## Final Report

# Improved fruit quality and robustness in avocado supply chains (mineral nutrition)

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Improved fruit quality and robustness in avocado supply chains (mineral nutrition) AV19004

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# Content

# Summary and Public Summary

Inconsistency in the quality of fruit supplied to consumers is a primary concern for the Australian avocado industry. Opportunity exists to potentially improve postharvest quality by producing fruit with a mineral nutrient balance high in calcium and relatively low in nitrogen, and also potassium and magnesium. However, orchard management practices required to achieve this balance are not well understood. This literature review based project set out to distil existing scientific knowledge of pre-harvest mineral nutrition effects, identify knowledge gaps for further research, and recommend strategies that could improve avocado postharvest storage and handling outcomes in an Australian production environment. The target audience was Australian avocado producers, agronomy consultants and other interested industry stakeholders.

A 6-month desk-top study was undertaken by the core project team. The members were experienced in research and/or extension in avocado nutrition, agronomy, pathology, postharvest physiology, and supply chains. The findings were documented in a comprehensive literature review collating information from over 180 scientific and technical articles. Perspectives from select consenting expert reviewers were sought and duly applied to fine tune the literature review document.

The key outputs from the project were the literature review entitled 'A review of pre-harvest mineral nutrition effects on avocado postharvest quality in Australia' and an attendant technical summary. In these documents, 'best bet' pre-harvest management strategies were identified as recommendations. Key messages were also captured in a draft article for potential submission to 'Talking Avocados'.

The anticipated consequence of these outputs is that Australian growers will be better informed as to their potential to manage fruit nutrient status and, thereby, to take steps to maximise fruit robustness at harvest. Anticipated downstream improvements to postharvest fruit quality will help meet the industry target that *"by 2021, over 90 per cent of avocados received by consumers will meet or exceed their expectations of quality"*.

*Strategies recommended to* ***improve avocado fruit robustness*** *at harvest as supported by the scientific and technical literature include*:

- Provide adequate Ca to trees, especially during flowering, fruit set and early development.
- Do fruit tissue analysis as a relatively reliable indicator of fruit Ca concentrations.
- Ensure leaf nutrient concentrations for N and K do not exceed the optimum range.
- Delay K application until latter stages of fruit development and only apply if needed.
- Achieve a good balance between vegetative growth and crop load.
- Select appropriate rootstocks when establishing new plantings.

*Attendant priority areas for* ***future research*** *include*:

- Mining big data sets to understand G x E x M interactions.
- Characterising production environments and practices governing 'good' vs 'bad' fruit nutrient status.
- Irrigation management.
- Wholistic approach to N management.
- Compost and mulch application.
- Soil application of additional Ca at fruit set.
- Timing and type of fruit tissue sampling for nutrient analysis.
- Rapid diagnostic tools for monitoring fruit nutrient status.
- Plant growth regulators for canopy management.
- Susceptibility to flesh bruising.

- Influence of the graft union on nutrient translocation.

## Keywords

Avocado, calcium, fruit, management, nitrogen, nutrition, preharvest, postharvest, quality, robustness.

## Introduction

Meeting the quality expectations of consumers has posed a challenge for Australian avocado producers. Despite progressive improvement in avocado fruit quality over the past decade (Tyas 2016), "*quality remains a significant challenge and needs to be addressed to ensure the continued success of the industry*" (Hort Innovation, 2017). Much emphasis is placed on careful postharvest handling and temperature management to maintain fruit quality through the supply chain. However, AV15009 (Joyce 2018) suggested that inherent fruit "*robustness at harvest*" can have an overriding influence on final fruit quality in supply chains to consumers. In that project, vastly different body rot incidence (0 vs 100%) occurred in ripened 'Hass' fruit sourced from two orchards. The profound difference was despite all fruit being harvested on the same day, packed into the same trays and distributed through the same supply chain. These responses were potentially linked to differing mineral nutrient levels detected in the fruit flesh.

An association between fruit mineral nutrient status and postharvest fruit quality has been recognised. High fruit nitrogen (N) and/or low fruit calcium (Ca) concentrations have been correlated with avocado postharvest defects, including body and stem end rots, diffuse flesh discolouration, vascular browning, pulp spot and discrete patches. High fruit potassium (K) and magnesium (Mg) levels have also been associated with poor fruit quality. This is largely due to their putative antagonistic effect on Ca uptake and function. AV14000 grower workshops and survey revealed that most Australian avocado producers are aware of these relationships. However, there is uncertainty around how to manage them effectively (Newett 2018).

Current project AV19004 set out to achieve the following objectives:

- Clarify existing scientific knowledge of pre-harvest mineral nutrition effects on avocado postharvest storage and handling outcomes and summarise this for an industry audience.
- In the course of this exercise, identify knowledge gaps in the existing scientific and technical literature.
- Identify and review pre-harvest mineral nutrition management strategies that could potentially improve avocado postharvest storage and handling outcomes from an Australian production environment.

This project is relevant to Outcome 2 of the Avocado Strategic Investment Plan objective that *"by 2021, over 90 per cent of avocados received by consumers will meet or exceed their expectations of quality"*. Within this objective, it contributes particularly to the Strategies of "*Establish objective evidence and understanding of the primary sources of continued quality issues*".

## Methodology

A 6-month duration desk-top study was undertaken by a project team comprising internationally-recognised researchers in plant physiology and plant nutrition (Dr Daryl Joyce, Dr Melinda Perkins), plant pathology (Dr Lindy Coates), soil and plant nutrition and agronomy (Simon Newett, Dr Stuart Irvine-Brown) and horticultural value chains (Dr Sohail Mazhar). Reputable scientific and technical literature accessed via DAF and UQ library resources, AAL's Best Practice Resource, and Avocadosource.com was collated and presented in a comprehensive literature review. This activity was guided by fortnightly team tele-meetings and a face-to-face team workshop.

The drafted document was subjected to peer review by expert and experienced colleagues, as follow in alphabetical order: Noel Ainsworth (Principal Supply Chain Horticulturist, Queensland Department of Agriculture and Fisheries), Dr Liz Dann [Assoc. Prof. (Plant Pathology), Queensland Alliance for Agriculture and Food Innovation], Mr Neil Delroy [Horticulturist and former co-owner of Jasper Farms], Mr Ben Faber [Advisor (Soils/Water/Subtropical Crops), Cooperative Extension, University of California], Dr Roberto Marques [Senior Technical Officer (Horticulture), Queensland Department of Agriculture and Fisheries], Hon. Dr Ken Pegg [Plant Pathologist (retired), Queensland Department of Agriculture and Fisheries], Dr Tim Smith [Director (Forestry and Biosciences R,D&E), Queensland Department of Agriculture and Fisheries], Dr Dario Stefanelli [Team Leader (Fruit Physiology), Agriculture Victoria], Mr Graeme Thomas (Managing Director, GLT Horticultural Services), Dr David Turner [Assoc. Prof. (Plant Physiology), The University of Western Australia] and Dr Nigel Wolstenholme [(Emeritus) Prof. of Horticultural Science (retired), University of KwaZulu-Natal, South Africa]. Refinements to project documentation were made based on their feedback. Findings were distilled into a technical summary and draft '*Talking Avocados'* article. Recommendations considered 'actionable now' and those 'requiring future research' were proposed.

# Outputs

Literature review: 'A review of pre-harvest mineral nutrition effects on avocado postharvest quality in Australia'. Technical summary: 'A review of pre-harvest mineral nutrition effects on avocado postharvest quality in Australia'. Draft article for publication in 'Talking Avocados': 'A review of preharvest mineral nutrition effects on avocado postharvest quality in Australia'. Summary of reviewer feedback: 'Anecdotal advice on managing avocado fruit nutrient status: Insights from the expert review panel'.

# Outcomes

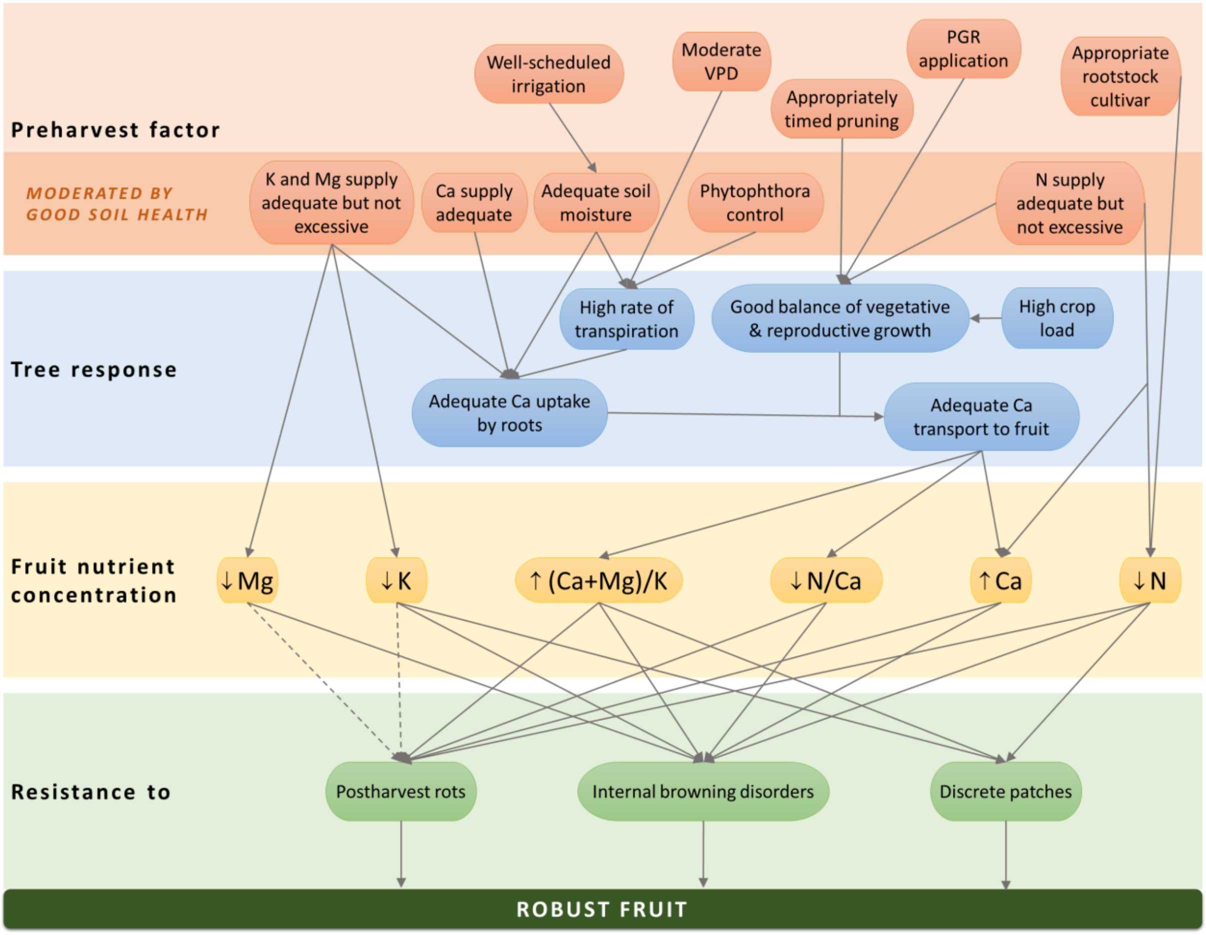
The project generated evidence-based recommendations for enhancing avocado fruit robustness at harvest. The findings are to be disseminated widely via the technical summary, subsequent article in 'Talking Avocados' and at AV17005 organised grower events. This information will provide Australian growers with better understanding of the reasons, ways and means to manage fruit nutrient status. Growers will be more informed to make decisions and take steps to maximise fruit robustness at harvest. The likely down-stream improvements to postharvest fruit quality will help meet the industry target that *"by 2021, over 90 per cent of avocados received by consumers will meet or exceed their expectations of quality"*.

# Monitoring and evaluation

Performance indicators were end-of-project delivery of a technical review along with documented recommendations to meet the target of "*informing and improving awareness towards practice change*". These criteria have been met. The goal of achieving "*fruit robustness at harvest and quality postharvest*" will be furthered by dissemination of project findings upon acceptance and approval of this final report.

# Recommendations

Evidence-based balancing of fruit mineral nutrient levels to maximize inherent fruit robustness is within reach based on due consideration of the interacting pre-harvest factors involved and summarized diagrammatically in Figure 1.




Note: Dashed lines indicate nutrient has been associated with both increased and decreased defect expression.

Figure 1. Robust avocado fruit are inherently resistant to the expression of postharvest rots and disorders. They tend to contain relatively high concentrations of calcium (Ca) and relatively low concentrations of nitrogen (N), magnesium (Mg) and potassium (K). Ratios of these nutrients in terms of low N/Ca and high (Ca+Mg)/K are correlated with greater robustness. Ca transport to fruit occurs more readily when vegetative growth is in balance with crop load and canopy transpiration is sustained. However, roots must initially be able to access Ca from the soil. Adequate soil Ca, enough soil water to dissolve it and limited interference from competing soil cations aid Ca uptake by root tips. Well scheduled irrigation to maintain soil moisture helps to optimise root health and nutrient uptake. Vegetative vigour can be checked by plant growth regulator (PGR) foliar sprays, appropriately timed pruning and avoiding excess or poorly-timed N application. Judicious N application and rootstock selection can also prevent over-accumulation of N in fruit. Soil health underpins many of these pre-harvest factors. For example, high soil CEC aids nutrient retention in the root zone, high soil biodiversity suppresses Phytophthora Root Rot (PRR), good soil aeration prevents root hypoxia and limits PRR, and high Water Holding Capacity (WHC) provides a buffer against water deficit stress. Ca accumulation in fruit is also affected by climate. Increasing atmospheric evaporative demand associated with high temperature and/or low relative humidity determines Vapour Pressure Deficit (VPD) and affects transpiration by leaves and fruitlets. Overly high VPD can trigger stomatal closure and reduce transpiration rate.

On the basis of scientific evidence, ***the following strategies to improve avocado fruit robustness are recommended***:

- **Provide adequate Ca to trees, especially during flowering, fruit set and early development**.

Small relatively frequent doses applied to the soil can help to keep Ca in soil solution and the root zone. This may be most important on sandy soils or in areas of high rainfall. However, a readily available supply of Ca in the soil does not necessarily guarantee elevated concentrations in the fruit. Other factors affect how much Ca is taken up by the tree and reaches the fruit.

- **Do fruit tissue analysis as a relatively reliable indicator of fruit Ca concentrations**.

Calcium is not distributed evenly between leaves and fruit. Also, once deposited, Ca cannot move from one organ to another. Thus, leaf Ca concentrations are not closely related to fruit Ca concentrations. Fruit tissue analysis is the only sure way of determining fruit Ca concentration. Analysis of fruit N at the same time will allow the N/Ca ratio to be calculated. This ratio tends to be a better indicator of fruit robustness than fruit Ca concentration alone. Fruit with N/Ca ratios in the high 30's or above are at risk of postharvest quality defects developing. Ideally, such fruit should not be placed into extended storage or subjected to long supply chains.

• **Ensure leaf nutrient concentrations for N and K do not exceed the optimum range**.
Unlike Ca, leaf concentrations of N and K reflect concentrations in the fruit. For 'Hass', leaf concentrations should not exceed the optimum range of 2.2-2.6% N and 0.75-2.0% K. (N.B. Based on new research from California, possibly no more than 1% K). Monitoring of leaf N and K throughout the season can allow for more timely adjustment of nutrient application rates and lessen the likelihood of fruit with poor nutrient balance.

• **Delay K application until latter stages of fruit development and only apply if needed**.Ca and K compete for uptake by plant roots and so should ideally not be applied at the same time. It is better to apply these nutrients when the fruit demand for each is highest. For Ca, peak demand is higher during the early fruit growth stages, whereas demand for K is higher in latter fruit growth stages. Speculation has it that some Australian orchards may be over-supplying K, thus it may be prudent to check leaf K concentrations before applying more.

• **Achieve a good balance between vegetative growth and crop load**.
Excessive vegetative growth can divert Ca from developing fruit. Canopy management through careful and appropriately timed PGR application, pruning, irrigation, and nutritional management may all help to control vegetative vigour and improve nutrient balance in the fruit. An important goal is that re-growth does not coincide with early fruit development.

• **Select appropriate rootstocks when establishing new plantings**.
Improved fruit quality and nutrient balance in 'Hass' and 'Shepard' fruit may be achieved by selecting rootstocks of Guatemalan or West Indian heritage over Mexican race rootstocks. 'Velvick' is a West Indian x Guatemalan hybrid that has been shown to perform consistently well in this respect. Nonetheless and although rootstock is a potentially important influencer, site and season effects may have overriding influence on fruit mineral nutrient status and yield should not be unduly compromised.

Fruit robustness is also likely to benefit from strategies that maintain optimal soil moisture (e.g. irrigation scheduling that accounts for spatial and temporal variations in water demand), improve soil health (e.g. compost and mulch application) and match N supply to tree demand. These areas have been relatively widely researched in terms of improving yield, but less so from a fruit mineral nutrient and postharvest quality perspective. Climate conditions are largely beyond the grower's control but also influence fruit nutrient status. The extent of these effects and the degree to which they can be moderated has largely not been quantified in avocado. Success in managing fruit nutrient status requires reliable monitoring tools since 'you can't control what you can't measure'. Tools that allow early diagnosis of fruit nutrient imbalances would provide opportunity for corrective action to be taken.

***The following research priorities are recommended*** to address knowledge gaps:

• **Mining big data sets to understand G x E x M interactions**.
Re-appraisal of existing data sets in new and/or different ways could help to enable interpretation of and decision making from otherwise overwhelming complex interactions, such as of genotype, environment and management; Earlier Hort Innovation avocado projects may, for example, have generated rich data sets pertaining to fruit nutrient status and quality. "In the data era, you want to take the data, get insight from it, and make it actionable." (https://www.delltechnologies.com/en-us/perspectives/welcome-to-the-data-era/).

• **Characterising production environments and practices governing 'good' vs 'bad' fruit nutrient status**.
Fruit nutrient data from orchards identified as producing fruit with superior or inferior postharvest quality could be related back to orchard activities and environment. Studies would cover multiple seasons and be informed by detailed production, management, and environmental records. Supporting leaf analysis data could be correlated to inform, for example, optimum leaf N and K guidelines. Acquiring data on fruit quality at retail level and subsequent trace-back to detailed orchard data could identify the key drivers for high quality fruit.

- **Irrigation management**.

Maintaining soil moisture within an optimum range is important for nutrient availability, uptake and translocation. However, evidence for irrigation effects on fruit nutrient status is conflicting and merit deeper investigation. Studies would qualify and quantify relationships between different irrigation regimes and vegetative/reproductive balance. Sophisticated irrigation practices like partial root zone drying (PRD) and regulated deficit irrigation have been applied to enhance fruit robustness an lessen fruit disorders, such as Ca related bitter pit of apple fruit.

- **Wholistic approach to N management**.

Relatively comprehensive studies on N management in avocado have been conducted. However, not in the context of Australian conditions. It is recognised that N management is a complex issue requiring site-specific and season-specific adjustment. In this context, value is inherent in developing 'best bet' guidelines for Australian growers in climatically distinct sub-tropical to temperate regions. Towards optimising fruit mineral nutrient status without compromising yield, studies might consider: (i) rates and timing of N application, as has been done for 'Hass' in California, (ii) dynamic contributions of compost and mulch to short, medium and long term N supply, (iii) sustained-release inorganic fertilisers and (v) nitrification inhibitors.

- **Compost and mulch application**.

Benefits of compost and mulch on root health and Phytophthora root rot suppression are well documented and have engendered their widespread use in Australian avocado orchards. However, the nature and composition of these organic materials is highly variable. As such, the magnitude and dynamics of their contribution to fruit nutrient status under Australian conditions is poorly understood. Important insight could be gained by comparing and contrasting different materials under a specific conditions. Also, mulch and compost options, including ratios, should be explored in conjunction with other orchard management practices towards an informed integrated approach to improving fruit nutrient status, as proposed above for N management.

- **Soil application of additional Ca at fruit set**.

Applying relatively expensive highly soluble forms of Ca (e.g., calcium thiosulphate, calcium nitrate) at fruit set is sometimes practiced in Australia. Current understanding around Ca uptake and transport by avocado trees casts doubt on the efficacy of such treatments when soil Ca concentrations are often adequate. Whether and to what degree fruit Ca concentrations may be enhanced by this relatively high cost practice awaits determination.

- **Timing and type of fruit tissue sampling for nutrient analysis**.

Fruit tissue analysis is typically conducted at harvest maturity and involves analysis of either the peel or flesh tissue. Good correlations exist between avocado peel and flesh Ca concentrations. However, this is not necessarily the case for other nutrients. Also, tissue type which provides the best indicator of fruit nutrient status and robustness remains to be thoroughly investigated. Sampling reproductive tissue at an early phenological stages (e.g., cauliflower stage inflorescence; CSI) provides scope for timely intervention to address nutrient imbalance. Optimum nutrient concentration ranges need to be established for specific phenological stages. Limited work in this area was conducted in South Africa for 'Pinkerton', but not 'Hass', fruit.

- **Rapid diagnostic tools for monitoring fruit nutrient status**.

