercial adoption

- Overall: R&D applications vs possible commercial applications…

Evolving recommendations

1. **Clarifying light requirements is critical**

   - Need to better define light conditions to maximise avocado yield potential
   - Directly linked to pruning and canopy decisions
   - Regional differences matter (light use efficiency varies)

2. **Linking canopy structure to light**

   - LiDAR-based approaches can accurately connect canopy structure with light environment
   - Range from simple (rapid, cheaper) to detailed (more expensive, more accurate and detailed) approaches

Evolving recommendations

3. **From simple to advanced approaches**

   - Simple: canopy volume + light interception models + total yield
   - Advanced: detailed canopy structure (segmentation of components including leaves and fruit) + light distribution modelling + flower/fruit distribution
   - Trade-offs between speed, detail and expertise required
   - Potential for automation (e.g. robotics)

4. **Linking LiDAR-derived maps and modelling**

   - Digital twins and integrated modelling to simulate pruning decisions
   - Integration of canopy, light and yield data

Queensland Government

Thank you

Project Team: Gerhard Rossouw, John Wilkie, Neil White

Hort Innovation AVOCADO FUND Wilkie Horticulture Queensland Government

gerhard.rossouw@dpi.qld.gov.au

Optimising Avocado Yield with Region-Specific Canopy Management: Insights from Light Interception and Canopy Modelling

AV24011 recommendations for future R&D

30 June 2026

Purpose of today

- **Canopy structure and light within the orchard** are important factors influencing yield
- The best canopy strategy will not be the same for every region or orchard
- AV24011 has identified key gaps in canopy management knowledge, with light and productivity highlighted as a priority area
- We considered how technologies, including canopy sensing and modelling, could support better canopy management decisions
- We propose a set of R&D investment options for future research in this area (*Can better light information improve avocado pruning decisions?*)

Why light matters

- **Photosynthetically active radiation (PAR)**
  - Drives carbohydrate and energy supply needed for flushing, flowering, fruit set, fruit growth and retention
  - Too much shade can create unproductive canopy zones
- Both **light interception and distribution** within the canopy are likely to affect productivity
  - We do not yet have clear, practical, yield-promoting light targets for avocado canopies
  - This makes pruning decisions harder than they should be
- Tools are needed to help growers assess canopy light and compare pruning options

The knowledge gap future R&D should close

1. How much usable light is needed (and when) in different parts of the canopy to support productivity?

2. How do canopy density, leaf distribution and pruning affect the productive light environment?

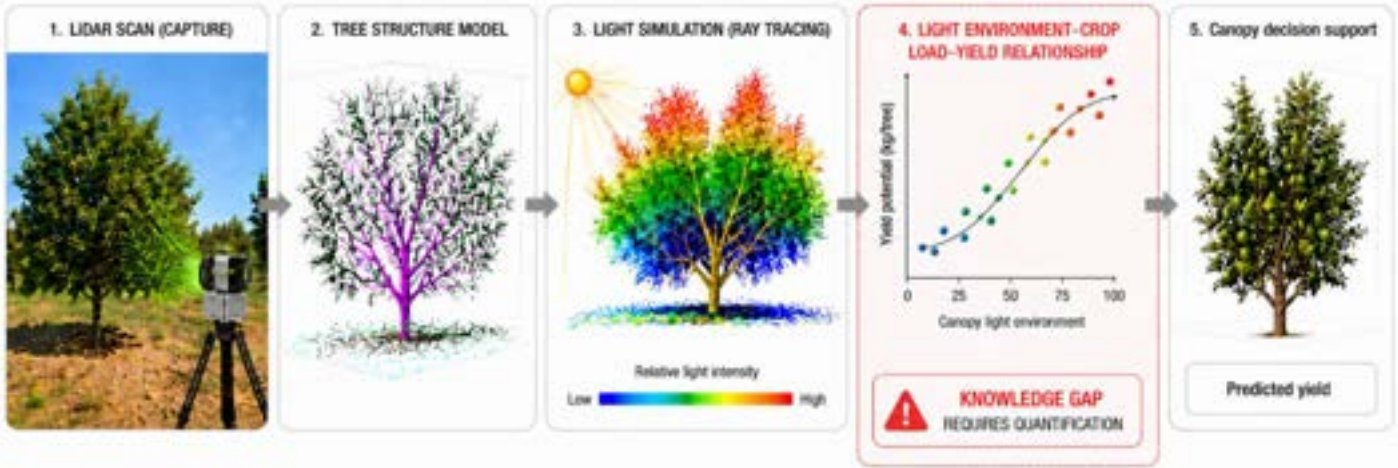
3. How do changes in canopy light translate into flowering, fruit set, fruit retention, fruit growth and yield?

4. Can we predict how different pruning choices are likely to affect productivity?

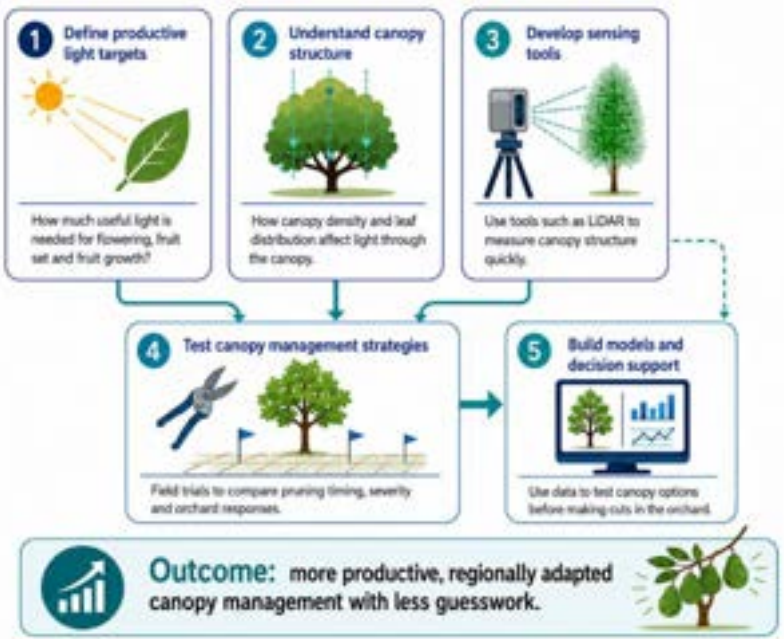
5. Do different growing regions require different canopy structures and light targets?

Recommended pathway: test ideas before cutting trees

- Build virtual orchard models from canopy measurements and light data
  - Compare pruning options virtually before intervention
  - Refine model predictions against commercial orchard trials
  - Translate validated outputs into practical decision support



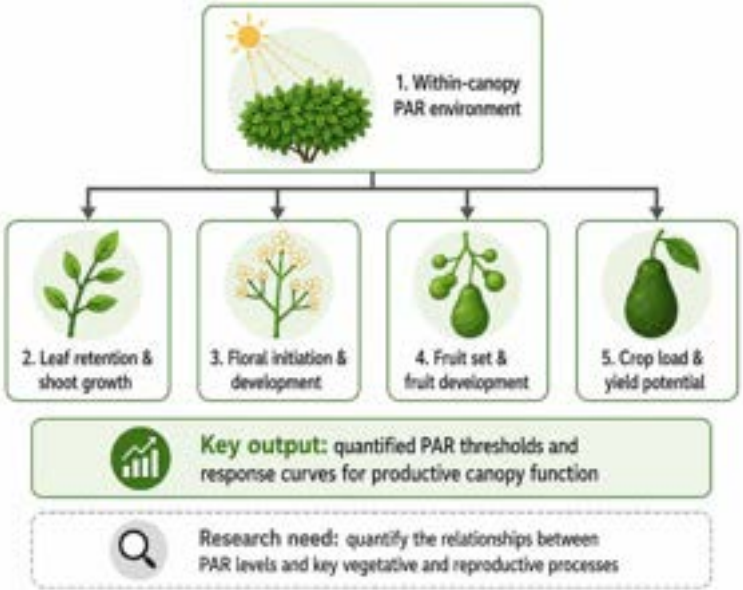
Recommended R&D approach



Technology readiness level (TRL) framing:

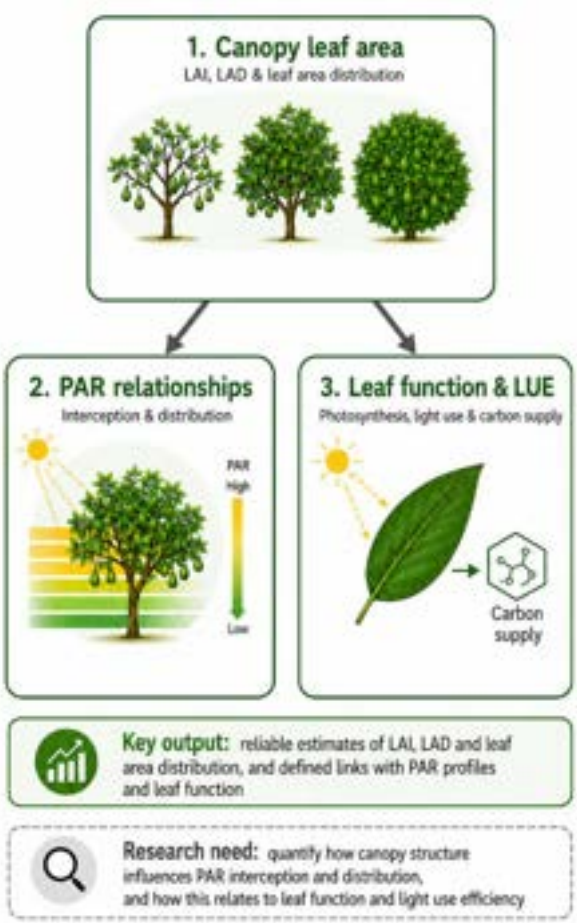
- **Current position**: mostly concept stage (TRL 1-2)
- **Recommended approach**: build the biological, sensing, pruning and modelling foundations toward orchard-scale validation (up to TRL 6)
- **Long-term opportunity**: commercial pruning decision-support tool (TRL 7-9)

Area 1: Define practical light targets



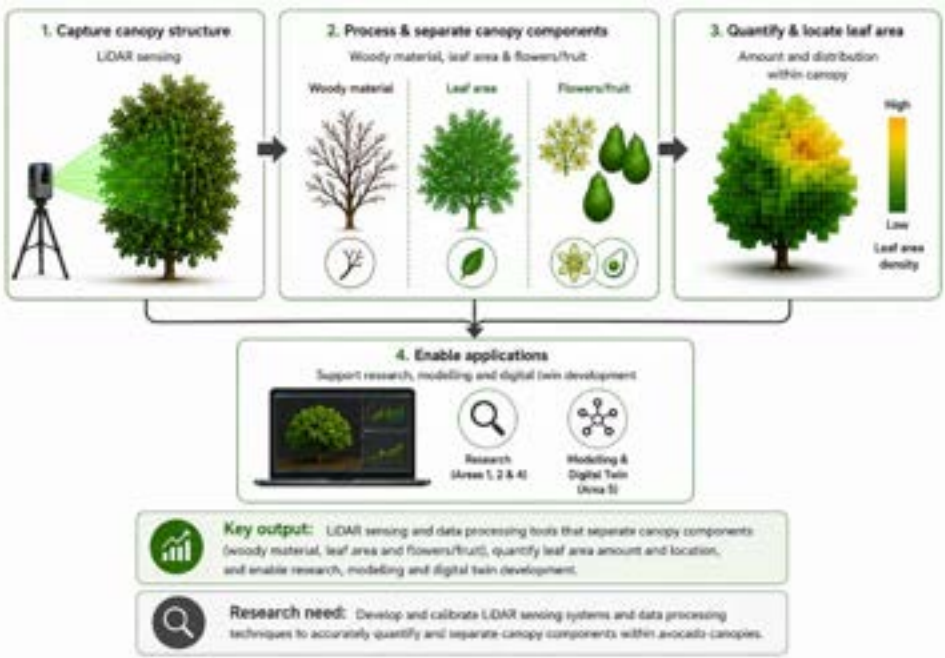
- **Current readiness**: TRL 1, conceptual link between light and productivity
- **Target**: practical light targets and response curves for identifying low-productivity canopy zones (TRL 6)

Area 2: Link canopy density to light and productivity



- **Current readiness**: TRL 1, canopy architecture affects light penetration
- **Target**: practical canopy density targets linked to PAR, leaf function and productivity (TRL 6)

Area 3: Evaluate canopy sensing tools

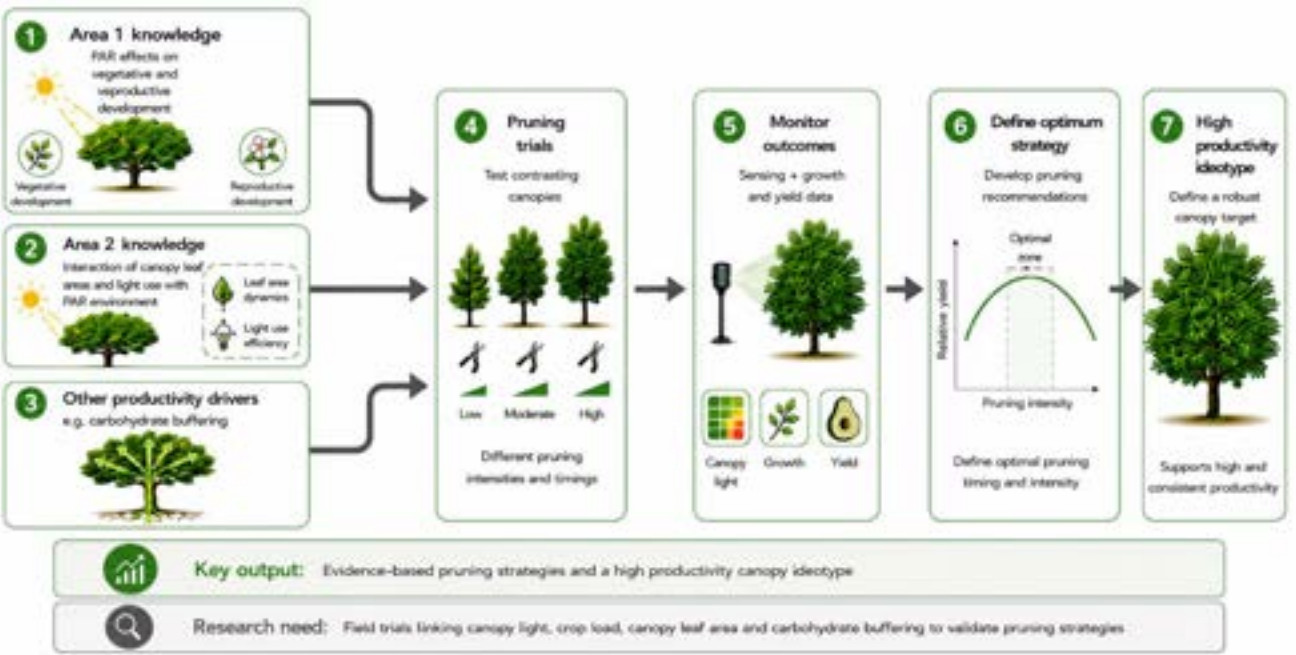


- **Current readiness**: TRL 2, feasibility of canopy scanning demonstrated to quantify canopy dimensions and density

- **Target**: canopy structural metrics produced to support pruning trials (area 4) and modelling/decision support (area 5) (TRL 6)

Area 4: Test pruning strategies in commercial orchards

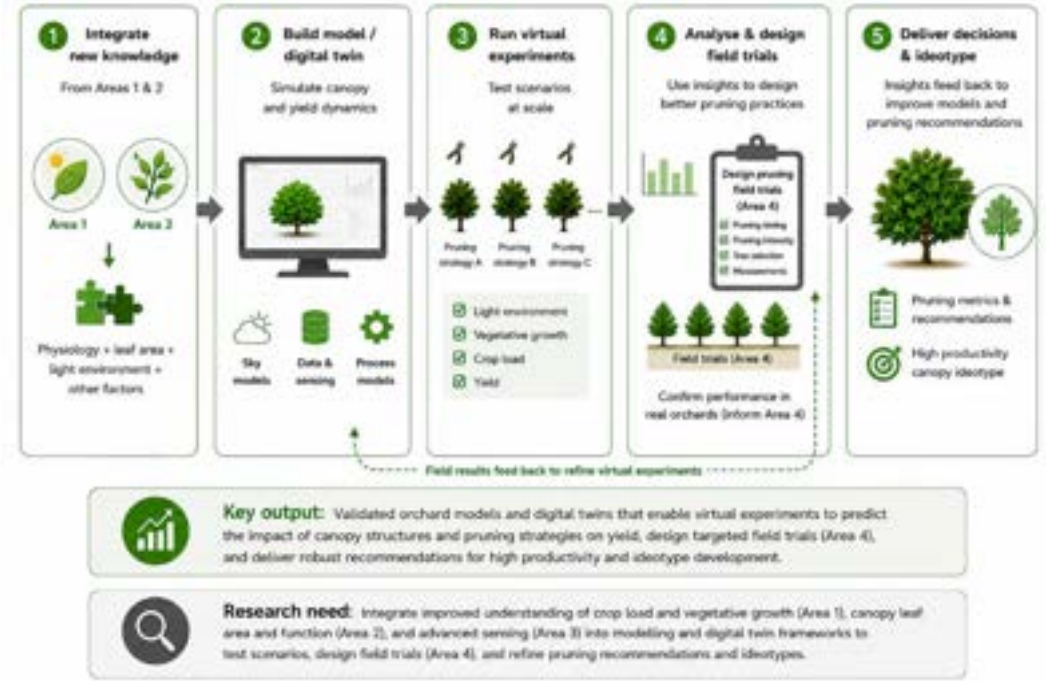
New Zealand Government



- **Current readiness**: TRL 1, pruning principles broadly identified but not yet validated against quantified canopy targets
- **Target**: commercial orchard demonstrations of physiologically informed pruning systems (TRL 6)
- **Future pathway**: foundation for data-enabled pruning decision-support tools (TRL 7–9)

Area 5: Develop modelling and decision support

Queensland Government



- **Current readiness**: TRL 1, modelling concepts identified but limited by gaps in canopy light and productivity data
- **Target**: research prototype used to run virtual experiments and refine pruning trials (TRL 6)
- **Future pathway**: commercial decision-support platform (TRL 7–9)

Summary: concept readiness

Observational/ awareness | Current status | Development pathway | Recommended target | Future pathway

Area	TRL 0	TRL 1	TRL 2	TRL 3-5	TRL 6	TRL 7-9
Area 1 Light targets		Light-productivity link	Progressive validation		Practical light targets	
Area 2 Canopy density		Canopy structure affects light	Progressive validation		Canopy density targets	
Area 3 Sensing tools			Scanning can quantify canopy structure	Workflow validation	Block-scale research tool	
Area 4 Pruning systems		Pruning alters light environment	Alternative systems proposed	Field validation	Commercial orchard demonstrations	Data-enabled precision pruning tools
Area 5 Modelling / digital twins		Modelling concepts identified	Concept formulation	Model proof of concept and validation	Research prototype	Commercial decision-support platform

Recommended next phase: build foundations to TRL 6. TRL 7-9 represents longer-term commercial translation, particularly through Areas 4 and 5.

Minutes – AV24011 PRG meeting

21 August 2025

Time: 10:30 AEST

Facilitator: Gerhard Rossouw

Attendees: John Wilkie, Neil White, Tom McCue, Mary Burton, Ben Norrish, Clayton Lynch, Alvaro Vidiella, Lisa Fyffe, Lawrence Massasso, Shane Singh

1. Welcome and introductions

- Meeting opened by Gerhard Rossouw.
- Introduction of the project team and PRG members

2. PRG role and Terms of Reference

- Purpose and expectations of the PRG outlined (technical and practical input, ensuring relevance, regional perspectives, confidentiality, meeting attendance, contributing feedback between meetings).
- Tom noted the PRG's role should also include guiding the commercial relevance and practicality of proposed solutions.
- Terms of Reference were circulated prior to meeting.
- The Terms of Reference were endorsed.

Outcome: ToR endorsed.

3. Project overview

- Overview provided of project aims, objectives, and methodology.
- Emphasis on the scoping nature of the project: 12-month literature review and analysis to identify gaps and inform future R&D.
- Key outputs: literature review, Talking Avocados article, R&D options paper, and end-of-project webinar.
- Ben explained that the original idea for this line of work came from discussions about whether it would be possible to develop a software tool for growers that could recommend best pruning practices based on canopy growth and light interception models. This concept has been raised in the PRG for several years, but had not previously progressed.
- He noted that the current project (AV24011) was framed as a first step, with the recommendation to start with a broad literature review to explore what modelling resources already exist. This includes:
    - Canopy growth and light interception models in other crops.
    - Models developed outside horticulture, such as those used in computer and gaming industries to simulate plant growth and light environments, which might be adapted.

- The aim of the review is to ground-truth feasibility: whether existing modelling approaches could be used or adapted to avocado, and whether this could ultimately lead to a tool with simple inputs (e.g. region, canopy characteristics) that provides growers with regionally relevant pruning recommendations.
- Rather than charging directly into tool development, this scoping project is intended to clarify whether the technology base is strong enough, and what gaps remain before a practical, grower-facing tool could be developed.

4. Discussion – Scope and focus

- Several members expressed a strong preference to narrow the focus to light interception as the central theme of the project, rather than a broad review of all canopy management factors such as wider physiological drivers of productivity.
- John raised concerns about assumptions: while light interception is important, we lack clarity on optimum levels and distribution for avocado productivity.
- There was agreement that identifying knowledge gaps on light interception and modelling potential is to be a key outcome for this project.
- Tom noted that while the project is rightly considering canopy structure, light distribution, and physiology, it is important to also look specifically at the effects of pruning activities and the related knowledge gaps.
- John asked whether the project's origin was solely about developing a software/tool for light interception modelling, or whether it was intended more broadly to encompass other research (including physiology) to underpin future canopy management strategies
- Tom responded that the original driver was to work toward a best-practice model that growers could use to optimise canopy management and fruiting potential. The view at the time was that light interception and distribution are major determinants of productivity, so the immediate focus needed to be on consolidating the latest knowledge in this space. The idea was that a tool for growers could eventually be developed, but first the literature gaps around light interception had to be addressed.
- Ben agreed, noting that while the current project (AV24011) is just a step along the pathway, the ultimate goal is a regionally tailored, adjustable model that growers can use in practice. He stressed that identifying information gaps and recommending further research is an acceptable and important outcome at this stage, as long as it clearly progresses the industry toward that longer-term end goal.
- Lawrence asked whether the project would include cost–benefit analysis of different pruning approaches, noting growers often question the "sweet spot" in how much time and cost to invest per tree.
- John responded that only a very basic cost consideration was planned for technology options (e.g. high-end vs low-cost tools), not detailed pruning cost–benefit. He suggested that assessing pruning methods against yield outcomes would be better suited to a future project.
- Lisa agreed, emphasising the importance of incorporating pruning cost–benefit analysis into future R&D, as current practice varies widely and cost-effectiveness is uncertain.
- Ben noted that defining the "ideal tree shape" (e.g. spherical, hedge, central leader) is a more immediate priority; the means of achieving that shape and associated cost–benefit would logically follow later. He stressed this is beyond the scope of AV24011 but important for future phases.

- Gerhard and John reiterated that AV24011 will consider cost ranges in relation to technology tools, but detailed canopy management cost analysis should be addressed in subsequent R&D.
- John also cautioned that while light interception is a central focus, the review will still need to acknowledge other interacting physiological factors influencing productivity.
- Mary noted that findings from intensification work in Bundaberg show that while planting density and light interception are important, the relationship with yield is not straightforward. The literature review might recognise that light interception is a starting point but not the whole story.
- Ben responded that AV24011 was specifically proposed as a light interception project, not a broad review of all avocado production challenges. While other elements may be relevant, the focus must remain on identifying the limitations and potential of light interception models.
- Tom agreed, stressing that the purpose is to reach a detailed understanding of how to optimise light interception across regions. There has been past work, but no clear management package or defined best practice has emerged, and this project should help fill that gap.
- John highlighted a key missing link: while total light interception is relatively well understood, there is poor knowledge of optimal light distribution within the canopy and the levels needed for different processes (leaf area, new growth, floral initiation, fruit set). He cautioned against making assumptions without sufficient evidence.
- Alvaro agreed that all were discussing the same core issue — the need to understand how much light is required, where in the canopy, and at what times — to inform optimal tree architecture and management. He suggested structuring the review around an index of questions to ensure completeness.
- Tom reiterated that this is exactly why a literature review is needed: to avoid misdirecting future R&D investment and to clearly identify where the gaps and opportunities lie.
- Gerhard noted that articulating these gaps will be one of the most important outputs of the project, as they will directly guide recommendations.
- Ben agreed, adding that while a tool may be many years away, this project's role is to clarify the critical gaps in light interception science. Keeping the scope tailored to light interception will ensure useful, targeted outcomes, which can then lead into future projects.

Outcome: Agreement that cost–benefit analysis of pruning and canopy practices is likely outside the scope of AV24011 but represents a priority area for future R&D.

Outcome: AV24011 should maintain a focus on light interception as a central theme. The project should aim to identify and articulate the knowledge gaps around light capture, distribution, and their impact on productivity, while trying to avoid dilution into broader avocado production issues. These gaps will guide recommendations and set the foundation for future R&D, including eventual development of grower-facing tools.

5. **Discussion – Industry engagement**

- Several members (Ben, Clayton, Shane, Alvaro) commented that planned grower visits/consultations were unnecessary and risked wasting resources
- View expressed that PRG input is sufficient to provide regional and commercial relevance at this stage.
- Lawrence asked whether grower visits could be used to make objective light measurements linked to fruit counts. It was clarified that this was not currently part of the project's scope.
- Mary noted some growers may believe they already have answers, so at minimum their perspectives should be acknowledged.
- John emphasised that regional perspectives could be missed without engagement, but acknowledged cost/benefit concerns.
- Alvaro suggested the PRG itself constitutes effective engagement and recommended instead holding a webinar at project end to present findings and gather grower feedback.
- A question was raised about the final position on regional grower visits.
- Gerhard explained that feedback from the PRG was to move away from extensive grower visits, and instead place stronger emphasis on the literature review. Grower feedback could be sought later through an online webinar at the end of the project.
- Tom confirmed he was comfortable with this shift, noting that early grower consultations risk producing only status quo views, which could skew the project. Instead, the priority should be to identify knowledge gaps in light interception first.
- He suggested using the PRG more actively, with members asked to provide their top five light-interception questions to help guide the review.
- Tom also noted that existing grower feedback already collated could be incorporated, and that later in the project there would still be scope to validate findings and priorities with industry.

Outcome: Suggested to reduce emphasis on regional grower visits. Instead, the PRG will contribute specific guiding questions to shape the review, and broader grower engagement will be deferred until later in the project (e.g. through an online webinar).

6. **Proposed guiding questions**

- Alvaro emphasised that the current project scope appeared very broad and complex, covering issues that have been debated globally for many years. He cautioned that unless the project identifies specific, focused research questions, resources risk being spread too thin without clear outcomes.
- He suggested that instead of generic questions, the PRG should help define precise, practical questions that can guide the literature review and ensure the project delivers useful recommendations. Alvaro noted that the PRG itself represents a form of industry engagement, and members' collective expertise should be used to refine scope and expected outputs.
- John responded that AV24011 is intended as a scoping project to make recommendations for future canopy management R&D, not to solve all issues in detail within one year. The broad approach reflects the need to balance available time and resources with the industry's need for direction.

- Alvaro clarified that in his view, the project is essentially about developing a canopy management R&D strategy for the avocado industry, and this requires clear prioritisation of questions from an industry perspective before diving too deeply into the literature.
- Ben added in the chat that some guiding question could be:
    - Can a regionally variable best practice light interception/canopy management model or tool be developed for avocados?
    - What are the barriers to developing a regionally variable best practice model for canopy management?
    - What are the variables that affect canopy management alongside light interception?
    - What are the knowledge gaps in the research on those variables, and does more need to be done? (Future recommendations)

  Outcome: Guiding questions should be worked out to inform project framing.

7. Discussion – Feasibility of modelling approaches

- Ben asked Neil for his perspective on the feasibility of developing a horticultural canopy/light model, noting the sophisticated models emerging from the gaming and film industries.
- Neil explained that while gaming models are visually impressive, they use shortcuts without scientific basis and cannot be directly applied. However, he saw a feasible pathway for horticulture through:
    - High-end light modelling and simulation work to capture canopy/light dynamics accurately (including reflection and transmission through leaves).
    - Using this data to train AI/machine learning systems, which could then deliver faster, rule-based models suitable for practical use (e.g., in an app).
    - He cited his prior work in the Tree Crop Intensification and Small Trees projects, where creating abstracted “canopy shapes” helped simplify modelling and speed up processing.
- John added caution, noting that while promising, such modelling brings complexities:
    - Trees actively respond to altered light environments and canopy structures (e.g., regrowth, flowering, fruiting responses), which need to be incorporated.
    - Models require large amounts of detailed data, and progress often reveals further challenges that must be accounted for.

Outcome: Recognition that modelling is feasible and promising, but will require substantial data, careful validation, and consideration of dynamic tree responses before it can underpin grower-ready decision-support tools.

PRG Meeting Summary – 21 November 2025

Attendees: Gerhard Rossouw, John Wilkie, Neil White, Geoff Dickinson, Tom McCue, Lisa Fyffe, Ben Norrish, Alvaro Vidiella

1. Overview of Project focus and direction based on discussion from previous PRG meeting:

The team confirmed that the central theme of AV24011 remains light interception and its relationship to canopy management, modelling, and productivity. This reaffirmation followed the PRG's earlier guidance to stay tightly focused on light-driven mechanisms and avoid drifting into broader avocado production topics unless they directly influence light capture, distribution, or utilisation.

The project will continue to identify knowledge gaps related to light interception, light distribution, canopy management, and modelling, and use these gaps to guide recommendations for future R&D and eventual development of grower-facing tools.

2. Clarified guiding questions (summary from last PRG meeting and endorsement from PRG):

The group endorsed four guiding questions:

- Can a regionally variable best practice model or tool for light interception and canopy management be developed for avocado?
- What are the barriers to developing such a model?
- How does the light environment influence crop load development and yield, and which canopy management practices interact with light?
- What knowledge gaps must be filled to answer these questions?

These questions now underpin the structure of the literature review and overall project logic.

3. Literature review overview

The team presented progress across the five major sections of the review.

3.1 Section 1 – Physiological drivers of productivity (Gerhard)

This section aims to clarify the unresolved link between light interception and yield, noting that total light intercepted sets the ceiling, but light use efficiency determines outcomes. The review explores:

- How leaves use intercepted light, including photosynthetic limitations and light saturation.
- Downstream processes linked to light, such as carbon allocation and hormonal controls.
- Reproductive development phases influenced by light.
- Regional differences in tree capacity to use light.

The aim is to identify knowledge gaps that prevent linking light to yield with confidence, and to set the foundation for later sections.

3.2 Section 2 – Orchard light environment (John)

John outlined how other crops, mainly apple and macadamia, provide a framework due to limited avocado-specific data.

Key topics include:

- Distinction between leaf-level, tree-level, and orchard-level light environment.
- Metrics such as total PAR interception and light distribution, including clear definitions, as these terms are often used loosely.
- Canopy structure effects on light, including leaf area index, leaf area density, planting density, tree height, row width, canopy complexity, and row orientation.
- Light quality and photomorphogenesis.
- Early concepts for an avocado canopy ideotype, acknowledging that current knowledge is insufficient but the process of defining one will reveal research priorities

Discussion highlighted the potential importance of daily light integral (DLI) as a physiological metric. Alvaro noted the need to understand minimum DLI requirements for vegetative and reproductive units (shoots, branches) to produce strong flowers and fruit, and the effect of DLI gradients within the canopy.

3.3 Section 3 – Canopy management (Gerhard)

This section examines canopy management as the operational lever for controlling light interception and distribution. It covers:

- Direct pruning strategies.
- Indirect methods such as plant growth regulators and rootstock effects.
- Timing of interventions and links with phenology.
- Regional considerations that affect canopy behaviour and management choices.

A major focus will be on explaining how canopy interventions change light capture and distribution, and how this relates to productivity.

3.4 Section 4 – Modelling (Neil)

Neil presented a historical and conceptual overview of modelling approaches, from early extinction-coefficient models to modern ray tracing and functional structural plant models. Key points:

- Many foundational light models (e.g. Beer's Law) are still widely used.
- Complex canopies require sophisticated modelling, but high data requirements and computational demands limit practical adoption.
- Some models developed overseas are not maintained or accessible, and many remain research tools rather than operational tools.
- Lidar data has potential but converting point clouds into functional canopy models remains difficult.
- Overly ambitious whole-tree or whole-orchard models risk becoming too complex to be useful as decision support tools.

The group agreed that targeted, question-driven modelling of specific components (e.g. light–budburst relationships, red–far red ratios, DLI thresholds) may be the most practical pathway.

3.5 Section 5 – Technologies and tools (Gerhard)

This section is mapping the landscape of tools for quantifying light and canopy structure, including:

- Foundational field tools (e.g., PAR sensors, ceptometers).

- Optical methods (e.g., hemispherical photography).
- UAV and ground-based lidar.
- 3D reconstruction technologies and digital twins.
- Cross-industry innovations (architecture, gaming, ray-tracing engines).
- Emerging lower-cost options such as smartphone-based light tools.

The section assesses practicality, cost, skill requirements, and potential for integration with canopy modelling and future decision support tools.

4. Regional differentiation discussion

The group explored how to incorporate regional considerations without returning to the original plan of large-scale grower visits. Key points:

4.1 Areas where regions clearly differ

- Phenology: Queensland has clear periods with no fruit, allowing greater pruning flexibility; WA and southern regions often have overlapping crops, reducing pruning windows.
- Climate and seasonal radiation: Latitude, elevation, solar angle, temperature, humidity, and rainfall all shape light patterns and canopy behaviour.
- Varietal distribution: For example, Shepherd in North Queensland.
- Growth patterns: Timing of flushes, crop maturity, and cycle overlap.

4.2 Areas with limited regional differentiation

Participants noted that actual pruning techniques (hedging, selective limb removal) appear consistent across regions, with more variation between individual growers than between regions. The diversity is driven more by cost, grower preference, orchard age, and risk tolerance than by geographic location.

Lisa noted that even within a region such as Bundaberg, approaches vary widely.

4.3 Recommended approach

Rather than categorising regions by what growers currently do, the team should explore:

- How light behaviour differs between regions (solar patterns, day length, row orientation effects, climate).
- How these differences shape optimal canopy structures or pruning timing windows.
- Consider dominant management techniques by broad zones (north, central, south, west) where patterns exist.
- Keep the focus on light interception and yield implications, not on cataloguing every regional practice.

Tom also highlighted the importance of noting where practices may limit yield, and whether evidence exists to quantify this.

5. Milestone planning and next steps

- The upcoming milestone requires commentary on regionally differentiated canopy approaches, which will be addressed using the light-focused, physiology-driven framework discussed.

- The team intends to continue engaging with experts in remote sensing, digital tools, and modelling to assess practical pathways for the second half of the project.
- A summary of the meeting will be circulated (this document).

AV24011 PRG Meeting Minutes

Project: AV24011
Meeting: Project Reference Group meeting
Date: 13 May 2026

Attendees

Gerhard Rossouw, John Wilkie, Neil White, Tom McCue, Alvaro Vidiella, Lisa Fyffe and Gemma Burger.

Purpose of meeting

The meeting was held to provide an update on progress in AV24011, including the literature review, technology and modeller engagement work, and the evolving recommendations for future R&D investment. The main purpose was to seek PRG feedback on the key knowledge gaps identified and on the draft recommendations being developed as a major project output.

1. Recap of previous PRG direction

Gerhard provided a brief recap of the previous PRG meeting, including the agreed focus on light environment, canopy management, technologies, modelling and productivity. The guiding questions endorsed previously were revisited:

1. Can a regionally variable best-practice model or tool for light interception and canopy management be developed for avocado?
2. What are the barriers to developing such a model?
3. How does the light environment influence crop load development and yield, and which canopy management practices interact with light?
4. What knowledge gaps must be filled to answer these questions?

Tom noted that, in addition to answering these technical questions, the project outputs should aim to address the “so what?” for growers. He emphasised that the recommendations should explain what the findings could ultimately mean in terms of grower decisions, applied management outcomes, and future practical tools.

Alvaro also reiterated that one of the central questions from the grower perspective is how much light, or accumulated light exposure, is required at a particular point in the canopy to support strong flowering and fruiting on a branch. This was noted as a key link between the literature review findings and future applied research.

2. Key gaps identified through the literature review

Gerhard, John and Neil provided an overview of the main gaps identified across the literature review sections.

2.1 Physiological drivers of productivity

The review identified that the relationship between canopy light environment and avocado productivity is conceptually well supported, but not yet well quantified. There is limited quantitative information linking canopy light environment to carbon assimilation, carbon allocation, crop load development and yield. Light use efficiency, meaning the conversion of intercepted light into carbon and ultimately yield, is also not yet well quantified for avocado, including how it varies across sites and regions.

2.2 Orchard light environment

John noted that there is some understanding of the relationship between total light interception and yield in conventional subtropical avocado orchards, but very limited understanding of whether this relationship differs across regions. The greater gap is within-canopy light distribution and its effect on crop load development.

Key gaps include limited quantification of leaf area index, leaf area density and leaf area distribution within avocado canopies, and how these attributes affect PAR distribution. There is also limited understanding of how local light levels influence processes such as floral initiation, floral development, fruit set, fruit retention, fruit growth, vegetative growth and leaf retention.

John noted that these gaps have major implications for canopy management, because growers can visually observe hollowing and reduced productivity in shaded canopy zones, but the underlying light thresholds and relationships have not been adequately quantified.

2.3 Canopy management practices

Gerhard summarised that the effects of canopy interventions, including timing, intensity and style of pruning, on light interception, within-canopy light distribution, canopy redevelopment and yield are not well characterised. Responses to pruning and hedging are highly context-specific and vary with site, region, canopy vigour, tree condition and other management factors.

This limits the ability to predict pruning outcomes and develop regionally adaptable canopy decision-support tools.

2.4 Light modelling

Neil outlined that different modelling approaches are available, ranging from static models of idealised tree shapes through to more advanced light modelling and digital twin approaches. He noted that high-resolution LiDAR and modelling work, including developments at UQ, may provide important future opportunities.

However, modelling requires reliable canopy structure inputs and a physiological basis for interpreting light levels. A key gap remains understanding how much light is required

at specific canopy positions and phenological stages to support robust flowering, fruit set and fruit development. Without this biological understanding, modelling outputs remain difficult to translate into yield or management recommendations.

2.5 Light assessment tools

Gerhard noted that many tools are available to quantify light or canopy structure, but their practical usefulness in dense avocado canopies remains limited. Measuring the outside of the canopy is relatively achievable, while internal canopy light distribution is much harder to assess at scale. A further gap is translating light measurements into practical canopy management recommendations.

3. Technology and modeller engagement findings

Gerhard summarised the technology and modeller engagement work, which included discussions with researchers, modellers, LiDAR specialists, robotics providers and applied technology users in other horticultural crops.

The main finding was that existing technologies can measure canopy volume, tree size, outer canopy structure and some light interception metrics reasonably well. However, internal canopy structure, separation of canopy components, and within-canopy light distribution remain more difficult to capture, particularly in dense avocado canopies.

LiDAR was consistently identified as the strongest current technology for canopy structure assessment. High-resolution systems can provide detailed structural information and may allow separation of leaves, branches and potentially fruit, but these systems are expensive and require specialist expertise and data processing. Lower-resolution or more scalable LiDAR approaches are useful for canopy volume, tree size and broad light interception estimates, but provide less detail on internal canopy structure.

John described recent LiDAR scans undertaken with RIEGL, noting that high-resolution scans were able to capture substantial canopy detail and, with limited effort, separate major branches from leaf material. Some occlusion remained, particularly in upper canopy zones, but the data suggested strong potential for accelerating canopy structure measurement compared with traditional manual methods.

The group discussed the potential for LiDAR, RGB imaging and machine learning to support future crop load estimation or fruit detection. Alvaro noted that related work is underway in protected avocado cropping systems, including the use of point clouds and AI models to identify fruit for yield forecasting. Gemma offered to connect the project team with the relevant internal team.

4. Digital twins and future decision-support pathways

Gerhard introduced the concept of digital twins as a potential long-term pathway for canopy decision support. Digital twins could allow different canopy structures, pruning scenarios or orchard configurations to be tested virtually before field implementation.

The group agreed that digital twins may provide a useful long-term platform, but the immediate R&D need is to build and validate the underlying sensing, modelling and yield-response relationships that would make such tools useful. In particular, a digital twin would need to link 3D canopy structure, light modelling, crop load, yield outcomes and management decisions.

A conceptual workflow was presented showing a possible pathway from LiDAR-based canopy reconstruction and light simulation through to yield prediction and pruning scenario testing. The group agreed that this type of visual was useful for explaining the project logic and should be included in the recommendations paper.

5. Discussion of draft recommendations for future R&D

John presented the draft investment model developed from the literature review and scoping work. The model identifies several linked areas of future R&D, including:

1. Understanding relationships between within-canopy PAR levels and avocado growth and development processes.
2. Understanding LAI, LAD and leaf area distribution, and their relationship with PAR distribution and radiation use efficiency.
3. Undertaking canopy management trials to test how pruning and other interventions affect light environment, canopy redevelopment, crop load and yield.
4. Using modelling and digital twin approaches to integrate knowledge and test canopy scenarios.
5. Developing and applying sensing technologies, including LiDAR, to improve data collection and support future decision-support tools.

John noted that the model aims to show a pathway from key knowledge gaps through to practical outcomes, including higher productivity canopy management strategies, better adaptation of canopy management across growing regions, and improved understanding of high-productivity avocado canopy ideotypes.

6. PRG feedback on recommendations

The PRG provided several important suggestions for complementing the recommendations paper.

Tom emphasised that each recommendation should include a clear statement of the potential eventual grower or commercial outcome. These outcomes may be direct grower outcomes, such as improved pruning guidance, or enabling outcomes, such as data and knowledge that support technology development, validation or automation.

Lisa supported this and suggested that the recommendations should make clear how each area could contribute to grower practices or technology development. She also suggested that the conceptual workflow diagram should be included near the start of the recommendations document, because it clearly explains the logic and shows why the light-yield relationship gap is central.

Tom suggested that similar visuals could potentially be developed for each of the five recommendation areas to make the pathway clearer and easier for readers to understand.

The group discussed the wording used in the recommendations paper. Alvaro and Tom suggested avoiding framing the work as “fundamental avocado tree physiology” because this may not communicate the applied value clearly enough to industry or funding bodies. Instead, the work should be framed as applied research needed to enable practical canopy management outcomes.

Tom suggested using Technology Readiness Level (TRL) concepts to frame the pathway from early-stage knowledge gaps through to validated grower tools or management packages. He explained that the current project has helped identify and define the early-stage concept, and future recommendations should show how the work could progress towards higher readiness levels over time.

The group discussed that a mature end point could be a grower or autonomous system that can confidently use canopy and light information to guide pruning or other management decisions, with low risk and clear expected outcomes.

7. Additional points raised

Several additional considerations were discussed:

- Future R&D could consider tree age and orchard maturity, including how light interception and canopy management needs differ between young, developing and mature orchards.
- Fruit quality, not only yield, could be considered where future work investigates the effects of light environment and canopy management.
- Practical outputs need to be simple enough for growers, contractors or pruning teams to use, especially given variable skill levels in the labour force.
- There may be opportunities to link future work with automation, robotics and AI-based pruning technologies.

- Tom suggested looking into BeagleTech as an example of a company using AI and vision systems for automated pruning or cutting decisions in other crops.
- Lisa noted that an ultimate pathway could include automated pruning, while recognising that interim grower-facing tools or pruning guidance may be more realistic in the medium term.

8. Summary

The PRG supported the overall direction of the literature review, technology scoping and draft recommendations. Feedback was that the final recommendations should attempt to more clearly communicate the applied pathway from knowledge gaps to theoretic practical grower outcomes. The group agreed that the project has identified important gaps around light thresholds, canopy structure, pruning responses, modelling integration and sensing capability, but that the final output should show how these gaps can be addressed through staged future R&D.

A key recommendation from the PRG was to attempt making components of the investment paper more outcome-focused, visually clear, and framed around a potential pathway toward practical decision-support tools or canopy management packages for growers.

AV24011 Optimising Avocado Yield with Region-Specific Canopy Management: Insights from Light Interception and Canopy Modelling

Literature Review synopsis

- This literature review highlights light interception and how light is distributed within the canopy as drivers of avocado productivity. However, these relationships remain poorly quantified, and quantitative relationships linking canopy light environment to yield outcomes remain largely unparameterised. As a result, the relationship between canopy light environment and yield remains difficult to predict, limiting the development of robust, quantitative decision-support tools.
- Light use efficiency, which determines how effectively trees convert light into growth and yield, is not well defined or parameterised in avocado systems and is influenced by tree health and environmental conditions such as nutrient status, water supply, temperature, and vapour pressure deficit. These interacting factors further complicate the relationship between light and yield, particularly across different regions.
- These limitations directly affect the ability to define measurable canopy variables (e.g. light interception, canopy porosity, and within-canopy light distribution) that can be used as model inputs, and to translate these into outputs such as predicted trends in carbon assimilation, fruit set probability, or yield potential under different canopy configurations.
- Although understanding of tree physiology, canopy management practices, and light sensing and modelling technologies has advanced considerably, these areas have largely developed in isolation from one another. At present, there is no clear pathway that links biologically meaningful light targets for high productivity to practical pruning decisions using scalable and practically applicable measurement and modelling approaches, which currently provide inputs for analysis rather than direct predictions of yield outcomes.
- Recent advances in canopy sensing (e.g. LiDAR, UAV imaging), digital twin frameworks, and functional–structural modelling provide a foundation for such integration, but remain insufficiently linked to yield prediction and decision-support frameworks for avocado. Bridging this gap requires the development of integrated frameworks that link measurable canopy attributes (e.g. light interception, canopy size and porosity, and phenological timing) to model inputs, and translate these into decision-support outputs such as pruning recommendations, canopy density targets, and region-specific management strategies.
- As a result, light-based canopy management in avocado remains largely based on assumptions rather than robust evidence, limiting the ability of growers to make confident, site-tailored pruning decisions.
- Commercial and adoption considerations are therefore relevant to the pathway from research insight to practical implementation, but are treated in this review as questions of commercial feasibility, scalability, implementation and grower uptake rather than as a detailed economic analysis of individual pruning systems. For light-informed canopy management to deliver industry impact, future approaches need to be biologically sound, technically feasible, practical within commercial orchard workflows, and capable of supporting clear decisions by growers. This requires attention to implementation barriers, validation requirements, cost and complexity of tools, and the likely pathway from research-grade measurement and modelling to practical decision-support applications.

- The literature reviewed in this document identifies several key knowledge gaps that constrain the development of predictive canopy models and practical decision-support tools. The most critical gaps relate to:
    - Defining biologically meaningful light targets associated with crop load development processes, shoot growth and leaf retention, which are required to establish model benchmarks and management thresholds
    - Establishing quantitative relationships between canopy light environment and yield outcomes including the role of light use efficiency within the broader canopy system, which are necessary for parameterising predictive models

  Secondary but enabling gaps include:
    - Understanding how pruning and other canopy interventions modify light distribution under different conditions
    - Improving the integration of sensing and modelling technologies to translate canopy structure into actionable insights

  Without addressing these critical gaps, the development of predictive models remains constrained, while the secondary gaps limit the refinement and practical implementation of regionally adaptable decision-support tools.

- Collectively, the literature aims to provide a framework for future research and development aimed at enabling more light-informed canopy management strategies that can improve avocado productivity and support grower decision-making, particularly through the integration of sensing technologies and modelling approaches into practical, grower-facing decision-support systems. In practical terms, this helps enabling a pathway from measurement (e.g. canopy light environment), to modelling (e.g. simulation of canopy structure and light distribution), to application (e.g. optimised pruning strategies and canopy configurations tailored to regional conditions).

A key conclusion is that if future investment is directed toward canopy management through the development of light-based decision-support tools, it should be grounded in clearly defined light targets supported by technology. The main limitation identified is the absence of an integrated and parameterised pathway linking:

1. biologically meaningful light targets that promote productivity,
2. quantified (or quantifiable) pruning effects on canopy light profiles,
3. scalable sensing and/or LiDAR-enabled modelling approaches capable of predicting pruning outcomes and associated yield benefits.

Following this synopsis, each literature review section is introduced with a brief summary highlighting the key concepts and their practical relevance. These summaries are intended to guide readers through the main physiological, technological, and management insights before presenting the more detailed discussion that follows in each section.

1. Physiological drivers of productivity

Avocado yield is affected by how well trees capture light and convert it into usable energy for growth and fruit production. Light interception and distribution are the starting points, but what matters just as much is how efficiently the tree uses that light. This efficiency depends on leaf health, water availability, nutrient balance, and environmental conditions such as temperature and humidity. Even when trees receive similar amounts of light, differences in these factors can

lead to very different yield outcomes. In practical terms, this means that improving productivity is not only about increasing light interception, but also about ensuring the canopy can use that light effectively.

Within the tree, carbohydrates act as the main link between light capture and yield. Leaves produce sugars from light, which are then used immediately for growth and fruit development or stored as reserves for later use. These reserves are critical during key stages such as flowering and early fruit growth, when demand exceeds current supply. When crop loads are high, reserves can be depleted, reducing flowering and yield in the following season. At the same time, plant hormones regulate how these resources are used, influencing whether buds become flowers, whether fruitlets are retained or shed, and how fruit develop. As a result, yield is largely determined by the balance between light capture, carbohydrate supply, and hormonal signals over multiple seasons.

These processes come together most clearly during flowering, fruit set, and fruit growth, where only a very small proportion of flowers develop into harvestable fruit. This low conversion rate reflects strong competition for resources within the tree, particularly under dense canopies where light is unevenly distributed. Management practices such as pruning, irrigation, nutrition, and the use of growth regulators all influence yield because they affect either the canopy light environment or the balance between sources (leaves) and sinks (fruit and growing shoots). Overall, this section highlights how the light environment and canopy condition together can determine how effectively the tree supports fruit development and maintains consistent yields across seasons.

The relationships between light interception, its utilisation through canopy carbon processes, and resulting yield outcomes are well supported conceptually but remain poorly quantified, limiting the ability to translate canopy light conditions into reliable predictions of yield outcomes.

2. The orchard light environment

At the orchard scale, productivity is determined not just by how individual trees capture light, but by how light is distributed across the entire planting. Trees shade each other, and leaves within the canopy compete for light, so the way light moves through the three-dimensional orchard space becomes critical. Two key concepts help describe this: how much total light the orchard captures, and how evenly that light is distributed within and between trees. High total light interception increases the overall energy available for growth, but if canopies become too dense, much of that light is concentrated in the outer canopy while the interior becomes heavily shaded.

Orchard design strongly influences both light capture and distribution. Factors such as tree size, planting density, canopy shape, row spacing, and row orientation all determine how light enters and moves through the orchard. For example, larger trees and tighter spacing can increase total light interception, especially in young orchards, but often lead to greater shading within the canopy as orchards mature. Similarly, row orientation affects how evenly light is distributed, with north–south rows generally providing more uniform light exposure than east–west rows. These design choices create trade-offs between maximising light capture and maintaining sufficient light penetration to support productive canopy zones.

Within the canopy, light levels decline rapidly with depth as leaves absorb and block incoming radiation. This means that only a portion of the canopy operates under optimal light conditions, while shaded interior zones contribute less to photosynthesis and may eventually lose leaves and productive capacity. In other tree crops, reduced light within the canopy has been clearly

linked to lower flowering, fruit set, and fruit size. While similar patterns are observed in avocado, the exact light thresholds required for these processes are still poorly defined and are not yet parameterised for predictive modelling. This limits the ability to confidently design canopies that balance light capture with effective light use throughout the tree.

Overall, this section shows that maximising yield is not simply about capturing as much light as possible, but about achieving the right balance between total light interception and effective light distribution within the orchard. Understanding how orchard design influences this balance is critical for developing canopy management strategies that support consistent crop load, fruit growth, and yield across different growing regions.

3. Canopy management practices

Canopy management is the main post-tree establishment way growers influence how light is captured and used within avocado orchards. While Sections 1 and 2 explain why light and canopy structure matter, this section focuses on how these factors are managed in practice. Pruning, training, growth regulators, irrigation, nutrition, and rootstock choice all affect how dense the canopy becomes, how quickly it regrows, and how evenly light is distributed within the tree. These decisions may directly influence flowering, fruit set, fruit quality, and the consistency of yield from year to year.

A key challenge is that improving light conditions is not simply a matter of opening the canopy. Removing too much growth can reduce fruiting wood, expose fruit to sunburn, or disrupt the balance between vegetative growth and reproduction. At the same time, insufficient intervention allows canopies to become dense and shaded, limiting light penetration and reducing productivity in the inner canopy. Effective canopy management therefore requires balancing these trade-offs, using the right combination of tools at the right time to maintain a canopy that is open enough for light, but still productive and protected.

The way canopy management is applied varies widely depending on site, climate, and cultivar. In warm, high-rainfall areas, trees grow quickly and require frequent containment to prevent shading. In cooler or drier regions, growth is slower and pruning must be timed carefully to avoid damaging flowering or developing fruit under a longer cropping cycle. Cultivar growth habit, rootstock vigour, and orchard design further influence how easily light can be managed within the canopy. As a result, there is no single best approach. Instead, canopy strategies need to be adapted to local conditions and aligned with tree physiology and seasonal timing.

Another important point is that canopy management is not just about pruning. Many indirect factors, such as irrigation, fertiliser use, and plant growth regulators, strongly influence how quickly canopies close and how much intervention is required. These factors can either support or counteract pruning efforts by affecting shoot growth, leaf renewal, and overall canopy density. Integrating these different management levers is essential for maintaining stable light conditions and reducing the need for repeated corrective pruning.

Overall, this section shows that canopy management is a dynamic, ongoing process aimed at maintaining a balance between light capture, canopy structure, and tree physiology. While many tools and techniques are available, their effectiveness depends on how well they are timed and adapted to local conditions. A major gap remains in understanding how specific canopy practices influence light distribution and yield under different Australian growing environments, highlighting the need for more quantitative, regionally tailored approaches that can support predictive canopy models and practical decision-support tools.

4. Modelling the light environment in orchards

Understanding how light moves through avocado canopies in the field is difficult, because it changes with tree structure, time of day, weather, and orchard design. Modelling provides a way to overcome this by creating virtual orchards where different canopy structures, pruning strategies, and planting systems can be tested without the time, cost, and risk of field trials. Instead of relying only on measurements from a single orchard at one point in time, models allow researchers to explore a wide range of scenarios and better understand how canopy structure influences light interception and distribution.

There are many different modelling approaches, ranging from simple methods that treat the canopy as a basic shape, to highly detailed simulations that represent individual leaves and branches. Simpler models are fast and useful for comparing broad factors such as row orientation or planting density, but they cannot describe how light is distributed within the canopy. More advanced models can simulate how light interacts with complex canopy structures, including reflection, transmission, and shading between leaves, but they require more data, computing power, and expertise. Choosing the right level of complexity depends on the question being asked, as more detail does not always lead to more practical insights.

A major challenge in applying these models is obtaining accurate data on tree structure. Technologies such as LiDAR, imaging systems, and canopy analysers can measure canopy volume, density, and leaf area, but each has limitations, especially in dense evergreen canopies like avocado where internal structure is difficult to capture. While these tools are improving rapidly, they often require significant investment, careful calibration, and complex data processing. As a result, there is still a gap between what can be measured in research settings and what can be applied easily at a commercial orchard scale, particularly in linking model outputs to practical management decisions such as pruning intensity, canopy structure, and orchard design.