Fruit nutrient analysis pertaining to critical imbalances (e.g., high N/Ca ratio) is currently costly, involving destructive sampling and typical turnaround times of a week or more. With Ca being a relatively reliable base measure of fruit robustness, merit lies in developing and optimising its cost effective rapid on-farm measurement, ideally along with the key co-determining nutrient N; viz., N/Ca ratio. More and more timely assessments could fine tune orchard management practices. Options currently in the offing that merit further investigation and adaption include ISE meters, XRF and Vis/NIR hyperspectral imaging.

- **Plant growth regulators for canopy management**.

PGRs use to control vegetative vigour is 'common practice' in Australia, and has been shown to promote Ca accumulation in avocado fruit when applied mid-anthesis as a single foliar spray. Anecdotal reports suggest that growers are applying PGRs in multiple, low doses during the 12 weeks following fruit set. At present, effects of such applications on fruit nutrient status and ultimately fruit quality are unknown and so warrant investigation.

- **Susceptibility to flesh bruising**.

Flesh bruising is a prevalent defect in Australian avocados at retail. However, its suspected relationship to fruit nutrient status is largely undefined. Preliminary research suggested bruise susceptibility in avocado fruit increases with decreasing flesh Ca concentration. Further investigation is, however, needed to confirm the role of Ca and determine whether B is also involved, given its co-involvement in cell wall strengthening.

- **Influence of the graft union on nutrient translocation**.

Preliminary studies have identified effects of grafting on nutrient translocation in avocado nursery trees. Further investigation to determine effects on mature trees would be valuable, particularly in the context of the apparent negative influence of Mexican race rootstocks on fruit quality in 'Hass'. Recent studies of the characteristics of xylem tissue in different avocado cultivars belonging to the three botanical races of avocado have highlighted important structural differences between the different races (Beier *et al*., 2020).

# Refereed scientific publications

None to report.

# References

Hort Innovation (2017), Avocado Strategic Investment Plan 2017-2021. https://www.horticulture.com.au/growers/funding-consulting-investing/investment-documents/strategic-investment-plans/. Accessed 28 Oct 2020.

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Newett, S. (2018), Achieving more consistent yields of quality fruit in the Australian avocado industry. Final report AV14000. Horticulture Innovation Australia, Sydney, Australia.

Tyas, J. (2016), Avocado industry fruit quality benchmarking. Final report AV11015. Horticulture Innovation Australia, Sydney, Australia.

# Intellectual property, commercialisation and confidentiality

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

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The project team would like to thank our expert reviewers for their invaluable contributions to the literature review. Dr Sohail Mazhar is gratefully acknowledged for his initial contributions to the project prior to his departure from DAF in September.

# Appendices

The following documents are supplied as separate files to final report:

**Appendix A.** Literature review
'Review of pre-harvest mineral nutrition effects on avocado postharvest quality in Australia.'

**Appendix B.** Technical summary
'Technical grower summary of the review of pre-harvest mineral nutrition effects on avocado postharvest quality in Australia.'

**Appendix C.** Draft article for publication in 'Talking Avocados'
**'**Review of pre-harvest mineral nutrition effects on avocado postharvest quality in Australia.'

Appendix A. Literature review -

# Review of pre-harvest mineral nutrition effects on avocado postharvest quality in Australia

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# 1 INTRODUCTION

Consistent supply of robust high quality avocado fruit is essential to build, grow, maintain and retain markets. However, meeting quality expectations of consumers has posed an ongoing challenge for the avocado industry. Negative experiences associated with poor avocado fruit quality continue to discourage repeat purchasing by consumers (Gamble *et al.*, 2010). Strategies to combat quality loss have tended to focus on postharvest handling and temperature management. But despite increasing adoption of refined handling and management strategies, variable fruit quality remains an issue.

Fruit quality cannot improve after harvest. It can and does deplete in the postharvest supply chain. The term 'robustness' has been co-opted to reflect a harvested fruits' ability to withstand the rigours of passage through the postharvest supply chain and into consumer's hands.

Fruit robustness as set at harvest is at least partly related to its mineral nutrient status (Lovatt, 2013). High fruit nitrogen (N) and low fruit calcium (Ca) concentrations have been implicated in modulating predisposition to and development of postharvest disorders and diseases. The contribution of other mineral nutrients to fruit quality stems largely from their interactive effects on Ca uptake and function. These effects may be synergistic, as is the case for boron (B), or antagonistic, as is the case for potassium (K) and magnesium (Mg).

The balance of mineral nutrients required to produce robust fruit is quite well understood for fruit in general. However, translating basic understanding into practice is another matter given complex interactions between genotypes, environments and management practices. Fruit Ca is notoriously difficult to manipulate through Ca fertilisation alone. Factors influencing avocado plant uptake of Ca include rootstock cultivar (Ben-Ya'acov and Michelson, 1995, Marques *et al.*, 2003, Whiley, 2013, Willingham *et al.*, 2001, 2006), soil type (Bonomelli *et al.*, 2019) and balance with other soil solution cations (Hofman *et al.*, 2005, Celis, 2016). Subsequent Ca distribution to the fruit is largely driven by evapotranspiration, which is in turn affected by tree health/vigour and water status (Bower *et al.*, 1989, Witney *et al.*, 1990a, Willingham *et al.*, 2004). As leaves transpire more than fruit, excessive vegetative growth can divert Ca away from developing fruit (Leonardi, 2005). Effective management of orchards to maximise fruit robustness at harvest merits understanding these and other salient inter-relationships.

This literature review considers the mineral nutrients responsible for avocado fruit robustness at harvest and their potential impacts on final fruit quality to consumers, particularly with regard disorders and decay. Pre-harvest practices thought to improve robustness through altered fruit nutrient status are critically analysed. Based on current knowledge, pre-harvest mineral nutrition measurement and management strategies that could potentially improve avocado postharvest storage and handling outcomes in an Australian production environment are recommended. Strategies with limited or contradictory evidence are highlighted as areas for future research.

# 2 OVERVIEW OF AVOCADO POSTHARVEST QUALITY

## 2.1 DEFINITION AND EFFECTORS

Fruit quality has been described as a dynamic composite of a fruit's physicochemical properties and its perception by consumers (Kyriacou & Rouphael, 2018). Intrinsic quality characteristics are governed by genotype, pre-harvest factors and postharvest management. How these characteristics are perceived by consumers also depends on extrinsic socioeconomic and marketing factors (Schreiner *et al.*, 2013). Consumer perceptions constantly evolve based on changing lifestyles, food trends, health concerns and product pricing (Jabs & Devine, 2006, Schreiner *et al.*, 2013). As such, a strict definition of quality is difficult to establish. In practice, avocado quality to consumers is ultimately 'fitness for purpose' (Juran & Gryna, 1980), such as sound and tasty firm-ripe fruit for use in a salad or sound and tasty soft-ripe fruit for use in guacamole.

According to studies over the last 10 years (Gamble *et al.*, 2010, Jones, 2014, Quantum Market Research, 2017, Obenland *et al.*, 2012, Hass Avocado Board, 2015), consumers consider avocado quality to be acceptable if the fruit has:

- Fresh appearance with minimal external blemishes.
- Reached or almost reached a ready-to-eat stage of ripeness.
- Smooth, creamy texture and nutty, buttery flavour.
- Internal defects affecting less than 10% of the flesh.
- Perceived 'value for money' pricing.

Fruit size also contributes to avocado quality, but preferences for size vary depending on the needs of the consumer. For example, larger avocados are preferred for multi-serve dishes, such as guacamole, and smaller avocados for single-serve use (Hass Avocado Board, 2013).

Although price is an important factor in avocado quality perception, consumers view it as secondary to the fruit's intrinsic quality characteristics (Gamble *et al.*, 2010, Hass Avocado Board, 2015). Furthermore, frequent avocado consumers are less price sensitive than are infrequent consumers (Quantum Market Research, 2017).

Examples of industry best practice in Australia (Avocados Australia Limited, 2020) to meet quality expectations include[a]:

- Nutrition programmes based on regular leaf and soil analysis.
- Maintaining adequate soil moisture and nutrient availability throughout the year.
- Ensuring soil moisture and calcium supply are optimum during the first 8 weeks after fruit set.
- Managing pests and diseases, including proper application of pre- and postharvest fungicide treatments.
- Keeping trees to a manageable (e.g. sprayable) size and maintaining a relatively open canopy for light and spray penetration.
- Harvesting fruit at or above a specified minimum maturity standard, but before fruit become over-mature.
- Grading fruit for external and/or internal defects.
- Implementing a library tray system to predict postharvest performance.

Pre- and postharvest fungicide applications reduce the severity and incidence of body and stem end rots in fruit on ripening (Everett *et al.*, 2007, Shimshoni *et al.*, 2020, Hassan & Dann, 2019). Postharvest fungicide treatments can be relatively less effective when disease pressure is high (Hassan & Dann, 2019). This has led to warnings against their use as a "Band-Aid" to cure infected fruit coming into the supply chain (Dann *et al.*, 2020). Good orchard hygiene and harvesting fruit dry are important general considerations.

[a] The effectors plant-soil nutrition and canopy management are discussed in sections 3 and 4.

Fruit maturity at harvest strongly influences final fruit quality (Hofman *et al.*, 2013). Careful pre-harvest management or postharvest handling cannot overcome likely poor quality resulting from harvesting immature or over-mature fruit. Maturity is closely linked to oil content, which in turn influences fruit flavour and texture (Obenland *et al*., 2012). Immature fruit have low oil content and develop a watery, rubbery texture with insipid flavour on ripening (Lee *et al.*, 1983). Immature fruit are also more sensitive to flesh bruising (Mazhar *et al.*, 2018), postharvest rots and uneven ripening (Pak *et al.*, 2003). Over-mature fruit may develop rancid off-flavours (Erickson *et al.*, 1970).

Dry matter proportion (%) is a good indicator of fruit maturity. Unlike oil content, it is relatively easy to measure. Lee *et al.* (1983) reported that a minimum dry matter content of 22.8% was important to produce an acceptable tasting 'Hass' fruit. Gamble *et al.* (2010) later showed that consumer liking for 'Hass' fruit increased as dry matter content increased from 20 to 38%. Minimum dry matter content currently recommended in Australia are 23% for 'Hass' and 21% for 'Shepard' (Avocados Australia Limited, 2020).

Library tray systems involve sampling fruit from the packing line (e.g., one tray per block/orchard per harvest) and holding them at room temperature (ca. 22°C) with a constant supply of ethylene [ca. 10 µl/l (ppm)] (Le Lagadec, 2011). The fruit generally ripen within 1 week under these conditions and are duly assessed for quality, including external and internal defects. This shelf life test system provides an indication of fruit robustness. It can be used to estimate marketability and provide feedback to supply chain stakeholders, from grower to retailer. Library trays are valuable for helping to judge the most suitable markets for batches of fruit; e.g., local rather than distant markets for fruit predicted to have a short shelf life. As library trays of avocados are not exposed to supply chain perturbations that trigger development of some specific postharvest quality defects, not all issues are detected. For example, development of flesh bruising requires exposure to physical impact, compression or vibration (Mazhar *et al.*, 2018, Arpaia *et al.*, 1987) and chilling injury expresses upon exposure to low temperature (Chaplin *et al.*, 1982).

## 2.2 COMMON QUALITY DEFECTS

Monitoring of avocado fruit quality sampled from Australian retail stores over an 8 year period revealed that flesh bruising followed by body rots were the most significant internal defects encountered (Tyas, 2016). Flesh bruising susceptibility is purportedly linked to fruit mineral nutrient status, but this is yet to be fully investigated. Reported associations between fruit mineral nutrient status and development of postharvest rots and other quality defects in avocado are summarised in Table 1. Descriptions of the relevant avocado postharvest quality defects are shown in Table 2.

## 2.3 CURRENT STATUS IN AUSTRALIA

Twenty years ago, ~40% of 'Hass' avocado fruit on retail display in Australia had internal quality defects affecting >10% of the flesh (Hofman & Ledger, 2001). Almost a decade later, this figure had declined to 28% and continued to do so over an 8-year period, reaching 20% when retail monitoring ceased in 2015 (Tyas, 2016).

**Table 1**. *Fruit mineral nutrients in the peel or flesh associated with increased (+) or decreased (-) expression of postharvest quality defects in avocado fruit. Blank spaces indicate no association or no information available. Supporting literature is listed in Appendix A*.

| Defect name | Mineral nutrient | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **N** | **P** | **K** | **Ca** | **Mg** | **B** | **Mn** | **Si** | **Zn** | **N/Ca** | **(Ca+Mg)/K** |
| Body rots | + | + | +/- | - | +/- | - | | - | | + | - |
| Stem end rot | + | | + | - | +/- | | | - | | + | - |
| Diffuse discolouration | +/- | +/- | + | - | - | - | - | | | | +/- |
| Vascular browning | + | | | - | | - | | | | | - |
| Vascular leaching | + | | +/- | - | - | | | | | + | - |
| Pulp spot | | + | - | - | | | | | - | | |
| Discrete patches | + | | + | | + | | | | | | - |
| Endocarp black spot | | | | | | - | | | | | |

Despite gradual improvement in quality, consumer dissatisfaction with avocado fruit remains an issue. In 2017, an online survey of 1000 avocado buyers found that half of them often will not buy avocado because they have been dissatisfied with the quality available (Quantum Market Research, 2017). This survey also revealed that 45% of buyers were at least sometimes disappointed with the quality once they cut the fruit open at home. It is, therefore, not surprising that Australian consumers view 'bad' avocados as an unavoidable reality (Jones, 2014) and that avocado wastage in the home is frequently reported (Quantum Market Research, 2017, Jones, 2014).

The above market research highlights a need to further improve avocado fruit quality to consumers. Current industry advice is focused on harvesting fruit at the correct maturity, applying appropriate fungicide treatments, minimising exposure of harvested fruit to mechanical damage and carefully managing postharvest temperature (Avocados Australia Limited, 2020). Although the contribution of mineral nutrition to fruit quality is recognised, the means to and clear guidelines for achieving optimal nutrient levels in the fruit are lacking. The next section aims to elucidate interacting underlying processes that link tree mineral nutrition to fruit quality aimed to identify practical and/or researchable strategies for managing avocado fruit mineral nutrient status.

# 3 Mineral nutrients associated with postharvest quality

## 3.1 Calcium

Calcium affects fruit quality in various ways. It forms cross-linkages with pectin gels in plant cell walls, thereby contributing mechanical strength to fruit tissues and conferring protection against cell-wall degrading enzymes (Hocking *et al.*, 2016, Wehr *et al.*, 2004). Ca also binds with lipids and proteins of plant cell membranes (Jacobson & Papahadjopoulos, 1975, Kirkby & Pilbeam, 1984, Legge *et al.*, 1982) such as to stabilise them and help maintain sub-cellular compartmentation (de Freitas *et al.*, 2011, Suzuki *et al.*, 2003). Additionally, fluctuations in Ca concentrations in compartmentalised plant cell solutions act as a signal to regulate metabolism; for example, to trigger plant defence processes against biotic (e.g., fungal pathogens) and environmental (e.g., heat) factors (White & Broadley, 2003).

**Table 2**. *Description and possible causes of postharvest quality defects associated with avocado fruit mineral nutrient status. Descriptions have been adapted from 'The International Avocado Quality Manual' (White et al., 2009), unless otherwise specified*.

| **Defect name** with synonym(s) | **Description** | **Possible causes** |
|---|---|---|
| **Body rots**<br>Anthracnose | Discrete hemispherical areas of discoloured flesh spreading from the skin into the flesh. May not be obvious when viewing uncut fruit. | Fungal pathogens (*Colletotrichum* species) invading through the skin during fruit development. |
| **Stem end rot** | Discoloured area of flesh, usually softer than the surrounding flesh, beginning at the stem end and spreading rapidly down the fruit as it ripens. | Fungal pathogens invading via the 'button' or via the picking scar if the stem has been removed. |
| **Diffuse discolouration**<br>Internal chilling injury<br>Mesocarp discolouration<br>Flesh greying<br>Grey pulp | Diffuse areas of grey or grey/brown flesh with poorly defined margins, usually starting at the base adjacent to the seed and spreading upwards and outwards. | Storage for too long at standard storage temperatures or holding ripening fruit at low temperatures. Symptoms can develop without storage in very mature fruit. |
| **Vascular browning**<br>Vascular streaking | Browning of the vascular bundles (the fibres) that run longitudinally through the flesh of the fruit. Discoloration is typically <1 mm in diameter. | Fungal diseases (defect is often associated with stem end rot) or physiological senescence of the fruit resulting from chilling injury. |
| **Vascular leaching** | Flesh discoloration >1 mm in diameter around the vascular bundles. Initially begins as a brown 'halo' around the vascular bundles. | Fungal diseases or very long storage times (longer than 6 weeks). |
| **Pulp spot** | Black/grey spots along margins of the vascular bundles and randomly distributed throughout, particularly, Fuerte, fruit. Symptom develops after storage. Spots increase in size for several minutes or more after cutting the fruit. | Poor postharvest temperature management or mineral nutrition. |
| **Discrete patches**<br>External chilling injury | Browning or blackening of irregular large solid areas or smaller discrete areas (usually >3 mm diameter) of the skin surface. Damaged areas are generally sunken and confined to the skin (i.e. adjacent flesh is unaffected). | Chilling injury: occurs at temperatures between 0 and 2°C in fruit of any maturity and between 3 and 4°C in less mature fruit stored for longer than 7 days. |
| **Endocarp black spot** | Localised greyish-black discolouration of the endocarp (inner layer of flesh around the seed coat) initially near the top of the seed cavity. In severe cases, blackening extends 10 mm above seed cavity and tapers down to 1-2 mm near the middle of the cavity. | Boron deficiency (Smith, 2004) |

Tissue Ca concentrations in 'Hass' avocado fruit vary greatly, ranging from 78 to 2500 mg $kg^{-1}$ dry weight (DW) in the flesh (Appendix B) and 230 to 1130 mg $kg^{-1}$ DW in the peel (Appendix C). Within-tree variation is also marked. Pedreschi *et al.* (2014) reported flesh Ca concentrations of ~800 to

~2500 mg $kg^{-1}$ DW for 100 fruit harvested from the one tree. Elevated Ca concentrations in avocado fruit have been linked to delayed ripening (Hofman *et al.*, 2002, Witney *et al.*, 1990a), greater firmness after storage (Defilippi *et al.*, 2015) and reduction in quality defects. These defects include body rot (Hofman *et al.*, 2002, Everett *et al.*, 2007, Whiley, 2013, Marques *et al.*, 2003), stem end rot (Whiley, 2013, Willingham *et al.*, 2006) and physiological disorders that include diffuse flesh discolouration (Marques *et al.*, 2003, Hofman *et al.*, 2002, Whiley, 2013), vascular browning (Marques *et al.*, 2003, Thorp *et al.*, 1997, Whiley, 2013) and vascular leaching (Whiley, 2013). Preliminary circumstantial evidence depicted in Figure 1 also suggests a possible link between avocado flesh Ca concentrations and susceptibility to flesh bruising (Perkins *et al.*, unpublished data).


**Figure 1**. *Flesh bruising in 'Hass' avocado fruit subjected to a 1 Joule impact (viz., ~40 cm drop height for a 250 g fruit) at the firm-ripe stage and assessed after 48 h at 20°C. Fruit with low flesh Ca concentration were sourced from vigorous trees in a commercial orchard in South-east Queensland. Fruit with high flesh Ca concentration were sourced from non-vigorous trees in the same orchard. Mean bruise volume was 43% larger in fruit containing low flesh Ca concentrations.*

Despite the importance of Ca to fruit quality, recommended fruit Ca concentrations for avocado are limited in the literature. A likely reason is interactions between Ca and other mineral nutrients. The balance of fruit Ca to other nutrients, particularly N, K and Mg, is evidently more important for avocado quality than is Ca concentration alone (Section 3.8). Kruger *et al.* (2000) proposed that 'Pinkerton' avocados sampled in the 50-100 g size range during fruit development should have >1000 mg Ca $kg^{-1}$ so as not to manifest diffuse flesh discolouration after cold storage. However, they later recommended limiting leaf N concentrations and complying with recommended Ca soil and leaf concentrations without reference to fruit Ca concentrations *per se* (Kruger *et al.*, 2004).

Calcium uptake by plants is a passive process, driven largely by transpiration pull and root pressure push (Palzkill & Tibbitts, 1977, Hocking *et al.*, 2016, Saure, 2005). Along roots, the rate of Ca uptake is greatest at the root tip (Clarkson, 1984). This has significant implications for the avocado industry in Australia because Phytophthora root rot is prevalent and the pathogen first destroys root tips. Calcium cations carry a positive charge as do other cations in the soil solution, such as $Na^+$, $K^+$ and $Mg^{2+}$, which compete with $Ca^{2+}$ for uptake (Hofman *et al.*, 2005, Celis, 2016). Increasing soil acidity also limits Ca availability and plant uptake (White, 2012). The recommended soil pH range based on 1:5 water extraction method for avocado in subtropical Australia is 5.0-5.5 (Wolstenholme, 2013).

Calcium is transported from the root to other plant organs occurs in water conducting xylem cells connected end-to-end through roots to branches in the vascular pathway. Calcium is dissolved in the water of the transpiration stream, but its movement is slowed by ionic drag associated with transient negatively charged sites on the xylem vessel walls (Saure, 2005). Calcium progresses upwardly once sites in the lower parts of the plant become saturated. Calcium uptake by plant organs is also driven by their export of an auxin (viz., indole-3-acetic acid; IAA), which tends to be greater during periods of high metabolic activity (Cutting & Bower, 1989). Overall, Ca mostly accumulates in plant organs that are actively growing and transpiring. Avocado leaves, have been shown to contain Ca concentrations four to six times that of the relatively low-transpiring skin of mature avocado fruit (Witney *et al.*, 1990b). Once deposited, Ca does not readily re-translocate to other organs. This lack of mobility and the initial uneven distribution of Ca to plant organs determine that leaf Ca concentrations are generally not a reliable indicator of fruit Ca concentrations (Hofman, 2006, Willingham *et al.*, 2006, Solis-Fraire *et al.*, 1998). In general, leaf Ca concentrations increase over time and are more indicative of leaf age (Lahav *et al.*, 1990).