More advanced modelling approaches, such as functional–structural plant models, aim to simulate not only the structure of the tree but also how it grows and responds to light, carbon allocation, and management practices over time. These models offer strong potential for testing new canopy management strategies and understanding long-term outcomes, but they are complex to develop and are currently used mainly in research rather than routine industry practice.

Despite these challenges, modelling and sensing technologies are becoming increasingly important tools for improving canopy management. They can help identify where light is limiting productivity, evaluate different pruning or orchard design options, and support more targeted management decisions. Emerging approaches, such as LiDAR-guided pruning and digital orchard platforms, show promise but still require further validation under commercial conditions.

Overall, this section highlights that modelling is not a replacement for field knowledge, but a complementary tool that can improve understanding and guide decision-making. The main opportunity for the Australian avocado industry lies in linking these modelling approaches with practical canopy management, so that light distribution can be measured, predicted, and ultimately optimised under different regional conditions.

5. Light environment assessment tools

To manage canopy light effectively, growers and researchers first need reliable ways to measure it. A wide range of tools is available, from simple handheld instruments to advanced digital systems, but each comes with trade-offs in cost, accuracy, and ease of use. Some tools measure light directly within the canopy, while others estimate light conditions indirectly by describing canopy structure. The challenge is not just collecting data, but doing so in a way that is practical and meaningful for real orchard decisions.

At the simplest level, tools such as ceptometers and in-canopy light loggers can provide useful information on how much light is intercepted and how it changes over time. These tools are relatively affordable and already used in research, with some potential for grower adoption. Other methods, such as hemispherical photography or drone-based imaging, can provide a broader picture of canopy structure and light distribution across whole orchards. More advanced technologies, including LiDAR and three-dimensional modelling, can reconstruct canopy architecture in detail to simulate how light moves through the canopy. While these approaches offer powerful insights, they are more complex, require specialised expertise, and are currently less accessible for routine use.

A key point is that no single tool provides a complete picture. Simple tools are useful for quick measurements and benchmarking, while more advanced systems are better suited to detailed analysis and modelling. Increasingly, the most effective approach is to combine multiple tools, linking ground-based measurements with aerial imaging and modelling frameworks. This allows canopy structure, light distribution, and tree performance to be assessed together, rather than in isolation.

Emerging technologies from other industries, such as low-cost sensors, advanced imaging systems, and real-time light simulations, also show potential for future application in orchards. However, many of these approaches still require validation under commercial conditions and may not yet be ready for practical use. The main opportunity lies in identifying which tools can be used immediately, which require further development, and how they can be integrated into systems that support grower decision-making.

Overall, this section highlights that improving canopy management is not limited by a lack of tools, but by the need to select, adapt, and combine them in ways that are practical, scalable, and aligned with orchard conditions. Developing reliable, user-friendly methods to measure and interpret the canopy light environment will be essential for translating research insights into better pruning and management decisions.

However, the main limitation is not the ability to measure light, but the lack of quantitative relationships linking measured canopy light environments to yield outcomes, which constrains their use in predictive modelling and decision-support systems.

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Section 1: Physiological drivers of productivity

G Rossouw, Queensland Department of Primary Industries

1.1. Context and scope

This section consolidates knowledge on key physiological processes that underpin avocado productivity, spanning light capture, nutrient requirements, carbohydrate reserves, hormonal regulation, and their interactions in regulating carbon availability and allocation to dictate reproductive development. It provides the biological foundation for understanding how these processes integrate to shape yield outcomes and identifies where knowledge gaps constrain the ability to model and manage productivity across diverse growing environments. In addition, this section highlights light use efficiency (LUE) as a key consideration, recognising that productivity is determined not only by the amount of light intercepted but more crucially, by how effectively that light is utilised by the tree.

Maintaining a light-focused perspective:

Section 1 recognises that light interception and distribution as mediated through LUE ultimately govern the rate of carbon capture and therefore form a central driver of avocado productivity. Accordingly, light is treated as the organising variable, while nutrient status, carbohydrate dynamics, and hormonal regulation are interpreted as processes that influence the efficiency with which intercepted light is converted into growth and fruit yield. This framing ensures that physiological insights remain directly relevant to the canopy light environment, supporting identifying knowledge gaps around light capture, distribution, and their impacts on productivity.

Why physiological determinants of yield matter:

Fruit yield in avocado arises from complex, multi-season source–sink dynamics largely initiated by light interception and its distribution within the canopy. The canopy's capacity to capture and distribute light sets the upper limit for photosynthetic carbon assimilation and therefore helps define potential yield. Nutrient balance influences how efficiently the intercepted light energy is transformed into carbohydrates and how effectively these assimilates are distributed to fruit and vegetative sinks.

Carbohydrate reserves buffer temporal mismatches between supply and demand, while hormones regulate the fate of buds, flowers, and fruitlets in response to these carbon signals. These processes explain avocado's heavy flower and fruitlet abscission, regulation of crop load, and tendency toward alternate bearing.

Because all major orchard interventions: pruning, irrigation, nutrition, and use of growth regulators, ultimately act by modifying either the canopy's light environment or the balance between sources and sinks, their productivity effects operate through these physiological pathways. Key findings from the literature include:

- Light capture and leaf function (how well that light is used) are determinants of canopy productivity. Canopy position, leaf age, and environmental stress exposure strongly influence photosynthesis, linking spatial light distribution directly to carbon supply and therefore reproductive success. However, the extent to which light interception translates to avocado fruit yield is not quantified, and relationships linking light interception → carbon assimilation → yield remain largely unparameterised and poorly defined in avocado.
- Nutrient availability influences photosynthetic capacity and therefore the efficiency with which light is converted to carbohydrates, by influencing chlorophyll content, stomatal regulation, and assimilate transport, thereby conditioning the canopy's capacity to convert light energy into carbohydrates.

- Carbohydrate reserves buffer yield fluctuations by integrating the implications of light capture over time. Starch and soluble sugars, accumulated during low-demand periods, are remobilised for flushing, flowering, and fruit growth; reserve depletion under heavy crops contributes directly to alternate bearing.
- Hormonal regulation controls the tree's response to light-driven carbon availability. Auxins, cytokinins, gibberellins, abscisic acid, and ethylene collectively determine bud differentiation, fruitlet survival, and ripening through close interaction with carbohydrate status.
- Reproductive development represents the physiological bottleneck where light capture, carbon economy, and hormonal balance converge. Despite prolific flowering, less than 0.1 % of flowers reach harvestable fruit, reflecting the combined influence of carbon limitation and hormone-mediated abscission.

Integrating physiology with light-focused outcomes:

Collectively, these insights confirm that yield outcomes in avocado result not from isolated factors but from the coordinated effects of carbon balance, nutrient sufficiency, and hormonal signalling within a light-driven framework. By interpreting each physiological process through its influence on light interception, the efficiency of carbon assimilation, or the translation of light energy into yield, Section 1 defines the biological context needed to quantify how the orchard light environment governs crop load and yield potential, and to support the integration of physiological understanding into emerging canopy sensing and modelling frameworks.

The literature reviewed throughout Section 1 identifies several knowledge gaps; however, these are not equivalent in their implications for light modelling and application. The most critical gaps relate to the absence of quantitative relationships linking canopy light environment to yield outcomes, including the roles of light use efficiency within the tree carbon balance framework, and the lack of biologically meaningful light targets that define productive canopy states. These gaps directly constrain the development of accurate, predictive canopy models. In contrast, secondary gaps, such as the detailed effects of specific management interventions, primarily limit the refinement and practical implementation of decision-support tools.

1.2. Background

Avocado yield is determined largely by a complex, multi-season balance between the tree's photosynthetically derived carbon supply, the carbon demands of vegetative and reproductive growth, respiratory carbon losses, and the physiological mechanisms that coordinate these processes (Hormaza et al. 2024; Whiley et al. 2024; Wolstenholme and Whiley 1995). Avocado is an evergreen species with a unique flowering system (protogynous dichogamy), where flowers first open in the female phase and later in the male phase. These phases occur at different times across the canopy, encouraging cross-pollination (Alcaraz and Hormaza 2019; Alcaraz and Hormaza 2024). It also experiences extremely high natural flower and fruitlet drop (abscission), such that only a small fraction of flowers develop into harvestable fruit (Garner and Lovatt 2016).

As a result, relatively small shifts in the canopy's capacity for light interception and within-canopy distribution, leaf photosynthetic performance, carbohydrate allocation, or reproductive intensity can potentially have large effects on yield consistency from year to year. Across cultivars and growing regions, these outcomes are thought to be influenced by how efficiently the canopy captures and distributes light across leaves of different ages and functional status (Schaffer et al. 1991), by non-structural carbohydrate reserves that buffer seasonal mismatches between carbon supply and demand (Liu et al. 1999a), by hormonal signals that set sink priority (which organs receive resources first) and regulate flower and fruitlet abscission thresholds

(Cowan et al. 2001; Garner and Lovatt 2016), and by nutrient status, which underpins leaf chlorophyll content, stomatal regulation, and assimilate transport (Gil et al. 2024).

Non-structural carbohydrates (starch and soluble sugars) form the primary integrator of carbon supply and demand because they provide energy and carbon for structural growth, act as osmotic regulators, and function as metabolic signals that influence flowering, fruit set, and abscission (Rossouw et al. 2024). In avocado, the availability and partitioning of carbohydrates therefore represent a key driver of productivity, serving as the physiological bridge that links canopy-level light capture and its spatial distribution to fruit yield and yield stability across regions and seasons.

The balance among these processes helps explain the regularity (or irregularity) of fruit bearing between consecutive seasons. In practice, heavy crops can deplete starch reserves and disrupt hormonal signals, reducing return bloom and fruit set, whereas seasons of moderate cropping allow reserves to be replenished and capacity rebuilt for the following year (Sharma et al. 2019; Wolstenholme 2010). These multi-season effects demonstrate that light interception, and the efficiency with which intercepted light is converted into assimilated and stored carbohydrates, underpins the long-term stability of yield. Understanding how light interception interacts with these physiological mechanisms is therefore fundamental to improving yield predictability. Quantifying these relationships under contrasting climates and canopy structures remains a major knowledge gap for avocado, directly relevant to the development of regionally adaptive light-interception models and grower-facing decision tools.

Accordingly, Section 1 establishes the physiological foundations: leaf function, nutrient supply, carbohydrate economy, hormonal control, and reproductive development, through the unifying lens of light interception. It examines how these mechanisms collectively influence the efficiency with which intercepted light is transformed into photosynthetic assimilates and, ultimately, yield. Section 2 builds on this foundation by exploring canopy-scale interception and distribution as the primary leverage points for enhancing productivity and yield stability across regions.

Figure 1 provides a conceptual framework illustrating the casual relationships among key drivers. Light interception acts as the initiating process, driving photosynthesis and subsequent assimilate allocation between vegetative growth, reserves, and developing reproductive structures. Nutrient supply and environmental conditions (water, temperature, humidity) modulate photosynthetic efficiency and assimilate transport, while carbohydrate reserves buffer seasonal demand peaks. Hormonal and sugar signalling integrate these processes to regulate floral initiation, fruit set, abscission, and maturation. This framework positions light interception as the entry point linking canopy structure, physiology, and yield, and highlights the knowledge gaps around how these processes and their relative importance vary regionally.

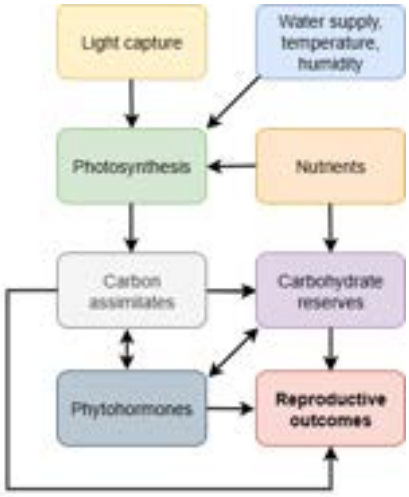

FIGURE 1. Conceptual framework of the physiological drivers of avocado productivity. Light capture initiates photosynthesis, which generates assimilates that are allocated between growth, reserves, and developing reproductive structures. Nutrient supply and environmental conditions (water availability, temperature, humidity) influence photosynthetic efficiency and assimilate transport. Carbohydrate reserves buffer seasonal demand peaks, while hormones and sugar signalling regulate floral initiation, fruit set, abscission and maturation. This framework emphasises light interception as the central driver integrating these physiological processes.

1.3. Light capture and leaf function

Light use efficiency (LUE):

Light interception defines the total energy available to the canopy, but the proportion of that energy converted into assimilated carbon depends on light use efficiency (LUE) (Rosati et al. 2002; Waring et al. 2016). LUE provides a measure of the productivity of trees in relation to the photosynthetically active radiation (PAR) absorbed by the leaves. PAR is defined as the radiation in the 400 to 700 nm waveband, representing the portion of incoming solar radiation that can drive photosynthesis (Meek et al. 1984). PAR is commonly quantified as photosynthetic photon flux density (PPFD), which expresses the number of photons within this waveband incident on a surface per unit time.

LUE therefore measures the efficiency with which plant canopies convert the sun's energy into the chemical energy stored in the products of photosynthesis, mainly carbohydrates, measured as dry matter (Waring et al. 2016). It is often expressed in units of dry matter produced per unit of PAR absorbed (Waring et al. 2016).

This distinction is important for modelling applications. While light interception and some leaf-level physiological responses can be measured or estimated, LUE itself is not currently parameterised for avocado systems and is instead inferred from general plant physiological principles and evidence from other crops. As such, LUE should be treated as a conceptual integrator of processes rather than a directly measurable or currently model-ready variable.

Research on LUE and its effects on productivity in avocado is basically non-existent, with no well-established empirical relationships linking LUE to yield outcomes. This creates a disconnect between the conceptual importance of LUE and its current ability to be parameterised in predictive models.

Nevertheless, LUE likely varies in response to leaf age, canopy position, microclimate, stomatal and mesophyll conductance, and environmental factors such as temperature, vapour pressure deficit (VPD) and water availability (Alon et al. 2022; Cui et al. 2024; Schaffer et al. 2024). These

constraints mean that two orchards with similar light interception can experience very different yield outcomes. Introducing LUE here provides the physiological bridge between canopy-level light capture and the carbon economy described throughout Section 1, although this link is not yet supported by avocado-specific quantitative relationships.

Another angle of LUE is photosynthetic LUE, which describes the efficiency with which absorbed light is converted into instantaneous photosynthetic carbon gain rather than longer-term dry matter production (Jayalath and van Iersel 2021; Song et al. 2022). Photosynthetic LUE is shaped by photochemistry, stomatal behaviour and mesophyll conductance, and declines under environmental stresses that limit CO_2 diffusion or impair photosystem II function (Dian et al. 2023; Jia et al. 2012). While dry-matter LUE integrates photosynthesis, respiration and growth-related carbon losses over longer time scales, photosynthetic LUE reflects a more immediate response of the canopy to light environment and internal leaf physiology. In fruit trees, both forms of LUE should in theory correspond with crop yield or yield efficiency, yet empirical relationships remain largely unquantified for avocado because long-term, integrated measurements of canopy carbon gain, partitioning and fruit yield are lacking.

Photosynthesis and leaf development:

Light availability is a primary environmental factor influencing net CO_2 assimilation in avocado leaves (Liu et al. 2002a). Light captured by chlorophyll in leaves drives the light-dependent reactions of photosynthesis (photosystems I and II), generating energy in the forms of adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH), which fuel the Calvin cycle, where CO_2 is fixed into carbohydrates (Avenson et al. 2005).

Avocado trees maintain an evergreen canopy with leaves that typically persist for 12–18 months, depending on cultivar, environmental conditions, and management practices (Schaffer et al. 1991; Wolstenholme and Whiley 1999). New leaf production occurs in discrete growth flushes, typically two major flushes (spring and summer), largely shaped by atmospheric temperature, water and nutrient supply, and crop load (Thorp et al. 1995; Whiley et al. 1988). At any given time, the canopy contains leaves of multiple ages with different photosynthetic capacities (Schaffer et al. 1991). Leaves that begin fully exposed are often shaded by subsequent flushes; this renewal pattern means canopy architecture and within-canopy light distribution govern the contribution of each leaf cohort to carbon supply and overall LUE.

Young avocado fruit also possess chlorophyll and stomata, permitting limited autotrophic CO_2 assimilation, but as fruit mature, respiration exceeds photosynthesis, making them entirely dependent on leaves or stored reserves for carbon supply (Whiley et al. 1992).

Leaf traits and source strength:

Leaf arrangement and density determine the canopy's potential for light capture, but how that intercepted light is distributed will be examined in Section 2. Leaves undergo a transition from carbon sink to source as they mature, with carbon source contribution and environmental responsiveness changing throughout development (Liu et al. 2002a; Wolstenholme 1990). Newly emerged leaves reach positive net CO_2 assimilation around full expansion, generally around 20 to 24 days after budbreak (Schaffer et al. 2024). Maximum photosynthetic capacity typically occurs 40 to 70 days post-budbreak (Liu et al. 2002a; Schaffer et al. 1991; Whiley 1990).

Leaf position (sun vs shade) strongly influences function, with avocado foliage showing shade-plant-like traits and relatively low light-saturation points, defined as the irradiance at which further increases in light no longer result in proportional increases in photosynthetic CO_2 assimilation (Schaffer et al. 2024; Scholefield et al. 1980). This means that a leaf's contribution depends on both its age and its light environment, directly influencing whole-canopy carbon

balance, and highlighting the importance of canopy structure in regulating spatial heterogeneity of light interception.

Although avocado leaves have relatively low light-saturation points compared with many other tree crops, high irradiance can reduce photosynthetic efficiency through photoinhibition (Powles 1984). When absorbed light energy exceeds the capacity of photosystem II to use it for electron transport, excess excitation energy leads to the production of reactive oxygen species (ROS) and damage to the photosynthetic apparatus (Demmig-Adams and Adams 1992). Photoinhibition is particularly pronounced when high light coincides with water or nutrient stress, which limit CO_2 assimilation and increase the risk of photodamage. In avocado, photo-oxidation: damage from excess light energy under cool temperatures, has been observed to cause leaf yellowing and a decline in photosynthetic performance (Mandemaker et al. 2005). Therefore, canopy management should optimise interception and distribution to maximise assimilation while avoiding photodamage, particularly under stress conditions that reduce repair capacity.

Not all assimilated carbon is available for growth and fruiting. As in other C_3 plants, a substantial proportion (estimated at 30–60%) of gross photosynthates is consumed by respiration for maintenance and growth processes (Amthor et al. 2019), which can be especially high in evergreen species such as avocado (Schaffer et al. 2024). This reduces the net carbon available for export to sinks, reinforcing the importance of sustained leaf function.

Leaf traits such as chlorophyll concentration and stomatal behaviour set the capacity for light absorption and carbon gain. Chlorophyll content peaks in mature leaves but declines with age, leading to progressively lower photosynthetic capacity (Liu et al. 2002a; Schaffer et al. 1991). In functional terms, avocado leaves follow a sink–source trajectory: young expanding leaves act as net importers of carbon, mature leaves become strong exporters, and senescing foliage gradually loses photosynthetic activity (Schaffer et al. 1991; Whiley 1990; Wolstenholme and Whiley 1999).

In avocado, maximum chlorophyll levels are typically reached in mature leaves several weeks after expansion, after which gradual pigment degradation occurs, influenced by environmental stress, nutrient status, and leaf position in the canopy (Schaffer et al. 2024). Photosynthetic capacity also differs between cultivars, for example, ‘Lamb Hass’ often exceeds ‘Hass’, partly due to higher leaf chlorophyll concentrations (Liu et al. 2002a). Shade leaves adapt structurally (e.g. lower chlorophyll a/b ratios) to capture diffuse light but contribute less overall carbon than exterior sun leaves, largely because of reduced stomatal conductance (Björkman 1981; Schaffer et al. 2024). This variation underscores how canopy light gradients create photosynthetic stratification.

Chlorophyll concentration determines a leaf’s potential for light absorption, but this does not always translate into efficient photochemistry. Chlorophyll fluorescence provides a functional measure of photosystem II efficiency, indicating how effectively absorbed light is used for carbon fixation versus dissipated as heat or fluorescence (Maxwell and Johnson 2000). Maximum quantum yield (Fv/Fm), measured under dark-adapted conditions, reflects the proportion of absorbed light that can be used for photochemistry, and declines when leaves experience stress or photoinhibition. In avocado, reductions in Fv/Fm have been observed under high light intensity combined with cool temperatures, consistent with photo-oxidative stress and reduced photosynthetic capacity (Mandemaker et al. 2005). Because fluorescence parameters integrate the impacts of light environment, stress, and nutrient status, they complement chlorophyll concentration as indicators of leaf photosynthetic performance and can provide practical diagnostics for mapping spatial variation in LUE across orchards.

Stomatal regulation and stress sensitivity:

Stomata, microscopic pores regulating CO_2 uptake and water loss, are located on the abaxial (underside) surface in avocado leaves, with density, size, and aperture control potentially varying by cultivar, leaf age, and canopy position (Mickelbart et al. 2000; Schaffer et al. 2024). While stomatal density is thought to be broadly similar in sun and shade exposed avocado leaves, conductance is lower in shaded foliage because of reduced irradiance, indicating a physiological response rather than structural difference (Mickelbart et al. 2000; Sterne et al. 1977). Thus, stomatal regulation is a key determinant of how efficiently avocado leaves convert CO_2 into carbon gain and therefore links microclimate, canopy structure, and carbon assimilation efficiency.

Avocado's xylem vascular system is also hydraulically vulnerable, predisposing the species to rapid declines in leaf water status under environmental stress. As a result, stomata close early in response to even moderate soil or atmospheric water deficits, a strategy that reduces embolism risk but limits CO_2 assimilation and leaf carbon source capacity (Michelakis et al. 1993; Reyes-Santamaría et al. 2002; Schaffer et al. 2024). This conservative water-use strategy helps survival but may constrain productivity in challenging environments and should be accounted for in models predicting regional differences in canopy light-use efficiency and effective interception–utilisation coupling.

Mesophyll conductance:

Beyond stomatal behaviour, the diffusion of CO_2 within the leaf mesophyll also imposes a major limitation on avocado photosynthesis. Mesophyll conductance (g_m) reflects the ease with which CO_2 moves from the intercellular airspace into chloroplasts, and is highly sensitive to environmental conditions, declining under high temperature, water deficit, or other abiotic stresses (Evans et al. 2009; Flexas and Medrano 2002; Flexas et al. 2008; Lloyd et al. 1992). Although g_m has not been widely reported for avocado, its relatively modest maximum photosynthetic rates compared with many other tree crops (Liu et al. 2002a; Schaffer et al. 1991; Scholefield et al. 1980) suggest that internal CO_2 diffusion may contribute significantly to limitation, particularly under stress conditions. This aligns with broader observations in evergreen subtropical trees where both stomatal and mesophyll resistances jointly constrain carbon gain. Quantifying mesophyll conductance and its environmental sensitivity represents a research gap for modelling canopy carbon balance, regional light-use efficiency, and ultimately productivity.

Environmental influences on leaf function:

Regional climate strongly influences avocado leaf function. Low temperatures impair stomatal behaviour and CO_2 assimilation, contributing to reduced photosynthetic performance in cooler environments (Schaffer et al. 2024). Net CO_2 assimilation in avocado leaves is generally maximised between 20–30°C, aligning with the optimal range for whole-plant growth (Schaffer et al. 2024; Scholefield et al. 1980). At high temperatures (>30°C), net CO_2 assimilation declines almost linearly, attributed to increases in stomatal and mesophyll resistances (Liu et al. 2002a; Schaffer et al. 2024). Growth and dry matter accumulation in 'Fuerte' and 'Hass' are considered optimal between 21–33°C (day) and 14–26°C (night) (Lahav and Trochoulias 1982). Importantly, 'Hass' shows greater adaptability to temperature extremes than 'Fuerte', sustaining growth under both cooler and warmer regimes. This adaptability likely contributes to its broad climatic success. These cultivar-specific responses emphasise the need for regionally parameterised light-response models that reflect environmental envelopes for photosynthetic efficiency.

Overhead shading during high-temperature events can lower leaf temperature and increase photosynthesis, even though overall light availability is reduced (Alon et al. 2022). In practice,

both light and temperature jointly define the physiological envelope of avocado leaf function, reinforcing the role of canopy management in moderating these stresses.

Avocado yields also differ across climates: in semi-arid and Mediterranean regions, average yields often reach only up to 8–12 t ha^{-1}, while humid subtropics can reach around 12–16 t ha^{-1} (Wolstenholme and Whiley 1999). One key driver of these differences is vapour pressure deficit (VPD). High VPD (low humidity combined with high temperature) negatively impacts flowering, fruit set, and yield, causing leaf, flower, and fruit abscission that irrigation alone cannot fully offset (Schaffer et al. 2024). Stomata are highly responsive to VPD fluctuations: conductance decreases as VPD rises (Bunce 2006; Grossiord et al. 2020). The decline in stomatal conductance is directly linked with reduced net CO_2 assimilation. In theory, high VPD increases atmospheric demand for water (through transpiration), but avocado leaves respond by closing stomata to prevent excessive water loss (Schaffer et al. 2024). This protective mechanism, however, comes at the cost of reduced carbon assimilation, helping to explain why Mediterranean/temperate orchards often yield less than humid subtropics. Accordingly, VPD-driven modifiers should be incorporated into light-interception/LUE models to capture realistic regional productivity patterns.

Water availability further constrains leaf function. Under drought, avocado leaves reduce stomatal conductance, stem water potential, and CO_2 assimilation, often within only a few days of soil moisture depletion (Carr 2013; Schaffer et al. 2024). In Mediterranean-type climates, the combination of high VPD and limited soil moisture accelerates stomatal closure, leading to sharp declines in leaf gas exchange and photosynthesis (Scholefield et al. 1980). Conversely, in the humid tropics, excess water can be just as damaging: seasonal waterlogging reduces transpiration, stomatal conductance, and carbon assimilation (Schaffer et al. 2024). Flooding also exacerbates photoinhibition, further suppressing photosynthetic capacity of the canopy (Lin et al. 2022; Reeksting et al. 2014).

Alongside these climatic drivers, nutrient supply exerts a fundamental influence on leaf metabolism and photosynthetic resilience. Because of its central role in sustaining canopy function and fruit support, nutrient dynamics are considered in detail in Section 1.4.

Light use - closing synthesis:

Ultimately, canopy carbon source strength depends not only on leaf age and light environment but also on maintaining leaf health. Any reduction in functional leaf area directly constrains carbon supply to fruit, underscoring the centrality of canopy condition in avocado productivity (Schaffer et al. 1991; Whiley et al. 1988; Wolstenholme 2010). Thus, while light interception initiates carbon capture, its contribution to yield ultimately depends on how effectively leaves maintain photosynthetic function, regulate water loss, and sustain assimilate export under varying environmental and crop load conditions.

Leaf carbohydrate status also feeds back on photosynthetic capacity: when sink demand is low (for example, low fruit load), accumulation of starch and soluble sugars in avocado leaves can downregulate further photosynthesis (Goldschmidt and Huber 1992; Paul and Foyer 2001). Conversely, strong sink demand (e.g. developing fruit) promotes continued carbon assimilation and export. Crop load is one of the strongest regulators of leaf source activity: high fruit demand maintains strong assimilation and sucrose export, whereas light crop years are associated with reduced export and accumulation of starch in leaves (Rossouw et al. 2024; Schaffer et al. 1991). These feedbacks between light environment, crop load, and carbohydrate status demonstrate the direct coupling between canopy structure and productivity. Quantifying these relationships (light gradients → leaf LUE → export → reserve dynamics) across regional climates is a key knowledge gap for predictive light-interception models and grower decision support tools.

This section highlights the physiological sensitivities that underpin yield variability and sets the stage for Section 2's focus on canopy-level light interception. Figure 2 complements this discussion by depicting the primary pathways and constraints at the leaf level, indicating where measurements (e.g. chlorophyll fluorescence, gas exchange, leaf N) could parameterise regionally adaptive light-response models.

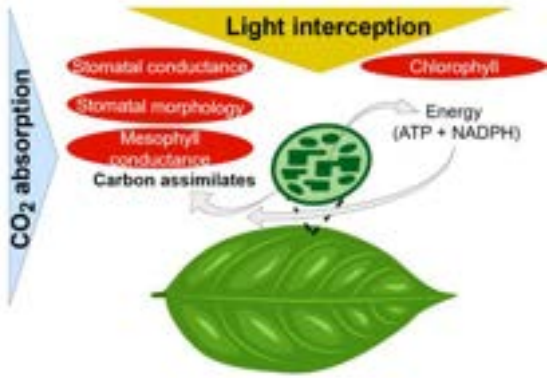

FIGURE 2. Simplified representation of leaf-level controls on photosynthesis in avocado. Light intercepted by the canopy is captured by chlorophyll in the thylakoid membranes of chloroplasts, driving the light-dependent reactions and generating energy (ATP and NADPH). In parallel, CO_2 enters through stomata, with uptake determined by stomatal conductance, stomatal traits (density and size), and mesophyll conductance. Energy from the light reactions and CO_2 together fuel the Calvin cycle, producing carbon assimilates. These assimilates are available for growth and fruiting or storage, although a large proportion is consumed by respiration. This schematic highlights measurable control points that link light interception to LUE and can be used to calibrate regional canopy models.

1.4. Nutrient influences on leaf function

Alongside the environmental influences on leaf metabolism described in Section 1.3, nutrient status strongly affects avocado leaf photosynthesis and canopy performance (Gil et al. 2024; Granja and Covarrubias 2018). In practice, nutrient balance acts as a first-order modifier of how efficiently intercepted light is converted into carbon assimilates. Similar to water stress, imbalances in nutrient supply can render leaves inefficient at using light, so that even with good light capture, photosynthesis is limited. Because nutrients form the biochemical foundation for light absorption, energy transfer, and assimilate transport, this subsection focuses on those elements most directly influencing the efficiency of carbon assimilation (thus, LUE). However, some broader physiological roles are also described where they help explain how nutrient function links to canopy performance and fruit productivity. Overall, nutrient balance therefore functions as a primary modulator of canopy LUE and the coupling between light interception and utilisation.

Nitrogen:

Nitrogen concentration is closely correlated with chlorophyll content and ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) enzyme activity, together setting the upper limit for carbon assimilation. Excess nitrogen, however, shifts carbon allocation toward vegetative growth at the expense of reproduction (Evans 1989; Leghari et al. 2016; Warren et al. 2000). A large proportion of leaf nitrogen is invested in chlorophyll–protein complexes within the thylakoid membranes, which determine light absorption and energy transfer (Evans 1989; Evans and Poorter 2001). Much of the rest is invested in Rubisco, the key enzyme that catalyses fixation of carbon in the Calvin cycle (Leghari et al. 2016; Warren et al. 2000). As a result, nitrogen supply directly defines both the light-harvesting capacity and the maximum carboxylation rate of avocado leaves (Evans 1989). Nitrogen deficiency reduces chlorophyll concentration and impairs Rubisco activity, leading to lower photosynthetic rates, while oversupply encourages

excessive vigour. Optimising nitrogen for efficient carbon assimilation and light-driven yield, rather than maximum vegetative vigour, is therefore critical.

Phosphorus:

Phosphorus is a fundamental component of cellular energy, present in adenosine triphosphate (ATP) and its cycling with adenosine diphosphate (ADP), nucleic acids, and membrane phospholipids, making it central to the energy transfer reactions that underpin photosynthesis and carbon assimilate metabolism (Poirier et al. 2022; Rychter and Rao 2005). When phosphorus is limited, leaves cannot use absorbed light effectively, leading to carbohydrate build-up in chloroplasts, photoinhibition, and reduced LUE (Carstensen et al. 2018). ATP production also falls, disrupting sugar export and canopy carbon balance. Although deficiency symptoms are relatively uncommon in avocado orchards, when they occur, leaves are typically small, leathery, and dull in colour with irregular necrotic spots, accompanied by premature leaf shedding and branch dieback (Gil et al. 2024). These visible changes mirror impaired energy metabolism and transport, linking phosphorus status to canopy function and yield. Operationally, phosphorus deficiency lowers the conversion efficiency of intercepted light and weakens the light interception–carbon export relationship.

Potassium:

Potassium plays a central role in stomatal regulation, enzyme activation, and phloem sugar loading, making it essential for both carbon assimilation and assimilate export (Shah et al. 2024; Tränkner et al. 2018). Adequate potassium supply promotes stomatal opening and maintains high mesophyll conductance, thereby supporting CO_2 uptake and photosynthesis under fluctuating environmental conditions (Hu et al. 2022). Avocado has a relatively high potassium requirement, with mature fruit often containing more potassium than nitrogen, so that heavy cropping places strong demands on potassium supply (Gil et al. 2024).

Potassium also underpins sucrose transport in the phloem, ensuring effective distribution of carbon to sinks (Tränkner et al. 2018). Deficiency first appears in the canopy as small, narrow leaves with necrotic spotting, later progressing to reduced growth and dieback (Gil et al. 2024). These symptoms reflect impaired stomatal regulation, photosynthesis, and sugar transport. In canopy-scale terms, potassium status influences the light interception–utilisation coupling by jointly affecting CO_2 entry and carbon export.

Magnesium:

Magnesium is the central atom of the chlorophyll molecule, and its availability directly determines chlorophyll content and light absorption capacity (Farhat et al. 2016; Tränkner et al. 2018). In addition, magnesium is a cofactor for hundreds of enzymes, including those required for ATP formation and utilisation, for CO_2 fixation in the Calvin cycle, and for sucrose loading into the phloem (Cakmak and Kirkby 2008; Kleczkowski and Igamberdiev 2021). Deficiency therefore impairs light capture, carbon fixation, and assimilate export. Because magnesium is mobile within the plant, deficiency symptoms in avocado first appear in older leaves, typically as interveinal chlorosis where veins remain green but interveinal tissue turns yellow, sometimes progressing to necrosis under severe deficiency (Gil et al. 2024). These visual symptoms reflect reduced functional canopy area and constrained assimilate supply to developing sinks. Thus, magnesium availability sets an upper bound on effective light absorption and sustained carbon assimilation efficiency.

Calcium:

Calcium is essential for cell wall structure, membrane stability, and intracellular signalling, making it a key determinant of leaf integrity and stress responses (Eckardt 2001). In leaves, calcium cross-links pectins in the cell wall, providing mechanical strength and conferring protection against wall-degrading enzymes (Gil et al. 2024; Hocking et al. 2016). It also functions

as a secondary messenger in numerous physiological processes, including stomatal regulation, stress perception, and defence responses (White and Broadley 2003), and supports electron flow through photosystem II (Umena et al. 2011; Wang et al. 2019), linking calcium status directly to the efficiency of photosynthetic energy conversion.

Because calcium uptake is largely passive and driven by transpiration, supply to leaves depends on sustained water flow from the roots (Hocking et al. 2016). Calcium is immobile in the phloem, and therefore symptoms develop primarily in young tissues with limited supply, though in avocado they are rarely observed under orchard conditions. When present, symptoms include scorched leaf tips, reduced leaf size, and occasional dieback, reflecting impaired wall and membrane stability (Gil et al. 2024). These changes reduce functional leaf area and compromise canopy resilience, constraining both light capture and assimilate supply. Calcium management therefore contributes to maintaining the functional canopy area required for efficient light interception.

Boron:

Boron is critical for both structural integrity of cells and for assimilate transport, making it a key determinant of leaf function and canopy performance. In cell walls, boron cross-links rhamnogalacturonan II, a pectic polysaccharide, thereby strengthening wall structure and maintaining porosity for normal expansion and transport processes (O'Neill et al. 2001). At the canopy level, boron is also essential for phloem function, influencing sucrose loading and assimilate partitioning, in part through the formation of borate–sugar complexes (Brown et al. 2008; Vera-Maldonado et al. 2024). In other fruiting species such as mango, boron is shown to be associated with enhanced chlorophyll and non-structural carbohydrate concentrations in leaves, improving the carbon-to-nitrogen ratio and thereby contributing to flowering, fruit set, and yield potential (El-Motaium et al. 2019; Shaban et al. 2019).

Boron deficiency is one of the most common nutritional disorders in avocado, particularly in acidic or low-organic matter soils (Gil et al. 2024). Early symptoms include shot-holed and brittle leaves, yellowing, and distorted growth, progressing under severe deficiency to swelling of nodes, dieback, and reduced apical dominance. These effects reflect impaired sugar transport and cell wall stability, reducing functional leaf area and limiting assimilate movement to sinks. Functionally, boron status influences both the stability of light-harvesting tissues and the efficiency of post-interception carbon export.

Iron:

Iron is indispensable for chlorophyll biosynthesis and electron transport, making it central to light capture and photosynthetic efficiency (Rout and Sahoo 2015). Within the chloroplast, iron is a cofactor for enzymes of the chlorophyll biosynthetic pathway and forms part of iron–sulphur clusters and cytochromes that mediate electron transfer in photosystems I and II (Briat et al. 2015). Deficiency therefore reduces chlorophyll content and disrupts electron flow, leading to interveinal chlorosis, reduced photosynthetic rates, and impaired carbohydrate production. In avocado, symptoms appear first in young leaves as interveinal yellowing with narrow green veins, progressing under severe deficiency to pale or even white leaves, marginal scorch, defoliation, shoot dieback, and fruit discolouration (Gil et al. 2024). This loss of chlorophyll reduces canopy efficiency and assimilate supply, constraining fruit development and yield. Iron availability therefore influences both absorption and photochemical conversion of intercepted light.

Zinc:

Zinc is essential for enzyme function, auxin synthesis, and chlorophyll biosynthesis, linking it directly to photosynthetic efficiency and leaf development (Broadley et al. 2007). It also serves as a cofactor in antioxidant enzymes, which protects chloroplasts from oxidative stress under high light or other environmental challenges (Cakmak 2000). As a structural or catalytic cofactor

for numerous enzymes, zinc contributes to protein and nucleic acid synthesis and regulates auxin metabolism, influencing shoot growth and leaf expansion (Brown et al. 1993; Gil et al. 2024). It also facilitates the conversion of sugars into starch and has a role in reproductive function through its influence on pollen viability and fruit set (Gil et al. 2024).

Deficiency reduces chlorophyll synthesis and photosynthetic activity, and is one of the most common micronutrient disorders in avocado worldwide, particularly in calcareous and sandy soils or under high nitrogen and phosphorus fertilisation (Crowley et al. 1996). Symptoms include leaf mottling between veins, reduced leaf size, shortened internodes, and rosetting of foliage, giving a "feather-duster" appearance (Gil et al. 2024). Severe deficiency leads to small, often rounded fruit and progressive canopy decline, ultimately reducing yield and tree health. These effects reflect disruption of both chlorophyll biosynthesis and auxin-mediated growth, reducing functional leaf area and assimilate production, with direct consequences for productivity. In functional terms, zinc status may alter effective light-intercepting area and carbon assimilation efficiency.

Manganese:

Manganese is a key cofactor in the oxygen-evolving complex of photosystem II, where it enables the photolysis of water and the release of electrons, protons, and oxygen (Millaleo et al. 2010; Sauer 1980). It also contributes to chloroplast formation, chlorophyll synthesis, nitrogen metabolism, and the activity of numerous enzymes involved in photosynthesis and oxidative stress defence (Gil et al. 2024). Deficiency therefore disrupts electron flow in photosynthesis, leading to reduced carbon assimilation and LUE. In avocado, deficiency is most often associated with alkaline or sandy soils and appears as interveinal chlorosis of young leaves that progresses to pale yellow or dull green foliage under severe stress. Manganese toxicity is more commonly reported in avocado. Excess accumulation, typically under acidic soils, produces interveinal chlorosis with reddish-brown or black spotting and has been associated with reduced rooting ability and lower productivity. Both deficiency and toxicity reduce functional canopy area and disrupt photosystem II activity, ultimately constraining assimilate supply and yield potential. Table 1 summarises nutrient functions most relevant to LUE and leaf photosynthetic performance. Although the table emphasises deficiency, toxicity under excess supply also disrupts canopy function and should be represented as penalties in modelled efficiency.

TABLE 1. Key nutrient roles in avocado leaf function and light use efficiency. The nutrients below influence light capture, photochemistry, CO_2 entry, and assimilate export. Many also affect carbohydrate partitioning, sink strength, and reproductive development; those broader roles are handled where relevant in subsequent sections.

Nutrient	Role in light use efficiency	Deficiency effects on photosynthesis
Nitrogen (N)	Major component of chlorophyll and Rubisco; sets capacity for light absorption and CO_2 fixation.	Reduced chlorophyll concentration, lower maximum assimilation rates.
Phosphorus (P)	Central to energy cycling (ATP/ADP); drives energy transfer for Calvin cycle reactions.	Energy (ATP) shortage, impaired light utilisation; carbohydrate build-up in leaves leading to feedback inhibition of photosynthesis; increases predisposition to photoinhibition.
Potassium (K)	Regulates stomatal opening and mesophyll conductance; supports CO_2 uptake.	Poor stomatal control, reduced CO_2 assimilation, lower light use efficiency.
Magnesium (Mg)	Central atom of chlorophyll, sets capacity for light capture; cofactor in ATP synthesis and Calvin cycle enzymes.	Reduced chlorophyll concentration, reduced photosynthetic efficiency, impaired CO_2 fixation.
Calcium (Ca)	Stabilises chloroplast membranes and cell walls; supports electron flow and stress signalling affecting stomatal regulation.	Reduced leaf integrity, impaired PSII stability leading to reduced photosynthesis; decreased light-use efficiency.

Boron (B)	Supports cell wall structure including chloroplasts and stomata; indirectly maintains leaf function.	Limited photosynthetic efficiency and assimilate movement.
Iron (Fe)	Essential for chlorophyll biosynthesis and electron transport during photosynthetic light reactions.	Reduced chlorophyll concentration, disrupted electron flow, reduced photochemical efficiency.
Zinc (Zn)	Cofactor for chlorophyll biosynthesis enzymes; protects against photoinhibition.	Impaired chlorophyll synthesis, reduced CO_2 assimilation.
Manganese (Mn)	Cofactor in oxygen-evolving complex during light reactions of photosynthesis; required for water splitting to generate energy that drives the Calvin cycle.	Disrupted electron flow, impaired carbon assimilation.
Sulphur (S)	Component of amino acids, chlorophyll-binding proteins, and Fe–S clusters in photosystems needed for light reactions.	Reduced chlorophyll and photosynthetic enzyme activity.
Copper (Cu)	Needed for functioning of the electron transfer chain to generate energy from light.	Impaired electron transport, reduced photosynthetic efficiency.
Chloride (Cl)	Cofactor in the oxygen-evolving complex of light reactions; supports stomatal regulation.	Reduced electron flow, poor stomatal function.

Other nutrients:

Several additional mineral nutrients play smaller but still important roles in sustaining avocado leaf function and canopy productivity. Sulphur is required for amino acids and proteins that form components of chlorophyll and photosynthetic enzymes, with deficiency leading to general chlorosis and reduced assimilation capacity (Shah et al. 2022). Molybdenum is a cofactor for nitrate reductase, enabling nitrogen assimilation and thereby indirectly supporting Rubisco activity and carbon fixation (Mendel and Hänsch 2002; Rana et al. 2020). Copper functions as the electron carrier plastocyanin in photosynthetic electron transport, and also supports lignin synthesis and defence responses (Yruela 2009). Chloride is required in small amounts for stomatal regulation and the oxygen-evolving complex of photosystem II, where both deficiency and excess can impair electron transport and water relations (Geilfus 2018; White and Broadley 2001).

Nickel, though needed only in trace amounts, is a component of urease and contributes to nitrogen metabolism and leaf longevity (Fabiano et al. 2015). Sodium is not essential but can substitute partly for potassium in stomatal function and osmotic regulation in some species; however, its accumulation under saline conditions is detrimental to photosynthesis and canopy productivity (Munns and Tester 2008). Avocado trees are highly susceptible to excess sodium (Gil et al. 2024).

While these elements are rarely limiting in well-managed orchards, their adequate supply is necessary to maintain the biochemical capacity of avocado leaves to capture and process light energy, assimilate carbon, and sustain reproductive sinks.

Nutrition - Closing synthesis:

Nutrient status fundamentally shapes the capacity of avocado leaves to act as effective sources, influencing chlorophyll concentration, stomatal regulation, energy metabolism, and assimilate transport. Although not all nutrient functions are directly related to light capture, their broader physiological roles collectively determine how efficiently light energy is converted into assimilated carbon and, ultimately, productivity. Deficiencies or imbalances in key elements reduce functional canopy area, constrain photosynthetic efficiency, and limit the supply of carbohydrates to developing sinks. In practice, nutrient status modifies the effects of light, water, and crop load, amplifying or moderating their influence on carbon balance. This interaction is regionally contingent, reflecting soil type, climate, and cultivar, and represents a practical barrier to a one-size-fits-all canopy model. Prioritised gaps include: (i) quantitative functions linking nutrient status to leaf-level light-response parameters; (ii) region-specific sufficiency ranges;

and (iii) integration of tissue diagnostics with canopy light models to improve prediction of interception–utilisation relationships. Because carbohydrate reserves and source–sink relationships ultimately integrate these inputs into patterns of growth, yield, and return bloom, the next section examines how reserve dynamics govern tree productivity. By conditioning leaf photosynthetic performance, nutrient balance underpins the light-capture processes discussed in Section 1.3 and provides key inputs for the canopy-scale modelling.

1.5. Carbohydrate reserves and source–sink relationships

Carbohydrates mediate how intercepted light is integrated over time into yield. Because reserve dynamics determine whether light-derived assimilates support flowering, fruit growth, and return bloom, this subsection focuses on reserves and source–sink relationships. We keep the emphasis on how canopy light environment and LUE translate into reserve formation and drawdown, but include selected avocado-specific features (e.g., C_7 sugars, oil synthesis) where they help clarify how light capture → carbon allocation → yield unfolds.

Source–sink allocation and reserve buffering:

Non-structural carbohydrate (NSC) partitioning in avocado is governed by the balance between carbon sources, primarily leaves, and sinks such as developing fruit, new shoots, and flowers. Leaves act as the dominant source, but during periods of high sink demand or reduced canopy assimilation, reserves in woody tissues and roots are mobilised to buffer supply (Liu et al. 1999a; Rossouw et al. 2024; Scholefield et al. 1985; Van der Walt et al. 1993; Van Vuuren et al. 1997).

Sugars produced in avocado leaves are first allocated to immediate needs: respiration, consuming a large share of daily assimilates, and growth of vegetative and reproductive sinks (Blanke 2009; Finazzo et al. 1994; Kozlowski 1992). When photosynthetic supply exceeds these demands, surplus sugars are translocated to storage organs and converted into starch. Reserves stored in leaves, branches, trunk, shoots, and roots sustain the tree during periods when photosynthesis cannot meet demand. This commonly happens during vegetative flushing, flowering, or fruit growth (Rossouw et al. 2024; Van Vuuren et al. 1997). Thus, reserve accumulation is a light-mediated outcome, constrained by interception, within-canopy distribution, and LUE.

Studies assessing carbohydrate reserves in avocado tree organs are scarce. However, Liu et al. (1999a) showed that in ‘Hass’ trees, shoots appeared to be the dominant seasonal buffer regarding reserves, with soluble sugars peaking after the spring flush and again in midwinter, while starch built up through winter to a maximum before flowering, then declined to a summer low. This seasonal cycling reflects starch–sugar conversion to support vegetative growth, flowering, and fruit development (Rossouw et al. 2024). Figure 3 illustrates these dynamics and links them to the canopy light environment, showing how leaf-derived sugars are partitioned to immediate demands, stored as reserves, and later remobilised to support phenological peaks (flushing, flowering, fruit growth).

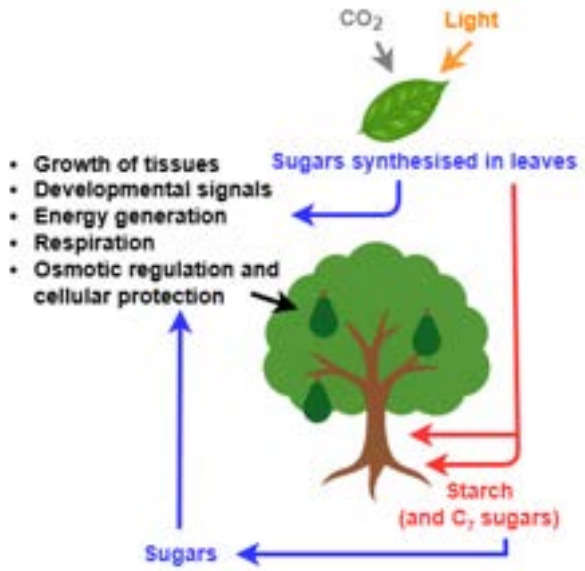

FIGURE 3. Carbohydrate source–sink and reserve dynamics in avocado. Leaves assimilate CO_2 and light into sugars (sucrose, glucose, fructose, and avocado's distinctive C_7 sugars, mannoheptulose and perseitol). These sugars are allocated to immediate needs including respiration, tissue growth, developmental signalling, energy generation, and osmotic protection, or stored as starch and C_7 sugars in woody tissues and roots. Reserves are later remobilised to buffer periods of high demand such as flushing, flowering, and fruit growth. Developing fruit represent dominant sinks, requiring carbohydrates both for mesocarp expansion and oil synthesis, creating competition with vegetative sinks and influencing reserve recovery and yield regularity.

Composition and distribution of reserves:

Like other trees, avocado contains carbohydrates as starch, and the soluble sugars, sucrose, glucose, and fructose (Liu et al. 1999a; Scholefield et al. 1985; Wolstenholme and Whiley 1997). Avocado is unusual among fruit trees in also producing the C_7 monosaccharide D-mannoheptulose and its polyol form, perseitol, compounds thought to play pivotal roles in carbon allocation, transport, and stress tolerance (Cowan, 2017, Liu et al., 2002b, Liu et al., 1999a). Together, these C_7 sugars can account for 40–90% of total soluble sugars across organs. Their seasonal fluctuations closely track those of shoot total soluble sugars (Liu et al., 1999a).

Starch is the immobile, osmotically inert storage form, while soluble sugars make up the transportable pool redistributed via the phloem (Kühn et al. 1999). Leaf starch follows a diurnal cycle: excess photosynthate accumulates during the day and is remobilised overnight as sucrose to sustain sink demand (Kötting et al. 2010). In contrast, woody tissues store starch over longer timescales, accumulating in low-demand periods and being remobilised during phenological peaks such as flowering and fruit growth (Loescher et al. 1990; Rossouw et al. 2024).

The trunk, branches, and large roots act as the primary long-term starch storage sites, mobilised whenever sink demand exceeds current photosynthesis (Rossouw et al. 2024; Van Vuuren et al. 1997). These tissues alternate between serving as sinks during replenishment and as sources during regrowth, flowering, and fruiting (Bihmidine et al. 2013). In avocado, shoots appear to dominate seasonal buffering (Liu et al. 1999a), although the relative contribution of trunk, branches and roots is less well quantified than in many other fruit trees.

Liu et al. (1999a) showed that among organs, the trunk contained the highest starch concentrations, followed by coarser roots (2 to 5 mm in diameter). However, the study assessed only stems, leaves, trunk, coarser roots, and fine roots. Interestingly, all organs were dominated

by soluble sugars. In stems, D-mannoheptulose was most abundant, followed by perseitol, and then the combined pool of sucrose, glucose, and fructose. In leaves, sucrose, glucose, and fructose predominated over perseitol and D-mannoheptulose. In the trunk and coarse roots, D-mannoheptulose was highest, with sucrose, glucose, and fructose occurring at similar levels to perseitol. Fine roots were dominated by D-mannoheptulose, followed by perseitol, with only minor amounts of sucrose, glucose, and fructose. These patterns highlight the distinctive carbohydrate economy of avocado and the organ-specific pools that buffer variation in carbon supply arising from light availability. A priority gap is organ-resolved quantification of pool sizes and turnover across regions to support the canopy-environment framing and future modelling.

Reproductive demand and sink competition:

NSC availability during reproductive development strongly influences avocado fruiting capacity (Liu et al. 1999b; Scholefield et al. 1985). All developmental processes including floral induction, fruit set, and early fruit growth depend on adequate sugar supply (Alcaraz et al. 2013; Chaikiattiyos et al. 1994; Rossouw et al. 2024). At the organ level, flower pistil starch status appears critical: flowers with higher style and ovary starch at anthesis were more likely to set fruit, while those with lower starch concentrations abscised despite pollination (Alcaraz et al. 2013). Style starch declines rapidly after anthesis, consistent with mobilisation to support pollen tube growth and initial ovary development. Variability in pistil starch within the same tree suggests floral carbohydrate status may predetermine reproductive potential. Since pistil carbohydrate status is likely influenced by whole-canopy carbon supply, the light environment and leaf function may influence the probability of fruit set.

Avocado fruit are further distinguished from many other fruit crops by the accumulation of considerable quantities of oil during maturation, in addition to carbohydrates (Pedreschi et al. 2019). Although lipids (mainly triglycerides) constitute the main storage product in the mesocarp, their biosynthesis relies heavily on carbohydrate-derived precursors and energy. Developing fruit therefore place a sustained assimilate demand on the tree. This demand covers fruit growth, and both direct carbohydrate accumulation and oil synthesis, reinforcing their role as dominant sinks during growth and maturation (Hormaza et al. 2024). Oil synthesis begins shortly after fruit set, proceeds most actively during the first half of fruit development, and continues until harvest, with the mesocarp reaching 60–70% oil on a dry weight basis (Kilaru et al. 2015; Pedreschi et al. 2019). The extent to which oil metabolism contributes to competition with vegetative sinks or reserve replenishment is not fully quantified. However, it likely amplifies the overall carbon cost of fruit development in avocado compared with carbohydrate-dominant fruit species. C_7 sugars may also help regulate oil biosynthesis during early fruit growth, adding another dimension to avocado's carbohydrate–lipid metabolic integration (Pedreschi et al. 2019).

Avocado fruit carbohydrate composition is further distinguished by high concentrations of the C_7 sugars mannoheptulose and perseitol, which dominate soluble carbohydrate pools in both the flesh and skin (Burdon et al. 2024). During ripening, mannoheptulose, perseitol, glucose, and fructose decline markedly, while sucrose remains relatively more stable, especially in the flesh. Starch is also present in the mesocarp but decreases during ripening and storage, with sharper declines observed in the skin. Tissue-specific contrasts are also apparent. For example, skin contains higher mannoheptulose concentrations, whereas perseitol predominates in the flesh. Sucrose is consistently more abundant in the flesh than in the skin (Burdon et al. 2024; Liu et al. 1999b; Liu et al. 2002b). These developmental and spatial patterns emphasise that fruit carbohydrate metabolism is dynamic, integrated with whole-tree phenology, and closely tied to ripening progression and storability. The decline of C_7 sugars in particular has been proposed as a key metabolic marker of fruit maturity and postharvest quality (Burdon et al. 2024; Liu et al. 2002b).

Sink strength is defined by both size and activity (Bihmidine et al. 2013; Marcelis 1996). Rapidly growing fruit represent strong sinks that can outcompete vegetative flushes or smaller fruit, contributing to the abscission of weaker sinks under heavy crop loads (Alcaraz and Hormaza 2019; Bangerth 2000). Competition between vegetative and reproductive sinks is particularly evident within indeterminate floral shoots, which bear both a vegetative apex and flowers. These shoots consistently show lower fruit set than determinate shoots that lack a vegetative portion (Hormaza et al. 2024; Salazar-García et al. 1999). Removal of the vegetative portion or application of paclobutrazol to suppress its growth has been shown to increase fruit set, consistent with reduced competition for assimilates (Hormaza et al. 2024; Wolstenholme et al. 1990). However, other studies observed that indeterminate shoots can export carbohydrates, and fruit abscission continued even after the period of active vegetative growth (Finazzo et al. 1994; Thorp et al. 1993). These findings suggest that while local competition contributes to fruitlet loss, abscission is not solely a consequence of carbohydrate limitation but is also influenced by hormonal regulation (Hormaza et al. 2024).

Beyond serving as substrates, soluble sugars also act as developmental signals and interact with hormones in regulating induction, set, abscission, and retention (Durán-Soria et al. 2020; Eveland and Jackson 2011; Rolland et al. 2006). This integration between carbohydrate and hormonal regulation is well described in other fruit trees but remains poorly understood in avocado, providing the foundation for Section 1.6. Clarifying these interactions will help explain why similar light environments can lead to different reproductive outcomes across sites and seasons.

Crop load dynamics and alternate bearing:

Reserve depletion during fruit growth can leave trees with insufficient NSC reserves to support return bloom, contributing to alternate bearing (Monselise and Goldschmidt 1982). Avocado fruit growth follows a sigmoid curve, requiring a continuous assimilate supply, especially during the rapid fruit growth phase spanning several months (Cowan et al. 2001; Van Vuuren et al. 1997). When reserves are heavily consumed in one season, incomplete replenishment may constrain reproductive performance in the next. Heavy crops not only deplete reserves but also suppress vegetative regrowth and may delay fruit maturation. They also reduce average fruit size and quality (particularly dry matter content). By contrast, light crops permit greater reserve accumulation and recovery of vegetative capacity (Scholefield et al. 1985; Sharma et al. 2019).

Crop load intensity therefore constrains both reserve replenishment and the number of vegetative shoots available for return bloom. As in other tree crops such as mango, the leaf-to-fruit ratio provides a useful indicator of source–sink balance (Rossouw et al. 2024). Too few leaves per fruit reduce assimilate supply, fruit size, and quality, whereas higher ratios favour reserve recovery and more consistent cropping (Scholefield et al. 1985; Sharma et al. 2019). Although no firm thresholds are set for avocado, the principle of adequate leaf area per fruit is well supported. This reinforces the canopy-level trade-off: interception and LUE per unit leaf area must meet current demand and rebuild reserves for the following season.

Cultivar differences in bearing regularity are widely recognised, but systematic comparisons in avocado remain limited. While rootstocks are known to affect vigour and stress tolerance, their influence on carbohydrate allocation and alternate bearing is poorly understood. These genotype effects likely mediate how effectively trees translate intercepted light into reserve recovery under contrasting climates.

Management implications and knowledge gaps:

The balance between sources and sinks is not only intrinsic to avocado physiology but is also shaped by orchard management. Interventions such as pruning, fruit thinning, irrigation, nutrient

supply, PGRs, or girdling alter the carbohydrate economy by changing either source capacity or sink demand. For instance, pruning and thinning shift the leaf-to-fruit ratio and influence reserve accumulation (Whiley et al. 2024), PGRs such as paclobutrazol and uniconazole can redirect assimilates toward reproductive sinks (Lovatt and Salazar-García 2006; Wolstenholme et al. 1990), and girdling manipulates carbohydrate distribution by restricting phloem sugar transport (Goren et al. 2003). These management strategies, discussed further in Section 3, operate through their effects on the canopy light environment and the reserve pathway, highlighting carbohydrate status as the physiological link between management decisions and yield outcomes and the capacity to rebuild reserves under a given light regime.

Despite the central role of NSCs, several uncertainties remain. The relative contributions of different organs to whole-tree reserves are not well quantified, nor is the extent to which crop load intensity shifts partitioning between vegetative and reproductive sinks. The physiological roles of avocado's unique sugars, mannoheptulose and perseitol, remain incompletely understood, though evidence points to functions in transport, signalling, and stress buffering (Cowan 2017; Liu et al. 2002b). Experimental studies directly linking reserve status to return bloom are limited. More broadly, sugars act as osmotic regulators and signalling molecules influencing stomatal control, induction, abscission, and sink priority (Paul and Foyer 2001; Rolland et al. 2006; Smith and Stitt 2007). For modelling canopy function and yield dynamics, reserves represent a critical but difficult-to-quantify variable. This highlights the need for improved methods to quantify and predict their behaviour (e.g. standardised, organ-resolved reserve assays across seasons; functions linking reserve status to set and return bloom; representation of C_7 sugars in transport/signalling modules).

Carbohydrates - closing synthesis:

Carbohydrate reserves integrate the effects of light capture (Section 1.3), nutrient balance (Section 1.4), and sink demand into the realised carbon supply for growth and reproduction. When reserves are ample, they stabilise flowering, fruit set, and early fruit growth; when depleted, they predispose trees to abscission and reduced return bloom. Because sugars also act as signals that shape sink priority, carbohydrate status interacts closely with hormonal regulation, the focus of Section 1.6, and ultimately determines reproductive outcomes, developed further in Section 1.7. Quantifying how the canopy light environment and its associated light-use efficiency govern reserve accumulation and draw-down is therefore key for improving understanding and prediction of yield stability across regions and seasons.

1.6. Hormonal regulation of growth and reproduction

Hormonal pathways regulate growth, flowering, fruit set, abscission, and ripening. While not all mechanisms are directly light-driven, their outcomes are typically constrained by the canopy light environment through effects on carbohydrate supply, sink strength, and stress status. Accordingly, this section focuses on hormone actions that (a) modify sink establishment and retention, (b) respond to carbon status derived from intercepted light, and (c) explain yield patterns across seasons and regions. Where avocado-specific evidence is limited, we draw on closely related fruit-tree systems and identify targeted gaps for future work.

Plant hormones regulate growth, flowering, fruit set, and abscission, acting as promotive or inhibitory signals depending on timing, tissue, and hormonal balance (Ozga and Reinecke 2003). In avocado, the interplay of gibberellins (GAs), cytokinins (CK), auxins, abscisic acid (ABA), and ethylene shapes developmental outcomes; however, direct avocado evidence is sparser than for other tree crops like apple, citrus, or mango. Because hormonal effects often manifest through carbon allocation and sink strength, we keep the light-centred focus by linking hormone action to carbohydrate status and the canopy light environment. Figure 4 summarises major hormonal effects relevant to light-constrained yield behaviour.

Gibberellins (GAs):

GAs promote vegetative growth through stimulation of cell elongation and expansion, but can inhibit flowering when applied exogenously (Salazar-Garcia and Lovatt 1998; Wilkie et al. 2008; Shahar et al. 2026). In avocado, high GA concentrations are associated with vigorous vegetative flushing and suppression of floral initiation (Hormaza et al. 2024).

Foliar applications of gibberellic acid (GA_3, the most widely used active gibberellin) at pre-inflorescence stages reduce inflorescence production and flowering, and promote vegetative shoots and canopy foliar coverage, while later applications can accelerate floral shoot development (Salazar-Garcia and Lovatt 1998; Salazar-García and Lovatt 2000; Shahar et al. 2026). GA_3 can also alter floral shoot morphology, shifting determinate towards indeterminate inflorescences (Shahar et al. 2026), and in some cases increase fruit size and yield when applied around the cauliflower stage of bud development (Hormaza et al. 2024). It may also lead to increased leaf chlorophyll, enhanced fruitlet retention, and increased yield in subsequent seasons (Shahar et al. 2026).

GA-like activity has been detected in the endosperm and seedcoat during early fruit development, but not in the mesocarp or embryo, suggesting a seed-derived role in early avocado growth (Cowan et al. 2001; Taylor and Cowan 2001). GAs also promote cell expansion during early fruit development, contributing to final fruit size (Devoghalaere et al. 2012; El-Sharkawy et al. 2017; He and Yamamuro 2022). Conversely, lower GA at shoot tips is linked with greater carbohydrate accumulation and floral induction, a pattern shown clearly in mango (Das et al. 2019; Nakagawa et al. 2012) and likely relevant to avocado.

The practical significance of this antagonism is highlighted by triazole PGRs such as paclobutrazol and uniconazole, which inhibit GA biosynthesis and thereby suppress vegetative vigour while often enhancing flowering (Whiley et al. 2024; Wolstenholme et al. 1990). These findings underline GAs' dual role in promoting vegetative and fruit growth while influencing reproductive fate, making their seasonal balance with carbohydrate availability a critical determinant of whether buds develop vegetative or reproductive structures. Nonetheless, direct quantification of endogenous GA fluxes in avocado is sparse, and their precise contribution to floral inhibition and fruit growth regulation requires further study. Practically, strong light interception that may increase carbohydrate supply can exacerbate GA-driven vegetative vigour unless restrained, with consequences for return bloom and within-canopy light distribution.

Cytokinins (CKs):

While GAs can act as inhibitors of floral induction, CKs generally exert the opposite effect. CKs stimulate cell division and contribute to carbon sink establishment by promoting sugar import and metabolism in developing organs (Werner and Schmülling 2009). Elevated CK concentrations are typically associated with young, rapidly growing tissues, where they enhance sink strength by stimulating cell proliferation and invertase activity, thereby supporting assimilate unloading.

In avocado, final fruit size depends more on sustained mesocarp cell division than on cell enlargement; CKs promote this division, whereas ABA and water stress can retard it (Cowan et al. 2005; Taylor and Cowan 2001). Direct evidence for a role in floral initiation remains limited. Nonetheless, CK activity is very high in the seedcoat and endosperm of developing avocado fruitlets, declining as fruit matures, suggesting a role in establishing sink strength during early fruit growth (Blumenfeld and Gazit 1970). By contrast, CK activity is typically undetectable in mesocarp tissue, implying that the developing seed/seedcoat is the primary cytokinin source driving early fruit growth (Taylor and Cowan 2001).

Studies of the phenotypically 'small fruit' variant, characterised by early seed coat senescence and cessation of growth (Cowan et al. 2005), further highlight this role: these fruit are characterised by early seedcoat degeneration, low CK concentrations, elevated ABA, and reduced cell numbers, while exogenous CK applications can partly rescue fruit size (Hormaza et al. 2024; Taylor and Cowan 2001). This phenotype is closely linked to a decline in the CK-to-ABA ratio, consistent with reduced sink strength and impaired mesocarp cell division (Moore-Gordon et al. 1998; Taylor and Cowan 2001).

Experimental applications of exogenous CKs have been shown to increase determinate floral shoot number and return bloom in 'Hass' orchards (Escobedo-Solórzano and Lovatt 2014; Hormaza et al. 2024). These findings support a promotive role for CKs in avocado flowering, consistent with evidence from other species (Bangerth 2009; Hanke et al. 2007). In practice, CK-driven sink establishment helps translate intercepted light into growth when phloem loading and sustained carbon supply are maintained.

Auxins:

Auxins, primarily indole-3-acetic acid (IAA), are central regulators of plant growth and development, influencing cell elongation, vascular differentiation, apical dominance, and abscission (Gomes and Scortecci 2021). Their roles in avocado reproduction are strongly context-dependent, acting differently in developing fruit versus buds.

Fruit growth and sink strength: In developing fruit, auxins are critical for establishing strong sinks, promoting assimilate import and maintaining vascular continuity (Taiz et al. 2015). In avocado, high auxin concentrations occur in developing seeds and seedcoats, with faster-growing fruit showing higher levels, underscoring a role in maintaining fruit sink strength (Gazit and Blumenfeld 1972; Taylor and Cowan 2001). Evidence from the 'small fruit' variant supports this view: these seeds contain less IAA than normal fruit, alongside elevated ABA and reduced CKs, leading to reduced cell division and impaired fruit growth (Cowan et al. 2005). Sustained mesocarp cell division also requires both IAA and CKs, highlighting that auxin acts in synergy rather than isolation (Cowan et al. 2001).

Fruit retention and abscission: Auxin export from developing fruit also plays a key role in fruitlet survival. In line with models from other fruit trees, transport of IAA out of fruit stabilises the abscission zone, whereas declining auxin export promotes fruit drop (Bangerth 2000). This provides a plausible explanation for avocado's massive early and mid-season fruit abscission: weaker sinks export less auxin and are preferentially shed, while stronger sinks maintain higher flux and persist (Alcaraz and Hormaza 2021; Garner and Lovatt 2016; Hormaza et al. 2024).

Auxins further interact with sugars to support reproductive development, stimulating invertase activity to enhance sucrose breakdown into glucose and fructose, and fuel tissue expansion (Durán-Soria et al. 2020). Auxins promote cell division during early flower development and, together with gibberellins, drive ovary growth into fruit, while sugars provide the carbon substrates (Mishra et al. 2022; Shinozaki et al. 2020). Under carbohydrate limitation, declining auxin export predisposes fruitlets to abscission through interactions with ABA and ethylene (Bangerth 2000; Xie et al. 2013).

Bud fate and return bloom: By contrast, in buds, auxin has a different role. Crop load modulates auxin activity in apical buds, with on-crop trees in alternate bearing orchards exhibiting high auxin-to-cytokinin ratios that suppress summer bud break and reduce return bloom (Hormaza et al. 2024; Lovatt and Salazar-García 2006). This supports the view that auxin exported from fruit accumulates in nearby buds, reinforcing apical dominance and suppressing further flowering. Removal of fruit can lower bud IAA concentrations while increasing CKs, releasing paradormancy

and enhancing both vegetative and floral shoot development at the subsequent bloom. This pattern mirrors observations in mango, where high auxin during fruiting suppresses vegetative bud outgrowth until fruit are removed, at which point declining auxin and rising CK restore shoot growth (Capelli et al. 2021). Experimental treatments combining the auxin transport inhibitor tri-iodobenzoic acid (TIBA) with CK have shown that reducing auxin signalling can increase floral shoot number in 'Hass' orchards (Hormaza et al. 2024).

While auxin has classically been viewed as delaying fruit ripening when applied exogenously (Durán-Soria et al. 2020), studies in climacteric fruits such as peach demonstrate that endogenous auxin levels rise during the transition to ripening, where they contribute to the initiation of ripening in concert with ethylene (Trainotti et al. 2007). Auxin levels then decline during late ripening, consistent with ripening completion and senescence. Whether avocado shares these dynamics remains untested, but seed- and mesocarp-derived auxin may similarly contribute to ripening-related signalling.

These findings emphasise that auxin operates in a tissue- and context-specific manner: in fruit it maintains sink strength and reduces abscission, while in buds it reinforces apical dominance and can suppress return bloom. Avocado fruit size and retention therefore depend on seed-centred auxin production and export, operating in balance with CKs and ABA to regulate mesocarp sink activity and bud fate (Bangerth 2009; Hanke et al. 2007). Auxins' specific involvement in floral initiation is considered further in Section 1.7, where their role is integrated with light, carbohydrate reserves, and other hormonal signals. Functionally, auxin export translates carbohydrate status, and thus the effectiveness of light capture, into fruit retention signals.

Abscisic acid (ABA):

ABA is a central regulator of stress physiology, mediating responses to water deficit, salinity, and other environmental stresses through effects such as stomatal closure and growth inhibition (Finkelstein 2013; Zeevaart and Creelman 1988). In fruit trees, ABA also influences reproductive development, with roles in fruit growth and abscission (Bangerth 2000; Shinozaki et al. 2020). ABA interacts closely with carbohydrate status and other hormones, often counterbalancing the growth-promoting effects of GAs, CKs, and auxins. In avocado, elevated ABA concentrations are associated with reduced cell division, enhanced abscission, and suppressed bud break, positioning it as both a negative regulator of yield when present in excess and a key integrator of developmental and stress signals (Cowan et al. 2005; Hormaza et al. 2024; Moore-Gordon et al. 1998).

Fruit growth and sink activity: In avocado fruit, ABA dynamics are closely linked to sink strength and cell division. High ABA concentrations are consistently associated with reduced mesocarp cell proliferation, particularly in the so-called 'small fruit' phenotype, which is characterised by early seedcoat degeneration, lower IAA and CK levels, and a correspondingly higher ABA:IAA ratio (Cowan et al. 2005; Taylor and Cowan 2001). This imbalance reduces auxin export, weakens sink activity, and impairs fruit growth. Normal fruit maintain lower ABA and sustained IAA transport, supporting stronger mesocarp division. Beyond its inhibitory role, ABA may also contribute positively to sink establishment by mobilising sugars, as shown in mango where ABA enhances the sink strength of floral buds (Upreti et al. 2013). These findings highlight that ABA's role in avocado fruit growth is not simply inhibitory but operates within a broader hormonal network, where the ABA:IAA:CK balance determines the extent of cell proliferation and, ultimately, fruit size (Cowan et al. 2005; Moore-Gordon et al. 1998).

Fruitlet abscission: ABA also plays a central role in avocado's high rates of flower and fruitlet abscission. Auxin transport from developing fruit normally stabilises the abscission zone, but when this flux declines, whether due to weak sink activity or carbohydrate limitation, ABA concentrations in the pedicel rise, promoting differentiation of the abscission layer and stimulating ethylene biosynthesis (Bangerth 2000; Xie et al. 2013). This interaction helps explain the massive early and mid-season fruit drop observed in avocado, where weaker sinks exporting less auxin are preferentially shed, while stronger sinks persist. Importantly, the timing and magnitude of abscission are not solely resource-dependent: studies in 'Hass' have shown that heavy crop loads amplify fruitlet drop without fundamentally altering its seasonal pattern (Garner and Lovatt 2008).

In avocado, fruit abscission is characterised by a massive early drop of flowers and fruitlets shortly after bloom, and a second drop of developing fruitlets several weeks later, after which abscission rates decline markedly (Alcaraz and Hormaza 2021; Garner and Lovatt 2016; Hormaza et al. 2024). These events are tightly regulated by carbohydrate–hormone crosstalk: low sugar supply promotes ABA and ethylene accumulation while reducing auxin export, predisposing fruitlets to abscission, whereas higher GA, CK, and auxin concentrations are associated with fruit retention (Gómez-Cadenas et al. 2000; Kuang et al. 2012; Sawicki et al. 2015). Evidence from model systems also suggests that trehalose-6-phosphate (T6P) signalling may mediate ABA's stimulatory role in abscission (Avonce et al. 2004), further emphasising the integration of carbohydrate status with hormone regulation.

Ripening and postharvest physiology: Evidence from mango and other fruit crops suggests that ABA also interacts with ethylene and sugar signalling during abscission and ripening (Rossouw et al. 2024). In avocado, ethylene produced in the seed precedes fruit abscission and postharvest ripening (Adato and Gazit 1977a; Adato and Gazit 1977b). In mango, strawberry, and apple, sucrose has been shown to stimulate ABA, which in turn promotes ethylene biosynthesis and sugar accumulation (Gupta et al. 2022; Jia et al. 2013; Luo et al. 2020; Ma et al. 2017). This ABA–sugar–ethylene crosstalk provides a plausible parallel for avocado, where sugar limitation and hormonal signalling converge to regulate fruitlet abscission.

These interactions suggest that abscission in avocado is largely hormone-driven, with ABA acting as a central mediator of sink competition and fruit survival under fluctuating carbohydrate supply. ABA also contributes to ripening-related signalling through its crosstalk with sugars and ethylene, providing a mechanistic link between preharvest carbohydrate status and postharvest behaviour. Because tree stress elevates ABA and reduces stomatal conductance, climatic differences in VPD and soil moisture couple light interception to hormonal control of abscission and growth.

Ethylene:

Ethylene is a gaseous hormone best known for its role in fruit ripening, but in avocado it also regulates abscission, flowering behaviour, and ultimately yield stability (Adato and Gazit 1977a; Hershkovitz et al. 2009; Ogawara et al. 2003; Sawicki et al. 2015). Its synthesis is tightly linked with carbohydrate status and other hormones, particularly ABA and auxin, making it a central mediator of sink competition (Durán-Soria et al. 2020). Developing fruit produce ethylene predominantly in the seedcoat (Sitrit et al. 1987), with elevated synthesis preceding abscission and correlating with fruit drop and inversely with fruit size (Adato and Gazit 1977a; Hormaza et al. 2024). The seedcoat is also the site of pre-climacteric ethylene production in harvested fruit, though this only triggers ripening once maturity has been reached (Adato and Gazit 1977b).

Elevated ethylene early in development promotes the abscission of weaker sinks, while later in the season it is required for normal ripening and postharvest softening (Arpaia et al. 2018; Sitrit

et al. 1986). Thus, ethylene acts as a terminal step in abscission rather than its root cause, with auxin decline and ABA accumulation setting the stage for its induction (Bangerth 2000; Hormaza et al. 2024). This dual role means that ethylene functions both as a regulator of fruit survival during development and as a trigger of ripening processes, directly shaping productivity, fruit quality, and storability.

Fruit retention in avocado likely reflects the same sugar–hormone interactions reported in other tree crops: high sugar levels favour retention, while declines predispose fruitlets to abscission through rising ABA and ethylene and reduced auxin export (Bangerth 2000; Sawicki et al. 2015; Xie et al. 2013). Ethylene is therefore likely the final signal for abscission, triggered when carbohydrate scarcity elevates ABA and reduces auxin, activating the abscission zone (Adato and Gazit 1977a; Garner and Lovatt 2016). Comparative studies in citrus and other fruit trees reinforce this view: sucrose limitation increases ABA and ethylene while reducing auxin, predisposing fruitlets to abscission (Gómez-Cadenas et al. 2000; Kuang et al. 2012). Conversely, adequate carbohydrate supply helps maintain hormonal profiles that favour retention.

In ripening fruit, ethylene interacts with ABA and sugar signalling through positive feedback loops. Ethylene promotes sucrose accumulation and is itself stimulated by sucrose and ABA, accelerating ripening progression (Chidley et al. 2017; Durán-Soria et al. 2020; Wu et al. 2022; Zaharah et al. 2013). These interactions likely reflect avocado's climacteric behaviour and link postharvest physiology to canopy carbon status. Ethylene thus serves as both the executor of fruitlet abscission and the primary driver of ripening, with major implications for productivity, fruit quality, and storability. Light-limited canopies that restrict carbohydrate accrual may indirectly increase ethylene-mediated abscission; conversely, balanced light distribution that sustains export should favour retention.

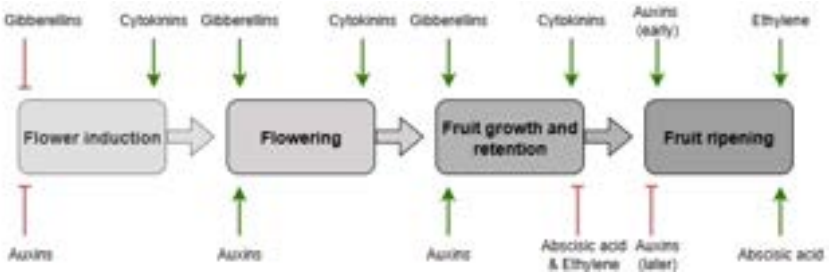

FIGURE 4. Conceptual roles of major phytohormones in reproductive development in avocado. Positive influences are shown with green arrows and inhibitory influences with red lines. Gibberellins (GAs) and auxins suppress floral initiation, whereas cytokinins (CKs) promote it. During flowering, GA, auxins, and cytokinins support floral shoot development, ovary growth, and reproductive success. Fruit growth and retention are enhanced by auxins, cytokinins, and GA, but limited when abscisic acid (ABA) and ethylene accumulate. Ripening is driven by ethylene and ABA, with auxin contributing positively at ripening onset but declining later to permit ripening progression. This framework highlights the stage-specific and sometimes contrasting roles of hormones in regulating avocado yield outcomes and their dependence on carbon supply derived from canopy light capture.

Other hormones:

Beyond the major hormones described above, several other regulators are increasingly recognised as important modulators of growth, stress responses, and reproductive development in fruit trees. Brassinosteroids (BRs) promote cell expansion and have been implicated in enhancing photosynthetic efficiency and stress tolerance, potentially supporting fruit size and retention indirectly (Vidya Vardhini and Rao 2002). Jasmonates (JAs) are well established as mediators of defence responses but also affect reproductive processes, including flower development, pollen viability, and abscission (Wasternack and Hause 2013). Strigolactones

(SLs) regulate shoot branching and resource allocation, potentially playing a role in shaping canopy architecture and the balance between vegetative and reproductive sinks (Brewer et al. 2013). Salicylic acid (SA) regulates plant defence and abiotic stress responses (Khan et al. 2015; Rivas-San Vicente and Plasencia 2011).

Recent avocado-specific studies have shown that hormone profiles in fruit vary strongly with cultivar and environment (El Kayal et al. 2025). JA, SA, zeatin (a cytokinin), ABA, and GA_3 all differed across altitudes and cultivars: for example, 'Hass' appears to have higher SA levels than 'Lamb Hass', whereas 'Reed' contains higher JA and lower zeatin compared with 'Pinkerton'.

Other signalling molecules such as polyamines, and melatonin have been implicated in fruit set, retention, and stress resilience in other crops (Arnao and Hernández-Ruiz 2017; Asghari and Aghdam 2010; Biasi et al. 1988), but remain unstudied in avocado.
Although these hormones have been studied in model systems and some fruit crops, direct evidence in avocado remains very limited. Given their known functions in modulating stress resilience and source–sink dynamics in other crops, these hormones represent promising but underexplored areas for future avocado research. Key gaps include organ- and stage-resolved hormone profiling across climates and cultivars, and experiments that couple light environment, carbohydrate status, and hormone fluxes.

Hormones - closing synthesis:

In avocado, auxin exported from the seed and seedcoat, together with the balance between ABA, auxin, and CKs, determines fruitlet survival and the extent of mesocarp cell division. GAs and CKs influence whether buds develop into vegetative or reproductive structures, while ethylene serves as the final signal for fruitlet abscission and the primary driver of climacteric ripening. Because these hormonal pathways are closely integrated with carbohydrate status, including leaf photosynthetic capacity, reserve buffering, and the ratio of leaves to fruit, the hormonal and carbohydrate frameworks must be considered together.

Interventions such as canopy pruning, crop load management, irrigation, and the use of plant growth regulators that alter hormonal balance can therefore directly affect yield outcomes. As a result, hormonal control provides the immediate mechanistic link between the carbohydrate economy outlined in Section 1.5 and the reproductive outcomes explored in Section 1.7. Orchard environment and management interact with intrinsic hormonal pathways to shape yield behaviour. However, large gaps remain in mapping endogenous hormone fluxes across tissues and phenological stages, limiting predictive modelling. Addressing these gaps will clarify how regionally distinct light environments translate, via carbohydrates and hormones, into crop load development and yield stability.

1.7. Reproductive development and yield determination

Reproductive development represents the growth stages where canopy light interception and its downstream physiological effects most directly determine yield outcome. While the basic biology of floral organogenesis, pollination, and fruit growth has been well described (Hormaza et al. 2024), the key question for productivity is how these processes are determined by source–sink balance and the hormonal and carbohydrate signalling networks operating within a light-defined canopy environment.

Avocado's heavy flower and fruitlet abscission, its reliance on cross-pollination, and its tendency toward alternate bearing arise from the combined effects of canopy light interception with carbohydrate reserves, hormonal dynamics, and environmental cues that vary among regions (Hormaza et al. 2024; Schaffer et al. 2024; Whiley et al. 2024). This subsection therefore focuses not on descriptive reproductive biology but on how light environment interacts with carbohydrate

and hormonal regulation to influence floral initiation, fruitlet survival, and carry-over effects that determine yield stability.

Floral initiation:

Floral initiation in avocado appears triggered primarily by cool temperatures, with short days and mild water stress potentially acting as supplementary cues depending on the region (Buttrose and Alexander 1978; Salazar-García et al. 1999). However, the extent of bud differentiation into inflorescences is not determined by temperature alone. It depends on the physiological status of the shoot, which in turn depends on its exposure to light, carbohydrate reserves, and hormonal balance (Alcaraz and Hormaza 2019; Hormaza et al. 2024). In practice, this means that regional differences in seasonal light climate and canopy structure can precondition shoots for stronger or weaker responses to inductive temperature cues.

Shoots that are well illuminated and have accumulated sufficient carbohydrate reserves are more likely to differentiate reproductive buds than shaded or weak shoots (Davenport 1986; Scholefield et al. 1985; Thorp and Sedgley 1993b). Light availability promotes both the maturation of current-season flushes and the accumulation of reserves in subtending wood, providing the substrates required for meristem transition. Conversely, shaded shoots, or those still in active vegetative growth, often fail to initiate flowers, indicating that the canopy light environment influences reproductive potential. This linkage identifies within-canopy light distribution and recent light history as candidate parameters for regionally adaptable canopy–yield models.

Elevated GA activity in vigorous shoot tips tends to suppress floral initiation, while relatively higher CK activity in mature, carbohydrate-rich shoots may favour reproductive differentiation (Hormaza et al. 2024; Lovatt and Salazar-García 2006). This antagonism underscores that floral fate is determined by both assimilate availability and the hormonal environment shaped by prior growth history and crop load. Because assimilate status is light-dependent, these hormonal effects are often expressed within a light-conditioned context rather than in isolation.

Importantly, crop load exerts a strong carry-over effect on floral initiation. Heavy fruiting in one season reduces the carbohydrate and hormonal conditions needed for return bloom, partly through reserve depletion and partly through auxin-mediated suppression of buds, as outlined in Section 1.6. This effect is magnified where canopy light penetration is low, limiting reserve renewal. Evidence from citrus and olive suggests that fruit presence enhances polar auxin transport in stems, elevating IAA concentrations in the shoot apex and reducing bud responsiveness to inductive cues (Haim et al. 2020).

Consistent with this, applied studies in apple, pear, and pecan show that inhibiting auxin transport increases flowering after heavy crop years, supporting the view that auxin flux is involved in repression of floral induction, even though direct evidence remains limited (Samach and Smith 2013). Thus, high IAA concentrations in buds appear to reduce the likelihood of floral initiation, whereas fruit absence or low crop load allows reserves to be replenished and auxin inhibition to lift, predisposing buds to floral fate. This dual mechanism, carbon depletion combined with auxin-mediated suppression, helps explain the alternate bearing tendency of avocado (Lovatt and Salazar-García 2006; Monselise and Goldschmidt 1982; Moore-Gordon et al. 1998).

These findings highlight floral initiation as a key control point where light environment, carbohydrate reserves, and hormone dynamics act together. Temperature may trigger the process, but whether buds respond productively depends on their prior physiological status, shaped by canopy light distribution and efficiency of light use. This creates regionally variable

thresholds for induction that should be captured in best-practice, light-centred canopy management models.

Pollination and fertilisation:

Pollination in avocado is complicated by its protogynous dichogamy, where flowers open first in the female phase and later in the male phase. This system promotes cross-pollination between cultivars, but synchrony is strongly influenced by temperature, canopy microclimate, and the degree of light interception across the canopy (Hormaza et al. 2024). Dense or shaded canopies can disrupt synchrony by altering within-tree temperature profiles and delaying floral development, while open canopies improve exposure and functional overlap between male and female phases. This highlights that canopy structure, by mediating both light and thermal gradients, indirectly governs floral synchrony and pollination potential.

Pollination efficiency is a major bottleneck for yield, with many flowers either not fertilised or aborting shortly afterward. Even when pollen is present, pistil carbohydrate status is critical: flowers with higher starch levels at anthesis are more likely to set fruit, while those with low reserves often abscise (Alcaraz et al. 2013). Since carbohydrate accumulation is light-dependent, pollination success may be influenced by canopy illumination, which determines both the local photosynthetic balance and carbohydrate supply available to support reproductive tissues.

Hormonal regulation interacts with these carbon signals. Evidence from model species suggests that auxin and GAs support stamen development, filament elongation, and pollen fertility, ensuring viable pollen and stigma–pollen interactions (Chandler 2011). JAs play a critical role in anther development and pollen maturation, while CKs and BRs support pollen viability and organ growth. Although avocado-specific data are limited, these conserved pathways likely underpin reproductive efficiency in the species. However, their effectiveness depends on the carbohydrate and energy status of the flower, which is ultimately a function of light-driven assimilate production and transport within the canopy.

Canopy structure and light exposure indirectly affect these processes by influencing both floral synchrony and assimilate availability. Flowers in well-lit canopy zones tend to receive more visits from pollinators and also likely have greater carbohydrate supply, reinforcing the link between light interception, source strength and successful fertilisation (Alcaraz and Hormaza 2024; Alcaraz et al. 2013). Regionally, canopy density, flowering phenology, and climatic differences in temperature and light regime all influence pollination dynamics, creating variability that should be captured in models aiming to predict yield formation under diverse orchard conditions.

Fertilisation success in avocado depends less on pollen presence alone than on the light-conditioned physiological readiness of the flower, shaped by carbon availability and hormonal balance. In other words, canopy light interception may function as a contextual control that integrates environmental, biochemical, and structural factors determining pollination success across regions.

Fruit set and early retention:

Avocado is characterised by extreme reproductive inefficiency, with only a small proportion of flowers typically developing into harvestable fruit (Garner and Lovatt 2016; Hormaza et al. 2024). Most losses occur during abscission waves: an early drop soon after anthesis and generally another several weeks later. These sequential losses are driven by both source–sink competition and canopy-scale light constraints. Understanding why so many fruitlets are shed is critical, as this stage largely determines the final crop load.

Carbohydrate availability strongly influences fruitlet survival. Flowers and fruitlets with greater starch reserves at anthesis are more likely to persist, while those with low carbohydrate status are more prone to abortion (Alcaraz et al. 2013). Heavy crop loads exacerbate competition for assimilates, particularly in indeterminate shoots where vegetative flushes compete with reproductive structures (Salazar-García et al. 1999). Light distribution within the canopy modulates this balance: shaded interior fruitlets receive less assimilate supply and exhibit higher abscission risk, linking fruit survival to the efficiency of canopy light capture and distribution of assimilate supply (Schaffer et al. 2024). In dense or suboptimally pruned canopies, this imbalance becomes spatially patterned: outer-canopy fruit benefit from superior light exposure and assimilate supply, while interior fruit are carbon limited and more likely to abscise.

Hormonal regulation operates alongside these carbon constraints to determine which fruitlets persist. In avocado, abscising fruit exhibit higher ABA concentrations than persisting fruit (Garner and Lovatt 2016). Elevated ABA is linked to ovule and seed coat deterioration, which in turn reduces sink activity and predisposes fruitlets to abortion. These findings support a model where weak or unfertilised fruit accumulate ABA, lose ovule viability, and are subsequently shed. Ethylene is considered the final trigger of abscission in many tree crops (Bangerth 2000), and while direct measurements in avocado are limited, its induction downstream of ABA and reduced auxin flux is consistent with observed fruit drop patterns (Hormaza et al. 2024).

Auxin transport also plays a decisive role. Export of IAA from developing fruit correlates with fruit growth and retention (Cowan et al. 2001; Garner and Lovatt 2016). When IAA export declines, the abscission zone is no longer stabilised, and fruitlets are shed. Garner and Lovatt (2016) found that abscising fruit often contained higher internal IAA concentrations during later drop periods, a pattern interpreted as reduced auxin export from fruit approaching abscission rather than greater functional auxin signalling. In contrast, persisting fruit maintained active auxin export, reinforcing their sink status. CK concentrations, particularly isopentenyladenine (IPA), were lower in abscising fruit than in persisting fruit at the beginning of the second drop and during late drop. Their role appears secondary compared with ABA and auxin, but reduced CK supply may contribute to weaker sink strength and higher abortion risk. Thus, hormonal gradients reflect source–sink dynamics that are themselves shaped by canopy photosynthetic performance.

Fruit set and early retention represent a physiological bottleneck where light interception, carbon supply, and hormone signalling converge. While pollination ensures ovule exposure to viable pollen, whether fertilisation translates into persistent fruit depends on light-driven carbohydrate availability and a hormonal environment that suppresses abscission. These interdependencies suggest that canopy light environment, through its influence on assimilate flow and hormonal stability, is a key determinant of yield efficiency. Capturing these relationships in canopy or region-specific light–yield models will help explain why fruit retention varies between orchard architectures and climates.

Fruit growth and maturation:

Following initial fruit set, avocado fruit develop over an unusually long period compared with many other fruit crops, with duration strongly influenced by cultivar and environment. Growth follows a sigmoid pattern with two main phases: an initial stage dominated by cell division and a later, longer stage of cell expansion and oil accumulation (Cowan et al. 2001; Pedreschi et al. 2019). The cell division phase occurs during the first several weeks after fruit set and establishes the final potential fruit size. CKs and auxins from the developing seed and seedcoat stimulate this division, while carbohydrate supply ensures the energy and substrates required for proliferation (Taylor and Cowan 2001). Fruit that maintain strong assimilate import during this stage develop more mesocarp cells and ultimately reach larger size, whereas fruit under carbohydrate limitation exhibit reduced cell numbers and are predisposed to remain small or

abscise (Moore-Gordon et al. 1998). This dependency on assimilate supply makes early fruit growth sensitive to light capture efficiency and canopy source strength.

During the subsequent expansion phase, fruit growth depends largely on cell enlargement and sustained carbon and water supply. Auxins and GAs promote expansion, while ABA accumulation under stress conditions can restrict growth (El-Sharkawy et al. 2017; Hormaza et al. 2024). Because this phase spans many months, its rate and duration are highly sensitive to canopy light interception, distribution, crop load, and environmental stresses that alter assimilate availability. In shaded canopy zones, fruit generally expand more slowly, reach lower dry matter content, and show higher risk of quality defects than fruit in well-lit positions (Schaffer et al. 2024). These within-canopy gradients are a direct outcome of light distribution, with fruit position relative to light exposure predicting differences in growth rate and composition.

Avocado fruit are further distinguished by their high oil content, which increases continuously during development and represents the major component of mesocarp dry matter at maturity. Oil synthesis relies heavily on carbohydrate-derived precursors and energy, making the balance between light-driven carbon supply and lipid metabolism central to fruit growth (Kilaru et al. 2015; Pedreschi et al. 2019). The dual demand for carbohydrate, both to sustain expansion and to fuel oil biosynthesis, reinforces the role of canopy photosynthesis and reserves in determining final fruit size and quality. This relationship also highlights why canopy management practices that improve light interception can indirectly enhance oil accumulation and fruit quality. Evidence also implicates avocado's unique C_7 sugars, mannoheptulose and perseitol, in supporting mesocarp metabolism and possibly regulating lipid synthesis, though their precise roles remain unresolved (Burdon et al. 2024; Liu et al. 2002b).

Hormonal changes accompany fruit maturation. Auxin and CKs decline as the seed and seedcoat mature, while ABA increases, contributing to the reduced sink strength of late-season fruitlets and predisposing weaker fruit to abscission (Garner and Lovatt 2016). Ethylene production, initially low, rises pre-harvest and drives the climacteric ripening process once fruit are detached (Adato and Gazit 1977b; Bower and Cutting 1988). Hence, fruit growth and maturation are largely sustained by canopy light capture and reserve mobilisation, while the transition to ripening is hormonally triggered. Maintaining a well-lit canopy throughout fruit development therefore supports not only carbon assimilation but also hormonal stability and sustained sink strength.

Productive canopies, those maintaining adequate light penetration and balanced crop load, are essential for supporting prolonged oil accumulation and achieving high-quality fruit. Regional differences in light climate, canopy density, and cultivar vigour will therefore influence the duration and efficiency of fruit development, suggesting that such parameters should be integrated into any predictive canopy–light–yield model.

Carry-over effects and alternate bearing:

Avocado is prone to alternate bearing, where seasons of heavy cropping are followed by light yields in subsequent years. This instability arises from the interaction of carbohydrate reserves, hormonal signalling, and environmental conditions, which together create strong carry-over effects from one season to the next (Monselise and Goldschmidt 1982; Wolstenholme 2010). These interactions occur within a light-conditioned framework, because the recovery of reserves and vegetative growth capacity between seasons depends largely on canopy light capture and its efficiency.

Heavy fruit loads consume a large share of current photosynthates and stored reserves, leaving insufficient carbon to support both fruit growth and the replenishment of starch in woody tissues

(Scholefield et al. 1985; Sharma et al. 2019). As a result, trees that carry heavy crops often enter the following season with depleted reserves and reduced capacity to support new vegetative flushes or initiate flowers. This is exacerbated in shaded or densely structured canopies, where limited light penetration and suboptimal light-use efficiency further constrain carbohydrate accumulation (Whiley and Wolstenholme 1990). Consequently, canopy architecture and light history influence whether a heavy-cropping season leads to full or partial reserve recovery.

Hormonal signals also contribute to carry-over effects. In avocado and other fruit trees, fruit presence is associated with altered bud hormone balances that reduce their capacity to initiate flowers. Buds on heavily cropped trees have been reported to show elevated auxin:CK ratios, a pattern associated with suppressed summer bud break and diminished return bloom (Hormaza et al. 2024). Evidence from citrus and olive similarly indicates that fruit presence enhances polar auxin transport in stems, leading to auxin accumulation in buds and reduced responsiveness to inductive cues (Haim et al. 2020). GAs are recognised inhibitors of floral induction when applied exogenously to avocado, stimulating vegetative shoot growth at the expense of inflorescence development (Hormaza et al. 2024; Salazar-Garcia et al. 1998; Salazar-García and Lovatt 2000). Bud ABA concentrations appear less sensitive to crop load, though ABA is strongly implicated in fruitlet abscission (Garner and Lovatt 2016). These findings indicate that altered auxin–CK balance in buds, combined with the potential influence of GAs, provides a hormonal pathway through which crop load exerts carry-over effects on flowering. In combination with depleted reserves, this hormonal environment reduces return bloom and promotes alternate bearing cycles.

Environmental stresses amplify these dynamics. In water-limited or high-temperature conditions, stomatal closure and reduced assimilation further limit reserve recovery during heavy crop years (Schaffer et al. 2024). Conversely, well-lit, moderately cropped canopies following a favourable season can promote both reserve replenishment and floral initiation, improving yield regularity.

Alternate bearing in avocado reflects the cumulative effect of physiological trade-offs across seasons. Heavy crops deplete reserves and shift hormonal balances in ways that suppress return flowering, while lighter crops allow recovery and more consistent yields. Because reserve renewal depends on photosynthate supply, canopy light interception and efficiency become a likely environmental lever for reducing biennial variability. Region-specific differences in light climate, canopy density, and cultivar vigour may determine how strongly these feedbacks operate, making them critical parameters for any regionally variable canopy–light–yield model.

Section 1 Summary and integration

Avocado productivity is determined by the combined effects of canopy light capture, LUE, nutrient status, carbohydrate reserves, and hormonal regulation, with canopy light capture and carbon assimilation largely governing, and the others modifying, reproductive success across multiple seasons. Leaves convert captured light into assimilates that sustain current growth and build reserves, while nutrients support chlorophyll content, stomatal function, and assimilate transport. These resources feed into source–sink dynamics where carbohydrates buffer demand peaks, hormones regulate bud and fruit fate, and environmental cues initiate reproduction. Across all stages, canopy light environment sets the upper limit for carbon supply, determining the capacity for reserve renewal.

The critical reproductive stages: floral initiation, pollination and fertilisation, fruit set and retention, and fruit growth, are all conditioned by this physiological network. Light environment sets the ceiling for carbon assimilation, determining how effectively nutrients and hormones can support reproduction. However, the translation of these physiological relationships into

quantitative yield prediction remains limited, reinforcing the need to still define measurable canopy attributes and parameterised relationships for modelling and decision support. Advances in canopy sensing (e.g. UAV imaging, LiDAR), digital twin frameworks, and functional–structural modelling provide opportunities to capture these relationships. However, their application remains constrained by the lack of robust physiological parameterisation linking canopy light environment to carbon assimilation and yield outcomes.

Heavy crop loads deplete reserves and alter bud hormone balances, reinforcing alternate bearing cycles. The magnitude of these effects varies with regional light climate, canopy architecture, and cultivar behaviour, identifying key knowledge gaps for model parameterisation.

Overall, Section 1 demonstrates that avocado yield is primarily driven by canopy light environment and carbon assimilation, with nutrient sufficiency, carbohydrate reserves, and hormonal regulation modifying how this carbon is allocated. Because canopy structure governs both the quantity and distribution of light available to support these processes, understanding and optimising light interception emerges as the central physiological leverage point for improving yield stability and orchard performance. For modelling, this implies that predictive frameworks should integrate canopy light distribution, reserve dynamics, and crop-load feedbacks to capture regional variability in yield outcomes. In practical terms, this requires translating physiological processes into measurable variables such as canopy light interception, within-canopy light distribution, leaf functional status, and crop load, which can serve as model inputs to predict yield responses and guide canopy management decisions. Table 2 summarises how these physiological drivers operate across each phenological stage of reproductive development, highlighting roles and direction of influence on yield outcomes, rather than quantitatively defined contributions.

TABLE 2. Summary of physiological drivers across phenological stages of avocado reproductive development and yield outcomes showing qualitative roles across phenological stages rather than quantified relationships.

Reproductive stage	Light environment	Carbohydrate status	Hormonal influence	Environmental modifiers	Outcome for yield
Floral initiation	Light exposure promotes bud maturation and carbohydrate accumulation	High carbohydrate reserves favour induction	High CK promotes; Elevated GA and auxin inhibits	Cool temperatures trigger; stress can modulate	More or fewer inflorescences
Flowering	Open canopy improves synchrony and pollinator access	High pistil starch promotes fertilisation success	Auxin, GA, CK, JA, BRs support pollen development and fertility;	Temperature affects synchrony	Fertile vs aborted flowers
Fruit set and retention	Sun-exposed canopies advantaged through improved assimilate supply	High carbohydrate reserves reduce abscission	Auxin export stabilises retention; ABA & ethylene promote drop; CK supports	Stress raises ABA/ethylene	Fruitlet survival or loss
Fruit growth and maturation	Fruit in shaded canopies smaller, lower dry matter	Sustained assimilate supply and reserves drive growth	Auxin, CK, GA promote expansion; ABA under stress reduces; Ethylene rises pre-ripening	Temperature and stress affect rate	Fruit size, dry matter, oil content
Inter-seasonal carry-over	Shaded canopies with inefficient leaves limit reserves' recovery	Heavy crops deplete reserves	High auxin in buds suppresses return bloom; GA inhibits; CK promotes	Stresses exacerbate depletion	On–off yield cycles

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Section 2: The avocado orchard light environment

Wilkie JD, Wilkie Horticulture

Background

Dry matter production by crops has long been known to be strongly related to the amount of radiation intercepted by their canopies (Monteith, 1977). The amount of radiation intercepted can be usefully expressed as either the cumulative quantity of radiation (Joules/hectare), or as the proportion of available photosynthetically active radiation (PAR) intercepted (percentage light interception). Research on the relationships between light interception and distribution, canopy characteristics and fruit production has led to improved understanding of the factors affecting early orchard yield and maximum orchard yield. Our purpose here is to review the literature on orchard light relations and discuss the implications for avocado canopy management strategies and the research required for their development.

The overwhelming majority of this research on orchard light relations has been undertaken in the temperate deciduous tree crop, apple (*Malus domestica* Borkh.). Apple orchard systems are very intolerant of within canopy shading due to the requirement for red colouration of the fruit, the sensitivity of floral initiation and fruit retention to shading and due to carbohydrates for fruit growth being sourced from nearby leaves. There are important differences in the physiology of apple and avocado trees. Foremost, apple is deciduous whereas avocado is generally considered to be evergreen although with relatively short-lived leaves and in cooler environments sometimes colloquially termed a 'winter green' due to significant leaf loss during late winter. Other significant differences include the timing and signals required for floral initiation (Wilkie e*t al.*, 2008; Ziv *et al.*, 2014) and the timing and style of vegetative growth.

Of subtropical and tropical tree crops, macadamia has been relatively well studied in terms of orchard light relations (McFadyen *et al.*, 2004; Olesen *et al.*, 2011). Macadamia, in contrast to apple, appears to be relatively tolerant of within canopy shading. For example, flower raceme production does not decline until extreme levels of shading and even though fruit retention is reduced with shading, fruit are still produced in locations of the canopy with less than 10% ambient light (Olesen *et al.*, 2011). Of course, there are still differences in the physiology of macadamia and avocado, however, both being subtropical evergreen, recurrent flushing rainforest trees induced to flower by cool temperatures, the differences are less extreme.

There has been a comparatively modest amount of orchard light relations research undertaken on avocado. The bulk of this was done relatively recently in subtropical eastern Australia (Wilkie *et al.*, 2019; Hofman *et al.*, 2021; Westling *et al.*, 2018). For our discussion of avocado orchard light relations, it is therefore necessary to use research undertaken in other tree crops, such as apple and macadamia, as a framework from which to understand avocado.

The orchard light environment

We farm at the orchard scale. The orchard scale integrates the fruitfulness of individual shoots, limbs and trees into a level of production per hectare (productivity). In terms of understanding our levels of productivity, the orchard scale provides us the most understanding. The same is true for our understanding of how the crop interacts with light. Understanding the effect of light at the leaf scale and the tree scale only provides us with partial understanding because leaves shade each other and trees shade each other. By understanding the light environment at the orchard scale, we consider how

light moves through the entire three-dimensional orchard space and interacts with the leaves, shoots and empty space within.

Annual field crops are often planted in rows, with the crop canopy emerging from below ground and the proportion of ground area covered increasing as the crop grows. The goal is generally for the crop canopy to expand so that it covers 100% of the ground area and intercepts a very high proportion of available light. These canopies are termed continuous canopies, as they are intended to cover the entire ground area.

Orchard crops are also planted in rows with the canopies increasing in size over the early years of orchard development and occupying increasing proportions of the ground area. However, orchard crops are usually intended to only ever occupy a portion of the orchard ground area. Some orchards, consist of so-called 'round headed trees', where the intention is that each tree will remain as a separate canopy, with access on all sides. Many orchards are now grown as hedgerows, where the individual tree canopies are allowed to join along the row but a clear alley way is maintained between the rows, which can be used for tractor operations (Jackson, 1980). Orchard canopies are termed discontinuous canopies, due to the interruption in the canopies between orchard rows.

Sunlight is composed of radiation of wavelengths across the electromagnetic spectrum from X-rays to radio waves with the visible light having the greatest intensity. Photosynthetically active radiation (PAR) is the portion of the radiation spectrum that is the primary energy source for the plant in the process of photosynthesis. PAR is approximately from 400 to 700 nm and is commonly estimated to make up around 50 % of the total radiation that hits the earth's surface (Robinson and Lakso, 1991).

Sunlight can reach the orchard as both direct light and diffuse light. Diffuse light has been scattered in the atmosphere by molecules or other particles and can arrive at the orchard from any direction. Direct light travels directly from the sun without its path being deviated (Iqbal, 1983). In non-netted orchards, cloud cover plays the biggest role in determining the proportion of direct and diffuse light falling on the orchard. Under clear blue-sky conditions (no cloud cover) both direct and diffuse light reach the orchard, however most of the incoming radiation is direct radiation, in the range of 80 to 85% of incoming PAR (Wunsche *et al.*, 1995; Lloyd *et al.*, 1995). Under cloudy conditions, as the intermittency of the cloud cover decreases and the thickness of the cloud increases, the percentage of radiation that is direct decreases until all incoming radiation is diffuse. Under these fully diffuse light conditions, PAR arrives evenly from all segments of the sky (Lloyd, 1995). Of course, under cloudy conditions the total intensity of incoming PAR also declines relative to clear blue-sky conditions. Even with a lower intensity of PAR under cloudy conditions, it has been reported that instantaneous whole tree photosynthesis can be greater than under clear blue skies due to better distribution of radiation under diffuse light conditions, resulting in a greater proportion of the canopy receiving PAR (Loyd *et al.*, 1995) and improved penetration of light into the canopy (Li and Yang, 2015).

From a horticultural perspective, to understand the light environment within an orchard it is useful to understand the total light interception of the orchard and the light distribution within that orchard. When discussing the orchard light environment, it is important to take some care in the use of terms to avoid confusion. Total light interception, which generally refers to total PAR interception, is an estimate of the proportion of incoming PAR that is intercepted by the orchard canopy, as opposed to falling in the alleyway between the rows (Wunsche *et al.*, 1995). Estimates of total PAR interception provide important information to the horticulturist on the gross energy producing potential of the canopy and the likely level of crowding and self-shading within. Total PAR interception is a metric that is used across a range of field and orchard crops and is useful to compare between orchard systems within the same crop (Monteith, 1977; Jackson, 1980). As such, certain conventions are used when

taking measurements to develop an estimate of total PAR interception so that estimates of this metric are comparable with others (discussed below). As light moves through the three-dimensional orchard space it is absorbed, transmitted and reflected by leaves and woody structures. Measurements taken to account for these variations in light levels are generally termed measurements of light distribution. These measurements of light distribution may be of variations in light intensity on the orchard floor, on the canopy surface or within the canopy (Hadari, 2004; Tustin *et al.*, 2001). Measurements of light distribution are taken for a range of purposes using a range of techniques, which are more focussed on providing measurements of use to the horticulturist's questions, as opposed to the measurement of a standard metric, as for estimates of total PAR interception.

As discussed above, the intensity of sunlight varies within the orchard canopy. However, wavelengths do not behave consistently across the spectrum when they interact with an orchard canopy, resulting in changes in the spectral composition of sunlight at different points within the canopy (Bastias and Corelli-Grappadelli, 2018). Therefore, light quality as well as light intensity varies within the canopy. For example, as sunlight moves through tree canopies red light is removed to a greater extent than far red light, resulting in a declining red to far-red light ratio (R/FR) as the level of canopy shading increases (Baraldi *et al.*, 1994). Blue light also declines with levels of shading within the canopy but generally declines proportionally with PAR. Photoreceptors within plant tissue detect and respond to different light wavelengths. Two important photoreceptors are phytochrome, that detect light in the red and far-red ranges, and cryptochrome, that detects light in the blue and UV wavelength ranges (Bastias and Corelli-Grapadelli, 2018).

In addition to the importance of light for photosynthesis and carbon assimilation, there are a range of plant development processes affected by light intensity and light quality. This mediation of plant development by light is termed photomorphogenesis. Shoot architecture can vary with position within the canopy through the light environment, with shaded areas of peach canopies having reduced axillary bud outgrowth and greater internode length (Baraldi *et al.*, 1994). Leaf morphology also varies with the level of shading within the canopy, with specific leaf weight (leaf weight per unit leaf area) declining as light levels decline in apple (Warrington *et al.*, 1996) and in peach (Baraldi *et al.*, 1994). This development response is seen to be consistent with the plant optimising the allocation of its resources and photosynthetic machinery to canopy locations most exposed to sunlight.

Light environment and leaf area

Within orchards, the major tree organs that are exposed to sunlight are leaves and stems which absorb, transmit and reflect this sunlight as it moves through the canopy. The number, size and arrangement of leaves within the three-dimensional orchard space play a significant role in the fate of sunlight within the orchard.

The amount of leaf within an orchard canopy is often expressed as the one-sided area of leaves, which integrates the number and size of leaves. This 'leaf area' is in turn often expressed as an area of leaves contained in the three-dimensional space above a certain land area. One widely used metric for orchard leaf area is the leaf area index (LAI; m^2 leaf area/m^2 land area), which is defined as total leaf area within an area of orchard divided by the area of orchard. The smallest area for which LAI can be calculated is the land area for an individual tree and is the total leaf area within the tree divided by the total theoretical area occupied by that tree in terms of the orchard spacing, not the silhouetted area beneath the canopy (Jackson, 1980). One important caveat here is that LAI can be calculated separately for the vertical stacks within the canopy. For example, Tustin *et al.*, (2001) calculated LAI for the lower, middle and upper canopy portions of apple canopies in a planting systems trial in New Zealand.

Leaf area can also be expressed as leaf area density, which is the one-sided area of leaves within any three-dimensional space within the orchard (m^2 leaf area/m^3 of orchard space). Leaf area density can be calculated for different areas within the canopy to understand how leaf area is distributed throughout the canopy (Tustin *et al.*, 1998).