Avocado fruit demand for Ca is greatest within the first 8 weeks after fruit set (Witney *et al.*, 1990a, Bower *et al.*, 1989). After this time, fruit stomata become non-metabolically functional lenticels (Blanke, 1995) and the waxy cuticle thickens (Coates *et al.*, 1993). These physiological, anatomical and morphological changes limit fruit transpiration rate. Thus it is important to create conditions that favour Ca transport to the fruit during the early stages of development.

Providing adequate Ca supply in the bulk soil is only part of the answer (Fig. 2). Efficient uptake by roots requires ionic balance among nutrients in the soil solution. Calcium supply and availability in the soil solution is dependent on and specific to soil type [e.g., sand vs. loam vs. clay, particle size distribution, inorganic matrix mineral composition, organic matter (OM) content, cation or anion exchange capacity (CEC, AEC), etc.], aeration and soil moisture content. Thereupon, Ca supply to fruit will primarily depend on xylem sap flow as influenced by its development stage mediated transpiration and competition from leaves (Leonardi, 2005, Montanaro *et al.*, 2015). Factors that reduce plant transpiration, such as low relative humidity and stomatal closure, or that increase the ratio of vegetative to reproductive material on the tree (e.g., over-supply of N fertiliser, low crop load, fruit thinning, insufficient or poorly-timed pruning) will likely limit fruit Ca uptake. Although the interactions are complex, there is scope to manipulate factors within a grower's control to help maximise fruit Ca concentrations (Section 4).

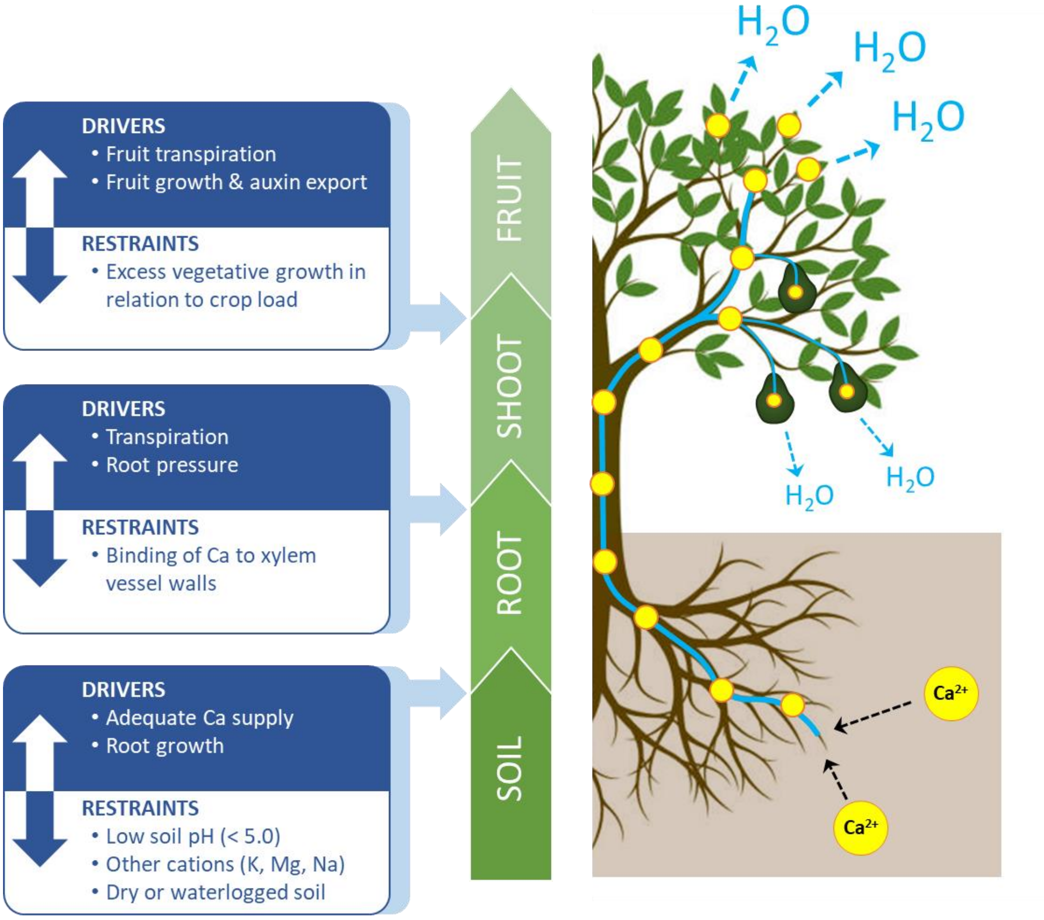


**Figure 2**. *Model depicting that Ca accumulation in fruit firstly requires an adequate Ca supply in the soil. How much of this Ca is available to the plant will depend on soil moisture, soil pH and the level of interference from other soil cations. Healthy roots are required for Ca uptake by the plant, so careful management of soil water is needed to minimise root hypoxia and Phytophthora root rot associated with overly wet soils and root desiccation arising from overly dry soils. Ca movement through the tree occurs in the water-conducting vessels of the xylem. Conditions that promote the flow of water (i.e. transpiration and root pressure) also aid Ca transport from roots to shoots. Binding of Ca to cation exchange sites on the walls of the xylem vessel can slow this upward movement. Partitioning of Ca between leaves and fruit depends on the relative sink strength for water in particular of each. Fruit transpiration rate and auxin export are highest during the early development stage and these draw Ca into the young fruit. However, excessive vegetative growth at this time can divert water and Ca away from the fruit and cause Ca to be deposited in the leaves. Once there, Ca cannot re-translocate to fruit.*

## 3.2 Nitrogen

The plant requirement for N is greater than any other mineral nutrient. Nitrogen is essential for growth as it is used to make amino acids and proteins as well as the chlorophyll required for photosynthesis to produce carbohydrates (Hawkesford *et al.*, 2012). Inadequate supply of N can result in low yields, small fruit and less vegetative growth to support flowering and fruit set in subsequent seasons (Lahav *et al.*, 1987). Timings and rates of N application need to achieve a balance between yield and fruit quality (Fig. 3). Over-supply of N during fruit development can negatively impact fruit robustness for the following reasons:

- Too much N supply promotes excessive vegetative growth (Wolstenholme, 2004) which creates a source of N for later translocation to developing fruit (Zilkah *et al.*, 1987), which diverts Ca from developing fruit (Leonardi, 2005, Witney *et al.*, 1990a).

- Elevated concentrations of N in the peel make fruit more vulnerable to fungal pathogen attack. *Colletotrichum gloeosporioides*[b], a common causal agent of postharvest rots in avocado fruit, secretes more of the tissue-degrading enzyme pectate lyase when exposed to increasing N concentrations in the surrounding environment (Drori *et al.*, 2003).

- Increased N supply may increase fruit size (Abou Aziz *et al.*, 1975) and this can reduce fruit quality by 'diluting' the fruit Ca concentration (Hofman *et al.*, 2002). Although, conflicting reports suggest that N has no effect on fruit size (Hofman *et al.*, 2005) or may result in smaller fruit (Arpaia *et al.*, 1996).

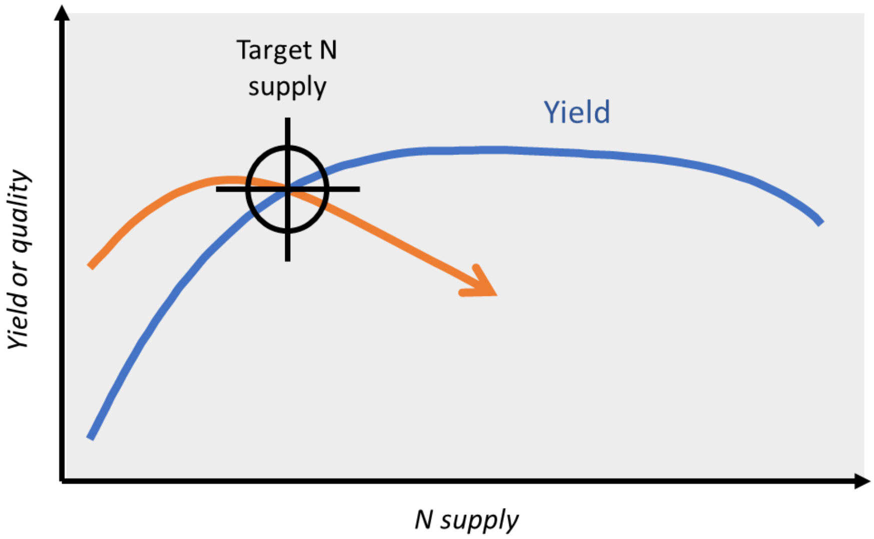


**Figure 3**. *Diagrammatic model showing the influence of N supply on the balance between yield and fruit quality [after Wiesler (2012)].*

Increasing concentrations of avocado fruit N have been linked to greater susceptibility to postharvest rots (Willingham *et al.*, 2006, Willingham *et al.*, 2001, Marques *et al.*, 2003, Whiley, 2013), vascular browning and leaching (Whiley, 2013, Marques *et al.*, 2003) and, in many instances, diffuse flesh discolouration (Marques *et al.*, 2003, Koen *et al.*, 1990, Snijder *et al.*, 2002, Van Rooyen & Bower, 2005). Conversely, Whiley (2013) reported negative correlations between fruit N concentration and diffuse flesh discoloration across multiple sites and seasons in Australia.

Reported concentrations of N in 'Hass' avocado fruit range from 0.5-1.7% DW in the flesh (Appendix B) and 0.8-1.4% DW in the peel (Appendix C). A similar flesh N range of 0.5-1.7% DW has also been reported for 'Pinkerton' fruit (Van Rooyen & Bower, 2005). Maintaining flesh N concentrations <1.7% in the mid-stages of fruit development in summer and <1.0% DW in the months leading up to harvest was recommended to minimise the risk of 'Pinkerton' fruit developing diffuse flesh discoloration after

[b]*Colletotrichum gloeosporioides* is now considered to be a species complex, which includes several individual species known to be associated with body rots (anthracnose) in avocado.

cold storage in South Africa (Kruger *et al.*, 2004). These threshold values were considered applicable to other cultivars subject to temporal adjustment for their different cropping times.

Other recommendations pertain to leaf concentrations, which are arguably proportionate to concentrations in the fruit (Arpaia *et al.*, 1996). For 'Hass', 'Pinkerton' and 'Fuerte' cultivars, "optimal" leaf N concentrations of 2.0, 2.3 and 1.7%, respectively, have been suggested for South African growing regions (Snijder & Stassen, 2000). These values reflect purported differing N requirements of each cultivar. For example, 'Hass' is generally less vigorous than 'Fuerte' and so requires more N to produce adequate leaf surface area to achieve reasonable fruit size (Wolstenholme, 2004). In Australia, recommended leaf N concentrations for fruit-bearing 'Hass' trees are 2.2-2.6% DW. A slightly lower range of 2.0-2.4% DW is recommended for 'Fuerte' and 'Sharwil' (Avocados Australia Limited, 2020).

## 3.3 Potassium

Potassium contributes to the osmotic regulation of cells (Hawkesford *et al.*, 2012), which is important for stomatal function and cell expansion, including fruit growth. Also, K supply to deficient plants increases pest and disease resistance (Huber *et al.*, 2012). However, Hawkesford *et al.* (2012) warned that increasing K supply beyond the minimum needs of the plant can result in 'luxury consumption' of this nutrient and possibly lead to K-induced deficiencies of Ca and Mg.

In avocado, high fruit K concentration has been linked with increased diffuse discolouration (Hofman *et al.*, 2005, Hofman *et al.*, 2002, Koen *et al.*, 1990), increased body rot severity (Hofman *et al.*, 2002, Marques *et al.*, 2006, Willingham *et al.*, 2006) and decreased ripening time (Hofman *et al.*, 2002). These influences on fruit quality are believed to stem primarily from the antagonistic effect that K has on uptake of other cations, particularly Ca, by the fruit (Hofman *et al.*, 2005).

Increasing K supply can improve fruit size in K deficient 'Hass' trees (Hermoso *et al.*, 2005). However, there may be questionable (Lahav *et al*., 1976) or no (Hermoso *et al*., 2005) such effect on fruit size in trees with adequate K status. Furthermore, K over-fertilisation may increase the risk of reducing yield and promoting alternate bearing (Crowley *et al.*, 2016).

Potassium is transported in both the xylem and phloem, the latter which allows it to readily translocate between tissues (Hawkesford *et al.*, 2012). The high mobility means that leaf K concentrations are generally a good indicator of fruit K concentrations (Willingham *et al.*, 2006). In Australia, optimal leaf K for 'Hass' is considered to be 0.75-2.0% (Avocados Australia Limited, 2020). However, modelling of data from Californian 'Hass' orchards indicated that optimum leaf K for high-yielding trees is 0.8% and that yield potential is suppressed above 1% leaf K (Crowley *et al.*, 2016). This has led to speculation that some Australian growers may be over-supplying K (Newett, 2018).

## 3.4 Magnesium

Correlations between fruit Mg concentrations and avocado quality tend to be inconsistent and, in some cases, contradictory. Postharvest body rots and stem end rot have been reported to have both positive and negative associations with fruit Mg concentration (Whiley, 2013, Hofman *et al.*, 2002, Marques *et al.*, 2006, Willingham *et al.*, 2006). Increasing fruit Mg concentrations have been linked with greater severity of discrete patches, but lower severity of diffuse flesh discolouration and vascular leaching (Whiley, 2013, Hofman *et al.*, 2002). Attention has been given to the balance between Mg, Ca and K cations in the fruit, as this seems to have a stronger association to avocado fruit quality than Mg alone (Section 3.8.2).

## 3.5 Boron

Increasing flesh B concentrations in 'Hass' fruit have been correlated to lower incidence and severity of diffuse flesh discolouration and vascular browning, as well as lower severity of body rots (Marques *et al.*, 2003). 'Pinkerton' fruit showed a decrease in flesh B concentration during the harvest season, which coincided with increased severity of diffuse flesh discolouration (Van Rooyen & Bower, 2005). Post-storage development of a localised flesh browning disorder referred to as 'endocarp black spot' was greatest in 'Hass' fruit from B deficient trees, and gradually declined as the rate of B fertilisation increased (Smith, 2004). This defect occurred near the top of the seed cavity (viz., stem end), the region of the fruit which inherently contains the lowest B concentration (Haas, 1943). Overcoming B deficiency in 'Hass' trees was also shown to increase fruit size by 13-18%, but had no effect on fruit number or total yield per tree (Smith, 2004).

Boron strengthens cells by cross-linking pectic substances in the cell wall (Ryden *et al.*, 2003) and acting as a bridge between the cell wall and membrane (Voxeur & Fry, 2014). Increased B concentration in apple fruit has been linked with lower electrolyte leakage (Xuan *et al.*, 2001), suggesting that B is also important for membrane stability. In other crops, B deficient tissues have greater polyphenol oxidase (PPO) activity and accumulate more phenolic compounds, the substrates for PPO-mediated browning reactions (Cakmak & Romheld, 1997, Mondy & Munshi, 1993, Perkins & Aronoff, 1956, Watanabe *et al.*, 1964). This biochemistry may contribute to the B-related physiological browning disorders reported above for avocado.

Mobility of B between plant tissues is species-dependent (Broadley *et al.*, 2012). The distribution of B in avocado plant tissues is indicative of a B mobile species (Smith, 2004). Furthermore, translocation of B from mature leaves to flowers and young leaves has been demonstrated in avocado (Minchin *et al.*, 2012, Coetzer *et al.*, 1993). Findings suggest that B can move through phloem vessels by forming a complex with perseitol, a C7 sugar alcohol found in avocado phloem sap (Minchin *et al.*, 2012). Hence, factors that influence the concentration and movement of perseitol in the phloem may also impact B concentrations in avocado fruit.

Boron concentrations in 'Hass' avocado peel correlate well with leaf B concentrations (Smith, 2004), as would be expected for a phloem-mobile nutrient. Smith (2004) reported a critical concentration of 46 mg/kg in summer flush leaves was required to achieve 90% maximum fruit size. This value corresponds with the 40-60 mg/kg optimum range recommended by AAL (Avocados Australia Limited, 2020).

## 3.6 Silicon

Although Si is not an essential plant nutrient, its presence has been shown to enhance mechanical strength of fruit tissues (Marodin *et al.*, 2016, Zhang *et al.*, 2017, Dehghanipoodeh *et al.*, 2016), as well as to activate plant defences against insect and pathogen attack (Islam *et al.*, 2020). Silicon may also have direct fungicidal effect against causal agents of body and stem end rots in avocado, at least in laboratory culture (Bekker *et al.*, 2006). Australian research on 'Hass' avocado found that soluble Si trunk injection at 8 weeks prior to harvest gave 80% reduction in the severity of postharvest body rots in the fruit (Anderson *et al.*, 2004). It was later shown that trunk injection of 1000 or 2000 ppm potassium silicate during early fruit development at 28 weeks before harvest reduced the incidence of postharvest body rots in 'Hass' fruit by at least 40% (Anderson *et al.*, 2005). However, Dann and Le (2017) found no such reduction in body rot development when Si was applied to trees as a foliar spray, soil drench or trunk injection. Slight reduction in stem end rot severity in response to soil drenching was reported, but this response was not observed in the following season. In a South African study, 'Hass' peel or flesh Si concentrations did not increase in response to repeated soil drenching with soluble Si (Kaluwa *et al.*, 2010).

## 3.7 ZINC

'Fuerte' avocado fruits displaying pulp spot were found to contain lower Ca and Zn concentrations than unaffected fruit, leading to speculation that Zn may have a role in maintaining postharvest quality (Vorster & Bezuidenhout, 1988). However, no further research appears to have been conducted to confirm the contribution of low Zn to pulp spot. Flesh Zn levels in 'Hass' avocados did not correlate with severities of body rots, stem end rot, diffuse discolouration and vascular browning (Marques *et al.*, 2006).

## 3.8 NUTRIENT INTERACTIONS

### 3.8.1 Calcium and nitrogen

In many instances, the N/Ca ratio in avocado fruit has proven to be a better indicator of postharvest quality than individual nutrient concentrations. For example, South African 'Pinkerton' fruit sourced from areas historically considered "high risk" in terms of diffuse flesh discoloration consistently had higher N/Ca ratios, but did not necessarily have lower Ca concentrations than fruit from "low risk" areas (Van Rooyen & Bower, 2005). Development of postharvest body rots in 'Hass' fruit has also been more consistently correlated with N/Ca ratio than with Ca concentration alone (Whiley, 2013, Willingham *et al.*, 2006, Joyce, 2018).

In Australia, N/Ca ratios ranging from 21-57 in the flesh (Appendix B) and 9-47 in the peel (Appendix C) have been reported for 'Hass'. Similar ratios have been found elsewhere in the world, with one study reporting a range of 8-60 with an average of 21 for 'Hass' fruit harvested from 42 orchards in central Chile over three consecutive seasons (Rivera *et al.*, 2017).

To minimise the risk of 'Pinkerton' fruit developing diffuse flesh discoloration after cold storage in South Africa, Kruger *et al.* (2001) recommended that the flesh in May at around harvest time contain >300 ppm Ca for every 1% N, equivalent to a N/Ca ratio of <33 (Sippel *et al.*, 1995)[c]. This threshold ratio also appears to be relevant for disease susceptibility. Studies on 'Hass' showed substantial development of postharvest body rots in fruit with flesh N/Ca ratios of 40-45 at harvest, but little or no body rot development when ratios were 33 or lower (Figure 44) (Marques *et al.*, 2003, Joyce, 2018). These findings are similar to those for apple, where a low N/Ca ratio of 10 was reported to indicate good storability whereas a ratio above 30 was associated with premature senescence and other disorders (Musacchi & Serra, 2018).

[c] Ratio calculated using N and Ca concentrations expressed in mg/kg, consistent with other N/Ca ratios reported in the literature. On a molar basis, this N/Ca ratio is 95.


**Figure 4**. *Body rot expression in 'Hass' avocado fruit at soft-ripe stage. Fruit were harvested on the same day from two orchards in Central Queensland and exposed to the same postharvest conditions. No fruit from the first orchard (left) developed body rots (0% incidence), whereas all fruit from the second orchard (right) developed body rots (100% incidence). After Joyce (2018).*

#### 3.8.2 Calcium and other cations

The balance of cations in avocado fruit, particularly the ratio of (Ca+Mg)/K, has been negatively correlated with body rots (Whiley, 2013, Everett *et al.*, 2007, Hofman *et al.*, 2002, Willingham *et al.*, 2006), stem end rot (Whiley, 2013, Willingham *et al.*, 2006), vascular browning and leaching (Whiley, 2013) and discrete patches (Whiley, 2013). Researchers in New Zealand recommended increasing fruit (Ca+Mg)/K ratio to >0.065 to reduce development of postharvest body rots in 'Hass' fruit (Everett *et al.*, 2007).

Reasons for this relationship between cation balance and fruit quality are unclear. One proposition is that K and Mg compete with Ca for binding sites on the plasma membrane[d], potentially disrupting normal membrane function and causing electrolyte leakage (Schonherr & Bukovac, 1973). Another possibility is that reducing the K/Ca ratio can increase the ability of cells to scavenge reactive oxygen species (ROS) and thereby result in less browning (Guo *et al.*, 2017). However, this finding was for Ca deficient cotton fibre cells grown under *in vitro* conditions and whether similar responses occur in fruit cells is undetermined.

# 4 PRE-HARVEST FACTORS INFLUENCING FRUIT NUTRIENT STATUS

## 4.1 GENOTYPE

#### 4.1.1 Scion cultivar

Fruit quality is strongly influenced by cultivar. Varietal differences for avocado have been reported in quality traits that include browning potential (Kahn, 1975, Kahn, 1977, Golan *et al.*, 1977) and postharvest disease susceptibility (Prusky *et al.*, 1988). However, little is known of cultivar-related effects on fruit mineral nutrient status. At a site near Pietermaritzburg in South Africa, 'Hass' fruit harvested from vigorous trees grown on West Indian seedling rootstock contained almost twice the Ca concentration of 'Fuerte' fruit from vigorous trees on the same site and also on West Indian seedling rootstock (Witney *et al.*, 1990a). The 'Fuerte' trees were larger, with larger leaves and a denser canopy, than the 'Hass' trees. These tree and canopy structural differences may have resulted in less Ca being allocated to the 'Fuerte' fruit. Flowering and early fruit development in 'Fuerte'

[d] The plasma membrane is the bounding plant cell membrane between the surrounding cell wall and the enclosed cell solution and sub-cellular organelles.

coincides with a vigorous vegetative spring flush (Cutting *et al.*, 1992), which may also have contributed to the low fruit Ca concentrations in this cultivar.

In Walkamin, Australia, and irrespective of rootstock or season, 'Shepard' fruit had higher Ca and lower N/Ca levels than did 'Hass' fruit harvested from the same site (Whiley, 2013). N/Ca ratios of 9-16 and 19-34 were reported in 'Shepard' and 'Hass' fruit, respectively, although no statistical comparison was made. 'Shepard' is a semi-dwarf tree with a compact growth habit and tends to flower when the spring vegetative flush is well advanced (Crane *et al.*, 2013). The apparent ability of this cultivar to readily accumulate fruit Ca may possibly be a function of relatively low Ca demand from vegetative tissues during early fruit development.

### 4.1.2 Rootstock

In Australia, Guatemalan race rootstocks (viz., 'Anderson 8', 'Anderson 10' and 'SHSR-03') and the West Indian x Guatemalan race rootstock 'Velvick' tend to surpass Mexican race rootstocks (viz., 'Duke 6', 'Duke 7', 'Parida 1', 'Barr Duke' and 'Thomas') in terms of improving fruit mineral nutrient balance and reducing body rot severity in 'Hass' fruit. 'Hass' trees on clonal 'Velvick' rootstock produce fruit with lower N and higher Ca and B concentrations in the flesh than for trees on clonal 'Duke 7' rootstock (Marques *et al.*, 2003). Subsequent studies confirmed the positive influence of 'Velvick' rootstock on fruit mineral nutrient status, along with relative reduction in postharvest body rots (Willingham *et al.*, 2006, Whiley, 2013, Dann *et al.*, 2016). 'Hass' fruit peel contained higher Ca, lower N and lower K concentrations when grafted onto 'Velvick' as compared to 'Duke 6' rootstock (Willingham *et al.*, 2006). However, the differences diminished over four consecutive seasons and were not detected in the fourth season of the study. In a 3-year study, 'Anderson 8' and 'Anderson 10' rootstocks produced 'Hass' fruit with lower N/Ca, higher (Ca+Mg)/K and lower body rot severity than did 'Parida 1' rootstock (Willingham *et al.*, 2006). However, these differences were detected only in the first season, and a better balance between vegetative and reproductive growth in 'Parida 1' in the latter two seasons was considered the likely reason.

In another Australian study spanning five seasons and four sites, Whiley (2013) found that 'Hass' and 'Shepard' trees on 'Velvick', 'Anderson 10' and 'SHSR-03' rootstocks generally produced fruit with better quality, which was linked to low N and high Ca concentrations in the fruit peel. In contrast, Mexican race rootstocks 'Barr Duke', 'Duke 7' and 'Thomas' were associated with relatively poor 'Hass' and 'Shepard' fruit quality. The quality parameters assessed included postharvest rots and physiological browning disorders.

Poor fruit quality associated with Mexican rootstocks is possibly due to inefficient translocation of mineral nutrients across the graft union. A comparison of leaf nutrients in potted nursery trees after fertilising found higher leaf concentrations of Ca, B, Mg and Mn in un-grafted 'Zutano' trees than in 'Hass' scion grafted onto 'Zutano' rootstock (Dann, 2016). Differences in leaf nutrient concentrations were not, however, observed between grafted and un-grafted 'Velvick' (predominantly West Indian) trees. There have been no studies to investigate the effect of grafting on nutrient uptake in mature avocado trees, although a recent study has identified notable differences in the structural characteristics of xylem tissue between different cultivars and races of avocado (Beier *et al*., 2020). Further investigation of these findings in relation to nutrient translocation would be of great value.

In the study of Whiley (2013), rootstock effects on fruit mineral nutrients appeared to be overshadowed by season-to-season and site-to-site variability. However, these factors were not statistically analysed. Confounding influences of site and season on rootstock performance were also reported by Dixon *et al.* (2007a). They concluded that "other as yet unknown orchard factors" play a greater role in determining final fruit quality than rootstock.

## 4.2 ENVIRONMENT

### 4.2.1 Edaphic factors

#### *4.2.1.1 Soil texture*

The effective supply of key nutrients to meet crop demand for growth depends not only on nutrient supply, but also on nutrient storage and accessibility by plant roots in the soil. Avocado orchards in Australia are predominantly located on free draining soil types (Whiley, 2000), which is important to help manage Phytophthora root rot . Wolstenholme (2013) observed that most Australian 'prime' avocado soils (e.g. krasnozems) have a low cation exchange capacity (CEC) of between 2-20 cmol/kg, and that other major soils on which avocados are grown (e.g., sandy loams) have even lower CEC due to a combination of coarse texture and low charge mineralogy. Hence, free draining soils in avocado production come at the cost of inherently low CEC and relatively high potential for leaching of soil-applied nutrients.

Soil texture also affects nutrient uptake by the plant. Young avocado trees grown in clay soils accumulated similar amounts of K, but only around half the Ca, of those grown in sandy loam or sandy soils (Bonomelli *et al.*, 2019). Despite soil Ca concentrations being adequate, Ca uptake was impeded in clay soil by poor root growth and reduced xylem sap flow.

#### *4.2.1.2 Soil water*

Avocado trees are sensitive to overly dry or overly wet soil (Schaffer *et al.*, 2013). Trees initially respond in both dry and waterlogged soils by closing their stomata (Neuhaus *et al.*, 2007, Ploetz & Schaffer, 1987). In turn, this restricts water and nutrient flow from roots to shoots. Stomatal conductance can be slow to recover in drought-stressed trees once well-watered conditions return (Sterne *et al.*, 1977). An extended period of water deficit stress induced formation of tyloses. Tyloses plug xylem vessel cavities to result in long-term disruption of xylem sap flow in 'Hass' trees (Neuhaus *et al.*, 2007). Tyloses persisted in the trunk beyond 84 d after watering was reinstated.

In addition to stomatal closure, waterlogging aids the spread of Phytophthora root rot and also reduces soil aeration, causing root hypoxia (Menge & Ploetz, 2003). The resultant root damage further impedes nutrient uptake (Broadbent *et al.*, 1989). Despite reduced uptake by the plant, fruit Ca concentrations can be higher in avocado trees with moderate Phytophthora root rot infection than in healthy trees (Willingham *et al.*, 2004, Witney *et al.*, 1990a). Healthy trees produce larger fruit with relatively more diluted fruit Ca. Also, greater vegetative vigour in healthy trees diverts Ca away from the fruit. However, Phytophthora root rot results in other negative effects, like diminished fruit number and size as well as increased incidence of sunburn and pepper spot.

Maintaining soil moisture within an optimal range has documented benefits of improved yield and reduced alternate bearing in avocado (Silber *et al.*, 2012, Silber *et al.*, 2018, Silber *et al.*, 2019, Lahav *et al.*, 2013). Effects on fruit nutrient status are less clear, with inconsistent results from irrigation studies (Section 4.3.2).

#### *4.2.1.3 Soil organic matter*

Improvements to soil health and fertility from the regular maintenance of soil organic matter (OM) in agricultural production systems are established (Price, 2006, Hall, 2008). Wolstenholme (2013) affirmed that a key aspect of sustainable management of major avocado production soils is maintenance of OM.

Moore-Gordon *et al*. (Moore-Gordon *et al.*, 1996, Moore-Gordon *et al.*, 1997) and Wolstenholme *et al.* (1997) highlight the virtues of OM additions in the form of mulches. Addition of mulch beneath orchard trees can improve crop yields through various mechanisms (Wolstenholme *et al.*, 1997, Whiley *et al.*, 2013). Benefits can arise from enhanced soil moisture availability, which directly links to the supply of critical nutrients for plant uptake when needed, and improvement in CEC, which leads to the retention and availability of nutrients. Moreover, a soil environment where soil biology flourishes has pest and disease suppression outcomes, such as suppression of *P. cinnamomi* (Dann *et al.*, 2013, Moore-Gordon *et al.*, 1997, Wolstenholme & Sheard, 2010).

However and to date, studies qualifying and quantifying direct improvements to soil water and nutrient availability from mulch and organic amendments for avocado are relatively few (Whiley *et al.*, 2013). As yet, there is a relative dearth of definitive published studies linking soil OM/mulching to enhanced fruit quality in terms of postharvest robustness.

### 4.2.2 Ambient factors

#### *4.2.2.1 Atmospheric temperature and relative humidity*

From a fruit Ca perspective, the most important climate factors are likely those that influence transpiration rate. High temperature and/or low relative humidity generate high evaporative demands. This is best characterised mechanistically as vapour pressure deficit (VPD). High VPD favours diffusion of water vapour out of and away from the leaf surface into the air. Also, the water vapour efflux rate can rise under increasingly windy conditions. At low VPD, there is less difference in water vapour concentration between leaf and air, giving low transpiration rates in avocado trees (Clearwater *et al.*, 2009).

Avocado trees respond to increasing VPD by closing their stomata (Whiley *et al.*, 1988, Scholefield *et al.*, 1980, Clearwater *et al.*, 2009) to limit transpiration. Hence, there is potentially a putative optimum VPD range for Ca accumulation. In kiwifruit, fruit Ca accumulation tended to increase linearly in response to transpiration rate (Montanaro *et al.*, 2015). However, the relationship broke down at very low (<0.5 kPa) VPD. Nevertheless, limited Ca uptake did occur under these conditions.

#### *4.2.2.2 Solar radiation*

As opposed to being shaded by the canopy, avocado fruit exposed to direct sunlight took longer to ripen and develop body rots (Woolf *et al.*, 1999, Woolf *et al.*, 2000). Moreover, they had relatively greater tolerance to postharvest chilling and hot water treatments. The tolerance of chilling and heat was generally more pronounced for the sun-exposed than for the shaded side of the fruit. Maintenance of high antifungal diene concentrations in the flesh during ripening was considered responsible for relatively less disease on sun-exposed fruit (Woolf *et al.*, 2000). High skin and flesh temperatures during sun exposure were considered to also enhance tolerance of thermal damage (Woolf *et al.*, 1999). Another possibility is that sun exposure promoted uptake and movement of Ca into the fruit. Boyd *et al.* (2007) reported a 16% increase in Ca in sun-exposed over shaded sides of immature 'Hass' fruit.

## 4.3 MANAGEMENT PRACTICES

### 4.3.1 Nutrient application

#### *4.3.1.1 Calcium*

Increasing rates of soil-applied Ca in various forms typically provide little or no increase in avocado fruit Ca concentrations (du Plessis & Koen, 1987, Hofman, 2006). Microfine gypsum application increased Ca concentrations in the soil solution and xylem sap of 'Hass' avocado trees. However, these increases did not carry through to the leaves or fruit (Hofman, 2006). This suggests governing importance of other factors for Ca transport and distribution within the tree. Gypsum does, however, act as a mild fungicide for Phytophthora root rot when applied annually at a low rate (Blakey and Wolstenholme, 2014). As such this may have an indirect effect of increasing Ca uptake through improved root health in orchards where Phytophthora root rot is a problem.

The availability of soil-applied Ca is linked with soil pH (Section 3.1). Most Ca is applied in the form of lime or dolomite. This is except when soil pH is already regarded within recommended guidelines or too high, in which case gypsum is applied (Newett, 2018). Some Ca is supplied as a component of super phosphate fertiliser and also as calcium nitrate. Soil applications of calcium thiosulphate (Newett, 2018) and/or calcium nitrate after fruit set are used by some growers in the belief that these more soluble sources of calcium will produce better results. However, this has yet to be investigated.

Ca application directly onto the canopy has been investigated as an alternative means of getting Ca into fruit, but results have been inconsistent. Canopy sprays of calcium nitrate had no effect on fruit Ca concentrations when applied within 4 months (Solis-Fraire *et al.*, 1998) or 6 months (Veldman, 1983) of harvest. Earlier applications commencing 9 months before harvest increased Ca concentrations in the peel and flesh, as well as reduced chilling injury in 'Fuerte' fruit (Saucedo-Hernández *et al.*, 2003). Canopy application of Calcimax® (8% chelated Ca and 0.5% B) at 3 weeks after fruit set reduced pulp spot and vascular browning incidence in 'Edranol' fruit (Penter & Stassen, 1999). However, the increase in fruit Ca concentration was not significant. Young fruitlets have a thin cuticle and wax layer which may allow greater Ca uptake as compared with more mature fruit. Ca absorption by leaves is unlikely to have any bearing on fruit Ca concentrations due to the poor mobility of Ca between plant tissues. Other pre-harvest factors may overshadow any potential benefits that might be derived from Ca application to the canopy. For example, early season Ca sprays substantially reduced grey pulp and anthracnose in 'Pinkerton' fruit during a high crop load 'on' year (Penter & Stassen, 2000), but not in the following 'off' year when high fruit N was an issue (Penter *et al.*, 2001). Hence, Ca application to the canopy may not be a reliable nor cost-effective approach for improving fruit nutrient status.

Given the known benefits of increasing fruit Ca concentration and aforementioned limitations associated with pre-harvest Ca application, some studies have investigated postharvest Ca application for improved fruit quality and shelf-life extension in avocado. Postharvest vacuum (viz., partial pressure) infiltration of avocado fruit with $CaSO_4$ (Tingwa & Young, 1974) or $CaCl_2$ (Wills & Sirivatanapa, 1988, Yuen *et al.*, 1994, Eaks, 1985, Wickramasinghe *et al.*, 2013, Wills & Tirmazi, 1982, Tingwa & Young, 1974) resulted in firmer fruit and delayed fruit ripening. In one study, 'Fuerte' and 'Hass' avocado fruit vacuum infiltrated with 0.2 M $CaCl_2$ for 1 minute had reduced diffuse discolouration as compared to untreated fruit (Eaks, 1985). However, reductions in external fruit quality in both cultivars were noted as a result of the treatment. Fruit dipped in 0.2 M $CaCl_2$ for 15 minutes without vacuum infiltration showed no delayed ripening or quality improvements. Postharvest Ca application was not considered practical due the need to additionally vacuum infiltrate fruit and the potentially negative impacts on external appearance. In terms of fruit Ca concentration following postharvest infiltration treatment, Wills and Tirmazi (1982) reported a 1.5 fold increase in peel Ca concentration from 0.015 to 0.023% FW in 'Hass' fruit infiltrated with 4% $CaCl_2$ as compared to fruit infiltrated with water. A similar, but slightly lower, increase (1.3 fold) was seen in flesh Ca concentration following infiltration with 4% $CaCl_2$.

Aimed at a safer alternative, postharvest Ca treatment was adapted in South Africa based on organically complexed Ca products, including Calcimax®. This compound was formulated specifically for improved Ca uptake/translocation and reduced injury to fruit (Penter & Stassen, 2000) as opposed to the inorganic Ca sources of earlier studies. Harvested 'Pinkerton' avocados were immersed in solutions of a range of different complexed Ca products without vacuum infiltration for 10 minutes and then ripened for assessment of quality parameters. Although the efficacy of individual products varied, the treatments at least halved the incidence of grey pulp and generally increased fruit firmness. Basfoliar Ca® more than halved anthracnose incidence and also reduced lenticel damage from ~29% to ~4%.

#### *4.3.1.2 Nitrogen*

Avocado trees are supplied with N in various inorganic forms, including urea, ammonium nitrate, calcium nitrate, ammonium sulphate, ammonium di-phosphate and potassium nitrate (Lahav *et al.*, 2013) applied individually or as part of a compound fertiliser blend (Newett, 2018). Nitrogen is also applied in the form of manure, compost and mulch. However, nutrient release from these forms can be variable. From a fruit quality perspective, there is concern that ammonium ($NH^{4+}$), being a cation, may compete with Ca for uptake by the roots and ultimately reduce fruit Ca concentrations. This has been reported for other fruit crops (Sokri *et al.*, 2015, Tabatabaei *et al.*, 2006). However, research by Willingham *et al.* (2006) found that application of high or low rates of nitrate or ammonium fertiliser to 'Hass' trees produced fruit with similar Ca concentrations.

Timing of N application can influence the final N concentration in avocado fruit. N concentrations in 'Hass' fruit flesh just before harvest were ~1.4% DW when N fertilisation was commenced after fruitlet formation as compared with ~2.0% DW when N fertilisation was commenced during flowering and ~1.9% DW when N was supplied continuously (Silber *et al.*, 2018). Avoiding large applications of N before and during flowering would, therefore, seem to favour robust fruit production. However, a double dose of N at flowering increased yields Californian 'Hass' trees (Lovatt, 2001).

The chosen N fertilisation strategy needs to provide sufficient N to support flowering, fruit set and fruit retention, without creating excessive vegetative vigour (Wolstenholme, 2004, Newett, 2018). Tree demand for N will depend on cultivar, climate and pruning practice. In warmer climates, flowering commences after the previous season's fruit have been harvested (Newett & Dixon, 2009). However, trees grown in cooler climates often have overlapping crop cycles, and managing the N demands of both can be challenging. Differing N requirements of trees during 'on' and 'off' flowering years also needs to be taken into consideration.

Site aspects, including soil texture, slope, rainfall and irrigation, will determine how readily N is leached away from the root zone. Recent research at a commercial avocado orchard in Queensland, Australia revealed that nitrate concentrations in soil solution can vary by more than 500 mg/L in the upper 0.3 m zone of maximum root occupation within the one block of trees (Stuart Irvine-Brown, pers. comm.). The differences were attributed to variability in nutrient uptake, drainage and soil water movement, showing the need for more spatially precise management of soil N supply.

Salinity can add another layer of complexity. Avocado trees are highly sensitive to chloride and application of nitrate N alleviates Cl toxicity symptoms by reducing Cl uptake by the roots (Bar *et al.*, 1987).

The dilemma of N nutrition in avocado has been recognised for many years as summarised by Wolstenholme (2004) as *"What is often not fully appreciated by growers and advisers is that N management strategies must be tailored to specific environmental and management conditions, to achieve the same desired effect of a balance between vegetative vigour and yield (and fruit quality)."*

#### *4.3.1.3 Potassium*

Oversupply of K in the soil has been shown to limit Ca and Mg uptake by 'Hass' avocado trees and duly reduce concentrations of these nutrients in the fruit flesh, resulting in increased diffuse discolouration (Hofman *et al.*, 2005). .

Given that recommended leaf K concentrations in Australia are higher than elsewhere in the world, Australian avocado growers may inadvertently apply too much K (Newett, 2018). This, along with the antagonistic effect of K on Ca uptake, has led to recommendations that K fertilisation of avocado trees be reduced overall, or at least during early fruit development when fruit Ca demand is highest (Newett, 2018, Rosecrance *et al.*, 2012, Hofman *et al.*, 2005). Potassium accumulates in avocado fruit mostly during the later stages of development (Rosecrance *et al.*, 2012, Silber *et al.*, 2018), and so delaying K application until this time bears logic.

#### *4.3.1.4 Boron*

Despite many studies on B nutrition of avocado trees (Lahav *et al.*, 2013), most have focused on improving fruit set and yield with little focus on fruit B concentrations. Soil-applied B has been shown to increase B concentrations in the peel and seed, but not in the flesh, of 'Hass' fruit, and to reduce the incidence of endocarp black spot (Smith, 2004). Foliar B application at rates of 1.2 or 1.6 g/L increased cell wall thickness in avocado buds, leading to speculation of better resistance to pathogen attack (González-Gervacio *et al.*, 2019).

In other crops, including apple (Dixon *et al.*, 1973), pear (Wojcik & Wojcik, 2003) and tomato (Islam *et al.*, 2016), foliar B application has been shown to enhance fruit Ca concentrations. Soil-applied B treatments by Smith (2004) had no effect on avocado fruit Ca concentrations. Whether foliar application of B to avocado trees increases fruit Ca concentrations may bear investigation.