The attenuation of PAR as it moves through an orchard canopy is dependent on the leaf area between the irradiated canopy surface and the point within the canopy in question, and the relationship between leaf area and PAR interception for the crop (Jackson, 1980). For crops such as apple, this relationship has previously been well explained by Beer's law, $I = I_o \cdot e^{-K \cdot LAD \cdot s}$ (Wagenmakers 1991). Where I is the PAR intensity at the point of interest within the canopy, I_o is the PAR intensity above the canopy, LAD is the leaf area per tree volume (m^2m^{-3}), s is the path length through the canopy and K is the light extinction coefficient. The light extinction coefficient can be calculated experimentally through measurements of I, I_o, and LAD and s. Thus, the greater the LAD or path length between the canopy surface and any point, the greater the attenuation of PAR. For example, for two contrasting apple orchard systems in New Zealand with similar LAIs, the system with a smaller canopy volume but greater LAD had significantly lower within canopy light levels than the system with a larger canopy volume but lower LAD (Tustin *et al.*, 2001). Similarly, Wagenmakers and Callesen (1995) found that maintaining shorter trees actually decreased within canopy light levels in apple orchard systems in the Netherlands because the tall tree and short tree systems had similar LAIs and thus greater LAD in the short tree system. Hadari (2004) measured and modelled the extinction of light within avocado canopies using the Beers-Lambert equation, which is a modification of Beer's law, that is based on path length through the canopy and assumes constant LAD. For the 'Hass' and 'Reed' canopies that were measured, PAR declined to approximately 20% and 5% of above canopy levels at 1 m and 2m below the canopy surface, respectively. In the same study (Hadari, 2004) the author attempted to use an indirect method to estimate LAI using measured within canopy light gradients, a parameter from their light extinction curves (not technically a light extinction coefficient), measured leaf angles and the equation developed by Campbell (1986). Unfortunately, because the modified light extinction coefficient calculated by Hadari (2004) was measured using path length and not LAD, the subsequently calculated values for LAI are unlikely to provide accurate estimates of the area of avocado leaves in those canopies. However, the estimates of LAI produced by Hadari (2004) may be useful for understanding of the relative distribution of leaves in the avocado canopies they studied. For example, for the low density, large tree orchards in their study, average LAI appeared to increase relatively linearly with a canopy depth up to approximately 2m from the canopy surface and then the LAI increased at a lower rate between 2 m – 4 m canopy depth and at a canopy depth of greater than 4 m, there appeared to be no accumulation of additional LAI.

This attenuation of PAR with leaf area also has implications for total PAR interception. Total PAR interception in apple orchards is curvilinearly related to LAI (Wunsche *et al.*, 1996; Wagenmakers and Callesen, 1995). As LAI increases from low levels, there is a strong linear increase in total PAR interception followed by a tapering and almost plateau of the increase in total PAR interception as LAI reaches its greatest levels. The tapering of this relationship as LAI reaches higher levels is due to an increase in mutual shading between leaves (Wagenmakers, 1991). Additionally, orchard canopies are discontinuous and so the relationship between LAI and total PAR is modified by the distribution of this LAI through the three-dimensional orchard space. For example, modelling simulations by Wagenmakers (1991) indicated that maintaining constant LAI while increasing tree density and increasing canopy volume by decreasing alleyway would result in greater total PAR interception. It was concluded by Jackson and Palmer (1980) that the more evenly the leaf area was spread across the orchard surface, the greater the interception of light per unit of leaf area, due to mutual shading of leaves being minimised.

No reliable estimates for LAI have been published for avocado orchards. However, the relationship between canopy volume and total PAR interception was established for 'Hass' avocado in central Queensland and was similar to that between total PAR interception and LAI in apple. There is a strong linear increase in total PAR interception at low levels of canopy volume per hectare followed by a tapering in the increase in total PAR interception at the higher levels of canopy volume per hectare that were measured (Fig. 1; Wilkie *et al.*, 2019). Although within canopy light distribution was not measured, the authors speculated that at the higher canopy volumes, total PAR interception was increasing at such a low rate due to the increasing levels of mutual shading between leaves, which would in turn lead to increasing proportions of the canopy volume being heavily shaded. This is supported by the within canopy light extinction reported by Hadari (2004), where 95% of light was attenuated at approximately 2 m from the canopy surface. The patterns of relative LAI and canopy depth presented by Hadari (2004) also indicate that as the increases in total PAR interception plateaued as canopy volume per hectare increased from 30,000 m^3 to 40,000 m^3 in the work of Wilkie et al. (2019), there would have been little to no increase in LAI.

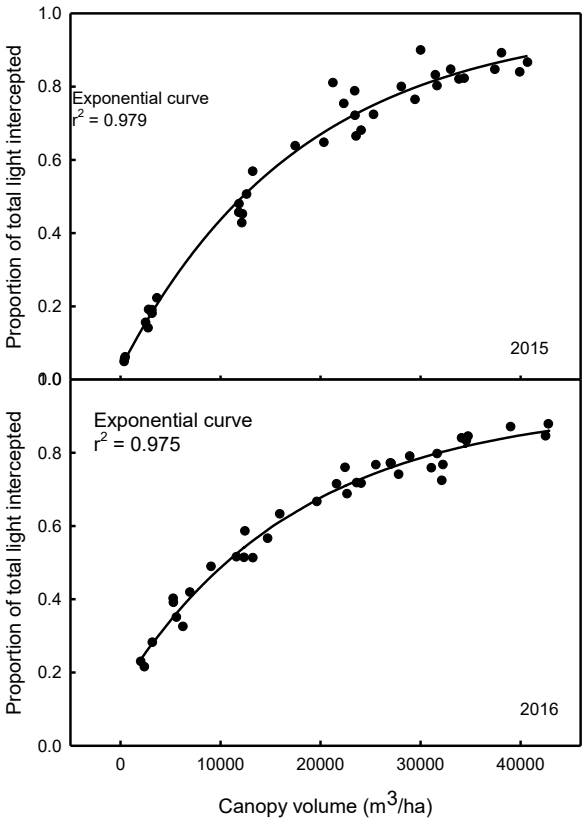

Figure 1. The relationship between canopy volume per hectare and the proportion of light intercepted by the canopy for conventional 'Hass' avocado planting systems in 2015 and 2016. The fitted curves are of the form $y = a + b \cdot r^x$ (from Wilkie *et al.*, 2019).

Much of the above discussion has been focussed on the effect of leaf area on PAR interception and distribution. However, for large tree subtropical and tropical tree crop systems with very high levels of PAR interception there are also portions of the canopy for which PAR intensity affects leaf area. For example, in a mature macadamia orchard planted at 7 m x 5 m, leaf density was greater in the upper canopy than the lower canopy and decreased exponentially with distance from the canopy surface in the lower canopy (Olesen *et al.*, 2011). Anecdotally, crowded, large tree avocado orchards often have voids within the centres of their canopies which have become so shaded that there is insufficient light

to sustain the leaf area within and once these leaves abscise, these portions of the canopy have insufficient light for growth to replace the lost foliage. Hadari's (2004) indirect relative LAI estimates support the anecdotal observations of the within canopy void, given the estimates of no increase in LAI greater than 4 m from the canopy surface.

Understanding of the relationships between leaf area, total PAR interception and within canopy light distribution have provided important fundamental information for the design of apple orchard systems. For avocado, there is a very limited body of information on within canopy light distribution, total PAR interception and leaf area. This is a significant limitation for orchard design and the development of more productive canopy management practices.

The effect of orchard design and location on the light environment

The amount and arrangement of leaf area within orchards is strongly affected by aspects of orchard design such as tree density, canopy size and shape, tree structure and row orientation. These aspects of canopy design in turn interact with latitude and affect the orchard light environment.

In any given orchard system, as the dimensions of the trees increase, so will the total PAR interception (McFadyen *et al.*, 2004; Olesen *et al.*, 2007; Wilkie *et al.*, 2019; Wagenmakers and Callesen, 1995). For example, for conventional avocado orchards with a row spacing of 10 metres a tree height of 5 m and and alley width 4.7 m resulted in total PAR interception of 51%, whereas tree height of 8.3 m and alley width of 1.9 m resulted in total PAR interception of 80% (Wilkie *et al.*, 2019).

This increase in tree dimensions, individual tree canopy volume or canopy volume per hectare will also generally result in increased proportion of the canopy volume that is heavily shaded (Palmer, 1989; Hadari, 2004). For example, simulations for model avocado orchards estimated that 7.5 m high trees with a row spacing of 7 m and 53,570 m^3 canopy volume/ha would have 80% of the canopy volume heavily shaded compared with 52% heavily shaded canopy volume for 4 m tall trees planted at 5 m row spacings with 18,000 m^3/ha canopy volume (Hadari, 2004).

Canopy dimensions can be modified by changes to tree height, canopy width or canopy shape and changes to any of these are likely to alter the total PAR interception and light distribution for the system (Olesen *et al.*, 2007; Hadari, 2004; Palmer, 1989; Jackson and Palmer 1980). For example, simulations using rectangular hedgerows with 6 m row spacing and 2 m alley indicated that tree heights of 2 m, 6 m and 10 m had estimated total PAR interception of approximately 86%, 94% and 97%, respectively (Olesen, *et al.*, 2007). It is worth noting that once tree height increased above a tree height to row width ratio of approximately 1, the increase in total PAR interception was small compared with the proportional increase in tree height. In another simulation model using rectangular hedgerows of height 3 m, total PAR interception was predicted to increase from 55% to 65% when canopy width increased from 0.3 m to 1.8 m, respectively, and row width was unchanged at 2.3m (Jackson and Palmer, 1980). As the shape of the hedgerow changes from a rectangular prism to pyramidal, while tree height and maximum canopy width remain unchanged, total PAR interception is reduced but the PAR exposure of the canopy sides increases (Olesen *et al.*, 2007).

Tree density is a strong determinant of orchard light relations both during the orchard development phase and the mature orchard phase. Increasing tree density leads to greater total PAR interception early in the life of the orchard and decreases the time taken to achieve maximum total PAR interception. This has been demonstrated extensively for apple

(Wagenmakers and Callesen, 1995; Robinson and Lakso, 1991), for macadamia (Wilkie *et al.*, 2021) and for avocado (Hofman *et al*., 2021). For avocado, total PAR interception of high density systems (4.5 m x 2 m; 1,111 trees/ha) reached a maximum PAR interception of 60% at three years after planting, whereas the conventional low density system (9 m x 5 m; 222 trees/ha) had a total PAR interception of approximately 20% and 40% three and five years after planting, respectively (Hofman *et al.*, 2021).

Tree density also affects within canopy light distribution, particularly when row spacing is decreased, due to the increased frequency of alley ways. Alley ways are strong determinants of the distribution of light within the orchard. This can be most simply demonstrated by examining the patterns of light reaching the orchard floor. For example, in a mature apple orchard systems trial the lowest level of incoming radiation reaching the ground was directly below the trunks and this increased to a maximum at the centre of the alleyway (Wagenmakers and Callesen, 1995). The proportion of incoming radiation in the centre of the alleyway tender to be greater in the systems with wider row spacings, leading to very uneven distribution of light on the orchard floor.

The orientation of the tree rows in orchards also has a significant effect on both total PAR interception and light distribution and the effect varies with latitude and time of year. For the percentage interception of total PAR, the simulation model of Palmer (1989) predicted that orchards of any row orientation would have a greater percentage interception of PAR at any time of year at higher latitudes (51.3°N compared with 30°N). Similarly, the simulation model of Olesen *et al.*, (2007) predicted a greater percentage of annual PAR interception at Alstonville (28.9°S) compared with Mareeba (16.9°S) and larger differences for E-W oriented rows than N – S oriented rows.

Regardless of latitude and time of year, orchard rows oriented N – S will have more even distribution of PAR over their canopy surface area and within their canopies than other row orientations, particularly E – W (Palmer, 1989; Olesen *et al.*, 2007). Simulations for Bundaberg in central Queensland (24.9°S) indicate that from approximately March to November the north face of E-W oriented hedgerows will receive six to eight times the PAR as the southern face (Olesen *et al.*, 2007). Palmer (1989) presented simulations on apple canopy light distribution for two row spacings, two row orientations (N – S and E – W) at two latitudes (30°N and 51.3°N) and two times of year (mid-summer and autumn equinox). At 30°N, N – S oriented rows consistently had more even light distribution within the canopy and a greater proportion of the canopy receiving 30% or more of incident PAR than E – W oriented rows. More often than not the same was true for 51.3°N, although for one of the four combinations of row spacing and time of year, the E-W oriented rows had a greater proportion of the canopy with greater than 30% incident PAR. The author concluded that the interactions of row orientation, latitude and orchard system (row spacing, tree height, canopy shape, etc) are complex and considerations need to be made for the times of year that yield limiting physiological processes require PAR.

Light environment and productivity

Total light interception

Total PAR interception has been known for several decades to be a significant driver of productivity in crops in general (Monteith, 1977) and specifically for tree crops, including apple (Palmer *et al.*, 2002; Robinson and Lakso, 1991), macadamia (McFadyen *et al.*, 2004; Wilkie *et al.*, 2021) and avocado (Wilkie *et al.*, 2019). The link is primarily due to the linear increases in dry matter production with increasing total PAR interception.

For apple, fruit yield increases linearly with PAR interception up to 60% to 70% (Palmer et al., 2002; Wunsche *et al.*, 1996), with reports of a plateau and then decline in yield as total PAR interception increases from 65% to 85% (Wunsche and Lakso, 2000). For macadamia, there is a similar largely linear increase in yield as total PAR interception increases from low levels up to approximately 80% to 85% (McFadyen *et al.*, 2004; Wilkie *et al.*, 2021), followed by a plateau in yield and then decline as total PAR interception increases above 85% to 95% (McFadyen *et al.*, 2004).

For 'Hass' avocado near Bundaberg, there was a similar approximately linear increase in yield/ha as total PAR interception increased from low levels up to approximately 80% (Fig. 2). As for other tree crops this increase in yield/ha as total PAR interception increases from low levels is likely due to increasing dry matter production. As total PAR interception increased above 80% and approached 90% the authors concluded there was either a plateau or decline in yield (Wilkie *et al.*, 2019). Curves were fitted for both plateauing and declining yields in both years of the study with the declining yield curves accounting for slightly more variance in yield than the plateauing yield curves but the evidence was not considered strong enough to conclude that the orchards at the highest levels of total PAR interception and crowding had declining yields. Rather, the authors concluded that there was no yield benefit for growers in allowing total PAR interception to increase above approximately 80% and they ran the risk of yield decline if they allowed it to approach 90%. The maximum yield per hectare, at approximately 80% total PAR interception, varied between the two years and was approximately 18 tonnes/ha in 2015 and 27 tonnes/ha in 2016. The work also related yield per hectare with canopy volume per hectare, with yield per hectare increasing approximately linearly as canopy volume per hectare increased from low levels and began to plateau as canopy volume per hectare approached 30,000 m^3 (Fig. 3). It was unclear whether yield per hectare plateaued or declined as canopy volume per hectare increased from 30,000 m^3 to 40,000 m^3 per hectare.

As far as we know, the only field trials relating avocado yield with total PAR interception have occurred in central QLD near Bundaberg (24.9°S). Given the Australian avocado industry is spread across a broad range of latitudes from Far North QLD to Southern Western Australia and the discussion above around the effects of latitude on total PAR interception, it is possible that the relationship between yield/ha and total PAR interception may differ with large differences in latitude. Therefore, field trials to document this relationship in diverse latitudes may be warranted.

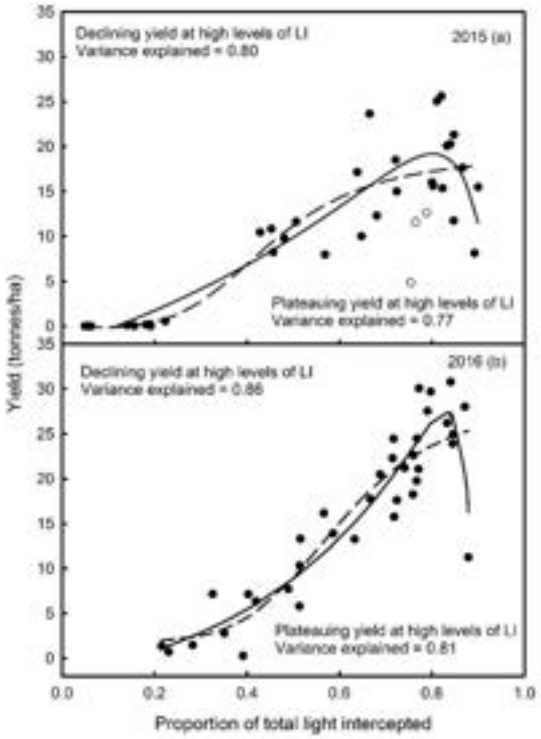

Figure 2. The relationship between yield per hectare and the proportion of light intercepted by the canopy for conventional 'Hass' avocado planting systems in subtropical Australia 2015 and 2016 (from Wilkie *et al.*, 2019).

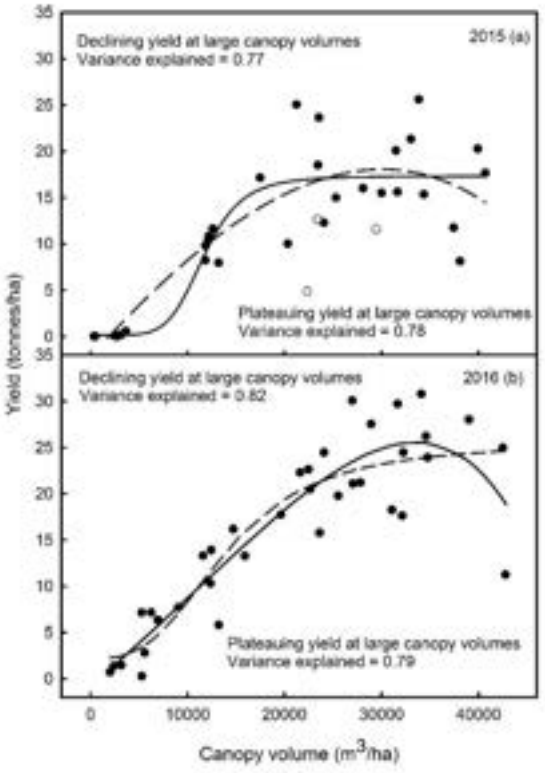

Figure 3. The relationship between yield per hectare and canopy volume per hectare for conventional 'Hass' avocado planting systems in subtropical Australia 2015 and 2016 (from Wilkie *et al.*, 2019).

Within canopy light distribution and the development of crop load

The effect of within canopy light distribution on the development of crop load has been extensively examined in other tree crops including apple and macadamia, providing a useful comparison for avocado. Due to the wide ranging effects of PAR on growth and development in trees, we need to consider the possibility that within canopy PAR levels are directly and indirectly affecting crop load development.

In apple, floral initiation is substantially reduced when within canopy PAR levels decline below 30% of ambient levels (Chan and Cain, 1971). Apple fruit set, fruit growth rate and final fruit size also decline as the level of local shading increases (Tustin *et al.*, 1988; Bepete and Lakso 1998). The effect appears to be due to spur leaves adjacent to the fruit being the primary source of carbohydrate in the weeks following fruit set and when these leaves are shaded by peripheral extension shoots, allocation of carbohydrates to the shaded developing fruit is reduced (Corelli Grappadelli *et al.*, 1994; Bepete and Lakso, 1998).

The effect of within canopy light levels on macadamia have also been studied. In addition to macadamia being a subtropical evergreen species, another important distinction between apple and macadamia is that macadamia tend to be grown in low density large tree systems prone to severe shading within the canopy. Raceme production in macadamia is unaffected by moderate to severe levels of shading but is reduced when PAR declines to 5% or less of ambient levels (Olesen *et al.*, 2011). Fruit set and retention per raceme within the canopy declines with the percentage of above canopy PAR reaching the racemes (Olesen *et al.*, 2011). This reduced flowering and fruit set is presumably at least partly due to declining local carbohydrate production due a direct effect of PAR on photosynthetic rates of the locally shaded leaves, however, the locally produced carbohydrates would be reduced further still due to the declining leaf density that also occurs with greater levels of shading (Olesen *et al.*, 2011). Of course, it is possible that other signals from the leaves, such as for floral initiation, may also decline as leaf density declines and negatively affect local development of crop load. Anecdotally, in the most heavily shaded portions of large macadamia trees, the leaf density decline continues and eventually results in shoot and branch death and the creation of voids in the shaded lower and inner portions of the canopy (Huett, 2004).

Within canopy light environment and the effect on crop load development has had minimal attention in avocado. The only known studies were undertaken for ‘Hass’ in a tree density and rootstock trial in Central Queensland where PAR measurements in vertical profiles along the canopy periphery or in horizontal transects through the canopy were compared with localised measurements of shoot growth, timing of inflorescence development, flowering intensity and fruit set (Hofman *et al.*, 2021). In general, the data was extremely variable, with the regression analyses generally providing poor correlation coefficients, however, many of the effects were still statistically significant. For example, as PAR levels declined there were also decreases in inflorescence intensity, fruit retained per inflorescence and indeterminate inflorescence vegetative growth. Unfortunately, due to the high level of variability it is difficult to specify PAR levels at which flowering intensity and fruit set were affected. The high variability was likely due to several reasons. First, the experimental method. Each PAR measurement was paired with flowering and fruiting observations within a section of the canopy in which the PAR levels were quite variable. Therefore, it is possible that the PAR environment the inflorescences and fruit were exposed to was quite different to that which was measured. Second, it is possible that alternative statistical methods may been more discerning in detecting the effects of PAR on flowering and fruiting. Third, these PAR measurements were undertaken during winter soon after

the trees had been pruned, but it is possible that many of the processes related to floral initiation had occurred during late autumn before pruning was undertaken and thus under a different light environment. Last, factors in addition to the light environment are likely to affect fruit set and retention and may have confounded the effect of light environment. For example, avocado fruit set is reduced by vigorous spring vegetative growth (Hofman *et al.*, 2018; Cutting and Bower, 1990) and spring vegetative growth declined with PAR levels, potentially moderating the effects of low PAR on fruit set and retention.

The negative impacts of shading on crop load development described above (Hofman *et al.*, 2021) are supported by other avocado studies where the effects of local PAR were not measured but may be inferred. For example, flowering intensity and fruit set from inflorescences that developed from the previous years spring flush was reported to be significantly less than for inflorescences that originated from the prior autumn or summer flushes (Thorp *et al.*, 1993). The authors speculated that the lower flowering intensity and fruit set of the spring flushes may have been due to their position further inside the canopy and thus being more poorly irradiated than the summer and autumn flushes, that occurred later. Additionally, mean fruit weight of 'Hass' declined as total PAR interception increased (Wilkie *et al.*, 2019), the authors speculated that as PAR interception increased, the proportion of the canopy that was highly shaded would have increased, with the greater shading leading to reduce rates of fruit growth, similar to that reported for apple above.

The indirect effects of within canopy PAR levels on crop load development through the loss of leaf area also needs to be considered. The indirect estimates of LAI by Hadari (2004) indicate that LAD declines significantly within the canopy to the point where there is little to no leaf area within the most shaded portions of large avocado canopies. Anecdotal observations consistently support this and also indicate that shoot and branch density declines in these highly shaded areas and are not replaced by new growth. Clearly, crop load development is not possible in the absence of shoots and branches and flowering and fruit development may be proportionally reduced in the moderately shaded areas of the canopy as the density of terminal shoots (flowering positions) declines (Hofman *et al.*, 2018). As speculated for macadamia above, declining leaf area may also affect localised development of crop load due to reduced local carbohydrate production or reduced signalling from leaves for other crop load development processes such as floral initiation (Ziv *et al.*, 2014).

The effects of within canopy PAR levels on crop load development requires additional work. Improved understanding of direct and indirect effects of within canopy PAR on crop load is one requirement for the development of ideal within canopy light environments and canopy ideotypes. The best understanding will come through consideration of the timing of key crop development processes, and thus the timing of measurements, the design of the field trials to minimise variability and undertaking these field trials in diverse growing regions.

Measuring the orchard light environment

PAR is most commonly the parameter measured when trying to understand the orchard light environment as it is more meaningful for plant function than a measurement of total solar radiation. The PAR can be expressed as the fraction of the incident PAR reaching the top of the orchard canopy (percentage PAR interception), or it can be expressed as the total moles of PAR intercepted over a certain period of time.

A range of sensing techniques were used to measure light interception and distribution in orchards during the later part of the 20th century, including fisheye photography (visible light),

point grid method (visible light) and selenium or silicon quantum sensors (PAR; Wunsche *et al.*, 1995; Jackson, 1980). The use of quantum sensors emerged as the favoured sensing technology. One of the major requirements of these sensors is that they are cosine corrected, which refers to the sensors ability to relatively evenly sense light that is incident on it from a range of angles. That is, the sensor should record approximately the same intensity of PAR for light of the same intensity coming from directly above the sensor and for light coming from an angle closer to the horizontal (Jackson, 1980). Each quantum sensor is quite small and so only samples a very small fraction of the canopy, however, multiple sensors can be deployed together in many different ways for flexible sampling over time and space. For example, commercially available products called ceptometers consist of large numbers of sensors arranged on a linear bar (commonly 80 cm in length) and allow the measurement and recording of PAR in the space occupied by the sensor. Ceptometers are extremely mobile and due to their length, a relatively large space can be sampled relatively quickly and with great flexibility in terms of length, width and height of placement. Individual sensors can be connected to data loggers by themselves or in groups. For example a group of sensors may be placed on a bar that is deployed in a tree canopy and left to log PAR over several hours or days. Another commonly used tactic is for several sensors to be placed on a bar and connected to a data logger and placed on a trolley that can be wheeled through the orchard. These 'light trolleys' allow rapid measurement of PAR across large areas or many experimental plots and with sufficient sensors they offer excellent sampling definition due to rapid data logging of individual measurements (Scalisi *et al.*, 2024).

The sampling techniques required for the estimation of total PAR interception of an orchard system and that of the measurement of light distribution are different. We must remember that for total PAR interception we are attempting to estimate the proportion of incoming PAR that is intercepted by the orchard system, as opposed to the PAR that is reflected or falls on the ground between the tree canopies. These estimates are undertaken so that comparisons can be made between systems in different trials and locations. The accurate estimation of total PAR interception in discontinuous orchard canopies usually requires the integration of measurements over time and space (Wunsche *et al.*, 1995). In terms of space, it is critical that a sampling strategy is considered for the entire area that the plot of trees being measured occupies (Wilkie *et al.*, 2019). For example, if total PAR interception is being measured for a plot of five avocado trees along a row and the tree spacing is 10 m between rows and 5 m between trees, the PAR sampling area needs to encompass 10 m wide (the row spacing) and 25 m long (5 lots of the 5 m tree spacing). If only the area under the canopy is considered in the sampling the total PAR estimate may be overestimated. The requirement to integrate measurements over time is due to the movement of the sun through the sky across the course of the day and these requirements vary depending on whether the measurements are to be taken under clear blue sky conditions (high proportion of direct radiation) or cloudy conditions (diffuse radiation). Wunsche et al., (1995) demonstrated that under cloudy conditions there is limited variation in the total PAR interception estimate for measurements that are taken at different time of the day because of the diffuse light environment. Whereas, for a discontinuous vertically shaped canopy under clear blue sky conditions, PAR measurements across the entire area occupied by the plot at solar noon will provide a significantly lower estimate of total PAR interception than measurements of the same plot taken when the sun is lower in the sky. The authors concluded that for discontinuous canopies, valid estimates of total PAR interception could be achieved with one set of measurements in a day under diffuse light conditions, but several measurement times were required under clear blue sky conditions.

The principles for measuring light distribution in orchards are centred around the individual questions the worker is attempting to answer. Measurements of light distribution can be used to understand the attenuation of PAR in relation to leaf area or to relate percentage available PAR with physiological parameters such as crop load development processes, photosynthetic performance or vegetative growth. Similar to measurements used to estimate total PAR interception of an orchard system, sampling across time and space also needs to be considered when measuring PAR distribution. In terms of the spatial distribution of the PAR measurements, the worker should consider the relative positioning of the PAR samples relative to the position of sampling of other parameters being measured that are to be related to the PAR interception, to minimise issues discussed for the work presented by Hofman *et al.*, (2021). In terms of time, the worker may wish to take measurements several times during the day to describe the effects of sun angle on canopy light distribution (Tustin *et al.*, 1998). Alternatively, the worker may take several measurements across the day or else log measurement continuously across several days in order to describe the effects of a daily integral of light levels within the canopy. Yet another possibility is that the worker may wish to take PAR measurements at different times of year (or phenological cycle) to understand the effects on certain physiological processes occurring at that time.

All investigations of the fractional interception of PAR (percentage of PAR intercepted) require that each below canopy or within canopy measurement be paired with an above canopy PAR measurement (ambient PAR). Modern PAR measurement systems allow for an above canopy sensor to be paired with the below canopy sensor and for both measurements to be taken instantaneously. If the PAR measurement system does not allow for the measurements to be paired, careful consideration needs to be given to the frequency that above canopy measurements will be manually taken and the method used to ensure they will accurately represent the ambient light conditions when the below canopy measurements were taken. For example, ambient PAR levels vary very little over periods of several minutes under blue sky conditions but can vary enormously in seconds in cloudy conditions or conditions of intermittent cloud (Wunsche *et al.*, 1995).

An avocado canopy ideotype

When all of the above is considered, what is the ideal avocado orchard design, tree structure and associated orchard light environment? In an effort to describe an ideotype for optimum avocado orchard productivity we may identify areas where understanding is lacking:

- Total PAR interception of the orchard system should be approximately 80%. At this level of total PAR interception, the orchard system is intercepting sufficient PAR to achieve maximum yield/ha and does not run the risk of yield decline due to canopy crowding. There is no information available on the interaction between different canopy management strategies, total PAR interception and yield per hectare. It is possible that optimum PAR interception may vary with pruning strategy.
- Canopy dimensions for conventionally spaced orchard systems (10 m to 11 m spacings) should have tree height up to approximately 8 m and an open alley way of 2 m to 3m. Tree dimensions of this range will lead to total PAR interception of approximately 80%.
- Ideal within canopy PAR levels for productive avocado orchards have not been determined. Anecdotal evidence suggests and scientific evidence hints that local PAR levels will affect the development of crop load through effects on the extent and intensity of flowering, fruit set and fruit growth. Anecdotally, local within canopy light levels also affect the retention of leaf area and branch survival.

- The ideal leaf area index for productive avocado orchards have not been determined.
- The ideal leaf area density and the distribution of the leaf area within the canopy for productive avocado orchards have not been determined.
- An optimum density of flowering sites will also be required within the canopy to produce the optimum yield. Some estimates of this are available (Hofman et al., 2018; Hofman et al., 2021). The ability of the canopy to achieve this optimum density of flowering sites may be affected by the availability of PAR within the canopy.

Synthesis

The relationship between total PAR interception and yield per hectare has been documented for conventional plantings in subtropical Central QLD. The main limitation of the previous work is that it failed to confirm whether yield decline occurs as the canopies crowd and total PAR interception increases above 80% and the critical level of PAR interception and canopy characteristics associated with the onset of yield decline. Additionally, we should not take for granted that the relationship between total PAR interception and yield/ha will be consistent between Australia's diverse growing regions. For example, the relationship may vary in temperate latitudes, due to differing light environments and warrant repeating in locations such as southern Western Australia.

There is limited understanding of how the processes in the development of crop load are affected by local light environment. How are floral initiation and development, fruit set and retention and fruit growth affected by within canopy light levels? Consideration needs to be given to the timing of key physiological processes for crop load development, which may vary with growing region, and thus the timing of measurements. This information is critical for understanding ideal within canopy light environments.

No work that we are aware of has investigated the relationships between different canopy management strategies, orchard productivity and total PAR interception.

There is little to no understanding of LAI, LAD and the distribution of this leaf area within avocado canopies. Understanding of these leaf area metrics was critical to the development of high productivity apple orchard systems and the corresponding poor understanding in avocado is likely hampering efforts to improve orchard design and improve canopy management strategies.

There is some understanding of avocado canopy light extinction, but this was measured according to distance as opposed to leaf area. This means this information is less transferrable between growing regions and planting systems. Understanding and documenting the relationship for attenuation of PAR with leaf area will facilitate the design of more productive avocado orchard systems and canopy management systems.

There is currently little understanding of the light requirements for avocado vegetative growth. This includes any requirement of PAR as a signal for the commencement of vegetative growth and PAR levels required for vegetative flush development.

There is currently little understanding of light requirements for leaf area retention and branch survival. It is possible this may be related to the PAR level for net positive carbon assimilation (photosynthetic compensation point).

Given the strong interactions between orchard latitude, time of year, row orientation and planting systems on within canopy light distribution, avocado orchard design would likely benefit from simulations using an avocado orchard light model for different avocado growing latitudes.

Previous work has identified that aspects of the orchard system in addition to the light environment have strong impacts on the development of crop load and final yield. The primary example of this is the competition between vegetative growth and fruit set and development for carbohydrates. This means that canopy design and canopy management strategies should consider potential interactions between the optimisation of the orchard light environment and competition for carbohydrates.

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Section 3: Canopy management practices

G Rossouw, Queensland Department of Primary Industries

3.1. Context for light-driven canopy management

This section consolidates current understanding of canopy management practices relevant to Australian avocado production, focusing on how interventions modify canopy structure, light interception and within-canopy light distribution, and integrates the physiological and environmental factors that determine productivity and yield stability (see Section 1). It provides the technical foundation for a light-centred approach, identifying regional considerations for canopy strategies, the related factors that influence light use efficiency (LUE), as a conceptional determinant of productivity, such as shoot vigour, sunburn risk, functional leaf renewal and carbohydrate dynamics. Additionally, the knowledge gaps to be addressed for ultimately developing a regionally variable best-practice framework and decision-support model, are explored.

Why canopy management matters for light use and productivity:

The shape, density, and leaf renewal dynamics of avocado canopies determine how sunlight penetrates to photosynthetically active zones and how efficiently that light supports flowering, fruit development, and carbohydrate reserve replenishment. While the direct causal link between improved light distribution and hectare-scale yield remains insufficiently quantified in avocado, structural attributes such as canopy size, volume, and external light interception can be measured relatively reliably. These measurable attributes, together with variables such as within-canopy light distribution, shoot density, leaf age structure, and crop load, provide a basis for defining model inputs that can be used to predict canopy performance and yield responses under different management scenarios. However, translating these measurements into predictions of carbon assimilation and yield remains a key limitation, reflecting the absence of well-defined relationships between canopy light environment and productivity.

Evidence from other tree crops shows that maintaining moderate, uniform canopy porosity promotes consistent flowering, higher fruit retention, and reduced alternate bearing. In avocado, however, achieving this balance is complicated by trade-offs between opening the canopy for light access and retaining productive fruiting wood, especially under high vigour or high-radiation conditions.

Effective canopy management therefore integrates structural design, timing, and vigour control to maintain internal light penetration while safeguarding the physiological and environmental conditions that sustain productivity.

Principles for light-driven canopy optimisation:

A light-centred canopy management framework is underpinned by several interrelated insights:

1. Physiology and timing govern success: Interventions must align with shoot growth status, leaf functionality patterns, carbohydrate turnover, and flowering cycles so that pruning, use of plant growth regulators (PGRs) and vigour containment improve light distribution without exhausting reserves or disrupting reproduction.
2. Multiple management levers interact: Structural pruning, chemical growth regulation, cultivar and rootstock choice, irrigation, and nutrition collectively shape canopy porosity, vigour, and light environment.
3. Regional and site adaptation is essential: Climate, phenology, and crop-cycle length differ sharply across production regions; practices effective in one orchard can cause yield losses in another.

4. System configuration defines feasibility: Intensified or mechanised systems may improve efficiency and uniformity of canopy management but may demand rigorous containment to prevent shading and loss of airflow, balanced carefully with bud development and internal resource dynamics.
5. Stress thresholds constrain optimisation: Canopy opening to enhance light must be balanced against sunburn, photoinhibition and disease risks, particularly under high radiation or humidity.

These principles define a management–light interaction framework, framing key research questions such as: *Under which regional and structural conditions do improvements in light capture and distribution translate into higher yield and what physiological or climatic thresholds limit these benefits?*

While Sections 1 and 2 established the basis for light-driven productivity, the application of these principles in canopy management remains constrained by a limited ability to quantitatively link changes in canopy structure to yield outcomes. In particular, the absence of biologically meaningful light targets and parameterised relationships between canopy light environment and yield directly limits the development of predictive canopy models. As a result, many canopy management strategies remain experience-based rather than quantitatively optimised. Secondary limitations relate to how specific interventions modify light distribution under different conditions, which primarily affects the refinement and practical implementation of decision-support tools. These gaps highlight the disconnect between physiological understanding and its translation into predictive and regionally adaptable canopy management frameworks.

Regional differentiation:

Canopy strategies must be adapted to the climatic and phenological diversity of Australia's avocado regions. Rather than describing region specific pruning programs, which vary substantially among growers, this section focuses on how regional climate, phenology and cultivar traits can modify the light environment and therefore influence the suitability and timing of different canopy management options. Examples of regional factors influencing canopy approaches include:

- Tropical humid, high vigour systems such as North Queensland, where high radiation alternates with extended cloudy periods and 'Shepard' flower early and regrow rapidly. These conditions influence how quickly internal shading develops and how frequently canopy renewal is needed to maintain light distribution.
- Warm subtropical systems such as Central Queensland, where rainfall is lower and less frequent than in North Queensland, and where a clearer post-harvest dry phase often provides more workable conditions for canopy opening or structural renewal that influence light distribution.
- Southern long cycle systems, including the semi-arid Tristate and Mediterranean South West WA, where lower humidity, higher VPD and overlapping crop cycles restrict the windows for canopy manipulation and increase the importance of maintaining internal light under extended fruiting cycles.

Together these systems illustrate how climatic drivers and phenology collectively shape light interception, within canopy distribution and rates of canopy closure. They also define the contrasting conditions that any future light-interception model or grower-facing decision tool must accommodate. This section establishes the conceptual foundation for positioning light interception and distribution as a central determinant of canopy performance. It highlights that:

- Regionally tailored canopy strategies are required due to climatic and phenological variation.

- Quantitative relationships between light distribution, LUE (as a conceptual variable), and yield in avocado remain under-researched.
- Key knowledge gaps include: (i) defining optimal canopy porosity and architecture for different regions and cultivars; (ii) quantifying the link between internal light environment and fruiting behaviour; and (iii) integrating region specific climatic modifiers into light interception and LUE based models.

3.2. Principles and strategies

Effective canopy management is fundamental to commercial avocado production, yet its value extends beyond maintaining tree size or orchard access. It is a primary mechanism for regulating how light is captured and distributed within and between trees and how this, in turn, may influence yield stability and productivity. When well aligned with tree phenology and local conditions, canopy management helps balance vegetative and reproductive growth, maintain uniform light environments, support fruit yield and quality, and improve labour efficiency (Leonardi 2005; Whiley et al. 2024; Wolstenholme and Whiley 1995). The relative emphasis on these outcomes varies with cultivar, region, and orchard system design.

Tailored approaches are essential because canopy behaviour differs markedly among environments. In tropical and subtropical climates, trees may produce multiple vegetative flushes per year, requiring more frequent containment to preserve internal light penetration. In Mediterranean or dry regions, extended fruit retention and overlapping crops demand selective, phenology-aligned canopy renewal. These contrasts, driven by region, cultivar, and crop-cycle duration (Cárceles Rodríguez et al. 2023; Schaffer et al. 2024; Wolstenholme and Whiley 1999), define the diversity of canopy strategies that need to be considered.

A central principle is that light interception and spatial distribution of photosynthetically active radiation (PAR) affect canopy productivity (Acosta-Rangel et al. 2021; Menzel and Le Lagadec 2014; Wilkie et al. 2019). Excessive or poorly structured growth increases self-shading, suppresses flower-bud initiation, and limits fruit set in the inner canopy. An open, well-managed structure improves light availability and is expected to improve LUE in productive zones, which is expected to support more uniform flowering and fruit distribution, although the orchard-scale yield response remains insufficiently quantified in avocado. Light penetration also directly influences the photosynthetic capacity of inner canopy leaves, affecting carbohydrate supply to developing buds and fruit (Schaffer and Whiley 2003; Shezi et al. 2019). Canopy interventions such as pruning or chemical growth regulation are therefore physiological levers that modify the light environment rather than end goals in themselves. Opening the canopy, however, can remove fruiting wood and alter carbohydrate reserves, highlighting a trade-off that requires region- and cultivar-specific calibration.

Figure 1 conceptually links these processes, from light interception through to fruit retention and crop load, showing where management interventions could influence physiological outcomes. This conceptual framework identifies key variables relevant to modelling light interception, highlights barriers to consistent practice among regions, and exposes gaps in the causal chain linking light environment to yield. While many of these pathways are well supported in other fruit species, causal proof in avocado remains incomplete, reinforcing the need for quantitative light and productivity studies to support future R&D and grower-facing tools.

Canopy openness also affects pollination ecology. Improved light and air movement increase flower exposure and pollinator access, alleviating shading-related constraints on reproductive development (Partida Jr 1996; Schaffer et al. 2024; Thorp et al. 1993; Wolstenholme and Whiley 1995). Although temperature is the dominant trigger for floral induction, light contributes by

promoting shoot maturity, bud differentiation, and carbohydrate accumulation, processes that determine a shoot's capacity to respond to inductive cues (Acosta-Rangel et al. 2021; Buttrose and Alexander 1978; Davenport 1986; Rossouw et al. 2024; Salazar-García et al. 1999). Thus, canopy interventions that optimise light exposure before the inductive period can indirectly influence flowering potential and fruit set.

Avocado's flowering biology adds further complexity. The species' protogynous dichogamy, flowers opening first as female, later as male, depends on temperature for phase synchrony between cultivars (Hormaza et al. 2024). Dense canopies modify microclimate and light, affecting synchrony and pollinator activity. By improving within-canopy illumination and moderating temperature extremes, appropriate canopy architecture may enhance functional overlap of male and female phases and thereby support more effective pollination (Davenport 1986; Hormaza et al. 2024; Sedgley and Annells 1981).

These principles emphasise that effective canopy management is largely process of light optimisation, not merely vigour control. Regionally tailored, physiology-informed strategies should aim to improve light capture and internal distribution, and maintain balance between vegetative growth and reproductive investment.

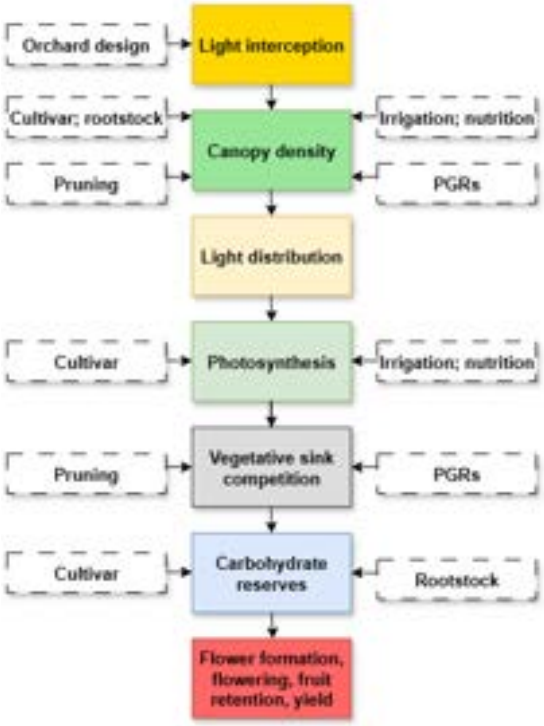

FIGURE 2. Conceptual framework linking canopy structure, physiological processes, and crop outcomes in avocado. Light interception and canopy density initiate a cascade of effects on photosynthesis, carbohydrate dynamics, and reproductive development. Management interventions such as orchard design, cultivar and rootstock selection, pruning, PGRs, irrigation, and nutrition influence key control points in this pathway. This framework is illustrative of hypothesised linkages; whether local light improvements scale to orchard-level yield remains a research question.

Structural traits and shoot renewal:

The physical structure of avocado trees plays a foundational role in orchard productivity. From a light-interception perspective, canopy architecture, branch orientation, leaf-area distribution, and shoot-renewal patterns determine how radiation is absorbed and distributed within the canopy volume (Leonardi 2005; Menzel and Le Lagadec 2014; Whiley et al. 2024; Wolstenholme

and Whiley 1992) (Figure 2). These traits influence key physiological processes: photosynthesis, floral development, fruit set and growth, and carbohydrate allocation, linking physical structure and light directly to productivity (Schaffer and Whiley 2003; Schaffer et al. 2024; Whiley and Wolstenholme 1990).

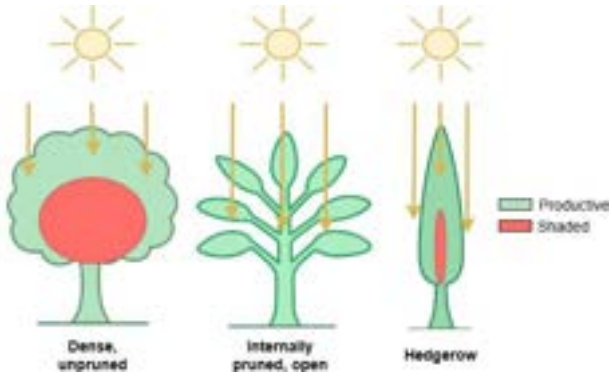

FIGURE 3. Comparison of contrasting canopy structures and their hypothetical influence on light distribution. Dense, unmanaged trees (left) limit light penetration into the inner canopy, pushing flowering and fruiting to the outer canopy and relying on older, unrenewed fruiting wood. Internally pruned, open canopies (middle) enable more uniform light distribution, support active shoot renewal, and help maintain the balance between vegetative growth and reproductive capacity. Structured, upright canopies (right), such as those in hedgerow or central leader systems, improve light exposure throughout the canopy, and are often more suitable for narrow, columnar cultivars used in high-density orchards. However, these systems may be less appropriate in high-vigour regions or sites where structural control is more difficult to maintain. Importantly, greater openness can also reduce current fruiting wood; thus, the net effect on yield remains context dependent. The goal is to match canopy type to site vigour and management capacity.

An optimal canopy improves light penetration to inner and lower zones, supports regular shoot renewal, and maintains a functional balance between vegetative and reproductive growth (Thorp et al. 1993; Whiley et al. 2024; Wilkie et al. 2019). As some orchard systems move toward intensification and more uniform tree forms, quantifying how canopy geometry regulates light distribution and renewal dynamics will be critical for developing regionally adapted management approaches and advancing light-interception models for avocado (Leonardi, 2005, Faber and Bender, 1999, Menzel and Le Lagadec, 2014).

Productive canopies rely not only on structure but on the continual renewal of fruiting wood. Avocado leaves live for roughly 12 to 18 months (Schaffer et al. 1991; Wolstenholme and Whiley 1999), so productivity depends on new shoots that can replace ageing wood and maintain light-harvesting surface. As a polyaxial species, avocado generates new axes that sustain canopy photosynthetic capacity. Flushes during warm seasons may exceed one metre in length, ultimately supplying leaf area for carbon assimilation (Paull and Duarte 2011). The timing, distribution, and management of these flushes are therefore critical variables for any light-based productivity framework.

Leaf physiology and light interception:

Canopy-scale photosynthesis depends on the persistence of well-lit, functional foliage. Avocado leaves transition from sinks to net sources within 20 to 24 days after budbreak, peaking in photosynthetic capacity between 40 and 70 days after unfolding (Liu et al. 2002a; Schaffer et al. 2024; Schaffer et al. 1991). Efficiency then declines as leaves age or become shaded. Maintaining a steady supply of young, illuminated leaves is thus essential for sustaining canopy carbon gain.

Fine-scale structural traits further regulate how light is intercepted. Leaf distribution, phyllotaxy, and angle determine how photons are partitioned between canopy layers. Avocado's spiral phyllotaxy creates patchy illumination patterns (Buzgo et al. 2007; Chanderbali et al. 2024), while horizontal leaf layers enhance self-shading. Without structural adjustment, dense outer foliage limits inner-canopy PAR and may constrain flowering potential. Pruning and training increase the proportion of well-lit, photosynthetically active foliage, although how these improvements translate to orchard-level yield remains uncertain, underscoring a major gap in understanding canopy light–yield relationships.

Cultivar and rootstock influences:

Canopy architecture differs markedly among cultivars, affecting both light interception and shoot renewal. Upright, columnar types such as 'Reed' and 'Gem' produce narrower canopies with higher internal light uniformity, making them more suitable for high-density or mechanised systems (Crane et al. 2024). Spreading cultivars like 'Hass' and 'Shepard' exhibit wider branch angles and stronger apical dominance, increasing shading risk if unmanaged (Crane et al. 2024; Thorp et al. 1993; Wolstenholme and Whiley 1999). Rootstocks further modify these patterns by altering vigour and internode length (Ben-Ya'acov et al. 1993). Understanding how genotype combinations influence canopy porosity, renewal rate, and light distribution will be essential for regionally variable best-practice models.

Structural balance and flowering patterns:

Without regular management, avocado canopies tend toward outer-canopy dominance, where dense terminal growth intercepts most light, forcing fruiting to the outer shell and suppressing inner flowering (Spann 2019; Wolstenholme and Whiley 1995; Wolstenholme and Whiley 1999). This imbalance reduces the effective photosynthetic and reproductive volume of the canopy. Long-term productivity therefore may depend on maintaining vertical and radial light balance through structured renewal and periodic adjustment.

Canopy architecture also influences where and when flowering occurs. Inflorescences may develop from terminal (determinate) or subterminal (indeterminate) buds, depending on shoot vigour and flush timing (Chanderbali et al. 2024). Light distribution and renewal rate may affect the proportion of these shoot types, shaping the spatial pattern of fruiting. Clarifying these architectural, reproductive linkages is essential for modelling how canopy structure translates to yield potential.

A physiological foundation for canopy management:

Effective canopy management is a proactive process that aims to optimise both the structure and function of avocado canopies to sustain light capture, carbohydrate supply, and yield regularity over time. Rather than simply removing excess growth, it requires an understanding of how light availability, carbohydrate partitioning, and shoot development interact dynamically throughout the crop cycle (see Section 1). Light interception is the primary driver of carbon assimilation, and its spatial distribution within the canopy determines where assimilates are produced and how they are allocated to growth, flowering, and fruit development (Rossouw et al. 2024; Schaffer et al. 1991; Whiley and Wolstenholme 1990).

Strategic interventions such as pruning regulate these processes by adjusting canopy density and improving the uniformity of internal PAR. These principles are particularly critical in high-vigour or high-density orchards, where shading suppresses inner-canopy photosynthesis and limits carbohydrate supply to developing shoots and inflorescences (Menzel and Le Lagadec 2014; Thorp et al. 1993). Strengthening this physiological link between canopy structure and

photosynthetic function remains a central research priority for clarifying how light environment influences crop load and yield.

Timing, carbohydrate reserves, and alternate-bearing risk:

The timing of canopy interventions is generally central to maintaining a positive carbon balance. Avocado trees typically produce multiple vegetative flushes per year (Olesen 2005), each progressing through expansion, maturation, and senescence (Liu et al. 1999a; Schaffer et al. 2024; Schaffer et al. 1991). The canopy's ability to supply photoassimilates during these stages depends on both light availability and leaf efficiency in capturing that light (Section 1). When photosynthetic supply declines, through shading, stress, or untimely pruning, trees draw on stored carbohydrates in woody tissues, a buffering mechanism common to fruit trees (Rossouw et al. 2024). Repeated or excessive reserve depletion impairs floral initiation and intensifies alternate bearing (Lovatt 2010; Monselise and Goldschmidt 1982).

Floral induction and early inflorescence development are especially sensitive to carbohydrate status during defined phenological windows that vary by region (Howden et al. 2005; Ramírez-Gil et al. 2023; Whiley et al. 1988). Sugars act both as energy substrates and as developmental signals (Lovatt 2010; Rossouw et al. 2024; Whiley and Wolstenholme 1990). Canopy interventions must therefore be timed to preserve sufficient assimilate supply for these reproductive processes, avoiding heavy pruning immediately before or during inductive periods. Aligning actions with local phenology and climate helps maintain carbon balance and reproductive potential and underscores gaps in knowledge of how canopy interventions interact with light environment and reproductive success.

Inflorescence type and reproductive balance:

Avocado's dual inflorescence types add physiological complexity. Determinate inflorescences, arising from terminal buds, terminate growth after flowering and concentrate resources on reproduction, generally achieving better fruit set. Indeterminate inflorescences, emerging from subterminal shoots that continue vegetative growth, draw assimilates away from developing fruit (Chanderbali et al. 2024; D'Asaro et al. 2021; Whiley et al. 2024). These shoots often have higher fruitlet abscission rates (D'Asaro et al. 2021).

Canopy structure and management practices influence the relative proportion of determinate versus indeterminate shoots, thereby shaping fruiting efficiency. For instance, pruning that increases light to sub-canopy regions may promote determinate shoot development and improve resource partitioning to fruit. Managing this reproductive balance is fundamental to synchronising vegetative renewal with fruiting cycles, key to understanding how light-mediated physiological responses can be modelled or targeted in management tools.

Pruning as a physiological intervention:

Pruning is a physiological lever rather than a purely structural task. Selectively removing vigorous or poorly positioned shoots, particularly in the upper canopy, reduces apical dominance and redistributes assimilates to renewal zones. It also promotes compensatory shoot growth and renewal of ageing wood, creating a canopy with younger, more photosynthetically active foliage (Schaffer et al. 2024; Wolstenholme and Whiley 1999).

The magnitude and timing of these responses vary by cultivar and region. For example, in vigorous tropical and sub-tropical environments, pruning intensity must offset rapid regrowth, while in cooler or long-cycle regions, excessive cutting can delay recovery and disrupt return bloom. Recognising these context-dependent responses helps define the practical limits of canopy adjustment, information directly relevant to developing regionally adaptable best-practice frameworks.

Canopy principals - synthesis:

- Light interception and canopy structure strongly influence photosynthetic performance and reproductive potential, though quantitative yield effects remain uncertain.
- Tree architecture, leaf renewal rate, and intervention timing collectively shape canopy light distribution; regional and genetic variation determine feasible strategies.
- Evidence gaps include defining optimal canopy porosity, quantifying light–yield relationships and integrating physiological understanding into region-specific management models.

3.3. Canopy management techniques

Training during orchard establishment:

Canopy management begins during orchard establishment. Early training of juvenile trees defines future canopy geometry and light distribution (Stassen et al. 1999b). Structural training creates a strong, well-spaced branch framework that supports fruit loads, maintains open light channels, and fits the intended orchard configuration (e.g., high-density vs. conventional systems). The principal canopy management approaches and their relevance to light access, shoot renewal, and structural balance are summarised in Table 1. Early shaping also prepares trees for mechanised cycles by standardising architecture and spacing. Without this groundwork, trees often develop narrow crotch angles, crowded scaffolds, or excessive vertical growth that later require corrective pruning which can hamper productivity, at least in the short-term (Faber and Bender 1999; Leonardi 2005; Whiley et al. 2024).

Intervention during the first two years after planting generally involves selecting three to five primary limbs, managing apical dominance to prevent overly upright growth, and encouraging balanced lateral development to form a stable canopy base (Hormaza et al. 2024; Wolstenholme and Whiley 1999). Pinching of growing tips can suppress dominance and enhance branching, producing a more compact, light-permeable structure (Paull and Duarte 2011). Training strategies must also reflect cultivar growth habit. Upright cultivars require stronger leader control, whereas spreading types benefit from early scaffold spacing and removal of low horizontal limbs.

Maintenance pruning in productive orchards:

Once trees reach production, canopy management shifts to maintaining light distribution, shoot renewal, and structural balance (Cutting et al. 1994; Snijder et al. 2000; Snijder and Stassen 1999; Stassen et al. 1999a). Regular maintenance pruning prevents dense shading and sustains fruiting on well-lit shoots.