Both soil and foliar B application may affect avocado nutrition. Given the role of B in pectin binding of the primary cell wall, B is required for all the growing points of the tree, including shoots, roots and young fruit. Foliar applications are considered an effective means of supplying B to reproductive tissues, as B can be remobilised from mature leaves to inflorescences (Coetzer *et al.*, 1993). In B-deficient 'Hass' trees, spraying Solubor® onto fully developed panicles at the beginning of anthesis caused a 42 % increase in fruit set (Smith, 2004). Avocado roots exhibit poor B uptake from the soil and restricted B translocation to aerial tissues (Whiley *et al.*, 1996, Coetzer *et al.*, 1993). However, soil application appears necessary to overcome chronic B deficiency commonly found in avocado orchards (Whiley *et al.*, 1996, Smith, 2004). The mobility of B through binding with sugar alcohols, such as perseitol, is based on demand for the sugar alcohols rather than demand for B. As such, supplementary soil B applications may be required when soil B levels are deficient to enable healthy root growth. Soil applications need to be carefully managed, as soil B concentrations can easily build up to levels toxic to avocado roots (Whiley *et al.*, 1996). Optimal soil B concentrations vary greatly depending on soil texture (Smith, 2004).

### 4.3.2 Irrigation

The importance of adequate soil moisture to assist nutrient uptake was introduced in Section 4.2.1. Both over- and under-irrigation can be detrimental to fruit quality (Bower *et al.*, 1989). 'Hass' trees irrigated when soil water tension at 300 mm depth reached -55 kPa had higher Ca concentrations in developing fruit 16 weeks after fruit set than was achieved with more (-35 kPa) or less (-80 kPa) frequent irrigation schedules (Bower *et al.*, 1989). Fruit from the -55 kPa treatment also had the lowest PPO enzyme activity, suggesting less browning potential (Kahn, 1975).

Irrigation at soil matric potentials of -20, -40 or -70 kPa produced no difference in fruit Ca concentrations at harvest (Vuthapanich, 2001). Similarly, irrigation based on 80, 100 or 120% evapotranspiration had no effect on fruit Ca concentrations (Arpaia & Eaks, 1990). However, fruit from the 80% treatment were less prone to internal breakdown upon storage as compared with the 100 or 120% treatments. For 'Hass' trees grown on sandy soil in Western Australia, withholding irrigation for an 8-month period between fruit drop and harvest did not affect fruit Ca, K or Mg concentrations as compared with daily irrigation and reduced fruit production for 2 years (Neuhaus *et al.*, 2009).

These conflicting results suggest involvement of other contributing factors. For example, periods of high environmental evaporative demand can induce stomatal closure even when soil water is adequate (Saucedo-Hernández *et al.*, 2003). Additionally, the extent to which irrigation alters the vegetative/reproductive balance will ultimately influence the amount of Ca distributed to the fruit.

#### 4.3.3 Canopy management

A balanced ratio of vegetative/reproductive growth is credited to enhance fruit quality. Avocado trees with low vegetative vigour and/or high crop load, such as during an "on" season or in response to mild Phytophthora root rot, tend to bear fruit with high Ca concentrations and few postharvest disorders (Willingham *et al.*, 2004, Witney *et al.*, 1990a, Blakey & Wolstenholme, 2014). Pruning to manipulate the vegetative/reproductive balance may have the same effect, if timed correctly (Leonardi, 2005). Pruning that limits vegetative growth at the critical time of fruit set and early fruit development has been shown to produce larger fruit, higher fruit Ca concentrations and fewer postharvest body rots, whilst still giving similar yields to unpruned trees (Cutting & Bower, 1992, Leonardi, 2005). However, pruning that stimulates vegetative regrowth at this critical time can have a negative impact on fruit quality. When vegetative regrowth after pruning coincided with reproductive growth, fruit from pruned as compared to unpruned trees contained less Ca and were more prone to body rots, stem end rots, skin spotting, discrete patches, vascular browning and diffuse discolouration (Leonardi, 2005). Hence, pruning can have a 'make or break' effect on fruit robustness and needs to be carefully timed. Pruning also impacts directly on disease development by removing sources of inoculum and increasing airflow and fungicide spray penetration within the tree canopy (Dann et al., 2013).

Paclobutrazol (PBZ) applied as a foliar spray suppresses vegetative growth and has been shown to increase fruit Ca concentrations and reduce body rot severity without sacrificing yield (Vuthapanich, 2001). Paclobutrazol foliar application also reduced the incidence of physiological disorders in 'Fuerte' fruit from treated as compared to untreated trees, but only during an "off" year (Kremer-Köhne *et al.*, 1991). In contrast, PBZ injection enhanced PPO activity in 'Hass' fruit (Cutting & Bower, 1992), which may increase the risk of postharvest physiological browning disorders. Wolstenholme and Whiley (1990) recognised that PBZ has a role to play in canopy management, but cautioned that it should only be used on vigorous healthy trees with well managed N concentrations.

#### 4.3.4 Compost and mulch application

Appropriate use of compost and mulch can improve avocado fruit size and total yield (Nzanza & Pieterse, 2013, Wolstenholme *et al.*, 1998, Moore-Gordon *et al.*, 1997, Ramírez-Gil *et al.*, 2017). However, few studies have investigated their effects on avocado fruit mineral nutrient status (Nzanza & Pieterse, 2013) and postharvest quality (Leonardi, 2005, Dixon *et al.*, 2007b). Compared with no mulching, a mulch of pine woodchip or pine bark applied to 'Hass' avocado trees at two Queensland sites in Childers and Bundaberg reduced the severity of diffuse flesh discolouration in the fruit after storage (Leonardi, 2005). Although fruit mineral status was not assessed, the high carbon (C) to N ratio of these mulch materials was believed to cause some N drawdown in the soil, which may have prevented excess N accumulation in the fruit.

A South African study found that mulching with composted eucalyptus woodchips increased K and P, but not Ca or Mg, 'Hass' fruit as compared with not mulching (Nzanza & Pieterse, 2013). The contribution to fruit K may have undesirable consequences for fruit quality. Newett (2018) recognised that mulch materials derived from grasses are generally high in K, and advised that mulch nutrient levels be taken into account when planning tree nutrition programmes.

Mulching may be of little benefit to fruit quality when applied to soils already rich in organic matter. A New Zealand study found that in such situations, postharvest development of body rots or stem end rot in 'Hass' fruit was unaffected by mulching with leaf litter, pine peelings or compost (Dixon *et al.*, 2007b).

# 5 MONITORING NUTRIENT STATUS IN AVOCADO

Assessing the prospect of production of robust fruit for quality to consumers requires regular and routine nutrient analysis. Monitoring soil nutrient levels is useful for testing if supply is prospectively adequate and for detecting potential cation imbalances that might restrict Ca uptake by roots. For mobile nutrients, such as N, K and B, leaf analysis is a generally useful indicator of expected concentrations in the fruit. However, this is probably not so for Ca, a key element of interest. Relatively immobile Ca may not partition uniformly between leaves and fruit. As leaves continue to accumulate calcium as they age and leaf Ca is more a reflection of leaf age than it is of fruit Ca concentration. Therefore, fruit tissue analysis is recommended for Ca.

### 5.1.1 Leaf analysis

Sampling mature leaves from the summer flush in autumn is recommended practice in Australia for monitoring avocado nutrient status (Avocados Australia Limited, 2020). Fruit set and early development have already occurred by this time (Newett & Dixon, 2009). Thus, any action to correct nutrient deficiencies or imbalances will benefit the following season's crop, but not the current crop. Sampling mature leaves from the spring flush in summer provides a second opportunity to assess and fine-tune nutrition programmes (Newett, 2018), and may offer better opportunity to influence fruit nutrient status. In both cases, selecting the most appropriate leaf material at the right time is critical as nutrient concentrations can change with leaf type, age and position on the tree (Lahav *et al.*, 1990).

### 5.1.2 Soil analysis

Soil analysis is generally recommended every second or third year and is best taken at the same time as leaf analysis so that results can be interpreted together. Soil analysis provides valuable information about soil chemistry and nutrient supply to the tree, often explaining why issues arise. However, it is important (Avocados Australia Limited, 2020) for: (i) ensuring nutrient supply is adequate, (ii) screening for potential issues, such as salt build up and toxic levels of elements like boron and manganese, (iii) checking soil pH, which influences availability of nutrients, and soil CEC, (iv) detecting cation imbalances, and (v) assisting with the interpretation of leaf analysis results. For example, excessive levels of phosphorus in the soil can impede the uptake of trace elements, such as zinc and iron (Simon Newett, pers. comm.).

### 5.1.3 Fruit analysis

Fruit nutrient analysis is not commonly used, but it is essential to determe fruit Ca concentrations and ratios with other nutrients. Sampling at harvest may help predict whether fruit can handle the rigours of storage and/or long supply chains. Sampling early provides some scope for correcting nutrient imbalances. Aimed to improve postharvest storage potential, Kruger *et al.* (2001) established target N/Ca ratios of 20, 25 and 33 for immature 'Pinkerton' fruit in each of the 3 months leading up to harvest in South Africa.

Both peel and flesh sampling have been used to characterise avocado fruit nutrient status. Each generates a different nutrient profile, with correlations between peel and flesh concentrations being reported for only six out of 14 mineral nutrients[e] analysed in 'Hass' fruit (Kämper *et al.*, 2020). Hence, it is important to consistently sample the same tissue type and establish optimum nutrient ranges for each.

The fruit sampling strategy should address the large variability in nutrient concentrations that can occur between trees (Marques *et al.*, 2006), between fruit from the same tree (Pedreschi *et al.*, 2014) and within the fruit itself (Boyd *et al.*, 2007). For mature fruit, plugs of tissue from the equatorial region provide good estimates of whole fruit nutrient concentrations (Boyd *et al.*, 2007). However, entire fruitlet sampling is recommended for immature fruit.

At farm level, one prospect for avocado fruit analysis is using relatively inexpensive ion-selective electrode(ISE) meters to measure nutrients in 'juice' pressed from the flesh of green mature fruit. The technique was tested to link Ca concentration with postharvest quality of 'Shepard' fruit from the Atherton Tableland in Australia (Ridgway & Wright, 2017). Juice Ca concentration in 'good quality' fruit (6.00 ppm) was significantly higher than that (1.29 ppm) in fruit from an orchard experiencing issues with rots, rapid breakdown and lenticel damage. Using a nitrate selective meter, no difference in juice nitrate-N concentrations was discerned between the samples. This prospective on-farm ISE nutrient diagnosis merits further testing.

Relatively novel portable X-ray fluorescence (XRF) technology may also represent a prospective tool for rapid non-destructive measurement of fruit mineral nutrient levels. Handheld XRF devices are currently used for on-site soil analysis of cations, including Ca, K, Mg and Na (Vanhoof *et al.*, 2019). Semi-quantitative analysis of Ca and K in intact apple and pear fruit has also been reported (Kalcsits, 2016). Current devices are expensive, but future advancements in the technology are likely to result in cost-effective models. Also, sharing and/or hiring of instruments is a way to spread or share cost.

Visible near-infrared (vis/NIR) hyperspectral image analysis of 'Hass' avocado fruit peel for commercial orchards in Childers, Queensland suggested that flesh B, Ca, K, Mg, Zn, iron (Fe) and sulphur (S) concentrations may be predicted from the images (Kämper *et al.*, 2020). As predictive models are refined and accuracy improves, vis/NIR hyperspectral imaging may become a useful tool for non-destructive assessment of key mineral nutrients associated with fruit quality.

### 5.1.4 Cauliflower stage inflorescence analysis

Californian research on 'Hass' trees showed that mineral nutrient concentrations in the cauliflower stage inflorescence (CSI) were a better predictor of yield than leaf nutrient concentrations (Campisi-Pinto *et al.*, 2017). Additionally, the cauliflower stage is easy to identify and collect, and so carries less risk of sampling the wrong tissue at the wrong time. Another advantage of CSI analysis is that it potentially allows time to correct nutrient imbalances before they can negatively impact yield, fruit size or quality. The technique merits further investigation.

[e] Correlations were found between peel and flesh concentrations of Ca, Na, Mn, B, P and Mg. No correlation was found for C, N, Al, Cu, Fe, K, S or Zn.

# 6 AVOCADO FRUIT ROBUSTNESS

In qualitative terms, robustness in avocado can be defined as the fruit's ability to withstand the rigours of postharvest handling to provide a quality product that maintains consumer satisfaction and drives repeat purchase. This characteristic is reflected in minimal development of postharvest diseases and disorders and maximal eating quality as perceived by consumers. Many postharvest quality defects encountered in avocado fruit have been linked to fruit mineral nutrient balance (Table 1). Key influencers of fruit robustness are depicted in Fig. 5. The complex interrelationships involved are detailed in Appendix D.

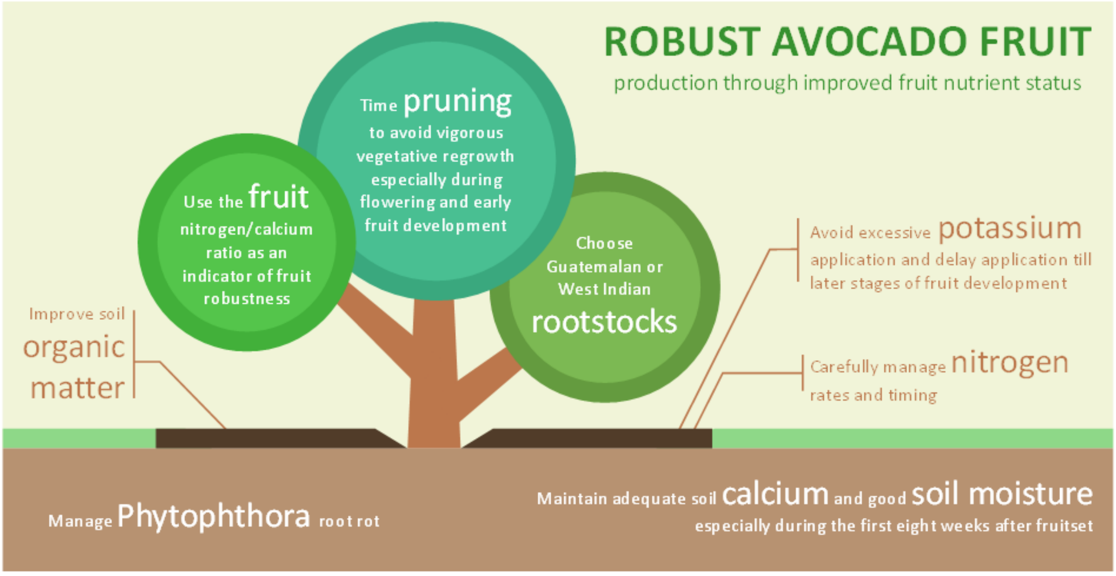


**Figure 5**. Preharvest factors for improving fruit quality, including through mineral nutrition.

The schematic (Fig. 5) depicts that relatively elevated fruit Ca in conjunction with relatively lowered fruit N, K and Mg lends to improved robustness. Pre-harvest factors that maintain transpiration and achieve balanced vegetative growth and crop load are likely give fruit relatively high in Ca (Appendix D). However, basal Ca supply and availability in the soil need to be sufficient and balanced with other cations so as to engender Ca uptake by roots. Healthy roots and adequate soil water in well aerated growth substrate are bases for adequate Ca uptake.

Soil health underpins and integrates many factors contributing to fruit robustness (Fig. 5, Appendix D). In line with the general principles and practices of sustainable agriculture, organic matter provided as mulch and compost improves soil structure, contributes to root system health and supports water-holding capacity, nutrient retention and biodiversity. Sustainable practices buffer extremes of soil temperature and water, Phytophthora root rot and climate variability and extremes.

# 7 CONCLUSION

Robustness of avocado fruit in terms of resistance to postharvest diseases and browning disorders is linked to mineral nutrient status. High Ca with low N, K and, possibly, Mg concentrations in fruit are consistently linked with better fruit quality. The ratio of fruit N/Ca concentrations is useful towards identifying fruit at risk of developing postharvest diseases and disorders. Increasing fruit B concentration is also important, despite there being fewer studies in this area.

Fruit Ca concentrations are highly variable and cannot be reliably manipulated through soil or foliar Ca application. Controlling vegetative vigour through thoughtfully timed pruning, N fertilisation and/or irrigation are relatively more agile approaches to achieving high fruit Ca. Success in this context depends also on environmental factors that are largely beyond grower's control; such as prolonged periods of high or low VPD during early fruit development. It is important to monitor fruit nutrient status and, based on key indices, especially N:Ca, channel relatively less robust fruit into short supply chains to market. Rapid nutrient analysis tools to better inform this decision process are becoming available, but require refinement and development for avocado.

More immediately, manipulation of fruit N rather than of fruit Ca may be easier to achieve because of N's greater mobility within plants. N fertilisation strategies should aim to limit fruit N uptake without compromising fruit set and retention. Nutrient monitoring is again pivotally important. However, fruit sampling is not essential because leaf analyses is temporally indicative of fruit N.

# 8 RECOMMENDATIONS

## 8.1 ACTIONABLE NOW

Based on evidence presented in this review, the following recommendations to improve fruit quality through mineral nutrition are made:

- **Provide adequate Ca to trees, especially during flowering, fruit set and early development.**
  Small relatively frequent doses applied to the soil can help to keep Ca in soil solution and the root zone. This may be most important on sandy soils or in areas of high rainfall. However, a readily available supply of Ca in the soil does not necessarily guarantee elevated concentrations in the fruit (Section 3.1). Other factors affect how much Ca is taken up by the tree and reaches the fruit (Fig. 2).

- **Do fruit tissue analysis as a relatively reliable indicator of fruit Ca concentrations.**
  Calcium is not distributed evenly between leaves and fruit. Also, once deposited, Ca cannot move from one organ to another. Thus, leaf Ca concentrations are not closely related to fruit Ca concentrations (Section 3.1). Fruit tissue analysis is the only sure way of determining fruit Ca concentration. Analysis of fruit N at the same time will allow the N/Ca ratio to be calculated. This ratio tends to be a better indicator of fruit robustness than fruit Ca concentration alone. Fruit with N/Ca ratios in the high 30's or above are at risk of postharvest quality defects developing (Section 3.8.1). Ideally, such fruit should not be placed into extended storage or subjected to long supply chains.

- **Ensure leaf nutrient concentrations for N and K do not exceed the optimum range.**
  Unlike Ca, leaf concentrations of N and K reflect concentrations in the fruit (Sections 3.2 and 3.3). For 'Hass', leaf concentrations should not exceed the optimum range of 2.2-2.6% N and 0.75-2.0% K. (N.B. Based on new research from California, possibly no more than 1% K). Monitoring of leaf

N and K throughout the season can allow for more timely adjustment of nutrient application rates and lessen the likelihood of fruit with poor nutrient balance.

- **Delay K application until latter stages of fruit development and only apply if needed.**

Ca and K compete for uptake by plant roots and so should ideally not be applied at the same time (Sections 3.3 and 4.3.1.3). It is better to apply these nutrients when the fruit demand for each is highest. For Ca, peak demand is higher during the early fruit growth stages, whereas demand for K is higher in latter fruit growth stages. Speculation has it that some Australian orchards may be over-supplying K, thus it may be prudent to check leaf K concentrations before applying more.

- **Achieve a good balance between vegetative growth and crop load.**

Excessive vegetative growth can divert Ca from developing fruit (Section 4.3.3). Canopy management through careful and appropriately timed PGR application, pruning, irrigation, and nutritional management may all help to control vegetative vigour and improve nutrient balance in the fruit. An important goal is that re-growth does not coincide with early fruit development.

- **Select appropriate rootstocks when establishing new plantings.**

Improved fruit quality and nutrient balance in 'Hass' and 'Shepard' fruit may be achieved by selecting rootstocks of Guatemalan or West Indian heritage over Mexican race rootstocks (Section 4.1.2). 'Velvick' is a West Indian x Guatemalan hybrid that has been shown to perform consistently well in this respect. Nonetheless and although rootstock is a potentially important influencer, site and season effects may have overriding influence on fruit mineral nutrient status and yield should not be unduly compromised.

## 8.2 AREAS FOR FUTURE RESEARCH

In no hierarchical order, research into the following areas is recommended focused on fruit quality related to fruit mineral nutrient status:

- **Mining big data sets to understand G x E x M interactions.**
  Re-appraisal of existing data sets in new and/or different ways could help to enable interpretation of and decision making from otherwise overwhelming complex interactions, such as of genotype, environment and management; Earlier Hort Innovation avocado projects may, for example, have generated rich data sets pertaining to fruit nutrient status and quality. "In the data era, you want to take the data, get insight from it, and make it actionable." (https://www.delltechnologies.com/en-us/perspectives/welcome-to-the-data-era/).

- **Characterising production environments and practices governing 'good' vs 'bad' fruit nutrient status.**
  Fruit nutrient data from orchards identified as producing fruit with superior or inferior postharvest quality could be related back to orchard activities and environment. Studies would cover multiple seasons and be informed by detailed production, management, and environmental records. Supporting leaf analysis data could be correlated to inform, for example, optimum leaf N and K guidelines. Acquiring data on fruit quality at retail level and subsequent trace-back to detailed orchard data could identify the key drivers for high quality fruit.

- **Irrigation management.**
  Maintaining soil moisture within an optimum range is important for nutrient availability, uptake and translocation (Section 4.2.1.2). However, evidence for irrigation effects on fruit nutrient status is conflicting (Section 4.3.2) and merit deeper investigation. Studies would qualify and quantify relationships between different irrigation regimes and vegetative/reproductive balance.

Sophisticated irrigation practices like partial root zone drying (PRD) and regulated deficit irrigation have been applied to enhance fruit robustness an lessen fruit disorders, such as Ca related bitter pit of apple fruit.

- **Wholistic approach to N management.**
  Relatively comprehensive studies on N management in avocado have been conducted. However, not in the context of Australian conditions (Section 4.3.1.2). It is recognised that N management is a complex issue requiring site-specific and season-specific adjustment. In this context, value is inherent in developing 'best bet' guidelines for Australian growers in climatically distinct sub-tropical to temperate regions. Towards optimising fruit mineral nutrient status without compromising yield, studies might consider (i) rates and timing of N application, as has been done for 'Hass' in California, (ii) dynamic contributions of compost and mulch to short, medium and long term N supply, (iii) sustained-release inorganic fertilisers and (v) nitrification inhibitors.

- **Compost and mulch application.**
  Benefits of compost and mulch on root health and Phytophthora root rot suppression are well documented and have engendered their widespread use in Australian avocado orchards (Section 4.3.4). However, the nature and composition of these organic materials is highly variable. As such, the magnitude and dynamics of their contribution to fruit nutrient status under Australian conditions is poorly understood. Important insight could be gained by comparing and contrasting different materials under a specific conditions. Also, mulch and compost options, including ratios, should be explored in conjunction with other orchard management practices towards an informed integrated approach to improving fruit nutrient status, as proposed above for N management.

- **Soil application of additional Ca at fruit set.**
  Applying relatively expensive highly soluble forms of Ca (e.g., calcium thiosulphate, calcium nitrate) at fruit set is sometimes practiced in Australia (Section 4.3.1.1.). Current understanding around Ca uptake and transport by avocado trees casts doubt on the efficacy of such treatments when soil Ca concentrations are often adequate. Whether and to what degree fruit Ca concentrations may be enhanced by this relatively high cost practice awaits determination.

- **Timing and type of fruit tissue sampling for nutrient analysis.**
  Fruit tissue analysis is typically conducted at harvest maturity and involves analysis of either the peel or flesh tissue. Good correlations exist between avocado peel and flesh Ca concentrations (Section 5.1.3). However, this is not necessarily the case for other nutrients. Also, tissue type which provides the best indicator of fruit nutrient status and robustness remains to be thoroughly investigated. Sampling reproductive tissue at an early phenological stages (e.g., cauliflower stage inflorescence; CSI) provides scope for timely intervention to address nutrient imbalance. Optimum nutrient concentration ranges need to be established for specific phenological stages. Limited work in this area was conducted in South Africa for 'Pinkerton', but not 'Hass', fruit.

- **Rapid diagnostic tools for monitoring fruit nutrient status.**
  Fruit nutrient analysis pertaining to critical imbalances (e.g., high N/Ca ratio) is currently costly, involving destructive sampling and typical turnaround times of a week or more. With Ca being a relatively reliable base measure of fruit robustness, merit lies in developing and optimising its cost effective rapid on-farm measurement, ideally along with the key co-determining nutrient N; viz., N/Ca ratio. More and more timely assessments could fine tune orchard management practices. Options currently in the offing that merit further investigation and adaption include ISE meters, XRF and Vis/NIR hyperspectral imaging (Section 5.1.3).

- **Plant growth regulators for canopy management.**
  PGRs use to control vegetative vigour is 'common practice' in Australia, and has been shown to promote Ca accumulation in avocado fruit when applied mid-anthesis as a single foliar spray (Section 4.3.3). Anecdotal reports suggest that growers are applying PGRs in multiple, low doses during the 12 weeks following fruit set. At present, effects of such applications on fruit nutrient status and ultimately fruit quality are unknown and so warrant investigation.

- **Susceptibility to flesh bruising.**
  Flesh bruising is a prevalent defect in Australian avocados at retail. However, its suspected relationship to fruit nutrient status is largely undefined. Preliminary research suggested bruise susceptibility in avocado fruit increases with decreasing flesh Ca concentration (Section 3.1). Further investigation is, however, needed to confirm the role of Ca and determine whether B is also involved, given its co-involvement in cell wall strengthening.

- **Influence of the graft union on nutrient translocation.**
  Preliminary studies have identified effects of grafting on nutrient translocation in avocado nursery trees (Section 4.1.2). Further investigation to determine effects on mature trees would be valuable, particularly in the context of the apparent negative influence of Mexican race rootstocks on fruit quality in 'Hass'. Recent studies of the characteristics of xylem tissue in different avocado cultivars belonging to the three botanical races of avocado have highlighted important structural differences between the different races (Beier *et al.*, 2020).

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# Appendix A. Studies showing an association between avocado fruit mineral nutrient status and postharvest quality defects.

| Defect name(s) | Mineral nutrient | Reference(s) |
|---|---|---|
| Body rots | Ca | (Whiley, 2013, Everett *et al.*, 2007, Hofman *et al.*, 2002, Marques *et al.*, 2006, Marques *et al.*, 2003, Willingham *et al.*, 2006) |
| | N | (Whiley, 2013, Marques *et al.*, 2003, Willingham *et al.*, 2001, Willingham *et al.*, 2006) |
| | K | (Whiley, 2013, Everett *et al.*, 2007, Hofman *et al.*, 2002, Marques *et al.*, 2006, Willingham *et al.*, 2006) |
| | Mg | (Whiley, 2013, Hofman *et al.*, 2002, Marques *et al.*, 2006, Willingham *et al.*, 2006) |
| | P | (Hofman *et al.*, 2002) |
| | B | (Marques *et al.*, 2003) |
| | Si | (Anderson *et al.*, 2004, Anderson *et al.*, 2005) |
| | N/Ca | (Whiley, 2013, Willingham *et al.*, 2001, Willingham *et al.*, 2006) |
| | (Ca+Mg)/K | (Whiley, 2013, Everett *et al.*, 2007, Hofman *et al.*, 2002, Willingham *et al.*, 2006) |
| Stem end rot | Ca | (Whiley, 2013, Willingham *et al.*, 2006) |
| | N | (Whiley, 2013, Willingham *et al.*, 2006) |
| | K | (Whiley, 2013, Willingham *et al.*, 2006) |
| | Mg | (Whiley, 2013) |
| | Si | (Dann & Le, 2017) |
| | N/Ca | (Whiley, 2013, Willingham *et al.*, 2006) |
| | (Ca+Mg)/K | (Whiley, 2013, Willingham *et al.*, 2006) |
| Diffuse flesh discolouration | Ca | (Whiley, 2013, Hofman *et al.*, 2002, Marques *et al.*, 2003, Thorp *et al.*, 1997, Hofman *et al.*, 2005, Snijder *et al.*, 2002) |
| | N | (Whiley, 2013, Koen *et al.*, 1990, Marques *et al.*, 2003, Snijder *et al.*, 2002, Van Rooyen & Bower, 2005) |
| | K | (Whiley, 2013, Hofman *et al.*, 2002, Koen *et al.*, 1990, Hofman *et al.*, 2005) |
| | Mg | (Whiley, 2013, Hofman *et al.*, 2002) |
| | P | (Hofman *et al.*, 2002, Koen *et al.*, 1990) |
| | Mn | (Van Rooyen & Bower, 2005) |
| | B | (Marques *et al.*, 2003, Van Rooyen & Bower, 2005) |
| | (Ca+Mg)/K | (Whiley, 2013, Hofman *et al.*, 2002) |
| Vascular browning | Ca | (Whiley, 2013, Marques *et al.*, 2003, Thorp *et al.*, 1997) |
| | N | (Whiley, 2013, Marques *et al.*, 2003) |
| | B | (Marques *et al.*, 2003) |
| | (Ca+Mg)/K | (Whiley, 2013) |
| Vascular leaching | Ca | (Whiley, 2013) |
| | N | (Whiley, 2013) |
| | K | (Whiley, 2013) |
| | Mg | (Whiley, 2013) |
| | N/Ca | (Whiley, 2013) |
| | (Ca+Mg)/K | (Whiley, 2013) |
| Pulp spot | Ca | (Vorster & Bezuidenhout, 1988) |
| | K | (Koen *et al.*, 1990) |
| | P | (Koen *et al.*, 1990) |
| | Zn | (Vorster & Bezuidenhout, 1988) |

| Defect name(s) | Mineral nutrient | Reference(s) |
|---|---|---|
| Discrete patches | N | (Whiley, 2013) |
| | K | (Whiley, 2013) |
| | Mg | (Whiley, 2013) |
| | (Ca+Mg)/K | (Whiley, 2013) |
| Endocarp black spot | B | (Smith, 2004) |

## Appendix B. Concentrations of N, Ca and their ratio (N/Ca) in 'Hass' avocado fruit flesh.

| Flesh concentration | | N/Ca | Rootstock | Region | Reference |
|---|---|---|---|---|---|
| N (% DW) | Ca (mg $kg^{-1}$ DW) | | | | |
| - | 1300-1650 | - | West Indian seedling | Pietermaritzburg (South Africa) | Witney *et al.* (1990b) |
| - | 1200-1570 | - | West Indian seedling | Pietermaritzburg (South Africa) | Witney *et al.* (1990a) |
| - | 314-535 | - | Unspecified | KwaZulu-Natal (South Africa) | Reddy *et al.* (2014) |
| 0.6-2.0 [6] | 78-388 [1] | 8-61 [3] | Unspecified | Various regions (central Chile) | Rivera *et al.* (2017) |
| - | 800-2500 [2] | - | Unspecified (all fruit from same tree) | Llay-Llay, Región Valparaiso (Chile) | Pedreschi *et al.* (2014) |
| 0.5-0.6 | 190-360 | 15-28 [3] | Mexican seedling | Coatepec Harinas (Mexico) | Solis-Fraire *et al.* (1998) |
| - | 780-840 | - | Unspecified | Coatepec Harinas (Mexico) | Barrientos-Priego *et al.* (2016) |
| - | 250-470 | - | Unspecified | Various regions (New Zealand) | Thorp *et al.* (1997) |
| - | 224-334 | - | Unspecified | Irvine, Cal. (USA) | Tingwa and Young (1974) |
| 1.6-1.7 | 410-440 | 40 | Guatemalan seedling | Adare, Qld (Australia) | Joyce (2018) |
| 1.0 | 250 | 43 | Unspecified | Childers, Qld (Australia) Orchard A | |
| 0.7 | 310 | 23 | Unspecified | Childers, Qld (Australia) Orchard B | |
| 1.1 | 510 | 21 | Unspecified | Fishermans Reach, NSW (Australia) | |
| - | 230-520 | - | Guatemalan seedling | Childers, Qld (Australia) | Hofman *et al.* (2002) |
| - | 280-450 [1] | - | Unspecified | Mt Tamborine, Qld (Australia) | Willingham *et al.* (2004) |
| - [4] | 309-372 | - | Unknown seedling | Bundaberg, Qld (Australia) | Hofman *et al.* (2005) |
| - | 109-502 [1] | - | Unknown seedling | Beerwah, Qld (Australia) | Marques *et al.* (2006) |
| - | 97-259 [1] | - | 'Velvick' (West Indian) seedling | Mount Tamborine, Qld (Australia) | |
| 1.0-1.1 | 180-250 [2] | 45-57 [3] | 'Duke7' (Mexican) clonal | Maleny, Qld (Australia) | Marques *et al.* (2003) |
| 0.9-1.0 | 210-300 [2] | 33-42 [3] | 'Velvick' (Guatemalan?) clonal | | |
| 1.0-1.1 | 190-270 [2] | 41-54 [3] | 'Velvick' (Guatemalan?) seedling | | |
| 1.3 | 0.012 [5] | | 'Velvick' (West Indian) seedling | Duranbah, NSW (Australia) | Willingham *et al.* (2001) |
| 1.2 | 0.008 [5] | | 'Duke 6' (Mexican) seedling | | |

[1]Estimated from FW values. [2] Estimated from graph. [3] Estimated from mean N and Ca concentrations. [4] N concentration measured, but data not reported. [5] Extremely low value - possible reporting error? [6] Units reported as g $kg^{-1}$ – possible reporting error?

## Appendix C. Concentrations of N, Ca and their ratio (N/Ca) in 'Hass' avocado fruit peel.

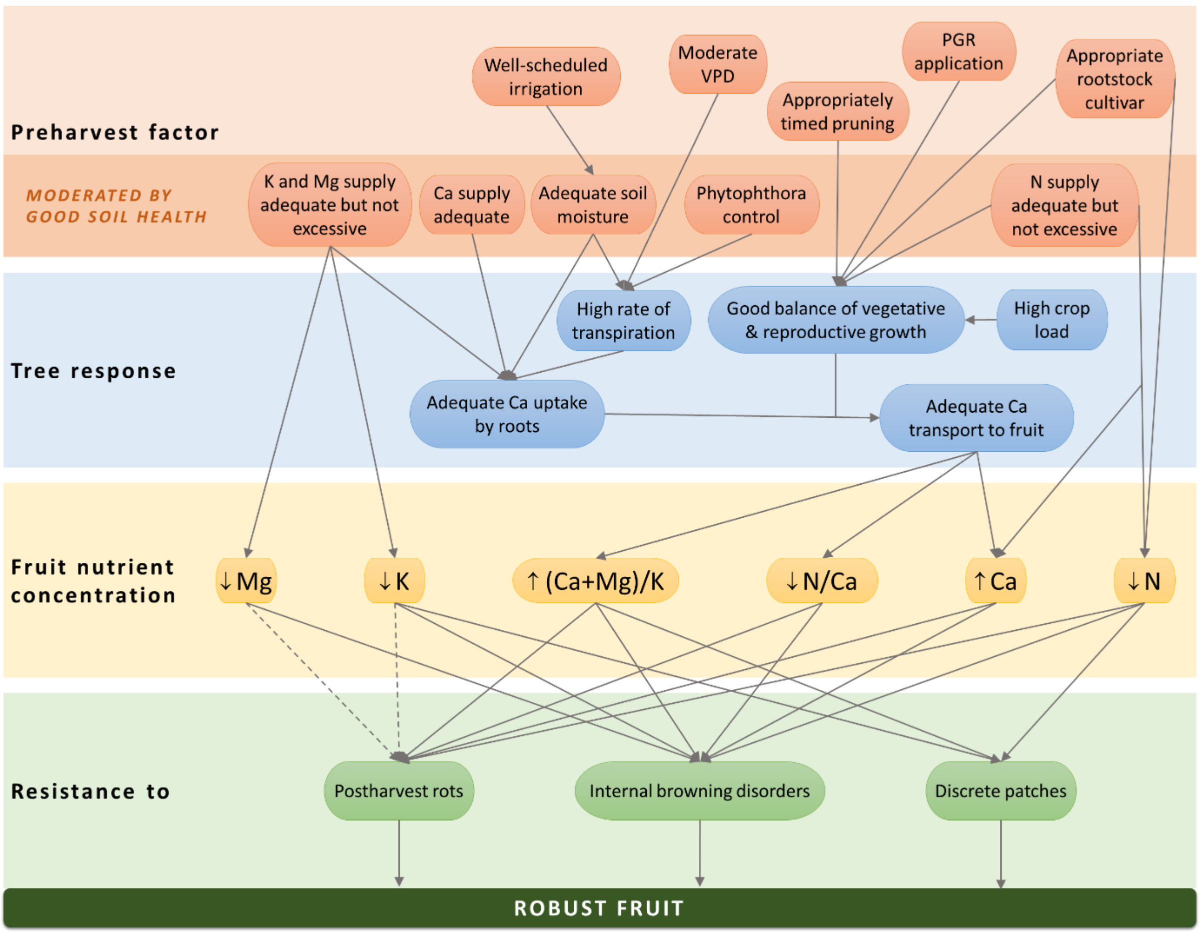
| Peel concentration | | N/Ca | Rootstock | Region | Reference |
|---|---|---|---|---|---|
| N (% DW) | Ca (mg kg$^{-1}$ DW) | | | | |
| 0.8-1.1 | 310-1010 | 9-30 | 'A10' clonal | Childers, Qld (Australia) | Whiley (2013) |
| 0.9-1.1 | 290-720 | 13-35 | 'Duke 7' clonal | | |
| 0.8-1.2 | 280-830 | 10-32 | 'Nabal' clonal | | |
| 0.9-1.2 | 290-880 | 14-33 | 'SHSR-03' clonal | | |
| 0.8-1.1 | 270-880 | 9-36 | 'Velvick' clonal | | |
| 1.0-1.1 | 260-740 | 14-40 | 'Zutano' clonal | | |
| 0.9-1.0 | 380-810 | 13-27 | 'A10' seedling | | |
| 0.9-1.0 | 340-710 | 12-29 | 'Nabal' seedling | | |
| 0.9-1.0 | 330-670 | 13-32 | 'SHSR-02' seedling | | |
| 1.0 | 330-890 | 12-31 | 'SHSR-03' seedling | | |
| 0.9-1.0 | 310-780 | 12-34 | 'Velvick' seedling | | |
| 1.0-1.2 | 380-640 | 21-28 | 'A10' clonal | Hampton, Qld (Australia) | Whiley (2013) |
| 0.9-1.3 | 250-370 | 29-39 | 'Duke 7' clonal | | |
| 1.0-1.4 | 230-440 | 28-47 | 'Hass' clonal | | |
| 0.9-1.3 | 280-300 | 35-46 | 'Reed' clonal | | |
| 0.8-1.2 | 280-560 | 23-36 | 'SHSR-03' clonal | | |
| 0.9-1.2 | 280-560 | 22-34 | 'Velvick' clonal | | |
| 1.0 | 280 | 37 | 'Zutano' clonal | | |
| 0.9-1.1 | 820-1100 | 10-14 | 'A10' clonal | Pemberton, WA (Australia) | Whiley (2013) |
| 1.0-1.2 | 580-700 | 14-22 | 'Barr Duke' clonal | | |
| 1.0-1.1 | 670-750 | 13-17 | 'Duke 7' clonal | | |
| 0.9-1.1 | 640-850 | 14-15 | 'Reed' clonal | | |
| 0.9-1.0 | 750-1130 | 9-15 | 'Velvick' clonal | | |
| 1.0 | 720-900 | 12-15 | 'Zutano' clonal | | |
| 1.0-1.2 | 420-580 | 19-29 | 'A8' clonal | Walkamin, Qld (Australia) | Whiley (2013) |
| 1.0-1.2 | 420-720 | 16-25 | 'A10' clonal | | |
| 1.1-1.2 | 430-630 | 20-34 | 'Duke 7' clonal | | |
| 1.1 | 400-670 | 18-31 | 'Reed' clonal | | |
| 1.1-1.2 | 320-620 | 20-34 | 'Velvick' clonal | | |
| 1.0-1.1 | 320-650 | 16-34 | 'Zutano' clonal | | |

| Peel concentration | | N/Ca | Rootstock | Region | Reference |
|---|---|---|---|---|---|
| N (% DW) | Ca (mg $kg^{-1}$ DW) | | | | |
| 0.9-1.3 | 500-610 | 17-22 | 'Velvick' (West Indian) seedling | Duranbah, NSW (Australia) | Willingham *et al.* (2006) |
| 0.9-1.5 | 450-700 | 19-33 | 'Duke 6' (Mexican) seedling | | |
| 0.8-1.2 | 500-600 | 14-27 | 'Anderson 8' (Guatemalan) seedling | | |
| 0.9-1.1 | 500-600 | 18-24 | 'Anderson 10' (Guatemalan x Mexican) seedling | | |
| 0.8-1.2 | 400-600 | 16-28 | 'Nabal' (Guatemalan) seedling | | |
| 0.8-1.2 | 400-500 | 18-35 | 'Parida' (Mexican) seedling | | |
| 1.1 | 366 | 30 [1] | 'Velvick' (West Indian) seedling | Duranbah, NSW (Australia) | Willingham *et al.* (2001) |
| 1.3 | 306 | 42 [1] | 'Duke 6' (Mexican) seedling | | |
| 1.0 | 660 | 16 | Unspecified | Childers, Qld (Australia) Orchard A | Joyce (2018) |
| 0.8 | 790 | 12 | Unspecified | Childers, Qld (Australia) Orchard B | |
| 0.9 | 600 | 15 | Unspecified | Fishermans Reach, NSW (Australia) | |
| - | 800-850 | - | Unspecified | Coatepec Harinas (Mexico) | Barrientos-Priego *et al.* (2016) |

[1]Estimated from mean N and Ca concentrations.

# Appendix D. The complex of interactions determining avocado fruit robustness.

Diagram showing that robust avocado fruit are inherently resistant to postharvest diseases/disorders and tend to contain relatively high concentrations of calcium (Ca) and relatively low concentrations of nitrogen (N), magnesium (Mg) and potassium (K). Ratios of these nutrients as low N/Ca and high (Ca+Mg)/K have been correlated with improved fruit robustness. Ca transport to fruit occurs more readily when vegetative growth is balanced with crop load and when transpiration rates are high. However, roots must first access Ca from the soil. Adequate supply of soil Ca, soil water to dissolve it and minimal interference from other soil cations aid Ca uptake by roots. Well-scheduled irrigation supports root health and nutrient uptake. Vegetative vigour can be checked by plant growth regulator (PGR) application, judiciously timed pruning, avoiding excess or poorly-timed N application and using appropriate rootstocks. Managed N application and rootstock selection contribute to preventing over-accumulation of N in fruit. Soil health underpins many of the pre-harvest factors. High soil CEC aids nutrient retention in the root zone, high soil biodiversity suppresses Phytophthora root rot (PRR), good soil aeration prevents root hypoxia and limits PRR and high water-holding capacity buffers against drought stress. Ca accumulation in fruit is also affected by increased evaporative demand generated under high temperature and/or low humidity. Integrated as vapour pressure deficit (VPD), these environmental factors can promote transpiration up to a point. However, overly high VPD may trigger stomatal closure and reduce transpiration rate.