Typical operations include selective thinning of crowded or inward branches, heading cuts to stimulate lateral branching, and removal of senescent interior wood. Maintaining a mosaic of differently aged, well-exposed shoots sustains canopy photosynthetic efficiency and internal PAR. Limbs encroaching into inter-row space are cut back, and heading cuts above the bud ring releases multiple buds and increases shoot complexity; cuts below the ring may release only one bud and reduce vigour (Cutting et al. 1994; Paull and Duarte 2011).

Pruning is normally timed after harvest but before floral initiation to avoid stimulating untimely regrowth or removing developing inflorescences (Cutting et al. 1994; Olesen 2005; Thorp and Stowell 2001; Whiley et al. 2024). In long-cycle or overlapping-crop regions, heavier work is best reserved for off-years (Lovatt 2010; Whiley et al. 2024; Wolstenholme 2010). In high-vigour or humid zones, more frequent containment may be needed. Canopy closure exceeding roughly 90 % of orchard floor area often signals reduced light penetration and potential productivity decline

(Paull and Duarte 2011). While manual pruning remains common, mechanical and chemical growth regulation aids are increasingly combined.

Past Australian benchmarking work, although limited, compared canopy systems not only by yield but also by productivity rating (tonnes ha^{-1} $year^{-1}$ averaged over multiple seasons) and canopy management cost ($ ha^{-1} $year^{-1}$) (Piccone 2004). Integrating such economic and biophysical metrics remains valuable for evaluating canopy strategies that sustain light penetration while remaining commercially viable. These metrics provided a framework for assessing not only biological performance but also the sustainability and feasibility of different light-management strategies over time. For example, manual pruning and hedgerow systems achieved medium-to-high productivity (13 to 24 t ha^{-1} $year^{-1}$), while drastic interventions such as stag-horning or top-working produced the lowest ratings due to multiple non-productive years.

Linking economic benchmarks with quantitative light-interception data in future research could identify canopy strategies that are both physiologically effective and economically sustainable across production regions.

Restorative and rejuvenation pruning:

In mature or crowded orchards, rejuvenation pruning aims to restore canopy light environment and fruiting wood turnover (Snijder et al. 2000; Stassen et al. 1999a; Whiley et al. 2024). These staged programs: thinning, height reduction, or major limb removal, seek to recover productivity by reopening the canopy and stimulating new growth while limiting carbohydrate depletion by managing the regrowth (Cutting and Bower 1992; Cutting et al. 1994). Severe topping to 1 to 3 m ("stag-horning") can rejuvenate trees but typically creates a two- to three-year non-bearing period (Paull and Duarte 2011); more moderate topping (~5 m) maintains partial yield while improving internal light (Crane et al. 1992).

Effectiveness depends on cultivar vigour, age, and site. Rejuvenation is particularly relevant where canopy neglect has produced dense, light-inefficient walls or when converting older blocks. Though labour-intensive, it aims to extend orchard life and resets light capture capacity (Snijder and Stassen 1999; Thorp and Stowell 2001).

Summer pruning to manage vegetative flushes:

In high-vigour orchards or warm, wet climates, spring flush growth can rapidly shade the canopy and compete with fruit for assimilates. Summer pruning, particularly shortening shoots before lignification, helps restore internal light and rebalance source–sink relations (Cutting et al. 1994; Whiley et al. 2024). Conducted in late spring or early summer, it removes over-extended or vertical leaders, improving light penetration and airflow. Well-timed summer pruning can reduce vegetative dominance and redirect carbohydrates toward fruit growth (Thorp and Stowell 2001).

However, in cooler or biennial-prone regions, mistimed summer cuts risk damaging developing fruit or inducing hard-to-control regrowth (Avocados Australia 2009; Cutting et al. 1994; Whiley et al. 2024). Precision timing relative to phenology and local radiation load remains a critical knowledge gap for modelling light–growth interactions.

Mechanical pruning: techniques, timing and limitations:

Mechanical pruning is increasingly adopted for efficiency in higher-density or labour-limited systems (all across Australian avocado regions), typically involving hedging and topping to maintain target alley widths and heights (Snijder and Stassen 1999; Whiley et al. 2024). Many orchards employ two cycles: a post-harvest reshape before flowering and a summer trim to

shorten spring flush (Avocados Australia 2009). In warm tropical and subtropical regions, delaying post-harvest pruning until autumn or early winter may help prevent excessive regrowth during flowering.

In long-cycle or overlapping-crop regions, mechanical pruning may damage developing inflorescences and is best restricted to off-years. While mechanical systems provide consistency and speed, their non-selective nature may eventually reduce inner-canopy light if repeated without periodic branch renewal cuts. Alternating mechanical and more intensive manual pruning every few years can help restore structure and maintain balanced light profiles. Cultivar habit also determines response, vigorous or spreading types often require more intensive follow-up (Snijder and Stassen 1999; Stassen et al. 1999a).

Advanced training systems and structural pruning options:

Advanced pruning strategies provide finer canopy control tailored to cultivar form, site vigour, and orchard layout. Central-leader or hedgerow systems commonly work well for upright cultivars such as 'Reed' or 'Lamb Hass' (Avocados Australia 2009; Whiley et al. 2024). These systems aim to suppress lateral spread and concentrate productive shoots within well-lit vertical planes. Modified multi-leader versions typically suit more vigorous environments.

Tipping or minor green pruning of young or rejuvenated trees helps manage dominance and promotes lateral branching (Hofman et al. 2018; Stassen et al. 1999b; Thorp and Sedgley 1993b). Selective limb removal: skirting, thinning of overlapping branches, or removal of dominant verticals, further improves internal illumination and canopy access. In hotter regions, retaining low limbs may help protect fruit and soil surface from excessive radiation.

Structured, staged limb removal can follow sequences (Avocados Australia 2009) such as:

1. Three-year manual side–centre–side cycles with water-shoot control;
2. Sequential mechanised topping and side-pruning followed by summer trimming; or
3. V-shaped pruning across rows to reopen alleyways and increase canopy light penetration.

These approaches tend to allow partial yield retention while progressively restoring structure. They aim to stabilise production by re-establishing uniform light distribution and regular shoot turnover, key parameters for any light-interception or modelling framework.

Selective hand pruning remains important wherever repeated mechanical hedging has created dense outer walls. Strategic manual cuts re-open light corridors, regenerate fruiting terminals, and can improve fruit quality (Cutting and Bower 1992; Cutting et al. 1994).

Across systems, effective pruning and training strategies are those that sustain internal light distribution, facilitate renewal of productive wood, and maintain manageable canopy dimensions. The relative success of manual, mechanical, or hybrid approaches depends on cultivar vigour, climate, and orchard design. Further quantification is needed to determine how these interventions modify canopy porosity, shoot renewal, and light interception under contrasting regional conditions in ways that can be measured and parameterised for modelling applications.

Management techniques - synthesis

- Formative training defines long-term canopy geometry and light pathways, establishing the basis for later mechanisation.
- Maintenance, summer, and rejuvenation pruning collectively influence shoot renewal and within-canopy light, though magnitudes of yield response remain uncertain.

- Mechanical and advanced pruning systems improve efficiency but can compromise inner-canopy light without periodic structural renewal.
- Evidence gaps include quantifying how pruning type and timing alter canopy porosity and light distribution across cultivars and regions.

TABLE 1. SUMMARY OF KEY AVOCADO PRUNING TYPES, THEIR OBJECTIVES, TIMING, APPLICATION ZONES, AND POTENTIAL ASSOCIATED RISKS.

Pruning type	Primary purpose	Typical timing	Target canopy area	Suitable for	Notes and considerations	Risk if misapplied
Formative pruning	Establish scaffold structure; improve light access	Early (2-3) years; after rejuvenation or major limb removal	Entire canopy; scaffold limbs	Young trees; trees recovering from severe cuts	Includes pinching to control apical dominance; cultivar growth habit influences scaffold design and light channels	Delayed training can lead to poor structure, crossing limbs, and internal shading
Maintenance pruning	Sustain light penetration; promote shoot renewal; structural balance	Postharvest and before floral initiation; timing varies by region and cultivar	Internal, outer and upper canopy	Mature orchard under regular management	Annual or regular practice in reproductive orchards; includes selective thinning, heading cuts, and fruiting wood renewal; not intended to reshape trees	Poor timing may reduce return bloom or stimulates unwanted vegetative growth; neglect leads to shading and yield decline
Summer pruning	Shorten spring flushes; control excessive vigour and maintain internal light	Late spring to early summer before shoot hardening	Areas with vigorous spring flush growth (e.g. upper and outer canopy zones)	High vigour trees or high-rainfall regions	Timing during active shoot elongation supports better light penetration and source–sink balance; tipping after hardening limits effectiveness	Tipping too late offers little benefit; pruning during flowering or early fruiting may reduce yield or increase sunburn risk
Rejuvenation pruning	Restore structure; reduce canopy size, improve light distribution, and reset tree architecture	Mainly post-harvest (e.g. every 3-5 years); summer or around flowering feasible depending on cut type and regional growth; off-years preferred in biennial systems; in warm regions, major shaping best delayed until autumn/winter to supress regrowth	Large limbs; whole scaffold level	Overgrown, neglected, or high-vigour trees	Best done in stages to reduce yield loss and regrowth issues; post-pruning recovery may benefit from summer tip pruning	Without follow up training, trees may regrow erratically or develop structural imbalances; sudden exposure to light may cause sunburn on wood and fruit
Mechanical pruning	Rapid containment of tree size and shape, maintain alley light penetration	Postharvest (autumn – winter) and/or summer; in cooler regions, preferably timed for off years	Entire tree (topping, hedging)	High-density orchards; labour limited regions	Non-selective; best combined with periodic manual pruning to restore structure; delaying until cooler weather helps avoid stimulating vegetative flushing during flowering	Poor timing may damage flowers or immature fruit, especially in overlapping crop systems; may cause dense regrowth and shading

3.4. Indirect canopy management

Indirect canopy management encompasses all practices and inputs that influence canopy vigour and light environment without physically altering tree structure. This includes chemical regulation through PGRs, water and nutrient management, and rootstock selection, as well as alternative and emerging approaches such as girdling, root restriction, interstocks, and reflective or shading technologies. Together with pruning, these levers shape canopy density, porosity, and renewal dynamics, determining how effectively light is intercepted and utilised within orchards across contrasting environments.

Role and rationale for PGRs in avocado canopy management:

Avocado trees are naturally vigorous, particularly in warm subtropical and tropical environments (Hormaza et al. 2024; Menzel and Le Lagadec 2014; Whiley et al. 2024; Wolstenholme 1987). This strong vegetative habit reduces internal light availability, elevates shoot-to-fruit biomass ratios, and can diminish productivity over time if not managed effectively. PGRs provide a chemical complement to structural canopy control, offering a means to moderate shoot extension and stabilise canopy light profiles in high-vigour or high-density systems (Lovatt and Salazar-García 2006; Whiley et al. 2024). By suppressing internode elongation, PGRs help maintain canopy dimensions, delay closure, and reduce pruning frequency. Triazole compounds also influence floral initiation and fruitlet retention, linking chemical canopy control directly to crop development processes (Hormaza et al. 2024).

In avocado canopy management, the gibberellin-biosynthesis inhibitors paclobutrazol and uniconazole are the most widely applied (Whiley et al. 2024). These triazoles inhibit gibberellin production by blocking ent-kaurene oxidation (Rademacher 2000), thereby reducing shoot elongation and overall vegetative growth. Their value is greatest in dense or vigorous orchards where mechanical containment alone cannot sustain adequate light penetration. Both soil and foliar applications can reduce shoot growth, improve within-canopy illumination, and extend the intervals between pruning cycles (Whiley et al. 2024; Whiley et al. 1991; Wolstenholme et al. 1990). Figure 3 illustrates the physiological mechanisms and application pathways linking triazole use to canopy light and renewal dynamics.

Factors affecting PGR effectiveness and application strategy:

PGR performance depends strongly on cultivar, climate, and soil environment, with rootstock–scion interactions also affecting uptake and persistence (Rademacher 2015). High rainfall or sandy soils can reduce the residual activity of soil-applied triazoles, requiring adjustment of dose or frequency (Whiley et al. 2024). This environmental variability presents a practical barrier to regionally consistent practice.

Timing relative to shoot development is critical. Applications during early shoot extension are most effective at reducing internode length, while late or excessive treatments risk over-suppression, delayed canopy recovery, or interference with reproductive development (Hormaza et al. 2024; Whiley et al. 2024). Optimising timing and dose to balance containment with adequate renewal remains a priority research need.

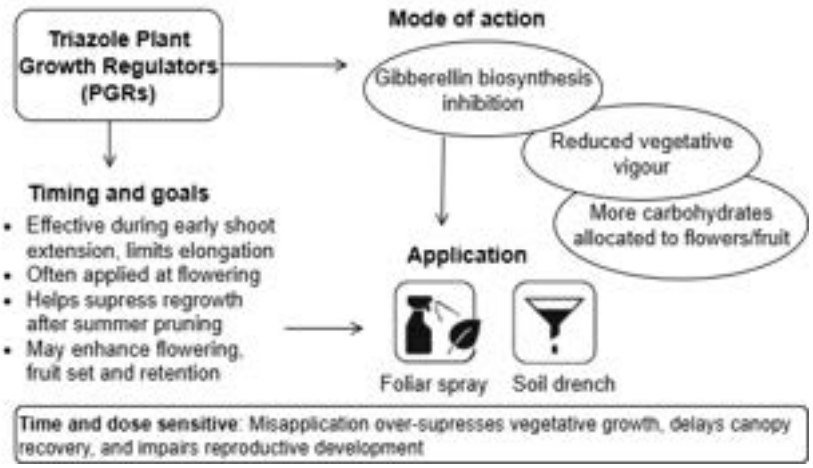

FIGURE 4. Mode of action, goals, and application of triazole plant growth regulators in avocado. Triazoles such as paclobutrazol and uniconazole inhibit gibberellin biosynthesis, reducing vegetative vigour and potentially supporting flowering and fruit set. They are applied as foliar sprays or soil drenches, with timing and dose being critical to avoid over-suppression and ensure reproductive success.

In Australia, paclobutrazol is typically applied as a foliar spray due to lower leaching risk than soil drenches (Avocados Australia 2009; Desta and Amare 2021; Whiley et al. 2024). Rates between 2.5 and 5 g L^{-1} can reduce spring-flush shoot length by about 40 % (Wolstenholme et al. 1990). Symons et al. (1990) observed dose-dependent suppression in potted 'Hass' with soil rates from 0.31 to 1.25 g m^{-2} canopy area, but field reliability under variable soil and rainfall conditions remains poorly characterised.

Commercial formulations such as Austar (250 g L^{-1} paclobutrazol) are applied at full bloom at 7 L 1000 L^{-1} for vegetative control (Avocados Australia 2009). Whiley et al. (1991) demonstrated that a single mid-bloom foliar application of paclobutrazol in 'Hass' increased yield and/or fruit size depending on concentration:

- 0.06 % a.i. increased yield by 43 % without affecting size;
- 0.125 % a.i. increased yield and fruit size by 40 % and 11 %, respectively;
- 0.25 % a.i. improved fruit size by 14 % with little yield effect.

These results illustrate the dual vegetative–reproductive role of triazoles and the importance of dosage calibration.

Uniconazole, also a gibberellin inhibitor, is mainly used as a foliar spray. Products such as SUNNY® (50 g L^{-1} uniconazole-P) are applied at mid-bloom (50 % flower opening) at 5–10 L 1000 L^{-1} to enhance fruit size and limit spring flush growth (Avocados Australia 2009). Follow up sprays on regrowth after summer pruning can help stabilise light penetration through the renewed canopy. In South Africa, two sprays two to three weeks apart at 2–3 L 1000 L^{-1} were shown effective in limiting regrowth (Whiley et al. 2024). Australian field trials using 0.025–0.05 % a.i. uniconazole improved fruit size, though yield responses were variable, underscoring the need for region-specific calibration.

Effects of triazoles on flowering and fruit development:

Beyond vegetative suppression, triazoles may enhance reproductive development by altering carbohydrate partitioning and hormonal balance. Gibberellin inhibition shifts assimilate use from vegetative sinks to reproductive tissues and may promote floral induction (Whiley et al. 2024; Wolstenholme et al. 1990). In mango and other crop models, this is linked to up-regulation of *FLOWERING LOCUS T* (FT) and accumulation of bud sugars (Blázquez et al. 2003; Nakagawa et al. 2012; Yamaguchi et al. 2014). While these molecular pathways are not yet confirmed in

avocado, similar expression patterns of flowering genes under inductive conditions (Acosta-Rangel et al., 2021, Hormaza et al., 2024) suggest comparable regulation.

Field evidence indicates that reducing vegetative flush intensity before or during anthesis can support flowering and fruit set (Adato 1990; Köhne and Kremer-Köhne 1987; Whiley et al. 1991). Paclobutrazol induced profuse flowering in both potted and field-grown 'Hass', while uniconazole produced similar outcomes in South African trials (Erasmus and Brooks 1998; Penter et al. 2000). Application around mid-bloom appears most effective for aligning carbohydrate availability with reproductive demand, but more frequent or higher dose application doesn't necessarily offer cumulative benefit (Adato 1990).

Consistency varies with cultivar, rootstock, and climate, but when strategically applied, triazoles may improve cropping regularity by moderating vegetative–reproductive competition and maintaining a more stable canopy light environment.

Other PGRs and research priorities:

Other PGR classes have been explored in avocado and other tree crops but play minor roles in canopy control. Gibberellic acid (GA_3) promotes flushing and is unsuitable for canopy containment (Lovatt and Salazar-García 2006). Ethylene-releasing compounds such as ethephon have regulated flowering and shoot maturation in mango and lychee (Cronje et al. 2022; Davenport 2009) but remain largely untested for avocado canopy use. Auxin analogues such as 1-naphthaleneacetic acid (NAA) are used in other crops to suppress regrowth after severe pruning (Arpaia et al. 2007), suggesting potential for structural management in high-density systems. However, these compounds might promote or alter vegetative activity rather than suppress it, and their integration into canopy strategies requires caution and further research.

Across all compound types, the key research need is to quantify how chemical growth control interacts with light environment, carbohydrate reserves, and reproductive timing under different climates and cultivars. Addressing these knowledge gaps will inform the integration of PGR use into regionally adaptive, light-based canopy management frameworks.

The influence of water and nutrients on canopy development:

Although irrigation and nutrition are not direct canopy management interventions, they can strongly determine vegetative vigour, canopy density, and light distribution in avocado (Carr 2013; Gil et al. 2024; Whiley et al. 2024; Wolstenholme and Whiley 1995). Excessive irrigation or nitrogen (N) fertilisation promotes vigorous shoot growth and dense foliage, reducing internal light availability and increasing reliance on structural pruning or chemical control. Conversely, insufficient water or nutrient supply restricts shoot renewal and leaf area expansion, which limits photosynthetic capacity.

Avocados are relatively high water users compared to many other fruit trees, and the interaction between water supply and canopy structure appears to be a major determinant of light interception efficiency (Cárceles Rodríguez et al. 2023). In high-rainfall tropical and subtropical regions such as Far North and Central Queensland, excessive vigour and frequent flushing are key challenges (Carr, 2013, Gil et al., 2024, Whiley et al., 2024). In contrast, in drier climates such as Western Australia, the Tristate region, and inland New South Wales, canopy management often focuses on sustaining leaf function and renewal under water-limited conditions (Cárceles Rodríguez et al. 2023; Carr 2013; Schaffer et al. 2024; Whiley et al. 2024). These climatic contrasts influence both light capture and canopy porosity, which creates regionally distinct constraints on consistent practice.

Irrigation strategies for regulating canopy vigour:

Irrigation regimes influence the rate, duration, and synchrony of shoot growth, with major implications for canopy light profiles and productivity. High and sustained soil moisture, especially in high-rainfall or poorly drained soils, can stimulate excessive flushing and canopy closure (Carr 2013; Gil et al. 2024). This reduces internal PAR and increases the frequency of pruning or PGR intervention. Conversely, well timed mild water restriction can suppress vegetative dominance and support floral induction (Cárceles Rodríguez et al. 2023; Carr 2013). These effects are highly sensitive to timing. Excessive stress risks yield loss or fruit size reduction and reduces light-use efficiency as stomata close and photosynthesis declines.

Regulated deficit irrigation (RDI) and partial rootzone drying (PRD) are used in other tree crops to modulate shoot growth and synchronise phenology (Fereres and Soriano 2006; Naor 2006). While not widely applied in avocado, they present opportunities to test controlled water management as a canopy-light optimisation tool, provided local validation accounts for avocado's shallow roots and sensitivity to stress. Quantifying thresholds that temper vigour without compromising renewal or light-use efficiency remains an open research need. When integrated with pruning and balanced nutrition, irrigation scheduling becomes an indirect but powerful means to regulate canopy density and the light environment across diverse climates.

Nutritional strategies for managing vegetative growth:

Nutrient management, especially nitrogen, plays a defining role in canopy architecture and renewal (see Section 1). Excess N stimulates prolonged vegetative growth and shading, particularly in fertile or humid environments (Gil et al. 2024; Silber et al. 2018). This can reduce internal light availability, delay floral initiation, and elevate the need for pruning or chemical suppression. Conversely, nutrient deficiency restricts leaf development and slows recovery after canopy interventions. Deficiencies also impair leaf functionality, which reduces light-use efficiency by limiting photosynthetic pigments.

The timing, formulation, and rate of N supply are therefore key levers for balancing vegetative and reproductive growth. Synchronising fertiliser application strategies with phenological stages such as post-pruning recovery, flowering, and early fruit set improves nutrient-use efficiency and minimises excessive canopy closure (Gil et al. 2024; Newett et al. 2018; Selladurai and Awachare 2020; Silber et al. 2018). Trees with adequate carbohydrate and nutrient reserves recover faster and produce more balanced flushes after pruning, although faster recovery may also accelerate canopy closure (Davie et al. 1995; Wolstenholme and Whiley 1997).

Soil chemistry also shapes canopy behaviour. Imbalances in pH or cation ratios (Ca:Mg:K) can restrict uptake (Newett et al. 2018), while waterlogging from poor drainage or high rainfall reduces foliar concentrations of N, P, K, Mg, Zn, Cu, Ca, and B due to impaired root activity (Schaffer et al. 2024). In contrast, Mn and Fe solubility may increase, causing additional imbalance (Tzatzani et al. 2020). Aligning irrigation and nutrient management is therefore critical for maintaining canopy light function and recovery capacity.

In Australian orchards, mature 'Hass' trees typically require ~110 kg N ha^{-1} yr^{-1}, but reported grower use ranges from 69 to 528 kg N ha^{-1} yr^{-1}, with an average of 212 kg N ha^{-1} yr^{-1} (Newett et al. 2018). Notably, high-performing orchards generally apply moderate rates (85 to 140 kg N ha^{-1}), showing that beyond an optimal range, additional N does not improve productivity and can instead degrade light-use efficiency through excessive vigour.

Climate further moderates nutrient response. In subtropical regions, extended warmth prolongs vegetative activity and amplifies responses to high N, whereas in Mediterranean climates,

shorter growth windows may allow slightly higher N inputs without canopy shading (Gil et al. 2024; Newett et al. 2018; Silber et al. 2018). These regional contrasts support the need for climate-tailored nutritional guidelines that integrate light and canopy parameters.

While N is the dominant driver of vigour, other nutrients contribute to canopy light-use efficiency and function. Potassium (K) regulates stomatal conductance and carbohydrate transport (Shah et al. 2024; Tränkner et al. 2018). Phosphorus (P) supports root growth and energy transfer (Rychter and Rao 2005), while calcium (Ca) strengthens cell walls implicated in leaf functionality (Eckardt 2001; Wang et al. 2019). Regular soil and tissue testing should be linked to canopy density targets and phenology, forming part of a holistic canopy light optimisation framework.

Rootstock influence on canopy development:

Rootstocks exert a strong yet variable influence on canopy vigour, architecture, and light distribution in avocado by modulating scion growth, phenology, and physiological responsiveness (Crane et al. 2024; Menzel and Le Lagadec 2014). Although most canopy management research has focused on pruning, irrigation, and nutrition, rootstock–scion interactions remain an underexplored determinant of canopy structure and light interception efficiency.

Rootstocks affect shoot extension, flushing frequency, and canopy density, while also conferring tolerance to biotic and abiotic stresses such as *Phytophthora cinnamomi*, salinity, drought, and calcareous soils (Ben-Ya'acov and Michelson 1995; Crane et al. 2024). Variations among Mexican, Guatemalan, West Indian, and hybrid races influence vegetative vigour, nutrient uptake, and overall canopy size, shaping how light penetrates through the canopy and how frequently structural containment is required (Ben-Ya'acov and Michelson 1995; Schaffer et al. 2024; Whiley et al. 2024). Rootstock choice therefore represents a strategic lever for moderating canopy light environment and long term pruning demand.

Dwarfing potential

The dwarfing potential of avocado rootstocks appears genotype-specific rather than race-specific. Selections such as 'Colin V-33', 'Nahlat', 'Ashdot', and 'Maoz' produce smaller trees under certain conditions (Crane et al. 2024; Lahav et al. 2024), which can substantially affect canopy renewal dynamics and the intensity of pruning required.

As orchards move toward higher planting densities and mechanisation, rootstocks that combine moderated vigour with strong yield efficiency, fruit quality, and stress tolerance will become increasingly valuable. Key priorities include understanding how rootstocks influence shoot growth rhythm, post pruning regrowth, and internal light distribution under Australian conditions. Table 2 summarises generalised effects of major rootstocks on canopy size, vigour control, and light distribution potential, though performance varies by scion, region, and site conditions.

Rootstock disease resistance and canopy implications:

Phytophthora root rot (PRR) remains one of the most serious constraints to avocado productivity worldwide. Consequently, commercial rootstock selection has prioritised PRR tolerance, with cultivars such as 'Duke 7', 'Dusa®', 'Bounty', 'Velvick', 'Zentmyer', and 'Steddom' widely adopted (Crane et al. 2024; Menge et al. 2012; Whiley et al. 2024). While these rootstocks enhance survival and yield on infested soils, their effects on canopy structure, renewal rate, and light interception differ across climates and soils are not yet well quantified. For example, 'Velvick' exhibits high vigour, often producing large canopies that require more frequent pruning, particularly in fertile soils or hedgerow systems (Menzel and Le Lagadec 2014; Whiley et al. 2024).

Additional pathogens such as *Phellinus noxius* have emerged in some regions, including Far North Queensland following extended wet periods (Dann et al. 2011). Very little is known about rootstock tolerance to Phellinus, reinforcing the need to evaluate rootstocks for both disease resilience and canopy-vigour moderation.

In Australia, 'SHSR-04' ('Procado') has shown promise, producing smaller, more efficient canopies when grafted with 'Hass' and 'Shepard' (Crane et al. 2024; Whiley and Dann 2021). 'Steddom' and 'Miriam' ('VC801') are also under evaluation for combining PRR tolerance with reduced vigour (Crane et al. 2024). Emerging clonal propagation and tissue-culture techniques may further enhance rootstock uniformity and consistency of canopy traits (Hiti-Bandaralage et al. 2017; Noguera et al. 2011).

Challenges and future directions for canopy-focused rootstock selection:

Many Australian orchards still rely on seedling rootstocks such as 'Velvick' and 'Reed' because of availability and propagation ease. However, seedlings display high genetic variability in tree size, vigour, and canopy form (Menzel and Le Lagadec 2014; Whiley et al. 2024), complicating uniform canopy management and reducing predictability of light distribution. 'Reed' is also susceptible to PRR (Smith et al. 2011), though it remains one of the few rootstocks produced via tissue culture, offering genetically uniform material (Hiti-Bandaralage et al. 2022).

As the need for more compact, mechanised, and light-efficient orchard systems increase, the development and local evaluation of rootstocks that balance disease tolerance, moderate vigour, and uniform canopy geometry will be increasingly important. Research priorities include:

- Quantifying rootstock effects on light interception, canopy renewal rate, and pruning frequency across regions;
- Identifying combinations that improve light use efficiency and yield stability under different climates; and
- Integrating these traits into orchard design and modelling frameworks.

Optimising rootstock use on a regional basis is therefore central to future canopy strategies that balance productivity, uniformity, and resilience while maintaining favourable light environments.

TABLE 2. Summary of suggested canopy-related traits [vigour, yield, phytophthora root rot (PRR) resistance, canopy implications and other considerations] for selected avocado rootstocks. Traits reflect generalised observations from published literature and field trials but may vary depending on site conditions, scion cultivar, orchard age, and environmental factors. Values are indicative and should be interpreted within the context of regional performance and management objectives.

Rootstock	Tree Vigour	Yield effect	PRR Resistance	Canopy Implications	Notes and considerations
Velvick	High	High	Moderate to high	Large, vigorous trees; frequent pruning required in high density or fertile sites	Widely used; variable performance due to genetic heterogeneity; best suited to conventional spacings or well-managed systems; clonal forms offer more consistency in replant situations
Ashdot	Low to moderate	High	Unknown or unconfirmed	Compact canopies under low–moderate vigour conditions; canopy control less reliable on fertile soils	Promising for high-density systems, especially with 'Hass'; performance varies with environment; less effective at controlling vigour on fertile soils or in warm, wet regions; may be sensitive to environmental stress (e.g. salinity, heat); several selections (e.g. Ashdot 17, 27)
Duke 7	Moderate to high	Variable	Moderate in field; inconsistent under high pressure or waterlogging	Canopies may require regular structural management; not well suited to poorly drained soils	Sensitive to trunk canker and waterlogging; performance depends on site conditions; less commonly used in Australia now
Reed	Generally high	Moderate or variable	Low	High variability in canopy size and structure when seedling rootstocks are used	Commonly used seedling rootstock in Australia; high genetic variability complicates uniform canopy management; not recommended for high-PRR-risk sites; tissue culture propagation now available to improve consistency
SHSR-04 (Procado)	Low to moderate	High	High	Smaller canopy under low–moderate vigour conditions; supports compact structure	Selected in a PRR-infested Australian orchard; grafted trees (e.g. 'Hass', 'Shepard') show precocity and reduced vigour; only tested under limited conditions.

Indirect management - synthesis

- PGRs, irrigation, nutrition, and rootstocks are indirect levers that influence vigour, porosity, and within canopy light, with likely effects on photosynthetic capacity and reproductive potential.
- Calibration to local conditions is essential. Variable soils, rainfall, phenology, and rootstock–scion combinations limit one size fits all guidance and explain inconsistent responses.
- Priority gaps include timing and dose thresholds for triazoles, water and nitrogen thresholds that temper vigour without undermining renewal, and rootstock effects on light distribution and recovery after pruning.

Alternative and emerging approaches:

In addition to PGRs, irrigation, nutrition, and rootstocks, several alternative or experimental techniques have been tested to influence avocado canopy structure and function. These include root restriction, trunk or branch girdling or scoring, interstocks, and physical modification of the root or shoot environment (Goren et al. 2003; Schaffer et al. 2024; Silber et al. 2012; Whiley et al. 2024). While most remain at limited-commercial or research stage, they may offer new avenues for managing canopy vigour and light environment in high-density, labour-constrained, or climate-challenged systems. Their potential lies in fine-tuning light distribution and source–sink relationships, although consistent evidence of productivity or quality benefits in avocado is still lacking.

Girdling and scoring as a targeted intervention:

Girdling and scoring have been investigated primarily for their ability to redirect assimilate allocation and enhance flowering intensity. Within a canopy management context, they have been tested as temporary vigour-suppression tools, particularly in high-vigour cultivars or dense plantings. By interrupting phloem transport, girdling induces carbohydrate accumulation above the girdle, which in some cases coincides with earlier or more intense flowering (Goren et al. 2003; Whiley et al. 2024).

Because phloem reconnection typically occurs within weeks, effects are transient. These techniques may be relevant for short-term adjustment of source–sink balance and canopy light exposure in environments where prolonged vegetative flushing restricts flowering. However, variability in response, potential impairment of root health, and risk of nutrient imbalances limit their suitability for regular use. Current evidence therefore supports only targeted, experimental application of girdling for canopy or light management.

Root-based interventions: restriction and pruning:

Root-zone modification is another area of exploration for canopy vigour control. Root restriction, imposed by containerisation, physical barriers, or dense soil conditions, can reduce shoot growth and canopy spread by limiting water and nutrient uptake (Silber et al. 2012; Whiley et al. 2024). This may improve manageability in high-density systems by constraining canopy volume and maintaining light access.

However, physiological studies indicate that severe root confinement reduces CO_2 assimilation and photosynthetic efficiency, linked to starch accumulation in leaves and feedback inhibition of carbon export (Schaffer et al. 2024; Whiley et al. 1999). This effect limits its practicality as light use efficiency may effectively be reduced.

Root pruning, used more successfully in crops like apple and peach (Ferree et al. 1992), has produced inconsistent results in avocado (Roe and Kohne 1996). It can temporarily suppress shoot growth but increases susceptibility to root pathogens. These root-based techniques therefore act indirectly on canopy structure via altered source–sink dynamics and light interception and require local validation before wider adoption.

Interstocks as potential vigour modulators:

Interstocks, short stem sections inserted between the rootstock and scion, have been tested as genetic vigour modifiers without altering the rootstock or scion genotype. In other fruit crops, interstocks can control vigour, enhance compatibility, or promote flowering (Di Vaio et al. 2009; Webster 1995). Preliminary avocado work using dwarfing types such as ‘Colin V-33’ suggests partial growth suppression is possible but highly variable (Barrientos Priego et al. 1987; Roe and Morudu 2000). By influencing hormonal or hydraulic signalling, interstocks could potentially delay flushing or improve canopy compactness in high-vigour cultivars.

However, results remain inconsistent, and cases such as ‘Fuerte’ interstock in ‘Hass’ have induced alternate bearing (Whiley et al. 2024). Propagation and compatibility constraints currently limit feasibility, but they represent a niche genetic tool for moderating canopy growth and internal light distribution where rootstock replacement is impractical.

Experimental approaches to light and shoot modulation:

Several exploratory techniques from other crops target light interception and microclimate rather than direct growth control. Examples include shoot bending, bark inversion, reflective groundcovers, and shade nets have been trialled internationally to alter shoot orientation,

canopy porosity, and light-use efficiency (Bastías and Corelli-Grappadelli 2013; Mupambi et al. 2018; Robinson 2003). While not common in avocado production, these techniques may hold value for fine-tuning canopy light profiles in high-density or climate-exposed systems.

Reflective mulches and shade nets, for instance, have improved light uniformity and reduced heat stress in apple and grape systems (Rana et al. 2004; Shahak et al. 2008). If strategically adapted for avocado, such interventions could complement pruning and PGR strategies by enhancing uniform illumination.

These alternative techniques highlight the diversity of tools with potential to modulate canopy light interception and source–sink balance, but their role in avocado remains largely experimental. Evidence for consistent effects on light distribution, yield, or uniformity is limited, and risks such as reduced root function, disease susceptibility, or irregular bearing remain poorly quantified. Addressing these uncertainties will require region-specific trials that combine physiological, structural, and light-modelling approaches to assess their feasibility.

3.5. Seasonal timing

The role of timing in light and canopy regulation:

Effective canopy management depends not only on the technique used but also on its alignment with phenological stage and environmental cues. Poorly timed interventions can suppress flowering, trigger unwanted regrowth, or reduce fruit quality, while well-timed actions help maintain a productive balance between vegetative and reproductive growth. Timing influences whether an intervention enhances or undermines light distribution, carbohydrate dynamics, and canopy renewal. This section builds on physiological principles, practical techniques, and indirect levers, including PGRs, described before, highlighting the seasonal synchronisation of canopy actions, a critical factor for sustaining productivity and stability across Australian regions.

Regional and cultivar-specific phenology

Canopy interventions such as pruning and PGR application are most effective when matched to the tree's phenological development. Avocado exhibits overlapping vegetative flushes, floral initiation, flowering, and fruit growth, with the timing and intensity of these phases varying by cultivar, region, and climate (Schaffer et al. 2024; Whiley et al. 2024). As outlined earlier, vegetative flushes compete with reproductive sinks for carbohydrates, meaning that mistimed interventions can disrupt the source–sink balance and reduce flowering or yield (Cutting et al. 1994; Lovatt and Salazar-García 2006; Whiley et al. 2024). In contrast, phenologically aligned practices tend to support shoot renewal, reproductive development, and more stable cropping cycles (Salazar-Garcia et al. 1998; Thorp and Stowell 2001).

Seasonal growth patterns differ markedly across regions. For example, in Far North Queensland, 'Shepard' typically flowers from around June, with spring flush from August and harvest from February to April. In the Tristate region, 'Hass' flowers in September–October, with harvest extending into early summer. Figure 4 illustrates these patterns for six key region–cultivar combinations, showing typical overlaps between vegetative flushes, flowering, fruit growth, and potential canopy-intervention windows. These differences confirm that regional flush calendars are guides, not rules, so intervention timing must respond to cultivar behaviour, microclimate, and real-time phenological cues.

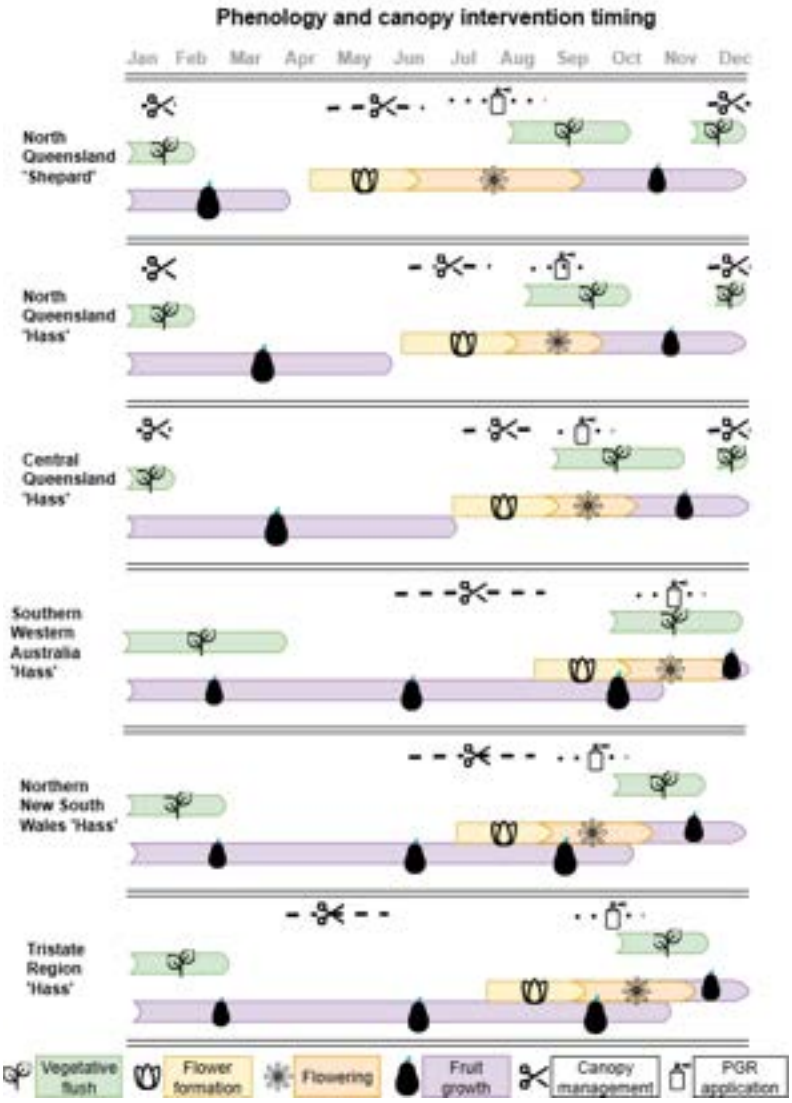

FIGURE 5. Generalised phenological development and canopy intervention timing across six avocado region–cultivar combinations in Australia. Timelines show the typical overlap and sequence of vegetative flushes, flower formation, flowering, fruit development, canopy management, and PGR application. Differences in phenological timing across regions highlight the importance of aligning interventions with local biological and environmental cues. Actual timing and practices vary between orchards within the same region. Adapted from the Australian Avocado Best Practice Resource (BPR) crop calendars.

Timing strategies for pruning and limb removal:

The optimal timing of canopy interventions varies with regional climate, technique, and canopy goal. In warmer tropical and subtropical regions, mechanical pruning or hedging is often performed post-harvest and sometimes again during summer, although major shaping interventions are typically delayed until late autumn or winter when cooler temperatures may suppress regrowth and favour floral induction (Avocados Australia 2009; Whiley et al. 2024). In some orchards, a summer prune is strategically applied to shorten spring flushes, improving light penetration and moderating shoot-to-fruit ratios (Whiley et al. 2024).

In cooler or drier southern regions, major pruning is usually timed for late autumn or early winter, especially during an off year, to minimise fruit loss from overlapping crop cycles and reduce sunburn risk. Selective limb removal follows similar logic, and late-season pruning often suppresses regrowth and helps preserves return bloom potential, while in alternate bearing systems, heavier interventions are reserved for off-years when carbohydrate reserves can

recover (Whiley et al. 2024). Regrowth is commonly tip-pruned during summer to encourage lateral branching and restore canopy structure. As with PGRs, phenology-aligned pruning is essential to avoid disrupting floral development or triggering vegetative flushes that compromise light balance.

Market-aligned canopy timing decisions:

Beyond physiology, timing decisions may also reflect market and labour dynamics. For instance, in North and Central Queensland, some growers coordinate major pruning with the alternate cropping cycle of Western Australia, reducing canopy volume when WA enters an on year to recover during low-price periods and target strong markets in the following off year. These timing adjustments illustrate how economic drivers intersect with physiological timing, influencing canopy strategies in ways that can ultimately affect light exposure, shoot renewal, and profitability.

Managing spring and summer flush timing:

Spring and summer vegetative flushes are pivotal for canopy renewal but must be managed carefully to maintain light availability and reproductive balance. These flushes shape canopy density and flowering potential, particularly in high-vigour orchards. In warmer tropical and subtropical climates, the spring flush commonly follows harvest and can quickly crowd the canopy. Post-harvest pruning in late autumn or winter can reset structure and help suppress premature regrowth. Some growers apply a summer prune during early shoot elongation, when shoots are ~50–100 mm long, to redirect assimilates toward fruit growth and limit shading (Avocados Australia 2009; Whiley et al. 2024). Tipping too late, after shoots have hardened, offers less benefit for light management or floral initiation. Monitoring shoot growth rate and phenological status in real time remains important for identifying effective pruning windows.

Avoiding pruning during reproductive phases

Pruning during floral initiation or early fruit development can disrupt reproductive success by altering hormonal balance, damaging buds, or stimulating vegetative regrowth that diverts carbohydrates from inflorescences (Lovatt 2006; Whiley et al. 2024). These risks are heightened in alternate-bearing orchards, where strong on crops deplete reserves and may suppress return bloom. In such cases, early pruning before anthesis can reduce current crop load and preserve carbohydrates for the next cycle (Farré et al. 1987; Whiley et al. 2024). Conversely, pruning after flowering or early fruit set seldom improves return bloom and may reduce yield in both years (Roe and Morudu 1999; Roe and Morudu 2000; Whiley et al. 2024). Late-autumn or winter pruning is therefore generally preferred to protect reproductive processes while benefiting from cooler, low-regrowth conditions.

Timing of PGR applications

The timing of triazole PGRs such as paclobutrazol and uniconazole is critical for achieving reliable canopy and yield outcomes. Mid-bloom foliar sprays can enhance fruit retention, fruit size, and overall productivity (Adato 1990; Erasmus and Brooks 1998; Penter et al. 2000; Whiley et al. 1991; Wolstenholme et al. 1990). Premature application may suppress necessary shoot development (renewal of functional, light-use efficient leaves), whereas late applications can interfere with inflorescence growth (Whiley et al. 2024). Efficacy depends on synchrony with source–sink transitions and reproductive sensitivity. Inappropriate timing can destabilise carbohydrate allocation, impair canopy renewal, and reduce yield potential, although effects are context specific.

Integrating timing into canopy-light optimisation

Ultimately, the success of any canopy intervention, mechanical, manual, or chemical, depends on its alignment with the tree's phenological stage, carbohydrate balance, and local climate. Well-timed actions are expected to support stable flowering, balanced vegetative growth, and favourable light environments, promoting consistent yields and canopy longevity. Poorly timed interventions can trigger regrowth, disrupt flowering, or accentuate alternate bearing.

Timing is a critical variable for understanding regional light interception dynamics and crop stability. Quantifying effective temporal windows will help identify physiological and operational barriers to consistent outcomes and clarify gaps in coordinating pruning, PGR use, and phenology. Aligning management timing with climatic and phenological signals is central to improving light use efficiency, yield stability, and the predictive capacity of canopy light models for Australian avocado production.

Interactions with reproductive development:

Pollination and floral exposure

Canopy management practices can indirectly influence pollination success and fruit set by modifying the light environment, floral exposure, and access for pollinators. In dense canopies, inner flowers often receive less light and are less accessible to bees and other pollinators, which may reduce pollination efficiency and fruit set (Garner and Lovatt 2016; Hormaza et al. 2024). Reduced light can also alter canopy microclimates, sometimes lowering pollen viability and stigma receptivity, contributing to fertilisation failure despite adequate pollen presence (Garner and Lovatt 2016). Appropriate pruning to open the canopy can improve floral visibility and internal microclimate, enhancing both pollinator access and fruit set outcomes (Partida Jr 1996; Wolstenholme and Whiley 1995). However, such opening also reduces fruiting wood and may increase sunburn risk, so the net effect on yield is context dependent.

Light distribution within the canopy not only affects pollinator movement but also the spatial synchrony of anthesis in Type A and Type B cultivars, potentially influencing effective cross-pollination (Hormaza et al. 2024; Schaffer et al. 2024; Schroeder and Hofshi 2006). Warmer, well-lit canopy zones may flower slightly earlier than shaded interiors, suggesting that canopy uniformity could help support overlap between complementary flowering types.

Canopy structure can also affect polliniser effectiveness, as dense interplant shading may limit cross-pollination where polliniser branches are poorly exposed. While some pollen transfer occurs via wind, insect-mediated pollination remains critical for achieving optimal yield in avocado (Dymond et al. 2021). A more open canopy generally improves both the frequency and effectiveness of pollination events, which can support fruit set. These interactions further illustrate how structural canopy traits and seasonal timing combine to influence reproductive performance.

Fruit set and early retention

Improved light penetration is generally associated with enhanced carbohydrate availability in developing inflorescences, which may support ovary retention and fruitlet growth (Hormaza et al. 2024). Where light levels are low or trees experience high reproductive demand, a source–sink imbalance may develop, limiting carbohydrate supply to developing fruitlets and contributing to early abscission (D'Asaro et al. 2021). Low light may also trigger hormonal imbalances, particularly elevated abscisic acid (ABA), that signal physiological stress and promote fruit drop (Garner and Lovatt 2016). Fruitlet retention is also affected by competition with vegetative

growth, carbohydrate status, and hormonal signalling, all of which are shaped by canopy structure and vigour (Lovatt 1990).

Strategic canopy management during key reproductive stages may help reduce early fruit loss, particularly in seasons of high flowering intensity or following suboptimal pollination. Excessive vegetative flushing during flowering, especially in unmanaged or overly vigorous canopies, can compete for carbon assimilates and further suppress fruit set or cause flower abscission (Whiley et al. 2024). These outcomes reinforce the physiological trade-offs described earlier and highlight the importance of canopy interventions that maintain source–sink balance. Whether local improvements in fruit retention consistently translate to higher yield per hectare remains uncertain in avocado. Determining how canopy light gradients translate into spatial fruit set patterns is a key data gap for future modelling.

Fruit quality

In addition to its effects on yield, canopy structure plays a critical role in determining fruit quality. Light exposure influences skin colour development, dry matter accumulation, and external finish, key factors for market acceptance and postharvest performance (Cutting and Bower 1992; Spann 2019; Wolstenholme and Whiley 1995). Dense or unpruned canopies often exhibit steep light gradients, with internal fruit developing under shaded conditions that can delay maturity, reduce dry matter content, and increase the risk of postharvest disorders. In contrast, fruit positioned in more open, well-lit parts of the canopy generally show improved skin colour, higher dry matter levels, and fewer quality defects. These effects are especially important in high-density orchards or with vigorous cultivars where internal shading is common, reinforcing the need for regular canopy opening.

Canopy openness also enhances air movement and reduces humidity, which may lower the incidence of fruit rots and post-harvest diseases (Schaffer et al. 2024; Whiley et al. 2024). In warm, wet regions such as North and Central Queensland, where vegetative vigour and rainfall are high, poor light and airflow can intensify internal shading and fruit quality issues. A Queensland study found that although total light interception increased with canopy volume, yields appeared to plateau beyond ~80% interception and mean fruit weight declined, likely due to excessive internal competition for light and assimilates (Wilkie et al. 2019). These observations suggest the importance of balancing canopy volume and porosity, particularly in humid regions. They also raise the possibility of diminishing returns in yield beyond a threshold light interception level, supporting the case for modelling canopy light saturation curves under regional conditions.

Conversely, in drier or cooler climates, excessive light exposure can increase sunburn risk, especially following aggressive pruning or during hot weather in sparsely foliated trees (Glenn et al. 2002; Whiley et al. 2024). Maintaining moderate porosity and ensuring some protective foliage near harvest is therefore critical in these regions to avoid sun damage while still enabling sufficient light penetration. These contrasting patterns emphasise that ‘optimal’ canopy openness is climate- and orientation-dependent. Finding a workable balance between shading and exposure is essential for consistent fruit quality.

Timing of interventions

To support fruit set and retention, canopy interventions should be timed to improve light exposure and airflow without disrupting floral development. In avocado, floral initiation occurs several months before anthesis, typically from late autumn to early winter in most Australian regions, making the post-harvest period a commonly cited window for structural pruning (Ahsan et al. 2023; Buttrose and Alexander 1978; Scholefield et al. 1985). For example, in ‘Hass’, floral initiation may begin as early as May–June in cooler climates. Pruning during or after this phase

can remove developing inflorescences or diverting carbohydrate resources needed for flowering. Ideally, pruning should be completed shortly after harvest to improve bud light exposure while preserving developing floral structures.

In warmer regions with earlier phenology, this pruning window shifts earlier, reinforcing the need for regionally adapted timing decisions. Interventions should also avoid stimulating vegetative flushes during reproductive phases, which could compete for assimilates and suppress flowering. Aligning pruning with local phenological calendars ensures that the structural benefits of canopy opening do not compromise flowering or fruit set. Integrating real time phenology monitoring or remote canopy sensing could improve predictive timing, providing data to support precision canopy management.

Cultivar and regional differences

The effectiveness of canopy interventions depends heavily on cultivar architecture and regional climate. Cultivars with spreading or dense growth habits, such as 'Hass', tend to exhibit more internalised flowering and foliage, increasing the risk of inflorescence shading. These cultivars are typically more responsive to structural opening, especially when floral development is concentrated within the canopy interior. In contrast, upright cultivars like 'Reed' often expose more flowering sites due to their open structure, which may reduce the need for aggressive pre-flowering pruning (Crane et al. 2024; Hormaza et al. 2024).

Regional climate further influences canopy density and intervention needs. In cooler, drier areas, lower disease pressure and more moderate vegetative vigour may reduce the urgency for pre-flowering pruning. However, in warm, wet regions, such as North and Central Queensland, frequent flushes and high humidity increase shading and disease risk, necessitating earlier or more frequent canopy opening. Where heavy flowering occurs, particularly in alternate-bearing-prone cultivars or regions, strategic pruning may help moderate crop load and support carbohydrate allocation to developing fruit (Lovatt 2010; Whiley et al. 2024). These strategies align with regional factors and cultivar considerations, highlighting the need to tailor canopy interventions based on both cultivar traits and environmental context.

Beyond immediate impacts on fruit set and retention, canopy structure also influences return bloom in the subsequent season. Excessive shading or sustained high crop loads can be associated with suppressed floral initiation by limiting carbohydrate availability and altering hormonal cues needed for inflorescence development (Scholefield et al. 1985; Whiley et al. 2024). This is particularly relevant in cultivars and regions prone to alternate bearing, where poorly managed canopies may exacerbate biennial cycling. Maintaining canopy openness throughout the year can help improve light penetration and support consistent carbohydrate accumulation in developing buds. Avoiding severe stress or resource depletion near the time of floral initiation is therefore critical for supporting return flowering and stabilising production.

From a research perspective, linking spatial and temporal canopy light profiles to flower and fruit set positions would directly support modelling of light driven yield variability. Clarifying these relationships provides a pathway for predictive, regionally adapted canopy design and management tools.

Timing - synthesis

- Timing is a key determinant of whether canopy actions improve light distribution, carbohydrate balance, and renewal, with responses varying by cultivar and region.
- Post harvest to winter windows are commonly used for major structural work, while carefully timed summer tipping can manage spring flush, though effects are context specific.

- PGR efficacy depends on synchrony with phenology, mid bloom timing is often cited, and mis timed applications can destabilise source sink relations.
- Priority gaps include quantitative definitions of effective timing windows by region and cultivar, and how temporal light profiles relate to fruit set, retention, and yield.

3.6. Cultivar considerations

Production context:

Australian production is dominated by 'Hass' (~80–85%), with 'Shepard' (~10–15%) being largely concentrated in North Queensland due to earlier flowering and harvest. Smaller plantings of 'Maluma', 'Reed', 'Lamb Hass', 'Wurtz', 'Gmax', 'GEM' and others target specific market windows or site conditions (Avocados Australia 2024). These cultivar differences in canopy architecture, growth vigour, vegetative flushing, pruning response, and internal light distribution are central to designing regionally adapted and physiologically aligned canopy strategies.

Canopy architecture and growth habit across cultivars:

Growth habit and canopy architecture vary notably among cultivars, shaping their suitability for different planting densities and canopy management approaches. 'Hass' typically forms a medium-to-large, semi-upright canopy with a rounded crown and dense internal structure that readily develops shading in the absence of regular containment pruning (Crane et al. 2024). This tendency toward internal shading can limit light penetration to mid-canopy fruiting zones, necessitating recurrent thinning to maintain fruit distribution and to help mitigate alternate bearing. In contrast, 'Shepard' is described as having a compact form, although under the warm, fertile conditions of North Queensland it can express high vegetative vigour and a sprawling canopy during rapid spring flushing. For 'Shepard' due to early maturity and fast canopy recovery, regular containment remains necessary to maintain light use and fruit quality (Crane et al. 2024; Whiley and Lavers 2021).

Several lesser grown cultivars, including 'Maluma' and 'GEM', display more upright architecture and lower vigour, providing advantages for hedgerow plantings and central-leader systems, particularly in higher-density or labour-limited orchards. 'Maluma' often maintains a restrained, open canopy with strong central-leader potential, while 'GEM' exhibits an upright, vase-like form that may support improved fruit set and reduced alternate bearing (Crane et al. 2024; Ernst et al. 2015). These growth habits tend to promote light distribution through the canopy and can reduce long-term pruning demand, though periodic selective pruning remains necessary to prevent the formation of overly dense internal foliage.

Cultivar-specific responses to growth regulators:

Cultivar responsiveness to triazole-based plant growth regulators (PGRs) may influence canopy management strategies. 'Hass' and 'Maluma Hass' generally exhibit strong suppression of spring flush following foliar paclobutrazol application, enabling effective canopy containment. 'GEM' shows a moderate response, while 'Shepard' is typically less responsive under comparable regimes (Whiley et al. 2024). As a result, chemical canopy control in 'Shepard' blocks is often limited, and mechanical reshaping combined with nutrient and irrigation moderation remains the main approach. Tailoring PGR programs to cultivar behaviour and site conditions can help improve light penetration and reduce canopy re-closure, while minimising negative impacts on flowering or shoot renewal.

Canopy management considerations specific to 'Hass':

The canopy and phenological traits of 'Hass' have important implications for timing and light management. A high proportion of 'Hass' spring shoots can be determinate, terminating in

flowers without producing new leaves (Crane et al. 2024). In some regions, particularly southern regions like tri-state and South-western WA, this behaviour can delay canopy re-establishment and temporarily expose developing fruit and limbs to high radiation and heat, increasing sunburn risk. In these contexts, new leaf cover may be slow to recover in spring, particularly in years with heavy cropping or depleted carbohydrate reserves, reinforcing the importance of managing light interception to protect both fruit and photosynthetic capacity. Vegetative flushes in avocado are tightly linked to carbohydrate dynamics and source–sink competition, making the timing of pruning and growth regulation crucial to avoid compromising canopy recovery and future productivity.

In most subtropical production regions, 'Hass' produces two to three vegetative flushes per year: a dominant spring flush followed by one or more flushes in summer or early autumn (Chanderbali et al. 2024; Whiley et al. 1988). Leaf expansion occurs over approximately 30 days, with net carbon gain beginning once leaves reach about 80 % expansion (Whiley 1990). These patterns influence both the timing and intensity of pruning or shoot removal needed to maintain a productive canopy architecture and to balance light penetration with fruiting wood renewal.

Shoot type and branching behaviour also affect canopy structure and trainability. 'Hass' produces both proleptic shoots (from dormant buds) and sylleptic shoots (from buds that grow immediately during shoot extension), resulting in a moderately upright form with reasonable branching potential. In Chile, for example, young 'Hass' trees in high-density orchards are trained by selectively removing proleptic shoots and retaining sylleptic ones, encouraging upright growth and faster canopy structuring (Chanderbali et al. 2024). These principles align with the structural goals discussed in Section 3.2, as maintaining light corridors and uniform canopy geometry are important considerations.

Timing remains one of the strongest determinants of canopy and light outcomes. Late-summer pruning can remove fruiting wood required for the following season, delaying canopy recovery and potentially reducing flowering potential. Prolonged on-tree storage of mature fruit further exacerbates alternate bearing by delaying flush renewal and reducing floral initiation capacity (Crane et al. 2024; Hormaza et al. 2024; Whiley et al. 2024). Strategies that reduce crop load, avoid delayed harvest, and support post-harvest carbohydrate recovery are therefore useful for maintaining stable canopy renewal and internal light environments.

The number, timing, and synchrony of vegetative flushes vary with climate, influencing the suitability and scheduling of canopy interventions. In most Australian regions, two distinct flushes dominate, a spring flush coinciding with or following flowering, and a summer or early-autumn flush (Whiley et al. 1988). In some international climates such as Mexico, California, and Chile, extended warmth allows three to four flushes annually (Chanderbali et al. 2024; Salazar-Garcia et al. 2006). Flush activity often is most vigorous in outer, non-fruiting canopy zones; without management, this drives internal shading and may reduce photosynthetic efficiency. Variations in flush synchrony and duration across climates and cultivars therefore have significant implications for light interception, shoot complexity, and the tree's capacity for canopy renewal. These phenological dynamics underpin both the physiological and operational timing of pruning and should be explicitly considered in regionally and cultivar-specific canopy strategies aligned with light-interception goals.

'Shepard': canopy traits and regional suitability:

'Shepard' is primarily cultivated in North Queensland due to its early harvest timing, compact canopy structure and adaptation to warm tropical climates (Whiley and Lavers 2021). Although its compact habit, under some conditions, is advantageous for medium- to high-density

systems, high vigour under fertile conditions can cause dense, rapidly closing canopies if left unchecked (Crane et al. 2024; Whiley and Lavers 2021). Its flowering cycle is relatively sensitive to low temperatures than that of 'Hass', resulting in erratic fruit set in cooler or elevated regions. 'Shepard' therefore performs best in reliably warm environments such as the Atherton Tablelands and parts of Central Queensland.

While early maturity allows timely fruit removal and faster canopy recovery, inconsistent cropping has been reported, potentially linked to pruning intensity or suboptimal flowering conditions. Its reduced responsiveness to triazole PGRs further limits chemical vigour control (Whiley et al. 2024). Consequently, canopy containment in 'Shepard' primarily relies on post-harvest mechanical shaping and summer shortening of the spring flush, timed to preserve interior light and manage vegetative dominance. Further evaluation of pruning techniques, polliniser arrangement, and rootstock compatibility could help enhance canopy stability and yield reliability for this cultivar.

Canopy strategies for contrasting cultivar growth forms:

Avocado cultivars can be grouped into broad growth-form categories that define their canopy management priorities, Figure 5. Highly upright cultivars such as 'GEM' and 'Reed' form narrow, columnar canopies well suited to central-leader or hedgerow systems, where height regulation and scaffold spacing are key to maintaining uniform light distribution (Crane et al. 2024; Spann 2022; Thorp and Sedgley 1993a). Intermediate-upright cultivars like 'Maluma' possess moderately open canopies that generally require only light post-harvest pruning to preserve internal illumination and fruiting balance, supporting high-density mechanised production (Crane et al. 2024; Ernst et al. 2015). Sprawling and vigorous cultivars such as 'Hass' and 'Shepard' develop broad, laterally dominant structures that easily shade interior fruiting zones (Crane et al. 2024; Whiley et al. 2024). These require formative training, periodic containment and selective thinning to maintain productive light profiles.

Across all growth forms, the goal is to maintain canopy porosity and structure that support interception and distribution of PAR within the productive canopy volume. Understanding cultivar architecture and its plasticity across environments provides a foundation for future light modelling and canopy-optimisation work.

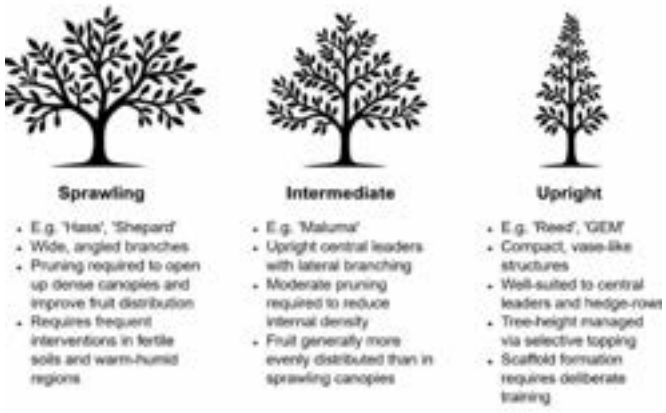

FIGURE 6. Generalised canopy forms of key avocado cultivars and associated management considerations. Sprawling types (e.g. 'Hass', 'Shepard') develop wide-angled branches, needing regular interventions to maintain light distribution. Intermediate forms (e.g. 'Maluma') have upright central leaders with lateral branching and moderate pruning needs. Upright types (e.g. 'Reed', 'GEM') are compact and suit central-leader or hedgerow systems, requiring scaffold formation through training and height control via selective topping. The intensity and frequency of canopy interventions vary with regional climate and soil fertility.

Integrating cultivar × rootstock × region:

Future orchard design will increasingly depend on integrating cultivar growth traits with rootstock choice and regional conditions to achieve canopies that are both light-efficient and operationally sustainable. Rootstocks that moderate scion vigour and improve uniformity can reduce pruning frequency and help stabilise within-canopy PAR distribution. However, many cultivar–rootstock combinations remain poorly characterised under Australian conditions.

Further research is required to quantify how cultivar-specific traits interact with light environment, rootstock influence and regional climate to shape canopy structure, renewal dynamics and yield stability. Such data are essential to build regionally variable, light-based canopy management models. Cultivar therefore represents a central variable in defining target canopy geometry, intervention frequency, and management intensity required to maintain light efficient canopies and consistent productivity across Australia's diverse growing regions.

3.7. Regional factors

Environmental drivers of regional canopy dynamics:

Canopy management strategies must be adapted to the diverse climatic conditions across Australia's avocado-growing regions. While preceding sections outlined physiological principles, cultivar traits and the influence of seasonal timing, the expression of these factors is strongly shaped by local environmental conditions. Temperature regimes, rainfall patterns, solar radiation, and seasonal predictability all influence vegetative flushing, flowering synchrony, canopy density and the risks associated with pruning. These risks include the removal of productive shoots, stimulation of excessive regrowth, and increased susceptibility to sunburn or disease (Schaffer et al. 2024; Whiley et al. 2024). As noted, poorly timed growth-regulator use under variable climatic cues can reduce efficacy or damage developing fruit.

Tailoring canopy interventions to regional environments is therefore important to maintain workable light distribution, fruit quality, and vigour management while aligning with local phenology. These environmental considerations reinforce the cultivar-specific patterns illustrated in Figure 4, showing that the timing and outcomes of canopy interventions vary substantially between regions.

In tropical and subtropical climates, temperature strongly influences flowering synchrony and the vegetative–reproductive balance (Crane et al. 2024; Whiley and Lavers 2021). Rainfall patterns shape shoot vigour and canopy density, with wet seasons often promoting frequent flushes and internal shading (Schaffer et al. 2024; Whiley et al. 2024). Solar radiation interacts with canopy structure to determine light interception and distribution, affecting both fruit cycles patterns and renewal pruning requirements (Ramírez-Gil et al. 2024; Whiley et al. 1988). The predictability of seasonal transitions further constrains scheduling; in cooler or longer-cycle regions, delayed pruning can overlap with flowering or fruit development, which may reduce productivity (Salazar-Garcia et al. 2006; Whiley et al. 2024).

Climatic zones and their relevance for canopy strategies:

To support regionally adapted canopy strategies, avocado production zones in Australia can be broadly grouped into two climatic categories based on temperature, rainfall and crop-cycle duration (Avocados Australia 2009; Avocados Australia 2024). Although finer distinctions exist, this simplified framework provides a practical starting point for regionally tailored decision-making and for developing the region specific light-interception models

The first category comprises warmer, wetter regions with summer-dominant rainfall and shorter crop cycles, typically less than 12 months from flowering to harvest. These include Far North Queensland, Central Queensland and coastal South-East Queensland around the Sunshine Coast. These regions may allow relatively flexible post-harvest or early-summer intervention windows but require precise timing to avoid excessive regrowth under high humidity and variable radiation.

The second category includes cooler, drier regions where flowering and harvest are separated by more than 12 months, often resulting in overlapping crops. These include the southern Queensland hinterland, northern and central New South Wales ranges, the Tristate region (Sunraysia and Riverland districts), and south-west Western Australia. In these zones, canopy work must align closely with floral development and fruit maturation to prevent disruption of either cycle. Altitudinal and coastal variation within subtropical zones can also mimic cooler climate behaviour, shortening the safe pruning window.

Key canopy management challenges, interventions and timing considerations for these regions are summarised in Table 3 and should be considered alongside cultivar-specific traits and phenological timing principles.

TABLE 3. Canopy management challenges, priority interventions, and cultivar/timing considerations for key climatic sub-classes of Australian avocado-growing regions. Information is generalised and may vary within regions depending on site-specific conditions and management objectives.

Regions	Key canopy management challenges	Priority interventions	Timing considerations
• **Far North Queensland (Atherton Tablelands)** • **Central Queensland (Bundaberg)** • **Coastal Southeast Queensland (Sunshine Coast)** (*Warmer, wetter regions; short crop cycle <12 months*)	– High vigour and rapid canopy closure, especially in fertile soils – Multiple flushes per year reduce internal light penetration – High humidity increases disease risk – Narrow windows between harvest and floral initiation	– Post-harvest or summer pruning to open canopy and improve light distribution – Strategic use of PGRs to suppress vegetative dominance and maintain canopy size – Disease management integrated with pruning timing	– 'Shepard' flowers early, less responsive to triazoles; requires adjusted PGR schedules compared to 'Hass' – Early-season market targeting may influence pruning intensity and timing – Containment pruning essential in vigorous sites to avoid internal shading
• **Southern Queensland hinterland** • **Northern & Central New South Wales** • **Tristate (South Australia/Victoria/Southwestern New South Wales)** • **Southwestern Western Australia** (*Cooler, drier regions; long crop cycle >12 months with potential crop overlap*)	– Overlapping crop cycles in 'Hass' complicate pruning and PGR timing – Narrow intervention windows due to sharp seasonal transitions – Risk of removing productive shoots needed for next crop – Greater exposure to heat extremes, drought, and sunburn after canopy opening	– Pruning after harvest to manage height and width – Major limb removal or heavy pruning in 'off' years – Phenology-aligned selective pruning and PGR use to protect return bloom	– 'Hass' prone to alternate bearing; delayed harvest can worsen biennial cycling – Flowering and final fruit maturation may overlap, increasing pruning risk – Timing critical to avoid disrupting floral initiation

Canopy management in warmer, wetter regions:

In Far North Queensland (FNQ), particularly across the Atherton Tablelands and surrounding areas, avocado canopy management is strongly influenced by the monsoonal tropical climate, characterised by high temperatures, humidity, and a distinct wet to dry seasonal cycle. The majority of rainfall occurs between December and March, with monthly averages exceed 200 to 300 mm, followed by a pronounced dry season from April to November with monthly rainfall commonly below 50 mm (Bureau of Meteorology). Warm air and soil temperatures, combined with abundant soil moisture during the wet season, tend to stimulate vegetative flushing. At the same time, persistent cloud cover and high humidity reduce incident solar radiation and slow canopy drying, which can together accelerate canopy re-closure and reducing internal light penetration (Chaikiattiyos et al. 1994; Whiley et al. 1988).

'Shepard', which is uniquely prevalent in North Queensland, tends to respond weakly to triazole-based growth regulators (Whiley et al. 2024; Whiley and Lavers 2021), meaning mechanical containment remains the principal canopy control strategy. To reduce regrowth, pruning is often concentrated in the late autumn to winter period when cooler conditions may suppress vegetative activity (Avocados Australia 2009; Whiley et al. 2024). In addition, shortening or suppressing spring flushes (early summer) may help moderate canopy density and maintain uniform internal light distribution under the variable solar radiation and heavy rains of the wet season (Leonardi 2005).

Central Queensland (e.g. Bundaberg and Childers) has a humid subtropical climate with lower annual rainfall and a shorter, less intense wet season than FNQ. Mean annual rainfall in Bundaberg is approximately 900 to 1000 mm, compared with about 1300 to 1400 mm in Atherton (Bureau of Meteorology). Rainfall is concentrated in summer but is more evenly distributed through the year, with a less pronounced dry period.

Higher average solar exposure (around 20 to 21 MJ m^{-2} day^{-1}) compared with northern regions (≈ 18 to 19 MJ m^{-2} day^{-1}) provides potentially favourable light conditions for external canopy light capture, though it can accelerate shading as canopies exceed optimal dimensions. The often more predictable post-harvest window than the tropics allows greater flexibility for mechanised pruning and selective renewal, and mid-bloom triazole sprays may be used selectively to limit excessive shoot vigour (Leonardi 2005; Whiley et al. 2024).

Along the coastal South-East Queensland belt, the climate is humid subtropical, representing an intermediate zone between the wetter regions to the north and the drier subtropical inland regions to the west. Conditions are typically warm and humid, with summer–autumn rainfall peaks and mild, drier winters. Annual precipitation in coastal SEQ ranges from approximately 1,100 to 1,400 mm, slightly higher than in central Queensland but lower and less seasonally extreme than in Far North Queensland (Bureau of Meteorology).

Like in other regions, avocado production in this region is dominated by 'Hass', with cropping cycles generally closer to a 12-month rhythm relative to regions further north, reflecting the more regular flowering and fruiting patterns typical of the subtropics (Schaffer et al. 2024; Whiley et al. 2024). The combination of summer rainfall and relatively high humidity promotes vigorous regrowth, which can increase shading if not managed soon after harvest (Avocados Australia 2009; Leonardi 2005). At the same time, fruit sunburn is a persistent risk during the clear, high-irradiance periods of spring and autumn, particularly in orchards with excessive canopy opening (Schaffer et al. 2024).

Canopy management strategies therefore emphasise timely integration of mechanised hedging and selective limb renewal to maintain canopy porosity, balanced light distribution, and protection of fruit from direct solar exposure. These operations are typically scheduled post-harvest and before floral initiation, aligning vegetative regrowth with early shoot flushes while minimising interference with reproductive development (Avocados Australia 2009; Whiley et al. 2024).

Across all warmer and, or wetter regions, maintaining regular pruning cycles that prevent canopy closure is essential for consistent internal PAR distribution and fruit quality. Priority research needs include quantifying canopy re-closure rates under different pruning intensities and timings, and modelling how variable radiation and humidity affect light-distribution stability and fruit microclimate throughout the season.

Canopy management in cooler and/or drier regions:

Cooler, drier regions are characterised by longer crop cycles (typically > 12 months) and overlapping crop loads, particularly in 'Hass', which complicates pruning and growth-regulator timing. Poorly timed interventions risk damaging inflorescences, disrupting carbohydrate allocation and can reduce return bloom (Salazar-Garcia et al. 2006; Whiley et al. 2024). Sharper seasonal transitions and cooler winter temperatures may further narrow the window for safe canopy intervention, especially when unseasonal rainfall or heat events delay access. Staggered or phenology aligned pruning approaches, for example hedging after harvest with heavier work in off years, are often advisable to sustain internal light and structural balance.

In the southern Queensland hinterland and northern New South Wales ranges, the climate transitions from humid subtropical to mild temperate upland, characterised by cooler winters, more frequent temperature fluctuations, and lower humidity than in the coastal subtropics or northern tropics. Annual rainfall typically ranges between 900 and 1,200 mm, with a summer–autumn peak followed by relatively dry winters (Bureau of Meteorology).

These cooler conditions, coupled with variable flowering and harvest overlap, constrain major pruning to late autumn or early winter, when regrowth risk is lowest and interference with reproductive development is minimal. Moderate canopy containment or selective limb renewal during 'off' years can help maintain internal light penetration and sustain bud development where alternate bearing is a concern (Leonardi 2005; Whiley et al. 2024). Because vegetative recovery is slower relative to the north, retaining some upper foliage may be important to protect emerging shoots and fruit from radiant heat. The cooler winter temperatures also increase the sensitivity of PGR application timing, as excessive suppression can delay spring flushing and disrupt floral initiation (Whiley et al. 2024). Further study is needed to define temperature thresholds that improve PGR reliability and pruning safety in these upland subtropical environments.

Further south, in the Tristate region, avocado production occurs under semi-arid to warm temperate conditions, with hot, dry summers, cool winters, and high irrigation dependency (Bureau of Metereology). Annual rainfall is typically below 300–400 mm, with low humidity and high solar irradiance creating a contrasting canopy management challenge to northern regions.

Maintaining adequate canopy porosity for light distribution must be balanced with fruit protection from photothermal stress, particularly on western canopy aspects exposed to afternoon sun (Schaffer et al. 2024; Whiley et al. 2024). Major structural pruning is generally confined to off-years or cooler post-harvest months, when evapotranspiration rates and heat loads are lower (Avocados Australia 2009). A progressive side–centre–side renewal sequence

may be adopted to refresh structural wood while sustaining fruiting potential and partial retention of foliage on western faces helps shield fruit from excess radiation. In this region, light distribution is often limited more by over-exposure than just by shading, and optimising canopy geometry to minimise sunburn is a primary management objective in such environments (Leonardi 2005; Schaffer et al. 2024). Modelling of sun angle geometry and canopy porosity could help define structural targets for safe light levels at the fruit surface.

In south-west Western Australia, avocado orchards experience a Mediterranean climate with cool, wet winters and mild to warm, dry summers, a pattern that differs markedly from the monsoonal and subtropical regimes of eastern regions (Bureau of Meteorology). Mean annual rainfall is about 800 to 1000 mm, falling mainly between May and September, with summers characterised by high solar exposure but more moderate humidity than the tri-state.

This climate supports a longer crop cycle and increases the risk of alternate bearing. Major pruning is typically conducted after winter rainfall subsides, reducing the risk of infection at pruning wounds. Maintaining sufficient outer foliage is important to protect fruit from high irradiance and heat load during summer (Schaffer et al. 2024). Canopy renewal is often phased over several years (side–centre–side cycles), with heavier cuts timed for off-years when carbohydrate reserves can recover (Avocados Australia 2009; Whiley et al. 2024). Triazole-based PGRs can assist canopy control, but their timing requires caution to avoid over-suppression of spring flushing and disruption of flowering in these longer-cycle environments (Whiley et al. 2024). The pronounced biennial tendency of orchards in this region also means canopy renewal is often integrated with alternate-bearing management, linking vigour control directly to light distribution and carbohydrate cycling.

Across all cooler and, or drier zones, successful canopy management relies on synchronising pruning and PGR application with regional phenology to balance light exposure and renewal. Region specific research priorities include quantifying how canopy openness, pruning sequence, and solar geometry interact to determine interior PAR distribution and fruit-surface temperature. Such data will support modelling-based identification of optimal canopy-openness thresholds that maximise yield and fruit quality while protecting against photothermal stress and alternate-bearing cycles.

Beyond physiology, market dynamics and logistics also influence regional canopy timing. Late-harvest fruit in cooler zones often targets export or processing markets, emphasising fruit size, quality, and uniformity. Interventions may be scheduled around heatwaves, labour availability, or packhouse throughput. However, there is limited documentation on how systematically these operational factors are integrated into canopy strategies. Targeted research into how regions coordinate canopy management with phenology, market cycles, and climate risk could refine evidence based, regionally tailored models for future light interception optimisation.

3.8. Mechanisation and orchard system

Structured systems and mechanisation potential:

Adoption of mechanical pruning in avocado orchards is increasing in response to rising labour costs, constrained workforce availability, and the need for scalable, efficient canopy management. Mechanical operations are most effective in orchards with structured tree forms and uniform architecture, particularly in hedgerow-style systems at moderate to high planting densities (Leonardi 2005; Whiley et al. 2024). These systems enable predictable machinery access and reduce the reliance on labour-intensive selective pruning. In contrast, unstructured or rejuvenated “stag-horned” trees tend to develop uneven, upright, and densely shaded

canopies that are poorly suited to mechanisation, often requiring more intensive hand pruning to maintain productivity.

While high-density orchards can improve the feasibility and efficiency of mechanical operations, they also usually demand more precise planning and more frequent interventions, meaning they may not be suitable for all growing regions or business models. Structured design and consistent tree form are foundational to successful mechanised canopy management, particularly when aiming for workable long-term light distribution, canopy uniformity, and carbon energy balance.

Mechanisation relies on canopy predictability: uniform tree height, alley width, and shoot orientation determine how consistently light is redistributed after each cycle. Inconsistent canopy structure can lead to patchy light profiles and non-uniform regrowth, limiting both the physiological and operational gains from mechanical pruning.

Mechanical pruning: efficiency and limitations:

Mechanical pruning may offer substantial labour savings by enabling rapid canopy intervention over large areas with minimal manual input. Topping and side-hedging operations can be scheduled to control tree height and alleyway access, potentially improving spray penetration, harvest efficiency, and overall orchard manageability (Avocados Australia 2009; Whiley et al. 2024). However, mechanical cuts are inherently non-selective. Without complementary hand pruning, they can lead to structural imbalance, excessive vegetative regrowth, or shading of internal fruiting zones (Snijder et al. 2000; Snijder and Stassen 1999).

Many growers therefore adopt a hybrid approach, integrating mechanised pruning with periodic manual cuts to restore light penetration, remove overcrowded wood, and help maintain canopy structure over time (Whiley et al. 2024). This integrated strategy can enhance both productivity and canopy balance, particularly in high-vigour orchards or dense plantings where vegetative growth is rapid. Nevertheless, the balance between labour savings and potential regrowth or shading issues varies considerably across orchards, and outcomes are not universally positive.

Ultimately, the effectiveness of mechanical pruning depends not just on the equipment used, but on its integration into a cultivar- and regionally tailored canopy management plan. A summary of the complementary roles, strengths, and limitations of mechanical and manual pruning in avocado canopy management is provided in Table 4.

TABLE 4. Roles, strengths, and limitations of manual and mechanical pruning in avocado canopy management (In practice, both methods are often integrated to optimise canopy structure, light distribution, and labour efficiency).

Approach	Primary role in canopy management	Strengths	Limitations	Typical integration strategy
Manual pruning	Selective removal of overcrowded, shaded, or unproductive wood; shaping scaffolds; fine-tuning canopy openness	High precision; targets specific branches; maintains structural balance; adaptable to any canopy form or terrain	Labour-intensive; slower over large areas; higher cost in regions with limited labour	Often follows mechanical cuts to restore light penetration and remove poorly positioned shoots
Mechanical pruning	Rapid height/width control; uniform canopy shaping; maintaining machinery access	High efficiency over large areas; reduces labour requirements; predictable timing	Non-selective cuts; risk of excessive regrowth; limited on steep/uneven terrain; requires structured canopy systems	Provides regular framework control between more detailed manual interventions

Site constraints and decision-making:

The suitability of mechanised canopy management depends heavily on site-specific factors such as terrain, tree vigour, orchard layout, and existing canopy structure. On steep or uneven ground, machinery access may be restricted, while in older orchards with irregular or widely spaced trees, mechanical pruning may deliver limited benefit unless preceded by canopy restructuring or replanting (Whiley et al. 2024). Similarly, blocks with significant cultivar variability in vigour may require additional manual intervention to maintain uniformity post-mechanisation.

Mechanical hedging also requires upfront investment in specialised equipment or access to contract services, which may not be economically viable in low-yielding or extensively managed blocks. These practical constraints reinforce the need for clear decision-making frameworks that define the primary goals of mechanisation, whether to reduce labour inputs, improve spray efficiency, or facilitate structural renewal, and evaluate how these align with site potential, operational resources, and canopy management objectives (see Table 4 for a summary of complementary roles and limitations of mechanical and manual pruning).

From a light-management perspective, terrain and row orientation strongly influence whether mechanisation improves or diminishes canopy illumination (Pham et al. 2024; Trentacoste et al. 2015). In flat, north–south-oriented orchards, mechanical hedging often maintains uniform east–west light penetration, whereas in sloping or east–west rows, shading asymmetry may increase unless offset by differential side trimming. Incorporating these design parameters into mechanisation decisions is essential for supporting light use efficiency and more uniform productivity.

Where site conditions are favourable, structured canopy systems designed with machinery compatibility in mind tend to offer the greatest long-term benefit (Hormaza et al. 2024; Whiley et al. 2024). Orchard design decisions such as row orientation, planting density, and access spacing play a pivotal role in enabling efficient mechanisation and should be considered in tandem with canopy goals. Conversely, in unstructured or transitional systems, mechanisation may best serve as a supplementary tool within a broader, gradually intensifying canopy strategy.

To refine adoption decisions, benchmarking mechanisation performance against predominantly manual systems, considering not only labour cost but also canopy light uniformity, fruit quality, and yield stability, remains a useful research direction. Integrating light-sensing tools or canopy LiDAR into mechanised systems could further enhance precision, enabling real-time adjustment of canopy interventions based on spatial light distribution and supporting the development of adaptive, data-driven canopy management systems.

Orchard layout and its influence on canopy development:

Foundational orchard design decisions, particularly tree spacing, row spacing, and row orientation, strongly influence canopy development, long-term manageability, and within-orchard light distribution. Structured hedgerow layouts with moderate to high planting densities are increasingly used in avocado systems to improve land-use efficiency, enable mechanisation, and support uniform light interception across rows (Menzel and Le Lagadec 2014; Whiley et al. 2024). However, these benefits depend on rigorous canopy management to prevent shading, overcrowding, and poor airflow. High-density orchards that are not regularly pruned may experience declining productivity due to excessive shading, reduced fruit set, and premature fruit drop (Razeto et al. 1992; Stassen et al. 1999b). Maintaining adequate canopy control is particularly challenging in high-vigour regions, areas with limited labour availability, or sites with difficult terrain (Roe and Kohne 1996).

Narrow inter-row spacing can enhance early productivity per hectare but increases the need for frequent pruning, earlier mechanisation, and careful cultivar selection to avoid canopy closure. Wider spacings reduce initial land-use efficiency but offer greater flexibility for long-term control, especially with spreading cultivars or in high-vigour regions (Hormaza et al. 2024). Row orientation also plays a pivotal role in the duration and intensity of canopy sunlight exposure, as considered below. Effective orchard layout therefore serves as the structural framework for light capture and utilisation across the orchard life cycle, and should align with cultivar traits, regional climate, and the grower's operational and mechanisation capacity to ensure structural sustainability and physiological balance.

Light dynamics, pruning needs, and productivity risks in high-density systems:

Planting density directly shapes canopy architecture and light distribution. In high-density orchards, mutual shading between adjacent trees can reduce light penetration into the lower and inner canopy, often resulting in non-productive zones (Hadari 2004a; Menzel and Le Lagadec 2014). Relative light levels have been reported to drop below 20% of full sun just one metre into the canopy in dense hedgerow systems (Hadari 2004a). This not only may limit yield potential but also can increases disease risk due to reduced airflow and elevated humidity.

Maintaining light distribution in these systems requires tailored, often intensive, pruning strategies. In vigorous climates or with spreading cultivars like 'Hass', mechanical hedging alone may be insufficient; supplementary hand pruning or structured training forms such as central-leader pruning or pyramidal forms are often needed (Leonardi 2005; Stassen et al. 1999b). In contrast, cooler or drier regions with slower vegetative growth may support high-density planting for longer with fewer interventions (Roe and Kohne 1996). In all contexts, planting design must weigh early yield benefits against long-term pruning logistics and the physiological need for balanced light environments, which underpin fruit set, quality, and return bloom.

Long-term productivity in high-density systems depends not just on early yield performance but on sustained canopy manageability. Without consistent intervention, overcrowding and shading can lead to premature productivity decline and tree removal (Menzel and Le Lagadec 2014; Razeto et al. 1992). These systems also compress labour needs into narrow seasonal windows, especially for pruning, spraying, and harvesting, placing pressure on operational capacity. Evidence from other fruit crops suggests these pressures can erode the initial efficiency gains of high-density systems if not carefully managed, but long-term avocado-specific data remain limited (Haque and Sakimin 2022; Robinson 2007).

Planting design must therefore be matched to the grower's ability to manage tree structure, integrate mechanisation, and maintain light interception throughout the orchard lifecycle.

Genetic compatibility with system configuration:

Cultivar and rootstock choice strongly influence planting system viability. High-vigour combinations can rapidly outgrow space constraints in dense systems, increasing pruning frequency and reducing labour efficiency. In contrast, upright or compact cultivars such as 'GEM' or 'Maluma', grafted onto moderately vigorous rootstocks, may be more compatible with structured systems and lower-input pruning schedules (Hormaza et al. 2024; Whiley et al. 2024). Rootstock–scion compatibility also affects vigour expression, flushing patterns, and canopy architecture, making it a critical factor in aligning genetic material with planting configuration and regional management constraints.

Future design frameworks should explicitly integrate genotype × environment × management (G×E×M) interactions to identify combinations that support light use efficiency and canopy

uniformity under regional climates. This remains a central evidence gap in Australian avocado system optimisation.

Row orientation and its physiological implications:

Row orientation can influence canopy light interception, temperature profiles, and water use efficiency. N–S rows typically provide more balanced light exposure across both canopy faces, which may support uniform shoot development and reducing sunburn risk. E–W rows can concentrate light exposure on one side (usually the northern face in the southern hemisphere), which can enhance flowering and fruit quality on the sunlit side but may increase heat stress and sunburn on western exposures, especially in warm climates (Glenn et al. 2002; Trentacoste et al. 2015). E–W rows also often intercept less annual radiation overall compared to N–S rows, which could reduce total photosynthesis and productivity if canopy form and porosity are not optimised (Connor et al. 2009).

Row orientation interacts with alley width, canopy porosity, and pruning approach to shape light dynamics. Its impact is further mediated by regional climate, cultivar growth traits, and operational factors such as mechanisation access. Strategic orientation choices should therefore be integrated with pruning regimes and orchard design to support light distribution throughout the canopy and across seasons.

Empirical validation of light-distribution models under different orientations is still limited in avocado. Quantifying diurnal and seasonal light asymmetry would be valuable for defining design standards that aim to maximise interception while avoiding photothermal stress.

Transferable principles from narrow orchard systems (NOS):

Narrow orchard systems (NOS), widely adopted in temperate crops such as apple and cherry, offer useful conceptual insights for avocado canopy management. These systems feature planar canopies, upright scaffolds, and high porosity, which can support enhanced light distribution, yield efficiency, and improved partitioning of assimilates to fruit (Grappadelli and Lakso 2007; Scalisi et al. 2024b). While empirical data on NOS in avocado remain limited, several physiological parallels have been identified. Avocado yield appears to correlate more closely with internal light distribution than with total intercepted light (Westling et al. 2018; Wilkie et al. 2019).

Structured, porous canopies that minimise lateral shading and promote within-canopy light availability may thus offer a viable path to sustained productivity in high-density avocado systems. Lessons from NOS, such as optimising scaffold angle, leader training, and alley spacing, provide practical conceptual guidance, but avocado responses require further empirical validation.

Developing a framework that translates NOS principles into avocado canopy models, incorporating porosity, light extinction coefficients, and vertical light gradients, would support quantitative assessment of how system architecture and planting density interact with regional climate to influence light use efficiency.

3.9. Summary

Canopy management is a central pillar of sustainable avocado production, influencing not only fruit yield and quality but also long-term orchard efficiency. Across all Australian growing regions, canopy structure governs how light is intercepted, how carbohydrates are produced and distributed, and how effectively vegetative and reproductive processes are balanced throughout the year. As emphasised throughout this review, canopy management is not merely a question

of tree shape or pruning frequency, but rather a physiologically based management process with direct impacts on productivity, fruit size, cropping consistency, and postharvest performance.

The review demonstrates that canopy performance is ultimately a function of light capture, light distribution, and the physiological use of that light (conceptually represented by LUE) to support carbohydrate balance and reproductive stability. Optimising these relationships forms the foundation for identifying regionally variable and light-based canopy strategies.

In practical terms, this requires defining measurable canopy and environmental variables, such as canopy light interception, internal light distribution, and crop load, that can be parameterised as inputs for predictive models. These models should aim to generate decision-support outputs, including optimal canopy structure targets, timing of interventions, and regionally adapted management strategies that maximise yield and fruit quality while minimising risk.

Effective strategies must integrate an understanding of shoot renewal, light penetration and porosity, carbohydrate dynamics, flowering biology and timing, and orchard system design and mechanisation. They must also account for interactions between canopy architecture, pollination and fruit-quality outcomes, and rootstock–scion influences. Applying this knowledge requires regionally adapted management sequences that align interventions with phenology, vigour behaviour, and local climatic conditions.

Multiple tools are available to manage canopy development and maintain productive light environments, each with specific advantages and constraints. Manual and mechanical pruning remain the most widely used and adaptable methods, enabling control over tree size, light distribution, and fruiting wood renewal. PGRs provide chemical options for moderating shoot vigour. Similarly, cultivar and rootstock choice influence architectural traits, flushing patterns, and pruning responsiveness. Alternative and emerging approaches, such as girdling, root restriction, or interstock use, may offer niche solutions for vigour control in specific production contexts.

Their success depends less on the tools themselves than on how precisely they are timed and integrated with phenology, system configuration, and regional growing conditions. When deployed as part of coordinated, context-sensitive systems, these strategies collectively improve light distribution, flowering synchrony, carbohydrate use efficiency, and long-term canopy manageability.

The success of canopy management depends fundamentally on regional adaptation. Australian avocado orchards span a wide range of climates, from the wet tropics of North Queensland to the cooler, drier zones of the Tristate and south-west Western Australia. These climatic gradients influence rainfall timing, temperature profiles, crop cycle duration, and flowering synchrony, all of which affect the timing, frequency, and intensity of canopy interventions. A practice that enhances light distribution or yield consistency in one environment may be ineffective or even detrimental in another if poorly aligned with local phenology, vigour potential, or climate variability. This reinforces the need to develop regionally differentiated canopy typologies that link climate class, cultivar habit, and canopy configuration to measurable light-use outcomes.

Despite the availability of diverse tools and approaches, several knowledge gaps still limit the development of fully optimised, regionally tailored canopy systems. Empirical data on light-interception efficiencies across canopy forms in Australian contexts are limited, as are long-term assessments of pruning cycles, PGR strategies, and rootstock–scion combinations across

climatic zones. Interactions between canopy structure and pollination success, particularly in dense orchards, require closer study.

Integration of these physiological and management parameters into predictive light-interception and canopy-function models remains underdeveloped. Addressing this gap will enable the creation of predictive, model-based decision-support tools that integrate canopy sensing, structural modelling, and physiological parameterisation to guide orchard design, canopy intervention, and regional optimisation strategies.

Not all knowledge gaps identified in this section are equivalent in their implications for modelling and application. The most critical gaps are the lack of quantitative relationships linking canopy light environment to yield outcomes and the absence of biologically meaningful light targets that define productive canopy states. These gaps directly limit the development of predictive, regionally adaptable canopy models. In contrast, gaps related to the optimisation of specific management interventions, including pruning strategies, PGR use, and irrigation or nutrition timing, primarily affect the refinement and practical implementation of decision-support tools once such models are established.

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Section 4: Modelling the light environment in orchards

N White, Queensland Department of Primary Industries

> *"…there is an optimum leaf quantity, for a given intensity, for productivity in the plant community."*
>
> Monsi and Saeki (1953) (translated in to English Monsi and Saeki 2005)

The review will expand to current and emerging modelling approaches, particularly their application in orchard light environment studies. Tools and technologies supporting canopy management, such as sensing systems and digital tools, and orchard mechanisation, will also be examined to identify opportunities for adoption or adaptation by the industry.

There are three parts to modelling the light environment of orchards, the representation of the trees, the representation of the light environment and how these interact. The level of detail required will depend on the questions being asked and research has been done from the simple, a geometric shape representing the orchard, to detailed representations of each leaf within a canopy.

Gathering data to support these does not necessarily increase in complexity and workload as realism increases. Early approaches were limited by the technology of the day in terms of data collection and computing power to run simulations at a meaningful scale. While a lot of hope pinned on LiDAR, the technology is still in its infancy in relation to producing useful tree architectures especially in evergreen species such as avocado.

This section of the review will consider what is involved in modelling the light environment of orchards at these different levels of complexity and the sort of questions that can be asked and the limitations of the approaches.

4.1 Modelling approaches

The light modelling approaches discussed here are applied within a virtual orchard or tree represented by a model comprising simple shapes to detailed information on the location, size, and orientation of leaves and in some cases structural elements. This infers that the architectural models faithfully represent the orchard. While it is possible to undertake measurements of light interception through a canopy, e.g. Hadari (2004) in avocado, the results are restricted to a particular orchard at a given time. Evaluating light intercept and distribution in a virtual plant allows a wide range of scenarios to be investigated.

Trying to understand the interaction between light and plant growth has a long history. The ideas proposed by (Monsi and Saeki, 1953, Monsi and Saeki, 2005) have been directly used in modern simulations, e.g. the wheat model in APSIM, (Zheng et al., 2014) which drives production from radiation interception and radiation use efficiency. This works well in uniform canopies such as grain crops, but as noted by Wagenmakers (1991) the complicated canopies of orchards requires a more dimensional approach. Modelling the light environment of crops has been undertaken since the 1980s for example the SUCROS model of Keulen et al. (1982) which was used in a simulation of oil palm growth by Van Kraalingen et al. (1989). The model developed by Wagenmakers (1991) was based on this, but extended the hemispherical model used for oil palm to four tree shapes and foliage distribution in individual trees. The model also accounted for diffuse and direct components of light and does so in three dimensions. Important assumptions of this model were that light is absorbed by all components, and these are evenly distributed throughout the canopy and were non-reflective and non-transmitting. Despite these

assumptions the model was able to predict that for fruit trees, essentially an apple orchard, a leaf area index (LAI) greater than three did not increase light interception.

The uniform distribution of leaves in a canopy is also a requirement of the Beer-Lambert law. Originally derived in relation to spectroscopy to account for light absorbed by a substance, it has been used in a form relevant to the light interception by plant canopies (Monsi and Saeki, 2005):

$$I_z = I_o . e^{-k.LAI_z}$$

where I_z light intensity at depth z, I_o is light intensity above the canopy, *k* is the light extinction coefficient, and LAI_z is leaf area index fraction at depth z.

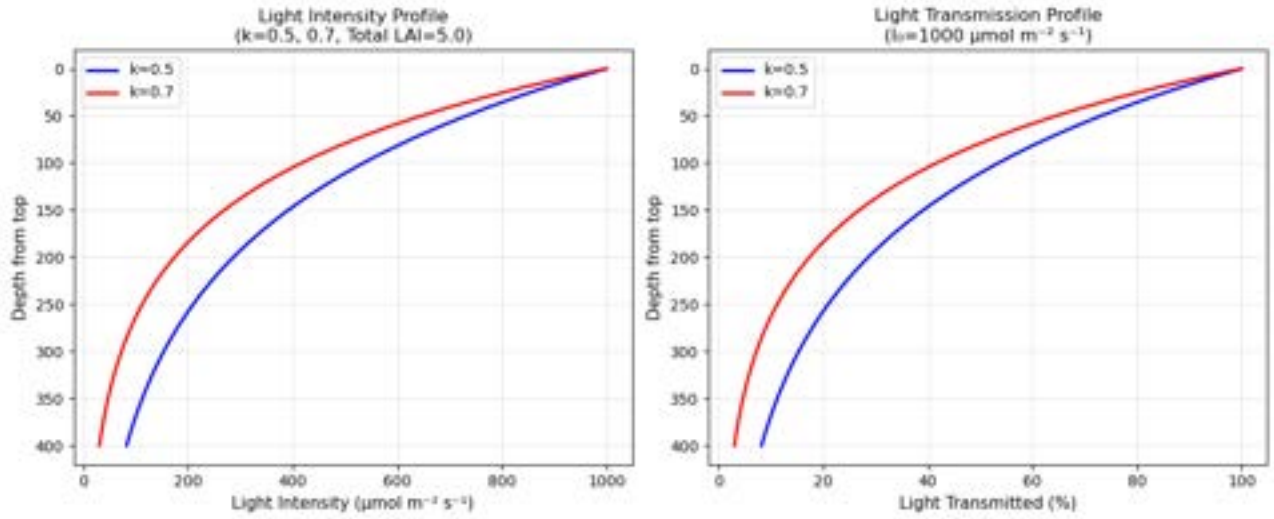

Figure 1. Example of light interception in a canopy for two extinction coefficients (k = 0.5 and k = 0.7). Calculations undertaken by NW.

A two-dimensional approach was developed (Annandale et al., 2004) where the fractional transmission within the through a canopy, τ, is calculated as

$$\tau = e^{(-0.5.\rho_f.S\sqrt{\alpha})}$$

where S is the distance that radiation moves through the canopy, ρ_f is the density of foliage (m^2 leaf per m^3 of canopy) and α the absorptivity of individual leaves for the specific wavelength of light of interest. Annandale et al. (2004) suggested α = 0.8 for PAR. Some aspects of his approach were used by Hadari (2004) to calculate Potentially Productive Canopy Volume for avocado by taking into account a saturation level of PAR that is viable for photosynthesis.

Field measurements of the PAR required for photosynthesis and photomorphogenesis will be required for scion and rootstock combinations to apply this approach across Australian growing regions.

A direct approach to calculate potential light interception using the calculations set out in Iqbal (1983) was undertaken for macadamia orchards (Olesen et al., 2007). The delineation of the orchard was done using simple shapes, i.e. rectangular vs tapered hedgerows. The model

calculated direct and diffuse radiation falling on inclined surfaces representing the sides and top of the orchard rows. It has the advantage of being very fast and using this technique they were able to compare locations and row orientations. It is limited in that it is only measuring the light falling on the surface and cannot be easily applied to complex shapes nor reveal anything about the distribution of light within the canopy. However, the authors evaluated the light interception for two row orientations, orchard layouts and considered Cairns, Bundaberg, and Alstonville. There were some useful insights gained using this approach and it can be easily extended to other growing regions. There was an attempt to model yield as a function of modelled and measured light interception, but this was generally unsatisfactory.

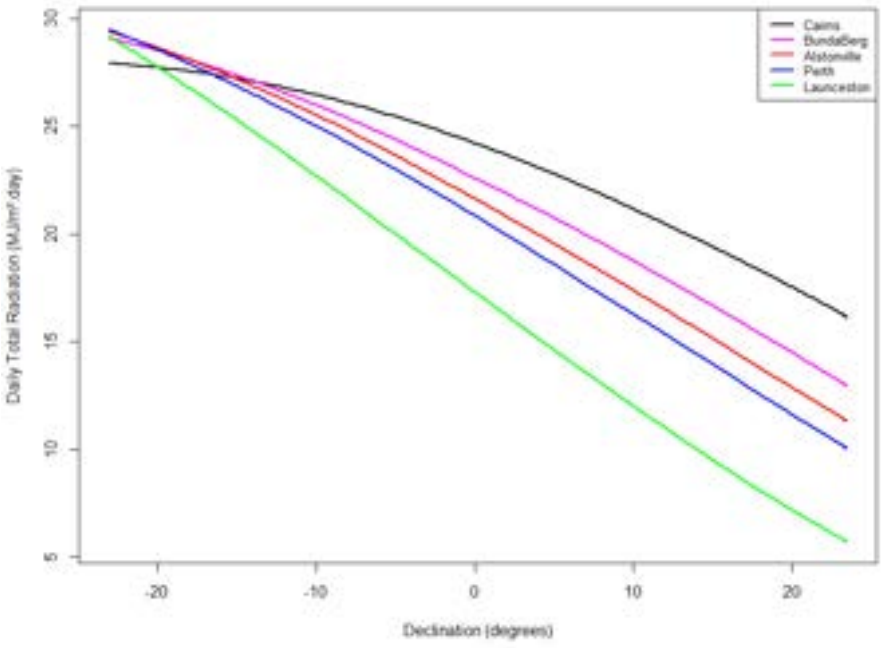

Figure 2. Daily radiation intercepted by a horizontal surface versus solar declination in four avocado growing regions. Adapted from (Olesen et al. 2007) and extended to Perth and Launceston by NW.

The Radiance model was introduced to provide a light rendering system for architectural use that was based on physical properties (Ward, 1994). It provided some useful characteristics that made it suitable for application to biological problems, i.e. curved surfaces, specular and diffuse reflection, and transmission of light. It was applied to avocado orchards in Israel (Hadari, 2004) by creating a virtual orchard in AutoCAD and exporting these shapes to the model. The Radiance model reduces the computation of raytracing from light sources in all directions by using backwards ray tracing, i.e. starting at a viewpoint, e.g. an eye looking at the scene, and following the path it takes as it is reflected or transmitted by objects within the scene, until it reaches a light source. The model required that the internal structure of the canopy of the orchard be represented by an extinction coefficient, scattering albedo and scattering eccentricity. Lighting for the scene is generated by GenSky, within the Radiance software, which produces a Radiance scene description for the CIE standard sky distribution at a given date. Hadari (2004) used this to calculate the Potentially Productive Canopy Volume of avocado orchards.

The limitation of the Radiance model is that the internal structure of the canopy is reduced to a set of optical parameters and is limited to geometric shapes. As such, it presents few opportunities to investigate agronomic practices such as limb removal but would be suitable to compare row orientation, orchard design and regional effects. The software is still maintained and available via https://github.com/LBNL-ETA/Radiance/releases for Linux, macOS and

Windows. The software consists of a suite of command-line tools and specifying geometries is difficult beyond simple shapes. The use of CAD software is recommended, as used by Hadari (2004), and it could be used to compare geometric shapes such as those used by in that study and Olesen et al. (2007)

Chelle and Andrieu (1998) proposed the nested radiosity model in which each organ is represented by a set of polygons in 3D. The nesting occurs because the model distinguishes between light coming directly from a light source, light scattered from polygons that are close by (with a sphere of radiance D_s) and light that scattered from far polygons. Direct light is computed using projection, whereas the exchanges between close polygons is calculated from the radiosity model and estimation of light from far polygons is undertaken by a multi-layer model. Direct light from the sun and sky hemisphere is discretised into angles that represents the light coming form that part of the sky. For each of these sources a projection screen that is normal to the light source is created and the polygons representing leaves etc are projected onto it. Polygons that are further away from the light source are partially or fully occluded and so only that area of the polygon that is exposed to the light is measured. Combined with the light received from near and far polygons a complete measure of light throughout the canopy can be derived. Larger canopies are made by replicating the smaller scene. The nested radiosity model has been implemented within the OpenAlea software (Pradal et al., 2008) as the CARIBU package (Chelle et al., 2004) and used to investigate the productivity of sorghum in response to leaf angle (Truong et al., 2015). Chelle et al. (2004) documents how the complex calculations required for light can be separated from the model defining the architecture and light interception at the organ level. This approach is used in many of the Functional Structural Plant Models, FSPM, (Godin and Sinoquet, 2005) investigating light interception within a canopy. OpenAlea is a research tool and while development is ongoing the documentation is often difficult to find and installing it problematic with limited support.

An alternative approach was adopted in MAppleT (Costes et al., 2008, Han et al., 2017) using Markov chains to generate the topology and appearance of different types of growth units. This is well suited to apple where the growth units can be conveniently described as short, medium, long and flowering. Here apple trees are simulated in 3D using a biomechanical model of branch bending and twisting. Instead of simulating the light environment directly, light interception was calculated by the silhouette to area ratio, STAR (Carter and Smith, 1985). In this way a tree or an orchard can be reduced to a collection of leaves and using the known size and orientation of the leaves STAR is calculated by:

$$STAR = \frac{PLA}{TLA}$$

where *PLA* is the total projected leaf area and *TLA* is the total leaf area and STAR ranges from 0 to 1. While MAppleT is a complete system for apple, the STAR methodology is generic and has application in the analysis of light interception and distribution in avocado.

The Multiscale Light Interception Model, MμSLIM, developed by Da Silva et al. (2008) attempts to overcome the limitations of the Beer-Lambert law that arise because of the heterogeneous nature of canopies in fruit trees. Their model was developed with application to peach and mango and although originally for single, isolated trees has been extrapolated to orchards. It uses calculations of STAR to estimate light interception, and at the sub-tree level, e.g. a branch or scaffold, these subcomponents are envisaged as convex envelopes. An envelope as an opacity p_x in relation to the angle of light Ω reaching it and PLA is calculated as PLA_x:

$$PLA_x = PEA_x . p_x$$

where PEA_x is the projected envelope area in the direction Ω. Calculations then proceed for a range of angles, Ω, and scales to produce an integrated STAR. A tree within the orchard can be

considered from a simple turbid medium defined by a single envelope to increasing levels of realism at the individual leaf level.

The data required for undertaking this approach is still demanding even at the crown level for a turbid medium (Da Silva et al., 2011). That study showed that individual crown shapes were required to get the best results due to the heterogeneity within a forest of conifer and deciduous trees. However, this may be simplified in orchards where the canopies meet along the row. Comparing between pruning systems in avocado orchards may require information at least the scaffold level and possibly a finer scale than that.

Sinclair (2006) reminds us that the assumptions for the Beer-Lambert law are mostly unmet but does provide two solutions that may ameliorate the errors. One is a correction factor to obtain an extinction coefficient representing the whole day which can be predicted from measurements taken at midday and the second approach is to estimate the time of day at which measurements should be taken to get a representative value for k. While such times of day could be found it was impractical as there was a dependence on leaf angle. Ponce de León and Bailey (2019) also question the use of the Beer-Lambert law in many cases leading to over prediction of light interception when compared to a detailed, 3-D path tracing model (Bailey, 2018, Bailey, 2019).

QuasiMC (Cieslak et al., 2008) is a path tracing algorithm that uses an efficient randomised quasi-Monte Carlo sampling method. Path tracing differs from ray tracing by sampling many different possible light paths, rather than recursively following a single reflected and refracted ray. Path tracing allows for diffuse light, reflection and transmission which are important in modelling light in canopies of leaves and can be used therefore to predict carbon production. QuasicMC has been used to model carbon dynamics in kiwifruit (Cieslak et al., 2011), light interception in macadamia canopies (White and Hanan, 2016), blush formation in mangoes (Yu et al., 2016) and fruit size and distribution in macadamia (Auzmendi and Hanan, 2018). A parallelised version of QuasiMC was developed that makes use of the capacity of modern computers and High-Performance Computing clusters. This greatly reduced the run time of this component of modelling the light environment. Unfortunately, it is no longer maintained but a new approach is in development.

QuasicMC is maintained and available on Windows, macOS and Linux. It can provide a standard sky model for any location for any day of the year. It does require calibration for each plant species so that the absorption, reflectance, and transmission of the light can be adequately modelled. This can be done using a CI-710s SpectraVue Leaf Spectrometer (CID Bio Science), LI-180 Spectrometer (Li-Cor Environmental) or an integrating sphere (a protocol is outlined in **dx.doi.org/10.17504/protocols.io.p8pdrvn**). These values have been measured for has avocado elsewhere (Heath et al., 2003, see Figure 7B) using the Li-180 but should be done for other cultivars.

4.2 Data acquisition

The use of LAI to understand productivity was proposed by Watson (1947) in studies of wheat, barely, and two varieties of beets. Getting a measure of LAI for large fruit trees such as avocado is problematic. Destructive techniques used for crops such as wheat cannot be readily applied. Indirect methods using vertical photography (Macfarlane et al., 2007) and hemispherical photography, e.g. using a fish-eye lens or canopy analyser such as Li-2200C Plant Canopy Analyzer (PCA) from Li-Cor (van den Berg et al., 2025). In the latter investigating white root in avocado the LAI was used as an indicator of the effect of the fungus causing loss of canopy. Treatment of symptomatic orchards with Fluazinam increased LAI to higher than 4 two years afterwards. The LAI of untreated orchards was about 2.5.

A PCA does not work out of the box and must be calibrated for the tree of interest because light scattering from leaves can cause an underestimation of LAI (Macfarlane et al., 2000,

Macfarlane et al., 2007). The calibration can be undertaken using destructive sampling or photographic methods. The advantage of a PCA is that once calibrated it can be used directly, but it is expensive. Photographic methods can be labour intensive but do lend themselves to automation. Peper and McPherson (1998) compared a destructive estimate of LAI for six mulberry and two cherry trees with the outputs from two PCA (Li-Cor LAI-2000, CID CI-100), a ceptometer (Decagon Devices AccuPAR) and a photographic system (Decagon Devices AgVision). Significant differences between measured and ceptometer and PCAs were found, but the image analysis and a logarithmic regression were not significantly different to the measured value. It should be noted that both PCAs used in this study have been superseded.

In a review of LAI methods Jonckheere et al. (2004) note that the LAI-2000 underestimates LAI in heterogenous canopies and that this cannot be adequately addressed using correction factors or adaptive radiation models. The updated version of the Accupar-80 used in this study can take leaf distribution into account, however radiation measurements are inherently variable, and adequate measurements need to be undertaken to provide reliable results.

In cherry trees, Carrasco-Benavides et al. (2016) assumed a k of 0.7 and then undertook ceptometer readings and vertical photography with an algorithm developed by Macfarlane et al. (2007) to calculate LAI. This relies on the Beer-Lambert law and included a parameter for clumping ranging from 1 for randomly dispersed leaves and where < 1 defines a degree of clumping. With the inclusion of clumping, it is referred to as LAI_e, the effective leaf area index.

Obtaining the measurements is cumbersome and can be done using YPlant (Pearcy and Yang, 1996) or combined with QuasiMC (Cieslak et al., 2008) in YplantQMC (Duursma et al., 2013) using hemispherical photography or by digitisation or digitisation and LiDAR. STAR is problematic as it requires detailed data on the location and orientation of leaves within a canopy.