Note: Dashed lines indicate nutrient has been associated with both increased and decreased defect expression.

# Appendix B. Technical summary -

**TECHNICAL GROWER SUMMARY OF THE REVIEW OF PREHARVEST MINERAL NUTRITION EFFECTS ON AVOCADO POSTHARVEST QUALITY IN AUSTRALIA**

**Project AV19004**

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**INTRODUCTION**

A consistent supply of good quality avocado fruit is essential to grow and retain markets, however the quality of Australian avocados reaching consumers often fails to be of an acceptable standard. In 2017, an online survey of 1000 avocado buyers found that half of them often won't buy avocado because they are not satisfied with the quality available. Several strategies are being pursued to achieve better fruit quality but one that has not been closely examined until now is the effect of the mineral composition of the fruit. Many pre-harvest factors contribute to this including scion and rootstock genetics, soil properties, soil moisture, fertiliser practices, canopy management, climate and weather.

This study examines existing evidence of the relationship between mineral composition and fruit quality, outlines steps that can be taken to improve fruit robustness through better mineral content and provides recommendations for further research on the topic.

Table 1 summarises the associations between fruit mineral nutrient status and the development of postharvest rots and other quality defects in avocado as suggested by research.

*Table 1. Fruit mineral nutrients in the peel or flesh associated with increased (+) or decreased (-) expression of postharvest quality defects in avocado fruit. Blank spaces indicate no association or no information available.*

| **Defect name** | **Mineral nutrient** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **N** | **P** | **K** | **Ca** | **Mg** | **B** | **Mn** | **Si** | **Zn** | **N/Ca** | **(Ca+Mg)/K** |
| Body rots | + | + | +/- | - | +/- | - | | - | | + | - |
| Stem end rot | + | | + | - | +/- | | | - | | + | - |
| Diffuse discolouration | +/- | +/- | + | - | - | - | - | | | | +/- |
| Vascular browning | + | | | - | | - | | | | | - |
| Vascular leaching | + | | +/- | - | - | | | | | + | - |
| Pulp spot | | + | - | - | | | | | - | | |
| Discrete patches | + | | + | | + | | | | | | - |
| Endocarp black spot | | | | | | - | | | | | |

**MINERAL NUTRIENTS ASSOCIATED WITH POSTHARVEST QUALITY**

**1. Calcium**

Calcium plays a dominant role in determining fruit quality. It combines with pectin in plant cell walls to give mechanical strength to fruit tissues and protection against degradation of the cell-wall. It also stabilises membranes and prevents leakage of cell contents. Fluctuations of calcium levels in cell sap act as a signal to trigger the plant's defence mechanisms against pathogen attack and environmental stresses (e.g. heat).

Elevated calcium levels in avocado fruit have been linked to delayed ripening, greater firmness after storage, reduction in quality defects (including rots associated with pathogens) and physiological disorders that include diffuse flesh discolouration and vascular browning. However total concentrations of calcium in 'Hass' avocado fruit have been found to vary greatly, ranging from 78 to 2500 mg $kg^{-1}$ (dry weight) in the flesh and 230 to 1130 mg $kg^{-1}$ (dry weight) in the peel. Within-tree variation is also marked, with flesh calcium levels ranging from ~800 to ~2500 mg $kg^{-1}$ (dry weight) in a sample of 100 fruit harvested from the same tree.

A likely reason for the wide range of calcium levels in the plant is interaction between calcium and other mineral nutrients. The balance of fruit calcium to other nutrients, particularly nitrogen, potassium and magnesium, is more important for avocado quality than calcium concentration alone.

Calcium uptake by plants is a passive process driven largely by transpiration. The rate of calcium uptake is greatest at the root tip which is also the first point of attack of Phytophthora root rot, making it a particularly important factor to consider in Australia where this disease is rife. It should also be borne in mind that other cations such as sodium, potassium and magnesium compete with calcium for uptake.

Transport of dissolved calcium from the root occurs through the transpiration stream via the xylem (water conducting tissue) to leaves, flowers and fruits. Calcium uptake by plant organs is also driven by the plant hormone auxin which tends to be greater during periods of high metabolic activity. Hence, calcium mostly accumulates in plant organs that are actively growing and transpiring. Once deposited, calcium does not readily translocate to other organs. Lack of mobility, initial non-uniform distribution to plant organs (e.g. leaf vs. fruit) and the fact that leaves continue to transpire for their entire lifespan but fruit don't mean that leaf calcium concentrations are generally not a reliable indicator of fruit calcium levels.

Avocado fruit demand for calcium is greatest within the first eight weeks or so after fruit set whilst they are transpiring through their stomata, however after this period the stomata on the fruit become dysfunctional, form lenticels and cease to transpire. It is therefore critical to create conditions that favour calcium transport to the fruit during this early period. Providing adequate calcium supply in the soil is only part of the answer (Figure 1). Uptake by roots requires a correct balance of soil nutrients and sufficient soil moisture for calcium to enter the soil solution. How much calcium then reaches the fruit largely depends on xylem sap flow as influenced by transpiration and growth rates and competition from vegetative tissues. Factors that reduce transpiration (e.g. low vapour pressure deficit and stomatal closure), or increase the ratio of vegetative to reproductive material on the tree (e.g. over-supply of nitrogen fertiliser, low crop load, fruit thinning and insufficient or poorly-timed pruning) will limit fruit calcium uptake. Although interactions are complex, there is scope within a grower's control to manipulate factors to help maximise fruit calcium levels.

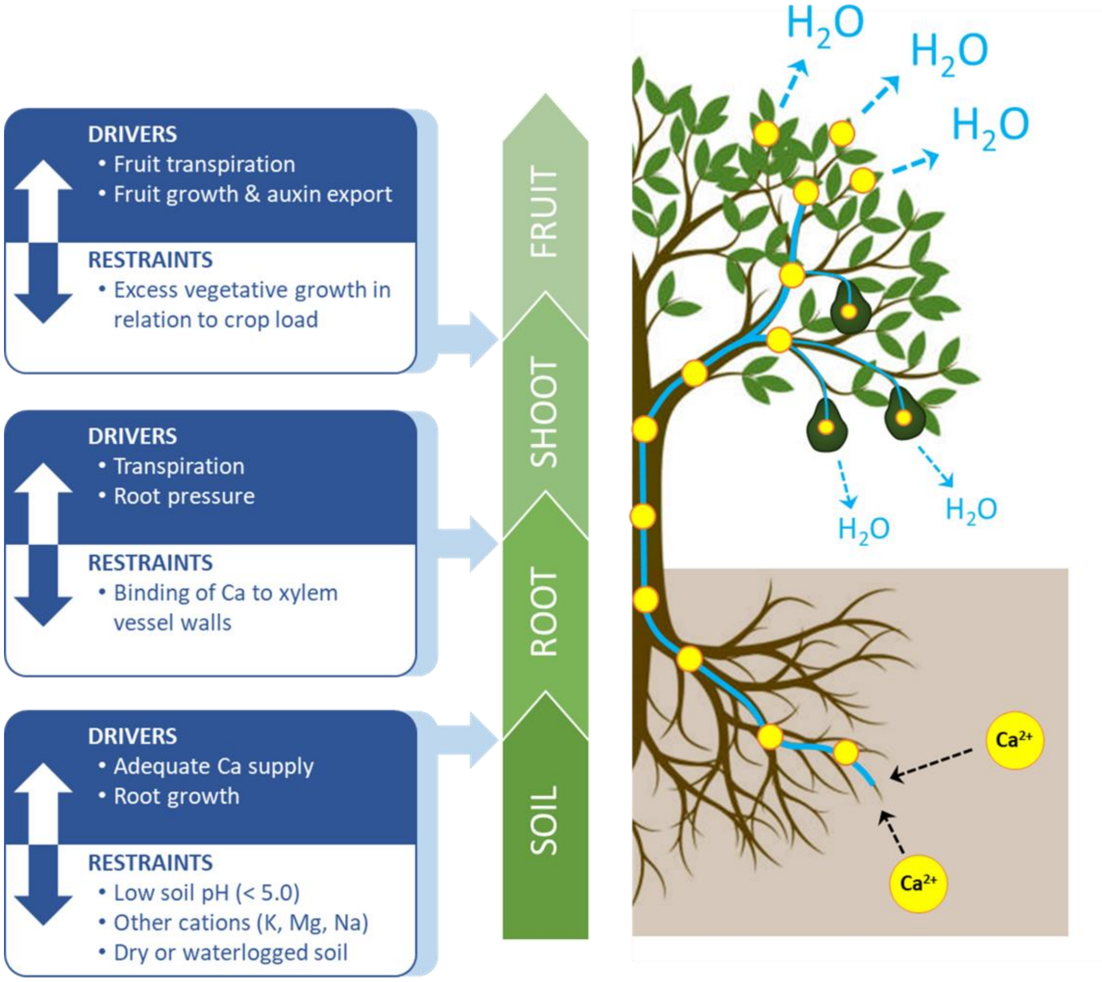


*Figure 1. Processes of calcium accumulation in avocado fruit.*

## 2. Nitrogen

Plant requirement for nitrogen is greater than any other mineral nutrient. An inadequate supply can result in lower yields, smaller fruit and less vegetative growth to support flowering and fruit set in subsequent seasons. On the other hand, an over-supply of nitrogen during fruit development can negatively impact fruit robustness because too much nitrogen promotes excessive vegetative growth and this diverts calcium away from developing fruit. Elevated levels of nitrogen in the peel makes the fruit more vulnerable to fungal pathogen attack such as anthracnose, whilst increasing levels of avocado fruit nitrogen have been linked to greater susceptibility to postharvest rots and vascular browning.

The timing and rate of nitrogen application needs to strike a balance between yield and fruit quality (Figure 2).

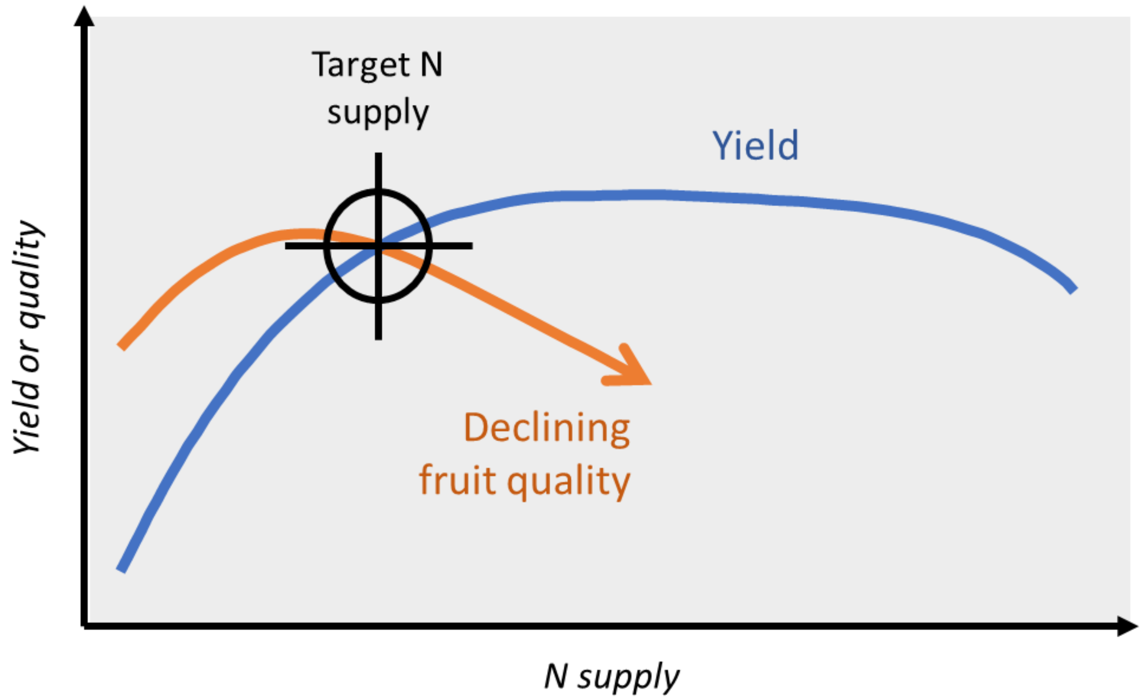


*Figure 2. Nitrogen supply management for balance between avocado fruit yield and quality.*

Reported concentrations of nitrogen in 'Hass' avocado fruit range from 0.5-1.7% dry weight in the flesh and 0.8-1.4% dry weight in the peel. Keeping flesh nitrogen levels below 1.7% in the mid-stages of fruit development and below 1% in the months leading up to harvest has been recommended for growing 'Pinkerton' in South Africa to minimise the risk of fruit developing diffuse flesh discoloration after cold storage.

Other recommendations pertain to leaf concentrations which are proportionate to levels in the fruit but are different for each variety. In Australia, recommended leaf nitrogen levels for fruit-bearing 'Hass' trees are 2.2-2.6% dry weight, with a slightly lower range of 2.0-2.4% dry weight recommended for more vigorous varieties such as 'Fuerte' and 'Sharwil'.

### 3. Potassium

Potassium contributes to the regulation of fluids in cells, which is important for stomatal function and cell expansion (i.e. fruit growth). Also, potassium supply to deficient plants increases pest and disease resistance. However, increasing potassium supply beyond the minimum needs of the plant can result in 'luxury consumption' of this nutrient and possibly lead to potassium-induced deficiencies of calcium and magnesium.

In avocado, high fruit potassium concentration has been linked with increased diffuse discolouration, increased body rot severity and decreased ripening time of fruit. These influences on fruit quality are believed to primarily stem from the antagonistic effect that potassium has on uptake of other cations particularly calcium.

Potassium is highly mobile in the plant which means that leaf potassium levels are generally a good indicator of fruit potassium levels. In Australia, optimal leaf potassium for 'Hass' is considered to be 0.75-2.0% however, modelling of data from Californian 'Hass' orchards indicated that optimum leaf potassium for high-yielding trees is 0.8% and that yield potential is suppressed above 1% leaf potassium.

### 4. Magnesium

Correlations between fruit magnesium levels and avocado quality tend to be inconsistent and, in some cases, contradictory. More attention has been given to the cation balance between magnesium, calcium and potassium in the avocado fruit as this seems to be of greater importance to quality.

### 5. Boron

Increasing flesh boron levels in 'Hass' fruit have been linked with lower incidence and severity of diffuse flesh discolouration and vascular browning, as well as lower severity of body rots. Post-storage development of a localised flesh browning disorder referred to as 'endocarp black spot' was greatest in 'Hass' fruit from boron deficient trees and gradually declined as the rate of boron fertilisation increased. This defect occurred near the top of the seed cavity (the stem end), the region of the fruit which inherently contains the lowest boron concentration. However, growers need to be mindful of the narrow window between boron deficiency and toxicity. In this regard, it is advisable to seek expert advice.

Boron strengthens cells by cross-linking pectic substances in the cell wall and acting as a bridge between the cell wall and membrane.

Translocation of boron from mature leaves to flowers and young leaves has been demonstrated in avocado. Boron concentrations in 'Hass' avocado peel correlate well with leaf boron levels as would be expected for a phloem-mobile nutrient. A critical level of 46 mg kg-1 in summer flush leaves was found to be required to achieve 90% maximum fruit size.

### 6. Silicon

The presence of silicon has been shown to enhance the mechanical strength of fruit tissues as well as activate plant defences. Some research has shown a reduction in fruit body rots as a result of trunk injection of soluble silicon during fruit development but other attempts at trunk injection, foliar spray or soil drench have resulted in no reduction.

### 7. Zinc

'Fuerte' avocado fruit displaying pulp spot were found to contain lower calcium and zinc concentrations than unaffected fruit, however severity of body rots, stem end rot, diffuse flesh discolouration and vascular browning were found to have no correlation with flesh zinc levels in 'Hass' avocados.

## Nutrient interactions

*Calcium and nitrogen*

In many instances, the nitrogen/calcium ratio in avocado fruit has proven to be a better indicator of postharvest quality than individual nutrient concentrations. For example, South African 'Pinkerton' fruit sourced from areas considered "high risk" in terms of diffuse flesh discoloration consistently had higher nitrogen/calcium ratios but did not necessarily have lower calcium levels than fruit from "low risk" areas. Additionally, the development of postharvest body rots in 'Hass' fruit has been more consistently correlated with nitrogen/calcium ratio than calcium concentration alone.

Studies on 'Hass' showed substantial development of postharvest body rots in fruit with flesh nitrogen/calcium ratios of 40-45 at harvest, but little or no body rot development when ratios were 33 or lower.


*Figure 3. Body rot expression in 'Hass' avocado fruit at soft-ripe stage. Fruit were harvested on the same day from two orchards in Central Queensland and exposed to the same postharvest conditions. No fruit from the first orchard (left) developed body rots (flesh nitrogen/calcium ratio of 23), whereas all fruit from the second orchard (right) developed body rots (flesh nitrogen/calcium ratio of 43).*

*Calcium and other cations*

The balance of cations in avocado fruit, particularly the ratio of (Ca+Mg)/K, has been found to be associated with better fruit quality. Fruit with higher values had fewer body rots, stem end rot, vascular browning and leaching, and discrete patches.

**PRE-HARVEST FACTORS INFLUENCING FRUIT NUTRIENT STATUS**

**Genotype**

*Scion*

Fruit quality is strongly influenced by choice of cultivar. In avocado, varietal differences have been reported for quality traits including browning potential and postharvest disease susceptibility but little is known of cultivar-related effects on fruit mineral nutrient status.

'Hass' fruit harvested from vigorous trees grown at a site in South Africa contained almost twice the calcium concentration of 'Fuerte' fruit from vigorous trees grown on the same site and rootstock. Competition from the vegetative flush was considered to be the main cause and since flowering and early fruit development in 'Fuerte' coincides with a vigorous vegetative spring flush this may have also contributed.

In another study, 'Shepard' fruit appeared to have higher calcium concentrations and lower nitrogen/calcium ratios than 'Hass' fruit harvested from the same site in North Queensland, irrespective of rootstock or season. Nitrogen/calcium ratios of 9-16 and 19-34 were reported in 'Shepard' and 'Hass' fruit, respectively. 'Shepard' is a smaller tree with a more compact growth habit and tends to flower when the spring vegetative flush is well advanced, hence the ability of this cultivar to readily accumulate fruit calcium may be a result of relatively low calcium demand from vegetative tissues during early fruit development.

*Rootstock*

In Australia, rootstock race has been found to influence the nutrient balance and quality of 'Hass' fruit. Fruit harvested from 'Hass' trees grafted to Mexican race rootstocks (e.g. 'Duke 6', 'Duke 7' and 'Thomas') generally had inferior quality and nutrient status compared with those grafted to Guatemalan (e.g. 'Anderson 10' and 'SHSR-03') or West Indian x Guatemalan (e.g. 'Velvick') race rootstocks. In 'Shepard', negative fruit quality issues and unfavourable nutrient balances were more often associated with Mexican race rootstocks than with Guatemalan or West Indian race rootstocks. It should be noted that in some of the studies, large seasonal effects and a high degree of site-to-site variability may have overshadowed rootstock effects on fruit mineral nutrients, indicating that other orchard factors may play a greater role in determining final fruit quality than rootstock.

**ENVIRONMENT**

**Soil texture**

In Australia avocados must be grown on free draining soils to help manage Phytophthora root rot, but this usually comes at the cost of cultivating them in soils with inherently low nutrient holding capacity (cation exchange capacity) and the potential for leaching of soil-applied nutrients.

**Soil water**

Avocado trees are sensitive to soils that are both too wet and too dry and respond by closing their stomata. Stomatal conductance can be slow to recover in drought-stressed trees and extended water deficit induces trees to produce permanent woody plugs (tyloses) in the xylem. These responses restrict water flow and thus reduce nutrient supply to the tree.

Waterlogging aids the spread of Phytophthora root rot and reduces soil aeration causing root hypoxia. The resultant root damage can further impede nutrient uptake. Although fruit calcium levels can be higher in trees with moderate root rot than in healthy trees, this is offset by other fruit quality issues such as sunburn, smaller fruit and a reduction in yield.

Maintaining soil moisture within an optimal range has well-documented benefits of improved yield and reduced alternate bearing. Effects on fruit nutrient status are less clear, with a number of irrigation studies producing inconsistent results. Since critical nutrients are often easily leached from the root zone, identification of critical periods of crop water and nutrient demand in relation to fruit robustness and quality could inform site specific irrigation management.

**Soil organic matter**

Improvements to soil health and fertility from the regular application of soil organic matter in agricultural production systems, including avocado, are well known. In avocado the addition of organic matter in the form of mulches can improve crop yields due to a reduction in crop stress. It is thought that the benefits from mulching relate to enhanced soil moisture availability and improvements in the soil's ability to hold nutrients (cation exchange capacity) which both lead to better retention and availability of nutrients. Also, the enhancement of a soil environment where soil biology can flourish has beneficial outcomes for the suppression of pest and diseases, most notably Phytophthora Root Rot. However, there are few definitive published studies linking soil organic matter and mulching to enhanced fruit quality.