Terrestrial LiDAR Scanners (TLS)

The use of TLS has become very popular with the advent of hand-held or backpack units which have been used extensively to measure canopy volumes and surface areas. There are trade-offs when using these compared to units that are position on a tripod and moved along the rows of the orchard. The principal trade-off comes when trying to collect detail within the canopy because much of the interior structure is blocked by the leaves on the outside. This is particularly noticeable in dense canopies such as avocado. The smaller portable units are limited in terms of segmentation, i.e. identifying leaves, fruit and branches, rather than simply returning a point cloud.

Arslan et al. (2021) used a Leica ScanStation C10 to make a compared a PCA (CI-110 referred to above) and TLS methods to measure LAI. This TLS is used from fixed positions with the instrument mounted on a tripod. The unit costs between US$6,000 and US$14,000 depending on the instrumentation. LAI calculations using the TLS was done using an unsegmented point cloud distribution (PCD), projection after a technique referred to as Connected Component Segmentation and projection after Neural Network Segmentation (NNS). There was the added process of projecting the PCD onto a unit sphere by transforming the Cartesian coordinates to a spherical coordinates. They concluded that segmentation techniques were useful in eliminating woody material from the calculations and that the lower estimates from using PCD with segmentation compared to the PCA was more indicative of the latter overestimating LAI. The NNS technique was found to be better and faster than CCS and offered other advantages such as obtaining LAI and volume and can be used on sub-sampled data allowing easier recovery in case of failure, rather than having to reanalyse the whole PCD.

A mobile, tractor mounted TLS (SICK LMS111) was used by Berk et al. (2020) evaluation of leaf area in apple orchards. This unit costs ~A$12,000 and has a maximum scanning distance of 20 m, compared to 300 m for the Leica C10, and a reduced resolution. The orchard sed in this case was a sparse trellis system with trees approximately 2.5 m tall. The problem of segmentation was avoided by attempting to derive a relationship between a manually measured leaf and the number of points in the PCD. Correlation coefficients were in the mostly in the range 0.7 to 0.83. These results would have been limited by registration of points from wood within the canopy as shown by points being recorded where the manual method showed no leaf area.

In Australia, Green Atlas combines a mobile LiDAR with RGB images and AI in their Cartographer platform. The details of the instruments used are not readily available, but (Scalisi et al., 2024a) used data derived from the platform to relate fruit number and peel colour in pear trees to some aspects of tree architecture. Their approach was simplified because of the largely 2D nature of the orchards they were working with, but the strength of the relationships was low with less than 40% of the variation accounted for by simple linear regression. The use of this methodology for complex avocado canopies is untested, but it unlikely that it would be easy to implement.

Leaf and wood classification from TLS is a desirable outcome and Vicari et al. (2019) presented a method a method to quantify the amount of wood and leaf material. Their approach can be implemented in an automated workflow with results like previous studies. Field trials on 10 trees using a Reigl VZ-400 (RIEGL Laser Measurement Systems GmbH) from different forests showed accuracies greater than 80%. The purpose of their study was to develop an automated system, however a software plug-in from Riegel is designed to achieve wood and leaf segmentation. This has been used by Liqi Han to develop digital twins to model light distribution and spray effectiveness. An early paper on the mitigation of spray drift in mangoes is presented in (Han et al., 2024).

4.3 Modelling tree architecture

Physiological crop models are an important part of research for farming systems. These models provide a way to conduct experiments that would be difficult or costly to establish using field experiments and allow novel approaches to be studied in a meaningful way and to examine the sensitivities of plant growth.

A functional structural plant model (FSPM) can provide a more complete and explicitly modelled 3D world and so tackle a class of problem where spatial distribution of resources (including the light environment) is important or interact with plant structure (including biomechanics and photomorphogenesis). Novel cultural practices, especially in long-lived fruit and nut trees, can be manipulated and tested against current practices even allowing for the time for model development. In the context of the present review, an FSPM could include distributions of leaves in various shapes, hedgerow, tapered hedgerow, trellis etc, or be created as full structural model in which the trees grow in response to light, carbohydrate allocation, and growth hormones. The “art” in modelling comes from developing a model that answers the questions required without unnecessary detail.

Early attempts at modelling plant form were based in fractal approaches, born out of the observation that many aspects of plant growth have similarities with fractals (Mandelbrot, 1977), although one of the earliest attempts of creating a model of tree form used a geometrical approach (Honda, 1971). A key development that allowed FSPM to develop was the use of L-systems to provide the formal language to describe a plant (Lindenmayer, 1968a, Lindenmayer, 1968b). This formalism was extended greatly through the 1990s to include randomisation, parametric L-systems, and environmental interactions.

The other important approaches to FSPM are LIGNUM, AMAP, another formal language of “stochastic sensitive “growth grammars” (Kurth and Sloboda, 1997) which have themselves

been extended as “relational growth grammars” (Buck-Sorlin et al., 2005). These aspects will not be pursued further in this report, but interested readers are directed to https://grogra.de for further information and software.

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A timeline of the major developments in FSPM

1968	Aristid Lindenmayer proposes a theoretical framework for the development of multicellular organisms (Lindenmayer 1968a; Lindenmayer 1968b) Largely used by computer scientists who develop the mathematical theory of L-systems.
1970-1973	First simulation program (CELIA) based on L-systems (Baker and Herman 1970).
1971	Modelling the form of trees using geometric approaches (Honda 1971)
1974	Branching structures introduced to L-systems, however, this was done externally to the program (Frijters and Lindenmayer 1974).
1979	Branching internalised using symbols (Hsee Prusinkiewicz (1997) for details H)
1984	Examples of high-quality computer graphic of plants were generated by .
1986	LOGO-style graphics (aka turtle graphics) (Prusinkiewicz 1986)
1988	L-Systems Siggraph papers (de Reffye et al. 1988; Prusinkiewicz et al. 1988)
1989	pfg introduced (plant fractal generator) by J. Hanan & P. Prusinkiewicz

1990	Publication of the Algorithmic Beauty of Plants (Prusinkiewicz and Lindenmayer 1990)
1992	Introduction of cpfg (Hanan 1992) AMAP (Atelier de Modelisation de 1'Architecture des Plantes) (Jaeger and De Reffye 1992)
	Floradig program developed to allow digitisation in 3D (Hanan and Room 1992)
1994-present	GroGra – Hgrowth grammar interpreter (Kurth and Sloboda 1997) Now a Java-based platform for developing FSPMs.
1996	Environmental impacts are modelled allowing for pruning, competition. These models exchange information to provide interaction between the plant and its environment (Měch and Prusinkiewicz 1996).
1996-present	LIGNUM. Developed in Finland this approach to FSPM uses process-based models and canopy architecture to model tree growth on a year time step (Perttunen et al. 1996) L-systems are not used as the computational overhead in a parallel system make application to trees time-consuming (Perttunen 2001).
1997	AMAPmod – a modelling and analysis package for plants. The concept of multiscale tree graphs is introduced as a way of documenting plant structure (Godin et al. 1997; Godin et al. 1999).
2000 - present	GreenLab – a collaboration between Chinese and French researchers. While somewhat like traditional crop modelling approaches, it is an FSPM style of programming using SciLab and a set of rules that describe plant growth and morphogenesis of plant organs. Central to GreenLab is the concept of source-sink dynamics (Yan et al. 2003; Yan et al. 2004). A useful synopsis of GreenLab can be found in (Fourcaud et al. 2008)
2002	Lpfg introduced (L+C modelling language). While the approach is similar to cpfg, it allows for the L-system to be developed such that many underlying processes can be incorporated using C++ (Karwowski and Prusinkiewicz 2003; Karwowski 2002). L+C extends the syntax of C++.
2002-2004	ALEA – a system for analysis and modelling. This takes over from APMAPmod.
2006-present	OpenAlea – a platform for plant modelling and analysis. Written largely in python it provides a suite of tools as python packages (Pradal et al. 2008). Visualea provides a GUI.
2007	GRAAL-CN – a model of Growth, Architecture, ALlocation for Carbon and Nitrogen. A source-sink model that incorporates roots as well as shoots (Drouet and Pages 2007).
1997-2008	AmapSim – the model is fixed, but also modular, different species are defined through parameters (Barczi et al. 2008).
2009	Introduction of self-organising tree algorithm (Palubicki 2013; Palubicki et al. 2009).
2018	Helios plant/light simulation (Bailey 2018) https://github.com/PlantSimulationLab/Helios

In contrast to traditional crop models in which the assimilation is modelled via a radiation interception parameter and leaf area index, FSPM allows for a detailed investigation of the characteristics of the light environment and how this interacts with plant geometry. In

greenhouses and other controlled environment systems the density of production imposes constraints on light interception caused by training systems.

4.4 Tools and technologies to support canopy management

Sensing systems

Westling et al. (2018) used LiDAR scans of avocado trees in Bundaberg and a whole sky model to compute light interception. In their approach they worked directly with the point cloud by creating a voxelisation of the tree after manually labelling points as stem and leaf. Although the labelling was incomplete it reduced the error compared with no labelling. They created a light model that worked with their methodology rather than fitting the point cloud to an existing model such as QuasiMC (see section 0). Their final parametrisation of the sky model required ~ 13 hours of computation time on an 8-core machine. The sky model used local acquired global sky irradiance from a weather station at a 30-minute interval or from records from the Bureau of Metrology at a daily timestep and interpolated to 30 minutes. The process used is here is very time consuming in terms of data collection, post-processing, and computation. Attempts have been made to automate the labelling of points returned from LiDAR. Working in mango in far north Queensland, Westling et al. (2020) compared manual light meter readings obtained from a light trolley comprising 15 Apogee SQ-100 PAR point sensors (Apogee Instruments) pulled through the orchard to a handheld LiDAR (GeoSLAM Zeb1) and a Simultaneous Location And Mapping (SLAM) algorithm. Data processing of the LiDAR data was undertaken using the snark and comma libraries (https://github.com/acfr/). These libraries are now archived and would need to be built for the recent versions of Ubuntu Linux although a method is provided to create a Docker image using Ubuntu 18.04. The LiDAR and manual methods had a correlation coefficient of 0.9, although there was not a 1:1 relationship and in this context, there is some argument as to what should be considered as the true reading. The orchards in which this work was done were established in early 2014 and at the time of the study were approximately 2 m high.

A similar LiDAR data collection and processing approach was undertaken on mature, commercial avocado orchard (Westling et al., 2021b). Labelling was undertaken in two passes, first to identify the tree and then as either woody or leaf material. Although the algorithms presented were advances on other techniques there clearly needs to be a large investment in this technology especially for complicated, dense avocado orchards.

Wu et al. (2020) undertook an estimation of tree height in avocado and mango orchards comparing terrestrial vs airborne laser scanning, WorldView-3 stereo-imagery, UAV-based RGB and multispectral imagery. The UAV gave worthwhile results but could cover only a limited area compared to ALS but this data is considerably more expensive. The benchmark for the methods was the TLS data.

Commercial systems are often aimed at predicting crop yield, e.g. Cartographer[1], but was used by Scalisi et al. (2024b) as the basis for a prediction of fractional canopy radiation interception ($fPAR_i$ is the fraction of PAR that is intercepted by the canopy and ranges from 0 to 1). A high correlation (r = 0.97) between observed $f\text{PAR}_i$ and predicted was achieved by including cross-sectional leaf area (CSLA), crop type, row orientation, canopy design, tree age and canopy height (in order of effect) as predictors. Of these, CSLA and canopy height were acquired using the Cartographer platform. CSLA had the largest effect, between 20 and 25, compared to the other predictors that were less than 10. Canopy height was marginally higher than a cutoff value of 1.96. This approach has some advantages over other LiDAR-based approaches (Westling et al., 2020, Westling et al., 2018) in which light interception was predicted using ray tracing as the most

[1] https://greenatlas.com/cartographer/

important predictor, CSLA, is derived by Cartographer. However, the regression approach does require an extensive program of field measurements

LiDAR assisted pruning

Westling et al. (2021b) developed and used algorithms applied to LiDAR-scanned trees to suggest where pruning could achieve an improvement in light distribution without adversely reducing tree volume. In the first phase this relied on scoring the quality of a tree shape based on light availability and size that was validated against yield in avocado and mango. An algorithm was developed to simulate pruning using structural analysis of the tree. The final stage was to suggest new pruning locations based on improving light distribution. The light distribution was improved by 25%, an improvement of 16% over commercial pruning decisions. The avocado trees used in this study were in a commercial orchard in Childers, Queensland. The scoring system was based on physiology of deciduous fruit trees (Marini et al., 2025), although the article does not mention light, and avocado (Stassen et al., 1999). In the that article there is an earlier reference to improving light in dense orchards. Furthermore, they rely on (Örn, 2016) and relationships found between light interception and total fruit weight. The relationship is stronger for tree volume (R^2 = 0.84) than for light interception (R^2 = 0.84). The data collected by LiDAR was found to be too noisy to detect how the pruning effects simulator was working, and so the remainder of the study relied on simulations of LiDAR points clouds using SimTreeLS (Westling et al., 2021a).

Digital Twins

It is important to distinguish between modelling in the sense of FSPM and digital twins. The former is very useful for developing a deeper understanding of plant processes and to explore different scenarios. Here experiments, basic laws and observations are used to construct a model at a particular scale. A period of validation and refinement is used to improve the predictions of the model.

A digital twin takes this two steps further as discussed by Purcell and Neubauer (2023) by first introducing a unidirectional flow of from the physical entity to the virtual one. In a complete digital twin information also flows in both directions. In this case changes that are occurring in the physical environment influence the response of the virtual entity and the state of virtual entity can affect the physical entity.

In their system review Purcell and Neubauer (2023) found few examples of digital twins in agriculture. Moghadam et al. (2020) presented some findings on the use of digital twins in orchard systems using LiDAR and cameras to provide real-time updates for decision support (this was a partial digital twin) to reduce labour inputs. This is like the work of Liqi Han (Han et al., 2024) in which the digital twin only receives information from the environment.

4.5 Summary

Modelling the light environment of crops has a long history. The difficulty of taking the measurements and the calculations results in broad assumptions and simplifications. Computer processing speeds have increased significantly allowing more detailed models to be developed and recent work using GPUs to run these in parallel has opened up new levels of realism (Bailey, 2018, Bailey, 2019, Han et al., 2024).

Data acquisition has changed from labour intensive to technology intensive, however, there will need to be a significant investment in validation for commercial avocado orchards. LiDAR comes with significant costs ranging from tens to hundreds of thousands of dollars. The data derived from high-end units may be necessary to derive the relationships that that can be interpreted later using rapid assessment using mobile units of the type developed by Green Atlas.

Linking detailed measurement with physiology and modelling approaches can greatly assist in testing ideas and developing field trials by focussing on those aspects that have a greater chance of success.

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Section 5: Light environment assessment tools

G Rossouw, Queensland Department of Primary Industries

This section reviews the tools available with potential for assessing the light environment in avocado orchards, spanning simple field instruments to advanced modelling and cross-industry innovations. Light interception and distribution strongly influence orchard productivity, yet their measurement must balance technical accuracy with usability in commercial practice. The review therefore considers not only the scientific capacity of different methods but also their approximate cost, scalability, and adoption potential. Technologies are grouped from foundational tools already in research and grower use, through intermediate and advanced methods, to emerging approaches drawn from other disciplines. Collectively, these tools represent efforts to integrate light quantification with canopy models and decision-support systems, providing a framework for more efficient, regionally tailored canopy management in the avocado industry.

5.1. Introduction

Understanding and managing the light environment in an avocado orchard requires reliable, scalable tools that quantify both overall interception and the distribution of photosynthetically active radiation (PAR) within canopies. However, while many of these tools can quantify light interception and canopy structure, their translation into predictions of yield remains limited. As such, most tools provide inputs for modelling rather than direct estimates of productivity.

When integrated within modelling frameworks, however, these tools can inform canopy management decisions such as pruning intensity, canopy density targets, and spatial optimisation of light distribution by providing measurable variables (e.g. fPAR, canopy volume, light gradients) that can be used as model inputs. This limitation reflects the absence of robust, quantitative relationships linking measured canopy light environments to yield outcomes, which constrains their use in predictive modelling and decision-support systems.

In practice, this includes both direct measurements of light and indirect structural proxies of canopy openness that influence light distribution. Accordingly, there is a need to develop decision-support tools that are both physiologically informed and practical for growers. These data can also be integrated with canopy models as outlined in Section 4. For instance, they provide the data needed to simulate light capture, evaluate canopy interventions, assess the consequences for productivity, and guide the development of decision-support tools.

Increasingly, the emphasis is shifting from isolated measurements towards integrated sensing frameworks that combine structural, spectral, and radiative information across scales. Rather than relying on a single instrument, emerging workflows fuse ground-based PAR measurements, UAV-derived imagery, and three-dimensional canopy reconstruction to generate spatially explicit representations of canopy structure and function (Shahar et al. 2026). Such multi-sensor approaches enable calibration of radiative-transfer models, scaling from sampled trees to orchard blocks, and closer linkage between canopy architecture and physiological performance. This integrative perspective underpins much of the recent technological development reviewed in this section and provides a conceptual bridge between field measurements and digital modelling frameworks.

A broad spectrum of technologies is available. These range from simple, low-cost tools such as handheld ceptometers (Wilkie et al. 2019; Wünsche et al. 1995) and in-canopy light loggers (Long et al. 2012; Muñoz-García et al. 2014), and other rapid field-based assessments of canopy

openness (Korhonen et al. 2006), through intermediate methods such as hemispherical photography (Bianchi et al. 2017; Rich 1990) and UAV-based imaging (Wu et al. 2019), to advanced LiDAR and voxel-based approaches that can reconstruct canopy architecture and simulate within-canopy light fields (Ross et al. 2022; Van der Zande et al. 2011). Each carries trade-offs in cost, complexity, and accuracy, and varies in its potential for adoption in commercial avocado orchards. These tiers of tools are summarised in Table 1, which provides an overview of their outputs, costs, strengths, and limitations before each group is discussed in detail below.

The evaluation of light environment assessment tools should extend beyond technical accuracy to include their feasibility in commercial settings. The overarching aim is to identify approaches that can help develop future decision-support systems for tailored canopy management strategies that optimise light interception and distribution. While advanced options such as LiDAR-based modelling provide the highest resolution insights, they require specialist expertise and generally, considerable investment (Ming et al. 2024; Münzinger et al. 2022; Westling et al. 2018). More accessible methods such as ceptometers, hemispherical photography, UAV imaging, and in-canopy loggers are affordable and relatively easier to deploy (Mathews and Jensen 2013; Pádua et al. 2018).

Emerging low-cost options, such as smartphone-based light sensor applications, could increase grower engagement, although their accuracy and calibration remain limited compared with dedicated quantum sensors, and most record illuminance (lux) rather than PAR (Di Laccio et al. 2024; Tabaka and Wtorkiewicz 2022). This section therefore reviews available tools across a gradient of complexity and scalability, with emphasis on their potential contributions both to advanced modelling and to practical decision-making in the avocado industry.

Beyond those already employed in horticultural practice or research, additional tools drawn from other fields highlight opportunities for further investigation. All-sky cameras and sky imagers, widely used in solar energy forecasting, can provide real-time partitioning of direct versus diffuse irradiance, and have been tested in forestry and ecological studies (González-Fernández et al. 2024; Inanici et al. 2023; Yamashita and Yoshimura 2019). Low-cost depth-sensing devices, such as RGB-D cameras (Red, Green, Blue) or tablet- and smartphone-integrated LiDAR units, have shown promise for forestry and urban tree monitoring but remain limited under dense orchard conditions (Brenner et al. 2023; Gollob et al. 2021; McGlade et al. 2023; Tavani et al. 2022).

Cross-industry approaches from architecture and construction, such as daylight ray-tracing models like Radiance, have long been used to translate 3D structure and sky conditions into detailed light environments (Andres et al. 2023; Wang et al. 2021; Ward 1994b). Remote sensing tools such as satellite-based solar-induced fluorescence add further possibilities in regional benchmarking of photosynthetic activity (Magney et al. 2019; Wang et al. 2022). Real-time rendering and ray-tracing techniques from the gaming industry demonstrate advances in efficient light simulations (Akenine-Moller et al. 2019; Friedrich et al. 2006) that could potentially be adapted for orchard canopies. Many of these methods remain experimental, but they illustrate a wide technological horizon. Recognising both current capabilities and emerging opportunities is useful in recommending future R&D directions that can help develop robust, grower-oriented decision-support tools for smarter canopy management.

While these tools enable increasingly detailed quantification of canopy light environments, the knowledge gaps constraining their application are not equivalent in their implications for modelling and decision-making. The most critical limitation is the absence of quantitative relationships linking measured canopy light environments to carbon assimilation and yield

outcomes, including robust quantification of canopy-scale light use efficiency. This gap prevents direct translation of light measurements into predictive models of productivity and therefore constrains the development of reliable canopy light–yield modelling frameworks.

Secondary limitations relate to how effectively different tools capture canopy structure and light distribution under varying orchard conditions, as well as how these measurements can be integrated into practical workflows. These gaps primarily affect the refinement, scalability, and adoption of decision-support tools, rather than the underlying modelling capability itself. As a result, current light assessment technologies provide strong inputs for modelling and decision support but remain limited in their ability to independently predict yield outcomes, reinforcing the need to prioritise development of quantitative light–carbon–yield relationships alongside improvements in sensing technologies.

TABLE 1. Spectrum of light environment assessment tools and their potential applications in avocado orchards.

Category	Examples	Outputs	Cost/complexity	Adoption potential	Notes
Basic field tools	Ceptometers; In-canopy data logging sensors; Spherical densiometers	PAR; light penetration; temporal dynamics (loggers); canopy closure/openness (structural proxy)	Low	Already used in research; feasible for growers	Affordable, simple; limited spatial resolution; structural proxy only; observer- and protocol-sensitive
Intermediate tools	Hemispherical photography (DHP); Smartphone light apps	LAI; canopy openness; PAR; light distribution	Low to moderate	Common in research; smartphone applications emerging for grower adoption	Sensitive to conditions & processing; smartphones often limited to illuminance rather than PAR
UAV platforms	RGB; Multispectral; Hyperspectral; Thermal; UAV LiDAR	Canopy cover, vigour maps, spectral traits; 3D canopy structure	Moderate–High	Growing research use; service-provider adoption	Needs calibration, expertise; higher costs
Advanced 3D models	Terrestrial, mobile, and airborne laser scanning (LiDAR) with voxel-based modelling	High-resolution 3D canopy structure; simulated light fields	High	Research-focused	Data- and compute-intensive; foundational for digital twins
Emerging lower-cost options	Tablet and smartphone LiDAR; Depth sensing RGB-D cameras	Approximate light intensity; 3D canopy sketches	Low to moderate	Accessible to growers but limited accuracy	Calibration issues; performance drops in dense canopies
Cross-industry innovations	All-sky cameras; Daylight models; Gaming engines; Satellite solar-induced fluorescence	Sky diffuse/direct partitioning; regional photosynthesis benchmarks	Variable (research-level) but generally moderate to high	Experimental in orchards	Potentially useful for modelling inputs & regional benchmarking

5.2. Foundational field tools

Overview and basic functions:

Handheld ceptometers and basic in-canopy light loggers represent easily accessible tools for quantifying orchard light environments. Ceptometers consist of linear arrays of PAR sensors that measure incident radiation above and below the canopy, allowing estimation of the fraction of intercepted PAR (fIPAR) (Johnson et al. 2010; Wünsche et al. 1995). In-canopy loggers, such as compact devices like HOBO Pendant tags, are inexpensive self-contained sensors that typically record broadband light intensity (lux) rather than true PAR. More specialised options, such as Onset HOBO quantum light loggers or Apogee Instruments' PAR loggers, can measure PAR directly but at a higher investment cost. Nevertheless, when deployed strategically within the canopy, these devices provide temporal records of light interception and some indication of vertical light gradients (Long et al. 2012; Muñoz-García et al. 2014).

Role of fPAR as a functional light-interception metric:

The fraction of photosynthetically active radiation intercepted by the canopy (fPAR or fIPAR) is a widely used functional index that links canopy structure to radiation capture (Liu et al. 2018). Leaf area index (LAI), defined as the one-sided leaf area per unit ground area, is often interpreted alongside fPAR because it provides the structural context required to understand how much leaf surface is available to intercept incoming radiation (Bréda 2003; Chen and Black 1992). LAI can be determined through direct leaf sampling, optical indirect methods such as hemispherical photography or ceptometer-based gap-fraction measurements, or increasingly via LiDAR-derived structural models, each providing an estimate of canopy leaf area at varying scales and levels of precision (Bréda 2003; Richardson et al. 2009). Whereas fPAR quantifies the fraction of incident light captured by the canopy, LAI describes the size and density of the leaf surface driving that interception, with the relationship between the two underpinning most canopy light-attenuation models based on the Beer–Lambert law (Campbell and Norman 2000).

fPAR can be derived from ceptometer measurements taken above and below the canopy, from line quantum sensors, or from time-series PAR loggers that quantify photosynthetic photon flux density (PPFD) within the PAR waveband (Long et al. 2012). fPAR has been used extensively across orchard crops, forestry, and agronomic systems to quantify canopy light capture and relate it to canopy structure, photosynthetic potential, and biomass production (Muñoz-García et al. 2014; Zhang et al. 2021). Despite its widespread use, fPAR represents a functional indicator of light capture rather than a direct predictor of yield, as the relationship between intercepted light, carbon assimilation, and fruit production remains poorly quantified in avocado systems. Its key limitation is that it represents a two-dimensional snapshot of light interception at a specific moment, even though fPAR varies with solar angle, sky conditions, canopy density and seasonal development (Urban et al. 2012). For this reason, meaningful interpretation of fPAR often requires repeated measurements or integration with models that simulate temporal changes in irradiance. Although fPAR alone cannot describe the three-dimensional distribution of light within complex avocado canopies, it provides a valuable ground-truthing metric for structural and radiative-transfer models. Studies have combined fPAR measurements with LiDAR-derived 3D canopy reconstructions to validate simulated light fields and assess the accuracy of voxel-based and ray-tracing models (Chasmer et al. 2008; Cifuentes et al. 2017). This positions fPAR as a practical functional indicator that complements high-resolution structural scans in the development of decision-support tools for canopy management. As such, fPAR extends instantaneous PPFD measurements into a functional indicator of canopy light capture.

Daily Light Integral (DLI), defined as the total number of photosynthetically active photons received over a 24-hour period, provides a time-integrated complement to fPAR for assessing canopy light availability (Faust and Logan 2018). DLI is calculated by integrating PPFD

measurements throughout the day and is generally expressed in mol m^{-2} day^{-1}. In practice, DLI can be derived from quantum sensors or PAR loggers positioned above or within the canopy, from ceptometers configured to record continuous PPFD, or from weather station irradiance that is converted to photon flux and integrated over time (Torres and Lopez 2002). For controlled environment and greenhouse crops, DLI has been shown to influence both vegetative growth and flowering responses (Fausey et al. 2005; Pramuk and Runkle 2005), which suggests that canopy zones experiencing chronically low DLI are less likely to accumulate the carbohydrate reserves and shoot maturity required for strong flowering. This makes DLI a useful conceptual and modelling bridge between canopy light interception patterns and the balance between vegetative and reproductive development in avocado. However, a research gap exists in terms of published DLI values for avocado orchards and studies that link DLI to physiological outcomes such as canopy growth or productivity.

Rapid structural proxies of canopy openness:

In addition to direct measurements of PAR, simple structural proxies of canopy openness can provide rapid, low-cost indications of the light environment. Spherical densiometers, originally developed for forestry applications, estimate canopy closure by quantifying the proportion of sky versus canopy visible within a defined field of view (Lemmon 1956). While they do not measure PAR directly, densiometers provide a coarse index of canopy openness that reflects the potential for light penetration, particularly when applied consistently across orchards or over time. Comparative studies have shown that spherical densiometers provide canopy openness estimates that are strongly correlated with hemispherical photography (section 5.3) and broadly equivalent at moderate to high openness levels, while direct PAR measurements remain more sensitive under very closed canopy conditions (Russavage et al. 2021). Such correlations have also been reported for gap fraction estimates derived from hemispherical photography, although results are sensitive to operator technique, sampling position, and protocol (Korhonen et al. 2006).

In orchard systems, spherical densiometry may therefore be useful as a rapid benchmarking tool to assess relative canopy openness following pruning or to track canopy re-closure trajectories during regrowth. Its simplicity and low cost make it accessible for repeated field assessments, including in commercial settings. However, its limited spatial resolution and inability to resolve directional or vertical light gradients constrain its utility for detailed light modelling. As such, spherical densiometry is best viewed as a complementary structural indicator that can support, but not replace, direct PAR measurements and more advanced optical or modelling approaches.

Strengths and applications:

The main strengths of these foundational tools are simplicity, affordability, and the ability to provide direct measurements of radiation with minimal user training. Ceptometers can be deployed reasonably quickly across multiple trees, enabling comparisons of canopy light interception within and between orchards (Westling et al. 2020b; Wilkie et al. 2019). In-canopy loggers extend this by capturing diurnal and seasonal variation, providing insights into how light penetration changes with canopy growth, pruning, or seasonal sun angles (Long et al. 2012). These attributes have made them common in research contexts.

Limitations and constraints:

Despite their advantages, these tools have important limitations. Ceptometers require manual placement and repeated readings, which makes them labour-intensive and prone to operator variability, especially in large orchards (Westling et al. 2020b). In-canopy loggers overcome this by recording continuously, but because they are fixed in position they provide limited spatial coverage and may not fully represent variability across a tree or orchard (Muñoz-García et al.

2014). Lower-cost models that record illuminance (lux) rather than PAR further constrain accuracy, particularly when diffuse versus direct light conditions change. As a result, they provide useful snapshots or trends but cannot resolve the full three-dimensional distribution of light needed for advanced modelling.

Role in research and practice:

In practice, both ceptometers and in-canopy loggers are already feasible for use in avocado research and, to a lesser extent, by growers. Their affordability and simplicity make them attractive entry-level tools for monitoring canopy light conditions. While they cannot provide the detailed structural information required for advanced modelling, their outputs are valuable for calibrating and validating more complex approaches, and for establishing baseline benchmarks of light interception across orchards. As such, these foundational tools play an important role in bridging research and practice, offering practical monitoring capacity today while supporting the development of more sophisticated decision-support systems in the future.

A comparison of representative foundational tools used to assess canopy light environments, including direct light-measurement instruments and simple structural proxies, is provided in Table 2.

TABLE 2. Comparison of foundational tools used to assess canopy light environments, including direct light-measurement instruments and structural proxies.

Tool/type	Example model	Output(s)	Approximate cost	Strengths	Limitations	Adoption/use context
Ceptometer (line PAR sensor array)	METER Group AccuPAR LP-80	PAR above & below canopy (PPFD); fIPAR; estimate LAI	~ USD 7274 base price	Rapid measurement, integrated above/below canopy reading, portable	Requires manual measurements, operator variability	Widely used in research; feasible for consultant use
In-canopy light logger (lux / broadband sensors)	HOBO MX2202 Pendant – Water Temperature/Light Bluetooth Data Logger	Illuminance (lux), time-series of light level	~ USD 191 base price	Cheap, simple, waterproof, long deployments	Fixed position; lux ≠ PAR; limited spatial coverage; multiple sensors needed across orchard	Common in research for trend monitoring
Quantum light logger / PAR logger	Apogee PQ-500 Par Meter| PPFD Logger | Full Spectrum Quantum Sensor	PPFD; supports fPAR estimation	~ AUD 1679 base price	More biologically relevant data, better for calibration	Higher sensors cost, calibration required, lower spatial coverage	Research / calibration tool
Line quantum sensor (under-canopy integration)	Apogee SQ-301X-SS: Line Quantum with 10 Sensors	Integrates PPFD along 1-m length under canopy, PAR spatial average; supports fPAR estimation	~ AUD 1624 base price	Smooth under-canopy integration; reduces point-sampling bias	Limited to linear coverage, calibration required	Useful for under-canopy profiling; supports research instrumentation setups
Spherical densiometer (canopy closure proxy)	Convex or concave spherical densiometer (e.g. Forestry Suppliers Model C)	Canopy closure / openness (%); structural proxy	~ AUD 280	Very low cost; rapid field assessment; no power or software required	Does not measure PAR; observer- and protocol-sensitive; coarse spatial resolution	Rapid benchmarking of canopy openness; tracking canopy re-closure following pruning

5.3. Intermediate optical methods

Overview and basic functions:

Digital hemispherical photography (DHP) and smartphone-based light sensing represent intermediate approaches between basic field tools and advanced canopy reconstruction methods. DHP uses upward-facing fisheye photographs taken under diffuse light conditions, which are then analysed with image-processing software to estimate canopy openness, leaf area index (LAI), and estimate the fraction of intercepted PAR (fPAR) (Bianchi et al. 2017; Rich 1990). Unlike simple structural proxies of canopy openness, hemispherical photography captures angular information on canopy gaps, enabling estimation of light interception and possibly supporting integration with canopy light models.

This typically requires a digital single-lens reflex (DSLR), or mirrorless camera fitted with a fisheye lens, mounted level on a tripod, though more recent approaches use compact cameras or smartphone panoramas. Smartphone-based approaches include both ambient-light sensors and camera-based applications that estimate canopy openness or light intensity. For instance, panoramic images captured by smartphones can produce hemispherical photos with canopy openness estimates comparable to those from traditional DSLR methods (Arietta 2021). While generally less precise than dedicated quantum sensors, these options provide low-cost, widely accessible means of approximating canopy light environments and can be used for rapid assessments in the field (Di Laccio et al. 2024; Tabaka and Wtorkiewicz 2022).

Advantages and potential:

The main advantages of hemispherical photography lie in its ability to capture detailed information on canopy openness and light distribution with relatively simple equipment. Once processed, DHP images provide robust estimates of LAI and gap fraction, and can be used to estimate fPAR (Rich 1990). When repeated across orchards, they allow benchmarking of canopy structure and light environments at moderate cost. Smartphones add a further layer of accessibility. The potential for engagement and awareness is high, and camera-based canopy apps or built-in sensors can deliver rapid, low-cost impressions of orchard light conditions (Arietta 2021; Tabaka and Wtorkiewicz 2022). These attributes position DHP as a research-ready method and smartphones as a tool with strong outreach and training potential, supporting both scientific studies and potentially, practical orchard decision-making.

Limitations and constraints:

Despite their utility, both DHP and smartphone-based hemispherical imaging methods have important limitations. For best results, DHP images are usually captured under diffuse sky conditions (e.g. overcast or twilight), which minimise glare and simplify image thresholding (Beckschafer et al. 2013; Jonckheere et al. 2004b). The method also requires the camera to be level, and image analysis is sensitive to thresholding settings and software choice, making results dependent on operator technique and potentially less consistent across users. Smartphones face even greater challenges. Built-in sensors typically record illuminance (lux) rather than PAR, and camera-based applications can be affected by device hardware, automatic image processing, and changing ambient light conditions (Di Laccio et al. 2024; Tabaka and Wtorkiewicz 2022). Although smartphone panoramas show promise for estimating canopy openness, they still require careful calibration and validation against reference instruments (Arietta 2021). These constraints mean that while both approaches can provide useful information, their outputs are less robust than those from dedicated ceptometers or quantum sensors.

Current role and outlook:

In practice, hemispherical photography is already a well-established research method and has been applied across a range of tree crops, including orchards, to quantify canopy light environments and benchmark canopy structure and light distribution. Its relatively low equipment costs and repeatability make it suitable for research and extension trials in avocado, particularly where comparisons between pruning regimes or canopy architectures are required. Smartphone-based tools, while less accurate, provide unique opportunities for grower engagement and training. Their immediacy and very low cost mean they can be used to raise awareness of light distribution concepts and to demonstrate the impact of canopy management. Within the context of future canopy light modelling tools for use in avocado orchards, DHP can serve as a mid-tier tool for validating canopy light models, while smartphones may act as an accessible entry point for growers, complementing more precise research-grade approaches.

A comparison of representative hemispherical photography and smartphone-based methods, including typical setups, outputs, costs, strengths, and limitations, is summarised in Table 3.

TABLE 3. Comparison of intermediate optical methods (hemispherical photography and smartphone sensors). Costs are approximate and vary by supplier; listed in available retail currency.

Tool/type	Example model	Output(s)	Approximate cost	Strengths	Limitations	Adoption/use context
Digital hemispherical photography (DHP)	DSLR or mirrorless camera (e.g. Canon EOS, Nikon Z series) + fisheye lens (e.g. Sigma 8 mm) + tripod; Image analysis in software such as Gap Light Analyzer (GLA), HemiView, or freeware (e.g. CAN-EYE)	Canopy openness (%), LAI, gap fraction, fIPAR	Camera body ~ AUD 500–2000; fisheye lens ~ AUD 500–2000; software often free or research license	Captures detailed canopy openness; repeatable; moderate cost; established in research	Requires diffuse light conditions; sensitive to thresholding/software choice; operator-dependent; moderate processing	Used in forestry; suitable for potential adoption in avocado pruning or canopy trials
Compact / consumer cameras for DHP	GoPro with fisheye lens; Ricoh Theta (360°)	Canopy openness; gap fraction (lower precision)	~ AUD 500–2000	Portable; easy deployment; lower entry cost	Lower resolution than DSLR; limited compatibility with specialised software	Exploratory research
Smartphone panoramas / camera-based apps	iPhone or Android smartphones with 360° panorama mode; apps such as CanopyCapture or custom research apps	Canopy openness estimates; approximate light intensity	Smartphone only; app cost usually free–~ AUD 50	Very low cost; highly accessible; rapid field use	Device variability; automatic image processing affects results; less accurate than DSLR-based DHP; requires calibration	Early-stage adoption in forestry; holds potential for use in orchards
Smartphone ambient-light sensors	Built-in light sensor on smartphones; apps such as PPFD meter	Illuminance (lux, proxy for light intensity)	Included in most smartphones	Extremely low cost; immediate feedback;	Lux ≠ PAR; sensitive to orientation and phone hardware; very coarse estimate	Useful for awareness of light environment; unlikely suitable for quantitative work

5.4. UAV platforms and remote images

Overview of UAV-based sensing:

Unmanned aerial vehicles (UAVs, or drones) equipped with imaging sensors represent a rapidly developing class of tools for assessing orchard light environments. Depending on the payload, UAVs can capture a wide range of imagery. RGB cameras can be used for canopy cover mapping (Schiefer et al. 2020), and, when flown with sufficient image overlap, can also be processed using photogrammetric Structure-from-Motion (SfM) workflows to generate dense 3D point clouds and canopy height models from standard imagery (Iglhaut et al. 2019). Multispectral sensors provide vegetation indices that indicate vigour and chlorophyll status (Chang et al. 2020). Thermal cameras can detect canopy stress (Zarco-Tejada et al. 2012). Hyperspectral sensors allow fine-scale characterisation of canopy physiology and pigment status, often using pushbroom systems that record many narrow spectral bands line by line as the UAV moves (Aasen et al. 2018; Lu et al. 2022). Finally, LiDAR payloads generate point clouds that enable structural reconstruction of tree canopies (Neuville et al. 2021). SfM-derived point clouds can provide lower-cost structural information than UAV LiDAR, but typically characterise canopy surfaces more reliably than internal foliage density, particularly in dense, multi-layered canopies. These approaches extend measurements beyond individual trees to orchard and landscape scales, offering repeatable, high-resolution data suitable for integration with Geographic Information System (GIS) platforms and canopy modelling frameworks (Mathews and Jensen 2013; Pádua et al. 2018).

Advantages and unique strengths:

The main advantages of UAV-based approaches lie in their ability to cover large areas quickly, generate spatially explicit datasets, and track changes across time. RGB and multispectral imagery can quantify canopy cover, vigour, and heterogeneity, while hyperspectral imagery provides spectral signatures that can be linked to leaf traits, canopy biochemical status, and light-use efficiency (Aasen et al. 2018). Emerging research has further demonstrated that hyperspectral reflectance can be associated with deeper plant functional processes, including photosynthetic regulation, although such approaches remain experimental and are discussed further in Section 5.6. LiDAR payloads allow three-dimensional reconstruction of canopy structure, enabling estimation of light penetration and potential shading patterns (Hackenberg et al. 2015; Torres-Sánchez et al. 2014). UAVs also allow flexible timing of surveys, which can be aligned with phenological stages or management interventions, providing insights into seasonal dynamics of light interception at scales relevant to growers.

Limitations and barriers to adoption:

Despite these advantages, UAV systems often involve higher costs and complexity than ground-based methods (for example, stationary or terrestrial laser scanning, TLS; see Section 5.5). Capital costs for UAVs and sensors, potential licensing requirements for pilots, and the need for data processing expertise remain barriers to commercial adoption (Pádua et al. 2017; Singh and Frazier 2018; Wallace et al. 2012). Moreover, while UAV-based LiDAR and multispectral imaging provide powerful datasets, their integration into operational decision-making still requires robust calibration against field measurements and adaptation of modelling tools for orchard-specific conditions.

In particular, hyperspectral pushbroom sensors generate very large datasets that demand careful calibration and correction for illumination, flight stability, and sensor artefacts, making them best suited to research rather than routine grower use at present (Aasen et al. 2018). Within orchard systems, UAV-mounted LiDAR (commonly referred to as airborne laser scanning, ALS) provides rapid, high-resolution canopy structure over orchard blocks, but remains constrained

by flight time, payload and weather, with positioning accuracy sensitive to inertial measurement unit (IMU) drift, the gradual accumulation of errors in drone orientation and position tracking.

Wu et al. (2020a) demonstrated ALS application for crown area assessment in avocado, macadamia and mango orchards, showing strong agreement with TLS for mapping the crown area, fractional cover and maximum crown height, but consistent ALS underestimation of crown volume due to reduced penetration into lower canopies. TLS additionally provided leaf area density profiles, while ALS offered efficient orchard-scale mapping of row structure and tree counts. Farhan et al. (2024) extended this by comparing ALS, TLS and mobile laser scanning (MLS) more broadly, outlining their respective advantages, limitations, and operational costs, while also situating LiDAR within the wider precision agriculture landscape. Their review highlighted its capacity not only for canopy reconstruction but also for yield forecasting, disease detection and autonomous navigation, while noting persistent challenges of cost, data processing demands, and limited canopy penetration in dense systems.

UAV imaging cannot independently measure fPAR, since fPAR requires both above- and below-canopy PAR measurements (Chen 1996; Gallo and Daughtry 1986). However, UAV LiDAR (ALS) and multispectral datasets can be combined with ground-based PAR measurements to calibrate canopy cover estimates or validate radiative-transfer models that simulate orchard light interception (Scalisi et al. 2024a; Westling et al. 2018). This integration has been used in tree crops and forestry applications and represents a practical workflow for linking structural UAV datasets with functional canopy light indicators. Experimental work in remote sensing and field and tree crops has explored mounting irradiance sensors on UAVs to characterise incident light fields around copies or tree crowns, although these approaches remain developmental and have not yet been demonstrated as reliable methods for estimating fPAR in orchard systems (Aasen et al. 2018; Burkart et al. 2014; Nevalainen et al. 2017; Zarco-Tejada et al. 2014).

UAV-driven multi-sensor fusion and scalable orchard mapping:

Recent work in tree crops has demonstrated how UAV platforms can function not merely as imaging devices, but as integration hubs for multi-sensor data fusion, linking structural, spectral, and ground-based measurements within a unified analytical workflow. In avocado, a recent study combined UAV multispectral imagery with three-dimensional canopy reconstruction derived from either structure-from-motion (SfM) photogrammetry or UAV-mounted LiDAR, alongside ground-based physiological and phenological measurements, to scale tree-level traits across entire orchard blocks (Shahar et al. 2026). Field measurements, including leaf chlorophyll content (SPAD), leaf area, and visual flowering intensity, were collected in close temporal alignment with UAV flights to ensure consistency between ground truth and remotely sensed predictors. This temporal coupling is particularly relevant for light-environment studies, where canopy structure and sky conditions vary dynamically across phenological stages.

The study implemented a structured processing pipeline in which multispectral imagery was radiometrically calibrated and georectified to generate reflectance mosaics, while point clouds were classified into ground and vegetation returns, normalised for height, and converted into canopy height models. Individual trees were segmented from the three-dimensional data, enabling extraction of per-tree structural variables, including canopy volume and height stratification metrics, alongside spectral indices derived from the multispectral imagery. Voxel-based representations of canopy structure were used to quantify leaf area distribution and density, providing explicit structural descriptors at tree scale. Random forest models were then trained to predict physiological and phenological traits for all trees in the orchard, demonstrating how fused structural and spectral predictors can be scaled from sampled individuals to orchard-wide maps.

Although the response variables in this study focused on flowering intensity, chlorophyll status, and canopy structure rather than direct measurements of PAR or fPAR, the workflow illustrates a transferable architecture for canopy light assessment. UAV-derived structural layers provide spatially explicit predictors of canopy geometry, while multispectral indices capture aspects of canopy condition and vigour. When coupled with strategically deployed ground-based PAR measurements, such as ceptometer grids or in-canopy loggers, this fusion framework could be extended to calibrate radiative-transfer simulations or predict spatial patterns of light interception across orchard blocks. In this sense, UAV-driven sensor fusion represents an intermediate step between platform-level remote sensing (Section 5.4) and the advanced structural modelling approaches described in Section 5.5, and provides a practical pathway for translating complex canopy datasets into spatially explicit management insights at orchard scale.

The structural component of such fusion workflows naturally links to LiDAR-based and voxel-based reconstruction methods. Once three-dimensional point clouds are segmented and voxelised, they can serve as the geometric foundation for ray-tracing or radiosity simulations of within-canopy light fields, as discussed in Section 5.5. The example above demonstrates how UAV LiDAR or photogrammetric point clouds can be processed into per-tree structural metrics suitable for modelling, while also highlighting the importance of calibration against ground-based measurements to translate structure into functional indicators of light interception. As analytical pipelines mature and integration with machine learning becomes more automated, UAV-driven multi-sensor fusion is likely to play a central role in bridging orchard-scale data acquisition with high-fidelity light-distribution modelling and, ultimately, decision-support systems for avocado canopy management.

Current role and outlook:

In practice, UAV imaging is increasingly accessible through commercial service providers and collaborative research projects, making it feasible for regional monitoring even if less practical for day-to-day grower use. UAV platforms can potentially bridge ground-based measurements and advanced 3D modelling, offering orchard-scale datasets for model calibration, validation, and scenario testing. Their role is likely to expand as sensor costs decline and analytical pipelines become more automated, positioning UAVs as a key intermediate-to-advanced tool in the development of decision-support systems for canopy management in avocado. A comparison of UAV platforms and sensor payloads, including typical outputs, costs, strengths, and limitations, is provided in Table 4.

TABLE 4. Comparison of UAV platforms and imaging payloads for canopy light assessment. Costs are approximate and vary by supplier; listed in available retail currency. Prices reflect equipment only and exclude pilot licensing and service-provider fees.

Tool/type	Example model	Output(s)	Approximate cost	Strengths	Limitations	Adoption/use context
RGB cameras	DJI Phantom 4 Pro; DJI Mavic series	Canopy cover, crown area, fractional cover, row structure	~ AUD 1,500–2,500 (UAV + camera)	Affordable; easy to deploy; good spatial resolution	Limited spectral info; only canopy cover and geometry proxies	Entry-level; service-provider and grower accessible
RGB photogrammetry (SfM)	Standard UAV RGB camera with photogrammetry workflow (e.g. Pix4D, Agisoft Metashape, OpenDroneMap)	Point cloud; DSM/DTM; canopy surface volume proxies	Low to moderate (software-dependent; often lower than LiDAR payloads)	Low-cost 3D reconstruction using standard imagery; scalable block coverage; compatible with per-tree segmentation	Limited canopy penetration; sensitive to image overlap, lighting, wind motion, and ground control; internal foliage density less reliable than LiDAR	Common in precision agriculture and mapping; accessible via service providers; useful for orchard-scale structure baselining
Multispectral sensors	Parrot Sequoia; Micasense RedEdge; DJI Phantom 4 Multispectral	Vegetation indices (NDVI, NDRE); vigour & chlorophyll status	~ AUD 1,000–10,000	Well-established; canopy vigour mapping	Specialist calibration required	Widely used in precision agriculture; emerging in orchards
Thermal cameras	FLIR Vue TZ20; DJI Zenmuse XT2	Canopy temperature; stress detection	~ AUD 5,000–20,000	Stress monitoring	Lower resolution; sensitive to ambient conditions	Used in stress/irrigation research; limited orchard uptake
Hyperspectral (pushbroom sensors)	Headwall Nano-Hyperspec; Cubert UHD	High spectral resolution; leaf pigments; canopy physiology	> USD 50,000	Detailed biochemical signatures; research-grade	Very high cost; heavy payload; complex calibration; large datasets	Research only; not commercial-ready
LiDAR (ALS, UAV-mounted)	RIEGL miniVUX; Velodyne Puck (on UAV)	3D canopy structure; crown height/area; voxelisation	~ USD 20,000–80,000 (sensor) + UAV	High-resolution 3D structure; canopy penetration; orchard-scale mapping	High cost; IMU drift; weather/flight constraints; large data	Specialist research; service-provider potential

5.5. Advanced 3D and spectral reconstruction

Overview and methods:

Light detection and ranging (LiDAR) technologies, coupled with three-dimensional (3D) modelling approaches, probably represent the most advanced current methods for reconstructing orchard canopy structure and simulating light environments. Three-dimensional point clouds can be acquired using active LiDAR sensors or derived from photogrammetric SfM reconstruction of overlapping imagery, although LiDAR generally provides more consistent structural sampling and better canopy penetration in dense systems (Wallace et al. 2016). Terrestrial laser scanning (TLS) refers to ground-based LiDAR, typically mounted on a tripod to capture dense 360° point clouds, though mobile variants (MLS) can also be mounted on vehicles, ATVs, or backpack systems for faster coverage (Côté et al. 2009). TLS can produce very high-resolution reconstructions of individual trees or orchard blocks, while UAV- or airborne-mounted LiDAR (ALS) typically provides broader but lower-resolution coverage (Wallace et al. 2012). These point clouds can be processed into voxel-based models, where canopy volume is divided into small 3D units that quantify foliage density and gap fraction (Van der Zande et al. 2011). When combined with radiative transfer or ray-tracing algorithms, voxelised canopies allow simulation of light interception and distribution within trees, offering unprecedented detail on how canopy structure influences light capture (Ross et al. 2022).

A related development is the emergence of hybrid 3D and spectral scanning systems that combine structural and physiological measurements within a single instrument. An example is the PlantEye (Phenospex), which uses active laser-line scanning integrated with RGB and NIR (near-Infrared) imaging to generate multispectral 3D point clouds of plant surfaces (Zieschank and Junker 2023). Each scan captures both geometric and reflectance data, enabling estimation of canopy height, projected area, biomass proxies, and vegetation indices such as the Normalized Difference Vegetation Index (NDVI), which indicates canopy greenness and chlorophyll content, and the Plant Senescence Reflectance Index (PSRI), which relates to pigment degradation and leaf senescence. Similar systems, including field-based phenotyping platforms such as GPhenoVision, are increasingly used in controlled environments and pilot field trials (Jiang et al. 2018). While their range is typically limited to small plots or individual plants, their ability to capture structure and function simultaneously makes them potentially valuable for calibration and validation of canopy light-distribution models and other 3D reconstruction workflows.

Advantages and applications:

The main advantages of LiDAR-based and hybrid 3D–spectral approaches lie in their ability to digitise canopy architecture with high precision and to provide structural information that can be directly integrated into light models. Systems such as the PlantEye combine this with spectral measurements, allowing concurrent assessment of canopy structure and physiological status. TLS offers detailed reconstructions of tree architecture, making it valuable for pruning studies and high-resolution model calibration (Côté et al. 2009). MLS, by contrast, is versatile for continuous, row-scale scanning of canopy volume, density, and navigation tasks in orchards (Farhan et al. 2024). Handheld or backpack-mounted mobile systems provide a complementary option, allowing operators to move through canopies and reduce occlusion compared with static TLS, while still producing dense point clouds suitable for voxelisation (Westling et al. 2018). In their avocado study, Westling et al. (2018) combined handheld LiDAR with a solar-geometric ray tracing model and validated the outputs against ceptometer grids beneath orchard trees (R^2 = 0.85). They demonstrated that accurate tree geometry, orientation, and neighbour interactions were critical for reliable light modelling, positioning handheld LiDAR not only as a practical means of reducing occlusion but also as a foundation for development of pruning decision-support systems. Underwood et al. (2016) demonstrated the utility of MLS by mapping flowers

and fruits in almond orchards using a robotic ground vehicle, where LiDAR-derived canopy volume showed a strong linear relationship with yield. Such studies highlight the structural basis for functional responses, with potential applications for inferring patterns related to light-use efficiency and crop prediction, although these relationships remain incompletely quantified in avocado systems.

Limitations and technical challenges:

Despite these advantages, limitations remain. TLS is time-consuming and subject to occlusion, requiring multiple scans per tree, while MLS depends on vehicle access and suffers from reduced resolution relative to static systems (Farhan et al. 2024). Westling et al. (2018) demonstrated the use of handheld mobile LiDAR (Zebedee scanner) in avocado orchards, showing that mobile scanning reduced occlusion compared with static TLS and could be validated against ceptometer measurements of PAR. Their workflow also highlighted practical limitations, including incomplete capture of neighbouring trees, the need for segmentation of wood and foliage, and high computational demands during voxelisation and ray tracing. Data are also intensive: large point clouds require powerful processing workflows and specialist software. Standard pipelines rely on sensors such as VLP-16 or FARO Focus and tools like CloudCompare, LiDAR360, and PCL, with QSM models (e.g., TreeQSM) extracting branch architecture for voxel/ray-tracing light simulations (Farhan et al. 2024).

Hybrid scanning systems such as PlantEye may mitigate some of the occlusion challenges of LiDAR by using active structured-light scanning, but their limited range and slower throughput restrict use to small-scale phenotyping rather than full orchard environments (Zieschank and Junker 2023). These systems are also currently prototyped for small plants rather than large trees, so further significant development would likely be required for their transitional use in orchards.

Current role and outlook:

In practice, advanced 3D reconstruction remains primarily a research tool rather than a grower-ready technology, but it plays a critical role in developing and validating light-distribution models. Because LiDAR point clouds can be voxelised into foliage volumes, they provide the structural backbone for ray- or radiosity-based simulation of within-canopy light fields (Farhan et al. 2024). Ground-based PAR measurements are commonly used as validation data for voxelised or ray-traced light models, since they provide a simple functional benchmark of canopy light interception that can be compared with simulated outputs (Scalisi et al. 2024a; Westling et al. 2020b). Because LiDAR-derived point clouds describe canopy structure rather than light interception itself, fPAR measurements provide the functional benchmark needed to parameterise foliage density, validate radiative-transfer performance, and ensure that simulated light fields reflect real orchard conditions.

While currently mostly limited to specialist research groups, the technology is advancing rapidly. These approaches are central to the development of predictive canopy models, where simulated light environments can be used to evaluate alternative pruning strategies, canopy architectures, and orchard designs prior to implementation. Miniaturisation of sensors, multi-wavelength integration, and automated pipelines using machine learning are expected to reduce barriers to adoption, positioning LiDAR and voxel-based modelling as key potential components of future decision-support systems for canopy management in avocado. This combination of 3D canopy structure from LiDAR and ground-based functional light measurements such as fPAR appears to underpin current high-fidelity light-distribution models in perennial crops.

While LiDAR and voxel-based reconstruction remain research-focused, hybrid structural–spectral systems such as PlantEye and GPhenoVision can help bridge laboratory phenotyping and field applications. Their integration into multi-sensor decision-support frameworks could provide a valuable intermediate step between detailed research models and grower-scale monitoring.

Emergence of digital twins:

Framing these approaches as orchard "digital twins" (DT) clarifies how structure and function are linked at per-tree scale: a digital twin is a virtual model of each tree and its surroundings that can be continuously updated and queried under simulated environmental and management parameters (Moghadam et al. 2019). In most current orcharding implementations, these systems operate as digital shadows (one-way data flow); a true digital twin requires a bidirectional, closed-loop link where model outputs drive actions (e.g., variable-rate pruning/irrigation) and new measurements re-synchronize the model (Zhang et al. 2025). Operational twins typically fuse in-orchard sensors, UAV/satellite imagery, and weather feeds via cloud/edge architectures, and increasingly pair with machine learning for prediction and decision support. CSIRO's AgScan3D+ exemplifies this direction by retrofitting a spinning 3D LiDAR plus cameras to a farm vehicle to generate orchard-scale twins of ~15,000 trees, and has been trialled for use with mango, macadamia, avocado and grapevines. The results can be used to model foliage density and light penetration distribution and provide real-time on-farm decision support (Moghadam et al. 2019). In this context, digital twins represent a potential endpoint for integrating sensing, modelling, and management, where canopy interventions can be tested virtually and optimised before being applied in the field.

Related perennial-crop work includes a vineyard digital twin built from UAV photogrammetry for canopy characterization, and forestry DT efforts that couple remote sensing with machine learning, pointing to pathways for scalable, tree-crop "twins" (Edemetti et al. 2022; Tagarakis et al. 2024; Zhang et al. 2025). For potential light-environment twins specifically, explicit sky models that partition direct and diffuse irradiance, ray-/radiosity tracing through point-cloud/voxel canopies, and validation against ground ceptometer grids are central, and have been demonstrated in avocado (Westling et al. 2018). Key adoption constraints remain heterogeneous data integration, lack of standardisation/interoperability, and implementation costs, areas repeatedly flagged in recent DT reviews (Tagarakis et al. 2024; Zhang et al. 2025).

A comparison of LiDAR-based reconstruction approaches and emerging digital twin frameworks is provided in Table 5.

TABLE 5. Comparison of advanced 3D reconstruction approaches (LiDAR and voxel-based modelling). Costs are approximate and vary by supplier; listed in available retail currency.

Tool/type	Example model	Output(s)	Approximate cost	Strengths	Limitations	Adoption/use context
Terrestrial laser scanning (TLS)	FARO Focus; RIEGL VZ series	High-resolution 3D point clouds; canopy architecture; branch/foliage segmentation	~ USD 50,000–120,000	Very detailed reconstructions; accurate for model calibration; valuable for pruning/yield studies	Time-consuming; multiple scans per tree; occlusion; high cost; specialist expertise required	Research only; foundational for model validation
Mobile laser scanning (MLS, vehicle or backpack)	GeoSLAM ZEB Horizon (handheld/backpack); RIEGL VMX (vehicle)	Continuous row-scale scans; canopy volume & density; navigation tasks	~ USD 40,000–100,000	Versatile; efficient orchard coverage; reduces occlusion compared to TLS	Lower resolution than static TLS; requires vehicle/ground access; specialist expertise required	Research & pilot trials; potential for semi-operational use
Airborne laser scanning (ALS, UAV-mounted LiDAR)	RIEGL miniVUX; Velodyne Puck on UAV	Orchard-scale canopy structure; crown area/height; voxelisation inputs	~ USD 20,000–80,000 (sensor) + UAV	(sensor) + UAV Rapid orchard/block coverage; integrates with UAV platforms	Reduced canopy penetration; IMU drift; limited flight time; high cost; specialist expertise required	Research & service providers; emerging in orchards
Handheld LiDAR	GeoSLAM Zebedee/ZEB Horizon; Leica BLK2GO	Tree-scale 3D scans; light interception modelling; validated against ceptometers	~ USD 30,000–60,000	Portable; reduces occlusion vs static TLS; practical for orchard trials	Incomplete neighbouring trees; segmentation required; high processing demands	Research validation; prototype decision-support tools
Hybrid 3D + spectral scanner	PlantEye F600 (Phenospex); GPhenoVision (University of Georgia)	3D point cloud with RGB + NIR spectral data; NDVI, PSRI, biomass and height metrics	~ EUR 40,000–60,000	Captures structural and physiological traits simultaneously; active illumination reduces dependence on ambient light	Limited range; slower throughput; mainly research phenotyping platforms developed for smaller plants	Controlled environment and pilot field phenotyping; potential calibration tool for orchard light models
Voxel-based modelling / ray tracing	Workflow: CloudCompare, LiDAR360, PCL; TreeQSM (for branch models)	Voxelised canopy volume; foliage density; simulated within-canopy light fields	foliage density; simulated within-canopy light fields Software: free to ~USD 10,000;	Explicit light simulation; links structure and function; underpins digital twin models	Requires high-performance computing; Intensive data processing; requires specialist expertise	Specialist research; highly relevant for light-distribution modelling
Digital twin frameworks	CSIRO AgScan3D+ (vehicle-mounted spinning LiDAR + cameras); Digital Orchard (OnePlanet)	Dynamic virtual orchard model; canopy light penetration; management scenario testing	System-specific; research prototypes only	Integrates LiDAR, imaging, weather & sensor data; supports scenario-based decision support	Still experimental; high cost; integration/standardisation gaps; high-level expertise required	Prototype systems; early-stage testing in orchards

5.6. Cross-industry and emerging technologies

Beyond the evolving horticultural toolset, a range of technologies from other industries offer potential to enhance light environment assessment in orchards. These approaches are not routine in horticulture research, let alone commercial settings, but they highlight opportunities for adaptation, low-cost engagement, or future research investment.

All-sky cameras and diffuse light dynamics:

Examples include sky-imaging systems developed for solar energy forecasting, consumer-grade depth sensors originally designed for gaming or mobile devices, and simulation frameworks from architecture and computer graphics. Remote sensing platforms, particularly satellites, also provide new ways to benchmark canopy function at regional scales. While many of these methods remain experimental or require validation in orchard settings, they broaden the technological horizon and can inform strategic directions for future canopy management research.

All-sky cameras and sky imagers, widely used in solar energy forecasting and atmospheric research, provide hemispherical views of the sky that can be analysed to partition direct and diffuse irradiance (González-Fernández et al. 2024; Inanici et al. 2023; Yamashita and Yoshimura 2019). This distinction is highly relevant for general canopy light models, since diffuse light penetrates deeper into canopies and supports more uniform photosynthesis compared with direct radiation (Gu et al. 2002; Urban et al. 2012). In avocado, Berry et al. (2022) demonstrated that leaf photosynthetic rates increased with higher proportions of diffuse light, driven primarily by changes in stomatal conductance rather than photosynthetic biochemistry. They also showed that green stems responded with increased conductance under diffuse conditions.

All-sky camera systems can deliver near real-time data on cloud cover and irradiance components (González-Fernández et al. 2024; Inanici et al. 2023). Although all-sky cameras and sky imagers rely on fisheye optics, these instruments differ from the hemispherical canopy photography (DHP) described in Section 5.3. Whereas DHP captures upward-facing images of the canopy itself to estimate openness and light interception, all-sky cameras capture the entire sky dome, enabling real-time classification of cloud cover and estimation of diffuse versus direct solar radiation. While such systems have not yet been applied to avocado orchards, they represent a potential source of valuable inputs for canopy light modelling and could help capture how changing sky conditions influence orchard light distribution.

Potential for distributed PAR sensing and UAV–ground fusion:

Another emerging area relates to distributed environmental sensing networks and their potential integration with UAV platforms (Jawad et al. 2017; Varandas et al. 2020). Low-cost PAR sensors, which have been used in ecological monitoring and environmental sensor networks, can operate in distributed arrays across heterogeneous environments (Ke 2022; Rankine et al. 2014; Rundel et al. 2009). When combined with UAV-based irradiance measurements or LiDAR-derived structural models, such distributed PAR observations could in future provide high-frequency above- and below-canopy light measurements to help constrain radiative-transfer simulations under dynamic sky conditions.

Consumer-grade depth sensors:

Low-cost depth-sensing devices, developed primarily for consumer electronics and gaming applications, also offer potential for canopy characterisation. Examples include RGB-D cameras such as Microsoft Kinect (Cai et al. 2017) and Intel RealSense (Brahmanage and Leung 2019), as well as LiDAR sensors now integrated into some tablets and smartphones (Costantino et al.

2022). These systems can generate three-dimensional point clouds by combining colour (RGB) imagery with depth information, potentially providing a rapid means of estimating canopy volume, height, and spatial distribution (Gené-Mola et al. 2020; McGlade et al. 2022). Their main advantages are affordability, portability, and ease of use, which make them attractive for exploratory research and grower demonstrations (Tatsumi et al. 2023). However, accuracy can be significantly limited in dense, multilayered canopies: performance of RGB-D sensors decreases under high ambient light (> ~2000 lux) and at greater distances (> ~3-5 m) from the target (Gené-Mola et al. 2020). Consumer LiDAR sensors (e.g. in tablets) may also show reduced detection or higher error in complex stands with dense understorey or overlapping branches (Gollob et al. 2021).

Simulation frameworks from other industries:

Cross-industry simulation frameworks provide another class of tools with potential to enhance canopy light modelling. An example is Radiance, a ray-tracing program originally developed for architectural daylight studies, which simulates the propagation of light through 3D spaces based on scene geometry and sky conditions (Brembilla et al. 2019; McNeil and Lee 2013; Ward 1994b). Radiance has been widely applied in building physics to optimise window placement, shading, and daylight availability, and its capacity to model direct and diffuse components could make it transferable to plant canopies once voxelised or point-cloud canopy structures are available. Furthermore, advances in real-time rendering and ray tracing from the computer graphics and gaming industries (Akenine-Moller et al. 2019; Friedrich et al. 2006) have yielded highly efficient algorithms capable of simulating light transport at interactive speeds. While these approaches require adaptation to biological structures and PAR-specific spectral ranges, they illustrate how cross-disciplinary innovations could accelerate canopy light simulations, making them more feasible for large-scale or real-time decision-support applications in horticulture. This would enable more rapid evaluation of canopy management scenarios and improve the feasibility of near-real-time decision-support tools.

Satellite-based perspectives:

Remote sensing platforms, particularly satellites, provide another complementary perspective for assessing light environments at regional scales. A key innovation is the measurement of solar-induced chlorophyll fluorescence (SIF), which serves as a proxy for photosynthetic activity and light-use efficiency across large areas (Liu et al. 2013; Wagle et al. 2016). Instruments such as GOSAT, OCO-2, and TROPOMI have demonstrated the capacity to retrieve SIF at spatial scales ranging from a few kilometres down to several hundred metres, enabling monitoring of vegetation function under varying sky conditions and climates (Frankenberg et al. 2011; Köhler et al. 2020; Magney et al. 2019). While the resolution of current satellite products is likely too coarse to resolve orchard canopies, SIF and related spectral measurements could be used for regional benchmarking of photosynthetic performance, complementing finer-scale UAV and ground-based measurements.

Emerging links between spectral sensing and plant functional biology:

Beyond structural and radiative measurements, recent cross-disciplinary research has demonstrated that hyperspectral reflectance at the leaf level can be statistically linked to underlying biological processes, including the expression of genes associated with photosynthesis, pigment metabolism, water relations, and stress responses (Chen et al. 2025). More broadly, hyperspectral approaches have been shown to relate spectral variation to photosynthetic capacity and light use efficiency proxies in a range of plant systems (Croft et al. 2017; Fu et al. 2019; Serbin et al. 2014). While these approaches remain experimental and are currently restricted to leaf-scale analyses, they highlight a potential longer-term pathway for bridging sensing technologies with the physiological processes that determine how efficiently

intercepted light is converted into carbon gain, a key knowledge gap identified in Section 1. As such, spectral approaches may eventually complement structural and radiative measurements by providing functional context, rather than replacing direct quantification of canopy light interception and distribution.

Implications for avocado canopy management:

In the context of avocado production, such top-down information may help identify regional differences in canopy function, support calibration of light-use models under contrasting environments, and ultimately inform broader decision-support frameworks. Together, simulation frameworks and satellite monitoring illustrate how cross-disciplinary and top-down approaches could complement orchard-scale sensing, expanding the scope of future decision-support systems for avocado canopy management. Emerging spectral approaches that infer aspects of plant functional status, including photosynthetic capacity or light use efficiency, may in the longer term provide additional biological context for these models, but are not yet suited to operational canopy management and do not provide direct measurements of canopy-scale light use efficiency.

Despite their promise, these emerging approaches face important feasibility constraints. Current costs, data-processing requirements, and the need for validation in orchard contexts remain barriers to widespread adoption, meaning their immediate use will be confined to research or pilot trials.

A comparative summary of representative examples, including all-sky cameras, consumer depth sensors, simulation frameworks, and satellite-based monitoring, is provided in Table 6.

TABLE 6. Cross-industry and emerging technologies with potential to inform orchard light environments or plant functional responses relevant to canopy light use.

Tool/type	Example models	Output(s)	Approximate cost	Strengths	Limitations	Adoption/use context
All-sky cameras / sky imagers	TSI TSI-880 Sky Imager; WAHRSIS (Wide Angle High-Resolution Sky Imaging System)	Partitioning of direct vs diffuse irradiance; real-time cloud cover	~ USD 5,000–20,000	Captures sky conditions driving canopy light; real-time; useful model input	Not yet used in orchards; requires calibration; high instrument cost	Established in solar forecasting & ecology; potential future input for canopy light models
Consumer depth sensors (RGB-D, tablet/smartphone LiDAR)	Microsoft Azure Kinect; Intel RealSense D435; Apple iPad Pro (LiDAR)	3D point clouds of canopy volume/height	~ USD 300–1,500	Very low cost; portable; easy to use; good for demos and exploratory research	Limited canopy penetration; reduced accuracy in bright light or dense foliage; short range (≤5 m)	Exploratory use in forestry & orchards; potential grower engagement/training
Simulation frameworks (cross-industry)	Radiance daylighting software; Unity/Unreal gaming engines with ray tracing	Ray tracing of light through 3D canopy structures	Mostly free (Radiance, open-source); commercial engines licensed (~ USD 1,000–5,000 for pro use)	Proven efficiency in architecture/graphics; handles direct & diffuse light; scalable to complex 3D models	Requires adaptation for PAR range and plant geometry; specialist expertise needed	Research potential; pathway to large-scale or real-time canopy light simulations
Satellite-based monitoring (SIF)	GOSAT; OCO-2; TROPOMI	Solar-induced chlorophyll fluorescence (SIF) as proxy for photosynthetic activity	Public data (free access via NASA/ESA)	Regional benchmarking of light use efficiency and canopy function; complements UAV/ground data	Resolution (100s m–km) too coarse for orchards; indirect measure	Research use for regional avocado benchmarking and calibration of light-use models
Hyperspectral sensing linked to plant functional traits (research-stage)	Leaf-level hyperspectral cameras; laboratory or field spectrometers	Spectral proxies linked to photosynthetic capacity, stress responses, and gene expression	High (research instrumentation)	Demonstrates potential to link sensing with underlying plant physiological processes; non-destructive	Restricted to leaf scale; experimental; not a direct measure of light interception or canopy structure; complex data analysis	Research-only; conceptual pathway for linking sensing with light use efficiency and plant function

5.7. Comparative evaluation and hierarchy of options

Spectrum of available tools:

The range of light environment assessment tools reviewed in Sections 5.2 to 5.6 spans a continuum from simple, low-cost field instruments to advanced modelling frameworks and cross-industry innovations.

At one end of the spectrum, ceptometers and in-canopy loggers provide straightforward, affordable measurements of light interception that are readily applied in both research and extension contexts. Intermediate approaches such as DHP and UAV-based imaging expand coverage and detail, enabling orchard-scale benchmarking of canopy openness, structure, and vigour. At the advanced level, terrestrial, mobile, and UAV-based LiDAR systems generate high-resolution 3D reconstructions that can be voxelised and coupled with radiative transfer models to simulate within-canopy light fields. Finally, emerging technologies from outside horticulture, including sky imagers, consumer-grade depth sensors, architectural daylight modelling frameworks, and satellite-derived solar-induced fluorescence, broaden the technological horizon by introducing new ways to quantify or simulate light environments. These remain potential or experimental in orchard contexts, but they highlight promising avenues for adaptation and future research.

This diversity of tools highlights a set of trade-offs in cost, accuracy, and feasibility that must be considered when prioritising technologies for future avocado canopy management research and decision-support tool development. However, across all tiers, the fundamental constraint remains the lack of quantitative relationships linking canopy light measurements to yield outcomes, which limits the development of predictive canopy models. Secondary constraints relate to tool-specific limitations in capturing canopy structure, scalability, and integration into practical workflows, which primarily affect the refinement and adoption of decision-support tools.

Tier 1: Grower-ready instruments

At the most practical level, tools such as ceptometers, in-canopy loggers, simple structural proxies of canopy openness (e.g. spherical densiometry), and, to some extent, smartphone-based light sensing are grower-ready. They are affordable, portable, and require minimal technical expertise, making them suitable for routine monitoring. Ceptometers provide rapid estimates of canopy light interception, while loggers capture diurnal and seasonal dynamics, offering growers and service providers straightforward benchmarks of the canopy light environment. Although their spatial resolution is limited and cheaper data loggers or smartphone apps may only record illuminance rather than true PAR, their simplicity and low cost make them effective entry-level tools for building awareness of canopy–light relationships and for validating more complex approaches. As such, they represent the foundation of current practice, bridging immediate orchard needs with research applications.

Tier 2: Research-ready methods

A second tier of tools can be considered research-ready, offering greater detail and scalability but requiring more expertise and investment. DHP is well established for quantifying canopy openness, LAI, and fPAR, making it valuable for research trials that compare pruning regimes or canopy architectures. UAV-based imaging expands assessments to the orchard scale, with RGB and multispectral sensors enabling vigour mapping and canopy cover estimation, and LiDAR payloads providing structural reconstructions for light interception studies. Terrestrial and mobile laser scanning (TLS, MLS) further enhance structural detail, capturing high-resolution 3D canopy information suitable for model calibration and scenario testing. While these methods

demand more specialised equipment, software, and operator skill than entry-level tools, they deliver robust datasets that directly support the development and validation of light-distribution models.

Beyond individual platforms, recent developments highlight the growing importance of structured multi-sensor fusion workflows in orchard systems. Rather than relying on a single data stream, these approaches combine UAV multispectral imagery, three-dimensional canopy reconstruction from LiDAR or photogrammetry, and targeted ground-based measurements to generate tree-level and orchard-scale maps of structural and functional traits. Such fusion pipelines demonstrate how spectral indices, voxel-derived structural metrics, and field-calibrated reference data can be integrated through statistical or machine learning models to scale from sampled trees to entire blocks. Although most current applications focus on vigour, flowering, or canopy structure, the same architecture is directly transferable to canopy light assessment when calibrated against fPAR or PPFD measurements. In this sense, research-ready tools are increasingly defined not only by sensor sophistication, but by their capacity for integrated, multi-layer modelling.

Tier 3: Emerging and cross-industry innovations

A third tier consists of emerging or cross-industry tools that remain largely experimental in orchard contexts but point to promising avenues for future research. All-sky cameras and sky imagers, developed for solar energy forecasting, could provide real-time inputs on direct and diffuse irradiance, improving the realism of canopy light models. Consumer-grade depth sensors, such as smartphone LiDAR or RGB-D cameras, offer accessible 3D data capture, though their range and accuracy are still limited under dense canopy conditions. Simulation frameworks like Radiance, originally designed for architectural daylight analysis, and real-time rendering engines from the gaming industry demonstrate how advanced ray-tracing algorithms might be adapted for orchard canopy light simulations. At the largest scale, satellite observations of solar-induced fluorescence (SIF) provide regional benchmarks of photosynthetic activity, complementing ground- and UAV-based measurements. In addition, emerging hyperspectral approaches that link spectral signatures to photosynthetic capacity or light use efficiency represent a potential future pathway for integrating sensing with plant functional biology, although these remain research-stage and are not yet applicable to orchard-scale decision-making. While each of these technologies requires further validation and adaptation before routine use, they broaden the technological horizon and highlight where strategic R&D investment could deliver breakthroughs in avocado canopy light management.

Integrating across tiers:

These three tiers of tools illustrate how different technologies can serve complementary roles rather than competing alternatives. Increasingly, their value lies not in isolated deployment but in deliberate integration, where simple ground-based light measurements are fused with UAV-derived structural and spectral datasets to constrain and validate canopy light models.

1) Grower-ready instruments provide immediate, affordable benchmarks of canopy light environments and serve as valuable training and engagement aids.

2) Research-ready methods offer the precision and scalability needed to develop and validate canopy light models, forming the backbone of scientific studies and regional monitoring programs.

3) Emerging cross-industry technologies, while not yet operational in orchard contexts, highlight potential directions for innovation and signal where investment could deliver transformative advances.

The integration of these tiers, linking simple, accessible measurements with advanced structural reconstructions and future-oriented simulation and remote-sensing approaches, will likely be central to developing robust, regionally tailored decision-support systems for avocado canopy management, enabling a transition from descriptive assessment of canopy light environments to predictive and optimised canopy management strategies.

Practical adoption will ultimately depend not only on technical capability but also on cost, ease of integration, scalability and demonstrated value under commercial avocado orchard conditions. The most useful pathway is therefore likely to combine simple grower-accessible measurements with more advanced research and service-provider tools, so that technical development is matched with practical feasibility and a clear pathway to industry uptake. This comparative hierarchy provides a basis for prioritising technologies for immediate implementation, targeted research investment, and longer-term development. Collectively, these tiers define a pathway from measurement to application, where canopy light metrics (e.g. fPAR, DLI, canopy structure) serve as model inputs, are integrated within light–yield frameworks, and inform decision-support outputs such as pruning thresholds, canopy density targets, and spatial optimisation strategies.

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AV24011

Modeller and technology engagements

A series of targeted engagements was conducted with researchers, technology providers, and modelling experts to assess current capabilities in sensing, canopy characterisation, and light modelling, and to evaluate their relevance to the objectives of AV24011. These discussions were designed to complement the literature review by providing a practical, current view of what is technically feasible, scalable, and applicable in future R&D and in commercial avocado orchards.

Across the discussions, a pattern emerged that current technologies are well developed for measuring canopy size and outer structure, but are more limited in their ability to directly assess how light is distributed within the canopy. Tools such as LiDAR, imaging systems including RGB and spectral sensors, and robotics platforms can efficiently help capture information on tree size, canopy volume, and in some cases overall density, and can be applied at tree-level and orchard or block scale. These capabilities are particularly useful for mapping variability across orchards and for quantifying structural changes resulting from canopy management practices such as pruning.

In practical terms, the following sensing capabilities appear currently well established:

- Canopy size and outer structure
- Light interception estimation
- Fruit detection using RGB imaging and machine learning (although this still requires development and validation for avocado systems)

In contrast, understanding the canopy light environment, particularly how light is distributed within the tree, remains more complex. While some approaches can estimate total light interception, accurately describing internal light distribution in dense avocado canopies is still challenging. This reflects both limitations in measurement, such as incomplete capture of internal canopy structure, and the need to rely on modelling approaches to interpret how light interacts with the canopy over time.

The following aspects remain more challenging to measure or quantify reliably:

- Internal canopy structure (including separation of leaves, branches, shoots, flowers, and fruit)
- Light distribution within the canopy
- Accurate canopy density and leaf area distribution

A strong point of agreement across stakeholders was that no single technology provides a complete solution. Instead, there is clear value in combining approaches. For example, structural data derived from LiDAR can be integrated with light measurements or ray tracing modelling to estimate canopy light environments, while imaging and machine

vision systems can provide additional information on canopy condition and crop load. More advanced modelling approaches can simulate the effects of canopy management on light and productivity, but currently require detailed inputs and are probably better suited to research applications than routine commercial use.

Another key theme was the trade-off between accuracy and scalability. High-resolution sensing and modelling approaches can provide detailed insights into canopy structure and light behaviour, but are often expensive, slow, complex, and resource-intensive. In contrast, more scalable systems can be applied across commercial orchards, but typically provide coarser information. Balancing this trade-off will be critical in identifying practical pathways for industry adoption.

A key implication of this trade-off is that higher levels of detail require higher sensing resolution, which in turn increases cost, data processing requirements, and technical expertise. Emerging software platforms that simplify processing of LiDAR and image-derived 3D plant models may help reduce this bottleneck, particularly for research applications, but these approaches still require further development and validation.

Overall, these engagements indicate that the main opportunity lies not in developing entirely new tools, but in integrating existing sensing and modelling approaches into practical, scalable workflows. In particular, there is a need to better link measurable canopy attributes, such as volume, porosity, density, and light interception and distribution, with yield outcomes, and to identify approaches that can be applied across different growing regions. The following sections summarise individual engagements, grouped into modelling approaches, sensing and automation technologies, and mapping and LiDAR systems.

1. Modelling approaches

Engagements with modelling experts, including University of Queensland modellers Inigo Auzmendi, Jim Hanan, and Liqi Han, focused on understanding how different modelling approaches can be used to simulate canopy light environments and their relationship with productivity. Across discussions, a clear range of modelling complexity was identified, from simple light interception models to highly detailed structural simulations, broadly spanning geometric, light extinction, and ray tracing-based approaches.

Simpler modelling approaches are generally based on canopy size and shape, and estimate light interception using broad geometric relationships. These methods are relatively easy to apply and can be scaled across orchards, making them useful for linking canopy structure with yield. In particular, relationships such as yield per unit canopy area or canopy volume provide a straightforward way to simulate canopy performance and compare management strategies, albeit broadly based on assumptions with limited validation or ground truthing in avocado.

More advanced approaches aim to represent how light is distributed within the canopy. These include light extinction models and ray tracing methods, which simulate how light penetrates through canopy layers. While these approaches provide a more realistic representation of the canopy light environment, they also generally rely on assumptions about canopy structure or require detailed structural inputs, which are often difficult to obtain in practice, particularly in dense avocado canopies where internal structure is not easily captured.

At a higher level of complexity, functional–structural plant models and digital twin frameworks represent two related but distinct modelling pathways. Functional–structural plant models focus on simulating the interactions between canopy structure, light interception, and physiological processes over time, and offer strong potential for linking pruning responses with factors such as carbohydrate dynamics, nutrient status, and broader source–sink behaviour. Digital twin approaches, in contrast, are built around high-fidelity virtual reconstructions of real orchard systems, typically generated from detailed LiDAR and RGB data, and can be used to simulate and evaluate management scenarios such as pruning or spray strategies before implementation in the field.

Both approaches offer significant potential for future decision-support tools, but they differ in emphasis. Functional–structural modelling is more explicitly process-based and biologically interpretive, whereas digital twins are more strongly centred on structural realism, simulation, and operational scenario testing. Both currently require high-quality data, significant computational resources, and specialised expertise.

A key limitation across all modelling approaches is the difficulty of accurately representing canopy structure. Even when LiDAR or imaging data are available, incomplete capture of internal canopy structure, particularly due to occlusion effects in dense canopies, limits the accuracy of model outputs, particularly for simulating light distribution. As a result, model outputs often depend on assumptions or simplifications of canopy architecture.

Modelling approaches involve a clear trade-off between simplicity, accuracy, and scalability. Simpler models are easier to apply at orchard scale, but provide limited insight into internal canopy processes. More complex models offer greater detail and predictive capability, but are currently constrained by data requirements and operational complexity, and are therefore likely often suitable for model development and scenario testing rather than direct large-scale application.

2. Sensing approaches

Engagements with sensing and remote sensing researchers, including Southern Cross University researcher Abe Gibson and University of Queensland researchers Stuart Phinn and William Woodgate, focused on evaluating current approaches for measuring canopy

structure and light environments, and their suitability for application in avocado orchard systems.

Across these discussions, a range of sensing technologies was identified, including LiDAR, multispectral and hyperspectral imaging, RGB imaging, and light interception sensors such as fPAR. These tools provide different types of information, ranging from canopy structure to physiological condition and light environment, and can be deployed using ground-based, mobile, or aerial platforms.

A consideration was to integrate structural and light sensing approaches, for example by combining LiDAR-derived canopy architecture with fPAR-based light interception measurements to generate spatially relevant light environment indices.

In practical terms, several sensing capabilities are currently well established. These include measurement of canopy size and outer structure, estimation of total light interception, and, in some systems, fruit detection using RGB imaging combined with machine learning approaches. These methods can be applied at tree to orchard scale and provide useful information for characterising canopy variability and supporting management decisions. However, some applications, such as fruit detection, still require further development and validation for avocado systems.

In contrast, several key aspects of the canopy system remain more difficult to measure directly. These include the internal structure of the canopy, particularly the separation of leaves, branches, and fruit, as well as accurate quantification of canopy density and leaf area distribution. Accurately describing how light is distributed within the canopy remains a major challenge. While some sensors can estimate light interception at a point in time, capturing spatial and temporal variation in light within dense canopies is not straightforward and often requires repeated measurements or modelling approaches, as point-based measurements such as fPAR represent only a two-dimensional snapshot of canopy light conditions and require additional sampling or modelling to capture temporal variation.

Current analytical workflows typically involve generating point clouds from LiDAR data, converting these into voxel-based canopy representations, and applying modelling approaches such as ray tracing to simulate light interception and distribution. However, these approaches are affected by occlusion effects, where parts of the canopy are not captured, with ground-based systems often missing upper canopy regions and aerial systems missing lower and internal structure.

A consistent theme across discussions was that sensing technologies are subject to trade-offs between resolution, coverage, and practicality. Lower-cost and more scalable approaches can provide useful information on canopy structure and light interception at orchard scale, but with limited detail. For example, canopy size and outer structure can be assessed using relatively simple and scalable approaches such as RGB imaging or

low-cost 3D sensing. Higher-resolution approaches can capture more detailed structural and light information, including canopy density and internal structure, but are typically slower, more complex, and require greater expertise and data processing capacity.

These engagements indicate that while a range of sensing tools is available, no single method can fully characterise the canopy light environment. Instead, there is strong potential in combining sensing approaches to improve interpretation of canopy structure and light conditions. However, the practical application of these approaches will depend on balancing data quality with scalability and operational feasibility.

Among sensing approaches, LiDAR was consistently identified as probably the most robust method for capturing canopy structure, and is therefore considered separately in the following section.

3. LiDAR applications

3.1. High-resolution LiDAR capability

Engagement with LiDAR technology specialists, including RIEGL representative Paul Salmon, together with insights from high-resolution modelling work by Liqi Han, provided insight into the capabilities of high-resolution LiDAR systems for detailed canopy characterisation. These systems likely represent the current upper practical limit of what is technically possible in capturing tree architecture and canopy structure.

High-resolution terrestrial LiDAR systems, such as the RIEGL VZ series, are capable of generating highly detailed three-dimensional representations of individual trees. Using static or mobile scanning approaches, these systems produce dense point clouds that capture fine-scale structural features, including branches, shoots, and canopy surfaces. When combined with dedicated analysis software, these data can be processed to extract a wide range of structural attributes, including canopy height, crown dimensions, branch architecture, and wood volume.

A key advantage of these systems is their ability to move beyond whole-canopy metrics and begin to resolve canopy composition. Through advanced processing and integration with RGB imaging, it is possible to distinguish between different canopy components, such as leaves, woody material, and fruit. This integration of LiDAR and RGB data enables more realistic reconstruction of canopy structure and provides a pathway toward estimating attributes such as leaf area, fruit size, and canopy composition.

These high-resolution datasets also support detailed analysis of internal canopy structure, including the spatial distribution of canopy elements and the arrangement of shoots and branches. This level of detail is particularly important for modelling applications, where accurate representation of canopy architecture is required to simulate light interception and distribution. In this context, high-resolution LiDAR

provides a critical foundation for advanced modelling approaches, including ray tracing and digital reconstruction of canopy systems.

Despite these capabilities, several practical limitations were highlighted. High-resolution LiDAR systems typically require multiple scans from different positions to fully capture canopy structure, particularly in dense trees where occlusion is significant. While static scanning provides the highest level of detail, it is time-consuming and better suited to small-scale studies. Mobile scanning approaches can increase efficiency but generally reduce structural resolution. In addition, data processing and analysis require specialised software and expertise, and although computing requirements are manageable, the workflow remains relatively complex.

Overall, high-resolution LiDAR systems provide an unparalleled level of detail for canopy characterisation and are particularly valuable for research applications, model development, and calibration studies. However, their use in commercial orchard systems is currently limited by the time, cost, and complexity associated with data acquisition and processing.

3.2. Practical LiDAR applications in orchard systems

Engagements with applied researchers, including Mahmud Kare (NSW DPIRD) who works in citrus systems, and Alessio Scalisi (Agriculture Victoria), who works on temperate tree crops such as stone fruit and apple in narrow orchard systems, provided insight into how LiDAR technologies are currently being used for canopy characterisation in orchard systems other than avocado. These applications typically focus on practical, scalable approaches that can be easier to deploy in orchards, rather than high-resolution structural reconstruction.

In these cases, LiDAR systems are primarily used to quantify whole-canopy structural attributes. These include canopy volume, tree height, canopy expansion over time, and, in some cases, canopy density proxies derived from point cloud data. Such measurements can be acquired relatively quickly using mobile or ground-based LiDAR platforms, allowing large numbers of trees to be scanned within short timeframes. This makes LiDAR well suited to assessing spatial variability within orchards and tracking structural changes associated with management practices such as pruning.

These structural datasets can also be integrated with light modelling approaches to estimate canopy light interception at a whole-canopy level. For example, LiDAR-derived canopy representations can be combined with sky models or simplified ray tracing methods to estimate total light interception or available energy within the canopy. While these approaches provide useful indicators of canopy performance, they generally do not resolve how light is distributed within the canopy.

A key limitation of more practical LiDAR systems is their inability to reliably distinguish between different canopy components, such as leaves, branches, and fruit. As a result, most analyses are based on aggregated canopy structure rather than detailed internal composition. Similarly, while canopy density can be estimated from point cloud data, these metrics are typically proxies and do not directly represent leaf area distribution or internal canopy architecture.

These constraints limit the ability of practical LiDAR approaches to analyse internal canopy processes, particularly those related to light distribution, fruiting patterns, and canopy function. While it is possible to infer relationships between canopy structure and productivity, for example by linking canopy volume or light interception with eventual yield, these relationships remain indirect and require further validation.

Despite these limitations, practical LiDAR applications offer significant value for orchard-scale characterisation. They enable rapid, repeatable measurement of canopy structure, support before-and-after assessment of pruning interventions, and provide a basis for comparing orchards, cultivars, or management strategies. When combined with georeferencing systems these datasets can also be linked to individual trees, allowing integration with yield data and other orchard information.

LiDAR in its practical, research-ready, scalable forms is currently most effective as a tool for rapid structural mapping and canopy characterisation at orchard scale. While it provides limited insight into detailed internal canopy structure and light distribution, it offers a practical and scalable foundation for linking canopy structure with productivity. These capabilities position LiDAR as a key component of canopy assessment workflows, particularly when combined with complementary sensing and modelling approaches.

4. Automation and commercial applications

Engagements with commercial technology providers, including Agricultural Robotics and Green Atlas, focused on how sensing approaches are being integrated into operational systems for orchard characterisation and decision support. These discussions provided insight into the current state of technology deployment and the direction of future development in commercial orchard systems.

A theme across was the integration of multiple sensing technologies into unified platforms. Rather than relying on a single data source, these systems may combine structural information from LiDAR or depth sensors with RGB imaging, and in some cases additional data streams such as yield mapping or environmental measurements. This integrated approach allows more comprehensive characterisation of canopy structure, crop load, and spatial variability within orchards.

Automation plays a central role in enabling these systems to operate at scale. Ground-based or mobile platforms can collect large volumes of data rapidly and repeatedly,

supporting whole-of-orchard assessment with reduced labour requirements. This improves consistency and allows monitoring of canopy development and management impacts over time, which is difficult to achieve using manual methods.

A further development is the increasing focus on prediction and decision support. These systems are moving beyond measurement alone toward generating actionable outputs, such as estimates of crop load, yield potential, or canopy performance. In robotics-based systems, this includes linking fruit detection with canopy structure to support early yield estimation and spatial prediction of production. In some cases, machine learning approaches are being applied to identify patterns and relationships within large datasets, supporting improved interpretation of canopy and production dynamics. However, these approaches remain dependent on high-quality training data and validation across different orchard systems.

Engagement with Quinlan Barthelme from Guass Technologies highlighted an additional emerging development: simplified software platforms designed to reduce the technical barriers associated with processing LiDAR and image-derived 3D datasets. The platform is being developing aims to convert LiDAR point clouds or photogrammetry-derived images, including smartphone-based scans, into usable 3D plant models that can be directly interrogated by users. This could allow researchers, consultants, or growers to select and measure specific canopy components, such as whole trees, canopy sections, leaves, or fruit, and quantify attributes including canopy volume, dimensions, leaf size, fruit size, fruit colour, or other structural traits without requiring advanced point-cloud processing expertise. Although this type of platform is still emerging and currently appears most relevant as a research tool, it may help address a key bottleneck identified across stakeholder engagements, namely the need for specialised expertise and complex workflows to extract meaningful metrics from 3D canopy data.

Despite this progress, several limitations remain. Many systems are still under development and require further validation, particularly in crops such as avocado, where canopy structure is more complex than in narrow orchard systems. In addition, while integration of multiple data streams improves system capability, it also increases complexity in data processing, interpretation, and implementation. As a result, the translation of these technologies into robust, user-friendly decision-support tools is still evolving.

These platforms provide a pathway toward more data-driven canopy management, but their effectiveness ultimately depends on the ability to reliably link measured canopy attributes, particularly structure and light environment, with productivity outcomes. This reinforces the importance of developing clear relationships between canopy structure, light environment, and yield, as identified in the literature review and earlier sections of this document.

Can better light information improve avocado pruning decisions?

AV24011 grower feedback webinar

10 June 2026

Introductions

Why we are here

- **Canopy structure and light within the orchard** are important factors influencing yield
- The best canopy strategy will not be the same for every region or orchard
- AV24011 has identified key gaps in canopy management knowledge, with light and productivity highlighted as a priority area
- We are considering how technologies, including modelling and light sensing, could support better canopy management decisions
- Today, we want your feedback on whether our recommendations for future R&D are useful, realistic and worth pursuing

Feedback we are seeking today

- Do you see these recommendations as a useful pathway towards improving pruning decision-making?
- Does the proposed approach seem realistic?
- Is this an area you see as worthwhile for investment through future R&D?
- If such a canopy management decision-support tool were developed, would you be interested in using it?

Why light matters

- **Photosynthetically active radiation (PAR)** is the light that leaves use for photosynthesis
    - Drives carbohydrate and energy supply needed for flushing, flowering, fruit set, fruit growth and retention
    - Too much shade can create unproductive canopy zones
- But both, **light interception and distribution** within the canopy affect productivity
    - We do not yet have clear, practical, yield-promoting light targets for avocado canopies
    - This makes pruning decisions harder than they should be
- Useful to develop the tools that will help growers assess canopy light and compare pruning options

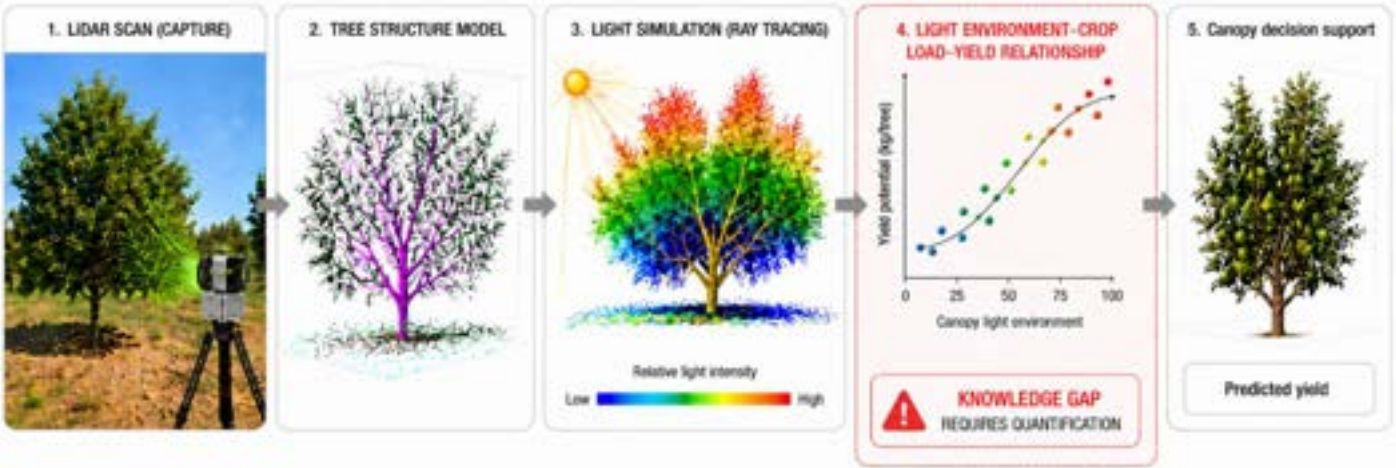
What future R&D needs to help answer

1. How much light is needed in different parts of the canopy?
2. Which canopy zones are productive, and which are mainly adding shade?
3. How do canopy density and pruning change the productive light environment?
4. Can we predict how pruning choices affect yield?
5. Do different growing regions require different canopy structure and light targets?

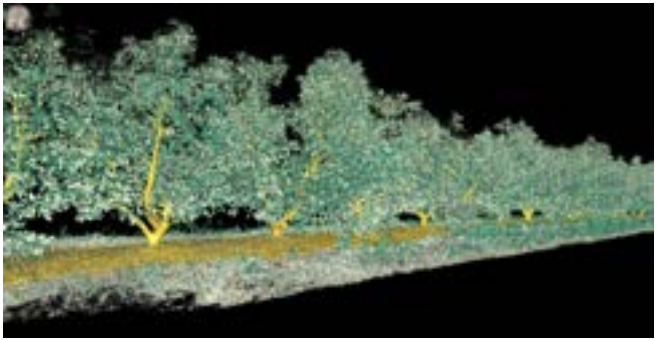
Ultimate aim: practical canopy management strategies that improve productivity and reduce guesswork

Recommended pathway: test ideas before cutting trees

- Use canopy measurements and light data to build virtual orchard models
  - Test different pruning options virtually
  - Refine model predictions against commercial orchard trials
  - Use the results to develop a practical decision support tool

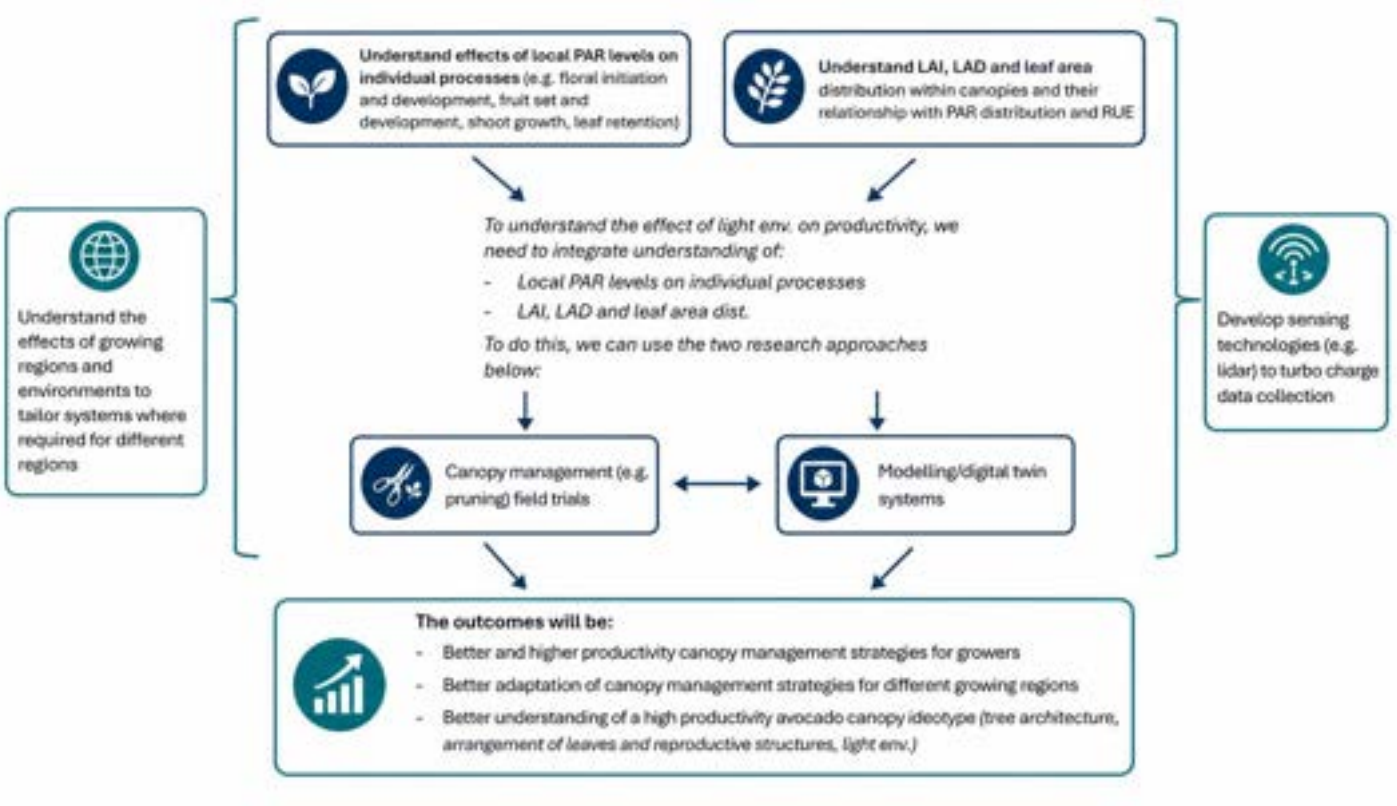


How LiDAR scanning/mapping could help



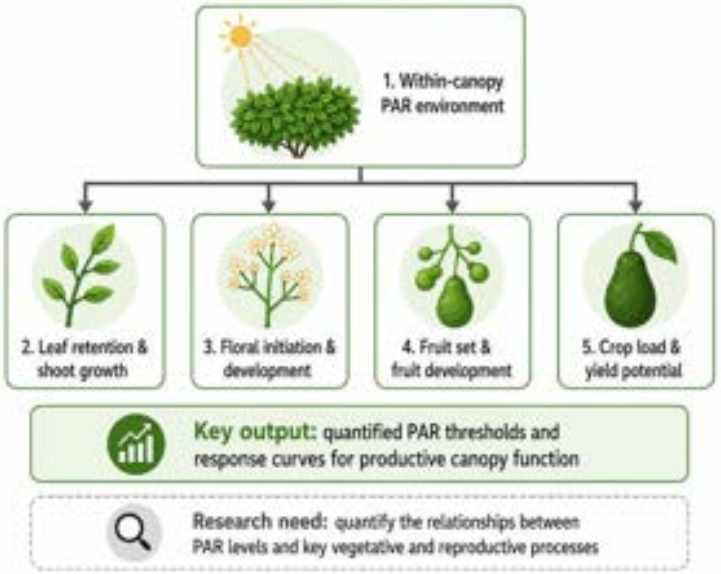
- LiDAR creates a 3D map of canopy shape, density and components
- This could help identify
  - Gaps or crowded areas
  - Internal shading dynamics
  - Differences between blocks or pruning approaches
  - Inputs for future canopy models or decision-support tools

Recommended process



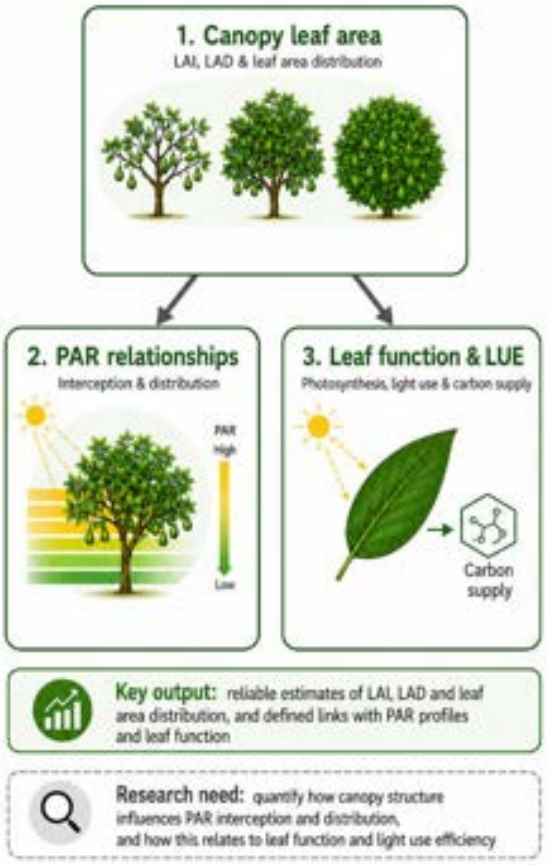
Area 1: Define practical light targets

- Measure light levels across the canopy and relate them to flowering, fruit set, fruit growth and shoot renewal
- This area of work allows:
  - Identification of non-productive canopy zones requiring intervention
  - Understanding of balance between vegetative and reproductive growth
  - Data inputs and clearer targets for where light needs to be improved in the canopy



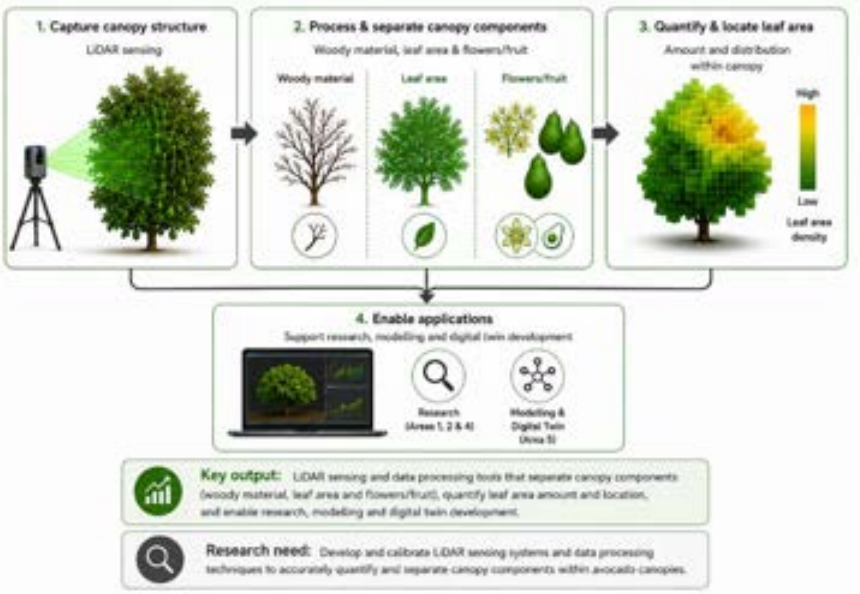
Area 2: Link canopy density to light and productivity

- Quantify how leaf distribution and canopy density affect light penetration and use efficiency
- Identify when canopies are too open, balanced or overcrowded
- This area of work allows:
  - Canopy density targets
  - Visual understanding of productive vs overcrowded canopies
  - Data input to design productive orchards



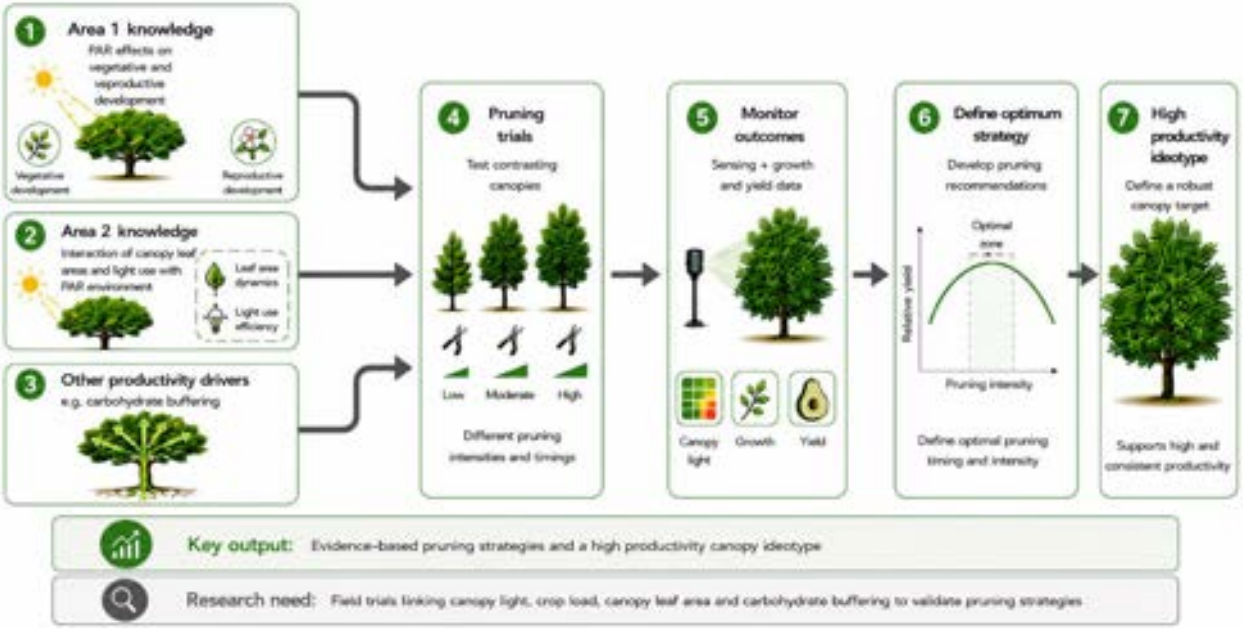
Area 3: Test canopy sensing tools

- Assess tools such as LiDAR, machine vision and image-based canopy assessment
- This area of work allows:
  - Inputs into advanced pruning decision support tools, automated technologies, orchard assessment tools and yield forecasting



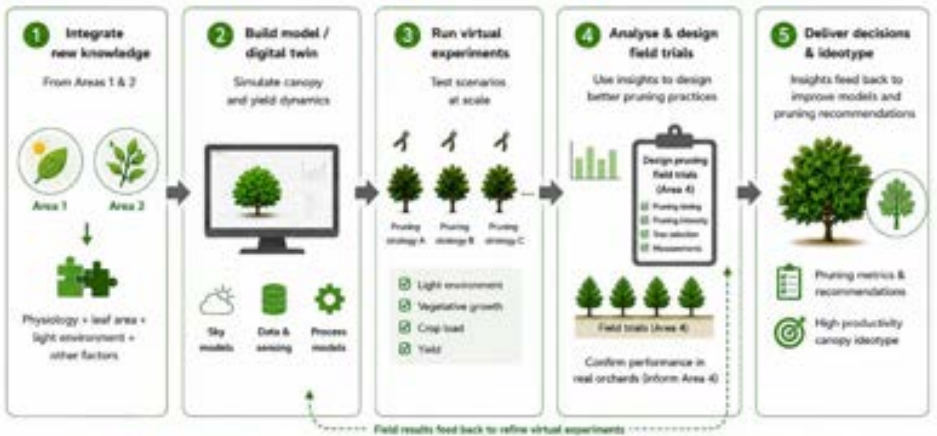
Area 4: Run pruning trials in commercial orchards

- Use light (area 1) and canopy density (area 2) targets to design pruning treatments
- Test effects on yield
- This area of work allows: Validation of high productivity pruning strategies



Area 5: Develop modelling and decision support

- Combine canopy sensing, light targets and pruning trial data to simulate pruning options before they are applied in the orchard
- This area of work allows:
  - Tools to help compare pruning options before committing time, labour and crop risk



Reminder: feedback we are seeking today

- Do you see these recommendations as a useful pathway towards improving pruning decision-making?
- Does the proposed approach seem realistic?
- Is this an area you see as worthwhile for investment through future R&D?
- If such a canopy management decision-support tool were developed, would you be interested in using it?