**Climate**

*Temperature and humidity*

From a fruit mineral nutrient perspective, perhaps the most important climatic factors are those that influence transpiration rate and, hence, calcium accumulation, since this mineral is conveyed in the transpiration stream. High temperature and/or low humidity produces a strong evaporative demand, which is often characterised in terms of high vapour pressure deficit (VPD). Such conditions favour diffusion of water vapour from the leaf surface to the air. However, avocado trees respond to increasing VPD by closing their stomata and this may ultimately limit transpiration. Hence, there is likely to be an optimum VPD range for maximising transpiration rate and calcium accumulation.

*Light*

Avocado fruit exposed to direct sunlight, as opposed to those in shaded areas took longer to ripen and develop body rots. They also had greater tolerance to postharvest chilling and hot water treatments, and this was generally more pronounced on the sun-exposed side than the shaded side of the fruit. Maintenance of high antifungal diene levels in the flesh during ripening was considered responsible for the greater disease resistance of sun-exposed fruit. High skin and flesh temperatures during sun exposure were considered to enhance stress resistance. Another possibility, however, is that sun exposure promoted uptake and movement of calcium. One study found a 16% increase in fruit calcium between the sun-exposed and shaded sides of immature 'Hass' fruit.

## MANAGEMENT PRACTICES

### Nutrient application

*Calcium*

Increasing rates of soil-applied calcium in various forms typically provides little or no increase in avocado fruit calcium levels. This indicates a reliance on other factors for transport and distribution within the tree.

Traditionally lime, dolomite and gypsum are the main sources of calcium applied to the soil. Soil application of calcium nitrate and/or calcium thiosulphate after fruit set is being used by some growers in the belief that these more soluble sources of calcium will produce better results, but this has yet to be investigated.

Foliar calcium application has been investigated as an alternative means of getting calcium into the fruit, but results have been inconsistent. Calcium absorption by leaves is unlikely to have any bearing on fruit levels due to the poor mobility of calcium between plant tissues.

Attempts to increase fruit calcium concentration with postharvest vacuum infiltration of calcium chloride or calcium sulphate did show an increase in calcium content of skin and flesh, and in almost every study resulted in delayed fruit ripening. One study reported a reduction in diffuse flesh discolouration although also observed a reduction in external fruit quality.

Postharvest immersion of 'Pinkerton' fruit in organically complexed calcium products such as Calcimex®and Basifoliar Ca® generally reduced the incidence of grey pulp and increased fruit firmness, while some also reduced anthracnose incidence and lenticel damage. The advantage of these products compared to inorganic forms of calcium (calcium chloride and calcium sulphate) used in early studies is reportedly improved calcium uptake and translocation, thus removing the need to apply using vacuum infiltration.

*Nitrogen*

Timing of nitrogen application can have a large influence on the final nitrogen concentration in avocado fruit. When three different timings of nitrogen application were tested, namely (i) commenced during flowering, (ii) commenced after fruitlet formation, and (iii) supplied continuously, the nitrogen levels measured in the flesh just prior to harvest were about 2.0%, 1.4% and 1.9% (dry weight) respectively. Avoiding large applications of nitrogen before and during flowering is therefore recommended to produce more robust fruit.

The chosen fertiliser strategy needs to provide sufficient nitrogen to fuel flowering, fruit set and fruit retention without creating excessive vegetative vigour. Tree demand for nitrogen will depend on cultivar, climate and pruning practice. In warmer climates, flowering commences after the previous season's fruit have been harvested, however, trees grown in cooler climates often have overlapping crop cycles and managing the demands of both can be challenging. The differing nitrogen requirements of trees during 'on' and 'off' flowering years also needs to be considered.

Site aspects including soil texture, slope, rainfall and irrigation will determine how readily nitrogen is leached away from the root zone. Recent research conducted on a commercial avocado orchard in Queensland revealed that nitrate levels in soil solution in the upper 30cm zone of soil can vary considerably (by more than 500 mg/L) within the same block of trees.

Avocado trees are highly sensitive to chloride and application of nitrate nitrogen has been proven to alleviate chloride toxicity symptoms by reducing chloride uptake by the roots.

The dilemma of nitrogen nutrition in avocado has been recognised for many years and was neatly summarised by Professor Nigel Wolstenholme (University of Kwazulu Natal in South Africa):

*"What is often not fully appreciated by growers and advisers is that nitrogen management strategies must be tailored to specific environmental and management conditions, to achieve the same desired effect of a balance between vegetative vigour and yield (and fruit quality)."*

*Potassium*

Oversupply of potassium in the soil has been shown to limit calcium and magnesium uptake and reduce concentrations of these nutrients in the fruit flesh. This fruit subsequently developed more extensive diffuse flesh discolouration.

Australian avocado growers may be applying too much potassium. This possibility, along with the antagonistic effect of potassium on calcium uptake, has led to recommendations that potassium fertilisation of avocado trees be reduced especially during early fruit development when fruit calcium demand is highest. Most potassium accumulation in avocado fruit occurs during the later stages of development, so delaying potassium application until this time would seem to be logical.

*Boron*

Given the role of boron in pectin binding of the primary cell wall, boron is required for all the growing points of the tree, including shoots, roots and young fruit. Most studies on boron have focussed on improving fruit set and yield with little focus on fruit quality. Soil applied boron has been shown to increase boron levels in skin and seed but not flesh. However, higher flesh boron levels in 'Hass' fruit have been linked with lower incidence and severity of diffuse flesh discolouration and vascular browning, absence of a postharvest flesh browning disorder (endocarp black spot) near the stem end of the seed cavity and lower severity of body rots. Soil applications need to be carefully managed, as soil boron concentrations can easily build up to toxic levels and optimal soil boron concentrations vary greatly depending on soil texture.

**Irrigation**

Conflicting results on fruit quality from various treatments that investigated the effect of a range of wetter and drier irrigation regimes suggest involvement of other contributing factors. For example, periods of high environmental evaporative demand can induce stomatal closure even when soil moisture is adequate. Additionally, the extent to which irrigation alters the vegetative/reproductive balance will ultimately influence the amount of calcium distributed to the fruit.

**Canopy management**

A balanced ratio of vegetative/reproductive growth is credited for enhancing fruit quality. Avocado trees with low vegetative vigour and/or high crop load tend to bear fruit with high calcium levels and few postharvest diseases and disorders. Pruning that limits vegetative growth at the critical time of fruit set and early fruit development has been shown to produce larger fruit, higher fruit calcium levels and fewer postharvest body rots, whilst producing similar yields to unpruned trees. However, pruning that stimulates vegetative regrowth at this critical time can have a negative impact on fruit quality.

When vegetative regrowth after pruning coincided with reproductive growth, fruit from pruned as opposed to unpruned trees contained less calcium and were more prone to body rots, stem end rots, skin spotting, discrete patches, vascular browning and diffuse flesh discolouration.

The plant growth regulator paclobutrazol applied as a foliar spray suppresses vegetative growth and has been shown to increase fruit calcium levels and reduce body rot severity without sacrificing yield. Paclobutrazol foliar application also reduced the incidence of physiological disorders in 'Fuerte' fruit from treated as opposed to untreated trees, but only during an 'off' year. Paclobutrazol should only be used on vigorous, healthy trees, with well managed nitrogen levels.

**Mulching**

Few studies have investigated the effects of mulch on avocado fruit mineral nutrient status and postharvest quality. The use of pine woodchip or pine bark mulch at two Queensland orchards reduced the severity of diffuse flesh discolouration which may have been the result of nitrogen drawdown in the soil preventing excess nitrogen accumulation in the fruit.

A South African study found that mulching with composted Eucalyptus woodchips caused increased potassium and phosphorus in 'Hass' fruit, but no change in fruit calcium or magnesium, as compared with no mulching. This contribution to fruit potassium may have undesirable consequences for fruit quality.

Mulching may be of little benefit to fruit quality when applied to soils already rich in organic matter. A New Zealand study found that in such situations, postharvest development of body rots or stem end rot in 'Hass' fruit was unaffected by mulching.

**MONITORING NUTRIENT STATUS IN AVOCADO**

**Leaf analysis**

Sampling mature leaves from the summer flush in autumn is the recommended practice in Australia but fruit set, significant development and even harvest (in the warmest regions) have already occurred by this time. Leaf analysis is a good indicator of mobile nutrients such as nitrogen, potassium and boron, however calcium is a relatively immobile nutrient that may be apportioned non-uniformly between leaves and fruit, and since calcium continues to accumulate in the leaf as it ages, a high leaf calcium level is more a reflection of leaf age than it is of fruit calcium content. Sampling mature leaves from the spring flush in summer may provide a better opportunity to influence the nutrient content of fruit. For leaf sampling selecting the right leaf material at the right time is critical.

**Soil analysis**

Soil analysis is required less often than leaf analysis but is important for ensuring that nutrient supply, especially of cations, is adequate and balanced. Soil pH (which can influence nutrient availability) can also be measured, and emerging issues such as the build-up of salt, and potentially toxic levels of chloride, boron and manganese which can all adversely affect fruit quality can be detected.

**Fruit analysis**

Fruit nutrient analysis is less commonly used but is essential for determining fruit calcium levels and its ratios with other nutrients. Sampling at harvest will help predict whether fruit can handle the rigours of storage and/or long supply chains. Earlier sampling provides some scope for correcting nutrient imbalances.

A promising development in avocado fruit analysis is the use of relatively inexpensive meters to measure nutrient levels in 'juice' pressed from the flesh of hard, green mature fruit. The benefit of rapid, on-farm nutrient diagnosis potentially offered by this technique warrants further investigation.

**Cauliflower stage inflorescence analysis**

Research on 'Hass' trees showed that mineral nutrient levels in the cauliflower stage inflorescence were a better predictor of yield than leaf nutrient levels. Additionally, the cauliflower stage is easy to identify and collect so carries less risk of sampling the wrong tissue at the wrong time. The greatest advantage is that it allows sufficient time to correct nutrient imbalances before they can negatively impact yield, fruit size or quality. For these reasons the technique is considered high priority for further investigation.

**PROPOSED MODEL FOR AVOCADO FRUIT ROBUSTNESS**

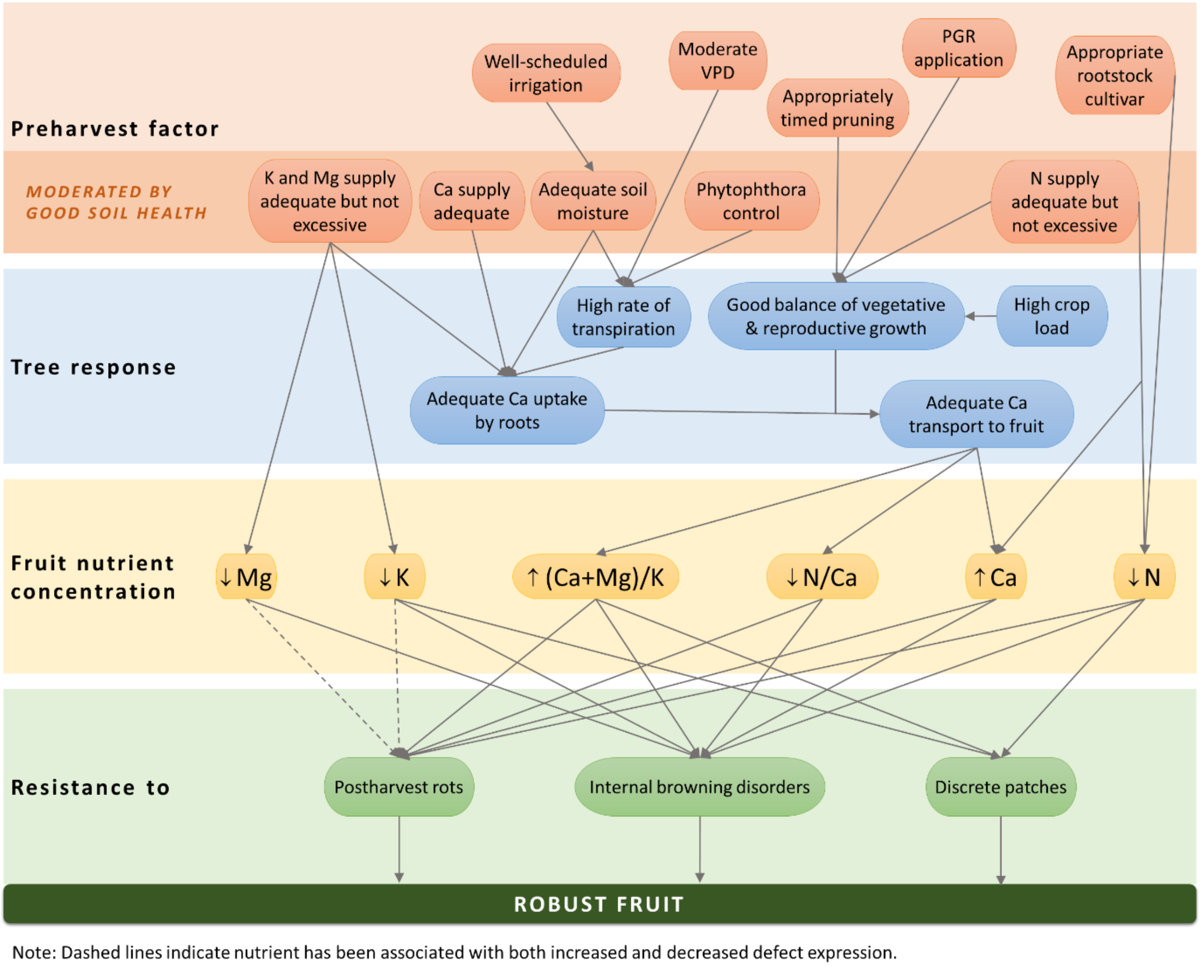


*Figure 4. Robust avocado fruit are resistant to postharvest diseases/disorders and tend to have a fruit nutrient balance that is high in calcium and low in nitrogen, magnesium and potassium. This balance is influenced by several interacting pre-harvest factors and is underpinned by good soil health.*

## CONCLUSION

The robustness of avocado fruit in terms of resistance to postharvest diseases and browning disorders is linked to its mineral nutrient status. A high level of fruit calcium, coupled with low nitrogen, potassium and (possibly) magnesium levels in the fruit has consistently been linked with greater fruit quality. However, since fruit calcium levels are highly variable a more useful measure may be the nitrogen/calcium ratio in the fruit flesh and this could be useful for identifying fruit at risk of developing postharvest diseases and disorders. Rapid nutrient analysis tools to better inform this decision process are becoming available but require testing and development. Increasing fruit boron levels are also considered beneficial to avocado fruit quality, however caution must be exercised as there is a narrow window between deficiency and toxicity. Since nitrogen can have a major influence on fruit calcium content and is easier to manage than calcium, the manipulation of fruit nitrogen rather than fruit calcium may be easier to achieve.

## RECOMMENDATIONS

### Actionable now

Based on evidence presented from this review, the following recommendations to improve fruit quality through mineral nutrition are made:

1. **Provide adequate calcium to trees, especially during flowering, fruit set and early development.**
   Small relatively frequent doses applied to the soil can help to keep calcium in soil solution and the root zone. This may be more important on sandy soils and in areas of high rainfall. Figure 1 illustrates other factors affecting calcium uptake.

2. **Use fruit tissue analysis as a relatively reliable indicator of fruit calcium concentrations.**
   Calcium is not distributed evenly between leaves and fruit, and once deposited, it cannot move from one organ to another. Thus, leaf calcium concentrations are not closely related to fruit calcium concentrations. Analysis of fruit nitrogen at the same time will allow the nitrogen/calcium ratio to be calculated, this ratio tends to be a better indicator of fruit robustness than fruit calcium concentration alone. Fruit with nitrogen/calcium ratios in the high 30's or above are at risk of postharvest quality defects developing and should not be placed into extended storage or subjected to long supply chains.

3. **Ensure leaf nutrient concentrations for nitrogen and potassium do not exceed the optimum range.**
   Unlike calcium, leaf concentrations of nitrogen and potassium reflect concentrations in the fruit. For 'Hass', leaf concentrations should not exceed the optimum range of 2.2-2.6% nitrogen and 0.75-2.0% potassium. (N.B. Based on new research from California, possibly no more than 1% potassium). Monitoring of leaf nitrogen and potassium throughout the season can allow for more timely adjustment of nutrient application rates and lessen the likelihood of fruit with poor nutrient balance.

4. **Delay potassium application until latter stages of fruit development and only apply if needed.**
   Calcium and potassium compete for uptake by plant roots and so should not be applied at the same time. It is better to apply these nutrients when the fruit demand for each is highest. For calcium, peak demand is higher during the early fruit growth stages, whereas demand for potassium is higher in latter fruit growth stages. Some Australian orchards may be over-supplying potassium, so check leaf potassium concentrations before applying.

5. **Achieve a good balance between vegetative growth and crop load.**
   Excessive vegetative growth can divert calcium from developing fruit. Canopy management through careful and appropriately timed plant growth regulator application, pruning, irrigation, and nutritional management may all help to control vegetative vigour and improve nutrient balance in the fruit. An important goal is that re-growth does not coincide with early fruit development.

6. **Select appropriate rootstocks when establishing new plantings.**
   Improved fruit quality and nutrient balance in 'Hass' and 'Shepard' fruit may be achieved by selecting rootstocks of Guatemalan or West Indian heritage over Mexican race rootstocks. 'Velvick' is a West Indian x Guatemalan hybrid that has been shown to perform consistently well in this respect. Nonetheless although rootstock is a potentially important influencer, site

and season effects may have overriding influence on fruit mineral nutrient status and yield should not be unduly compromised.

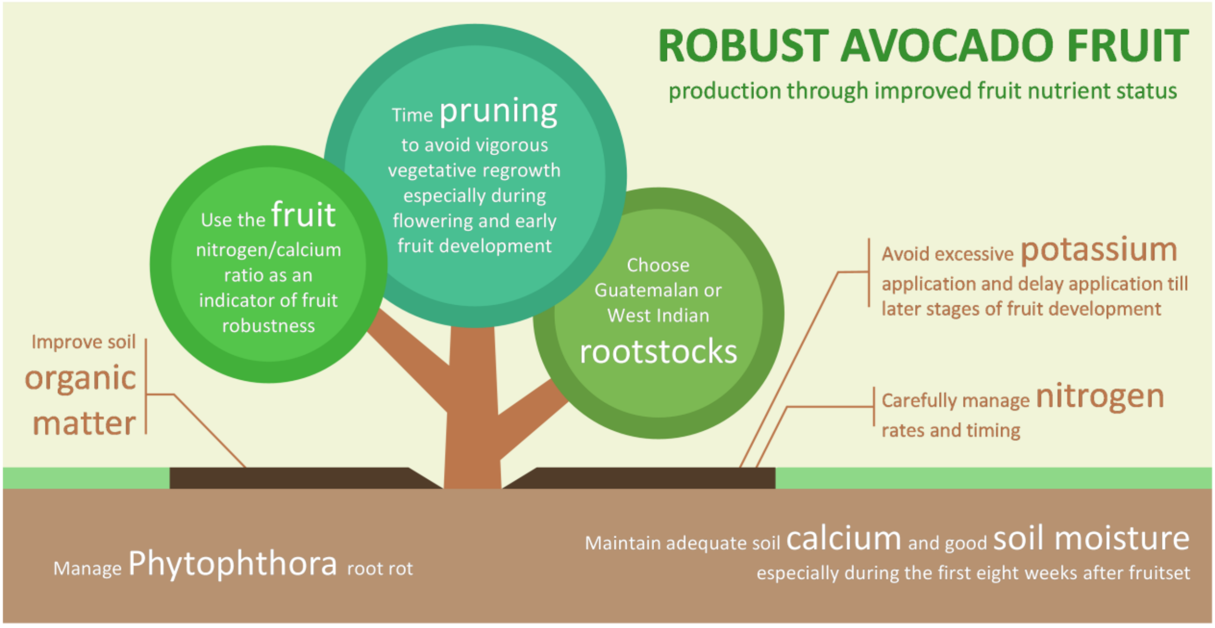


*Figure 5. Orchard practices for improving avocado fruit quality through mineral nutrition.*

**Areas for future research aimed at improving fruit quality**

In no particular order, research into the following areas is recommended.

1. **Mining big data sets to understand genetics, environment and management interactions**
   Re-appraisal of existing data sets in new and/or different ways could help to enable interpretation of and decision making from otherwise overwhelming complex interactions. Earlier Hort Innovation avocado projects may, for example, have generated rich data sets pertaining to fruit nutrient status and quality.

2. **Characterising production environments and practices governing 'good' vs 'bad' fruit nutrient status**
   Fruit nutrient data from orchards identified as producing fruit with superior or inferior postharvest quality could be related back to orchard activities and environment. Studies would cover multiple seasons and be informed by detailed production, management, and environmental records. Supporting leaf analysis data could be correlated to inform, for example, optimum leaf nitrogen and potassium guidelines. Acquiring data on fruit quality at retail level and subsequent trace-back to detailed orchard data could identify the key drivers for high quality fruit.

3. **Irrigation management**
   Maintaining soil moisture within an optimum range is important for nutrient availability, uptake and translocation. However, evidence for irrigation effects on fruit nutrient status is conflicting and merit deeper investigation. Studies would qualify and quantify relationships between different irrigation regimes and vegetative/reproductive balance.

4. **Wholistic approach to nitrogen management**
   Relatively comprehensive studies on nitrogen management in avocado have been conducted but not in the context of Australian conditions. It is recognised that nitrogen management is a complex issue requiring site-specific and season-specific adjustment. In this context, value is inherent in developing ‘best bet’ guidelines for Australian growers in climatically distinct sub-tropical to temperate regions. To optimise fruit mineral nutrient status without compromising yield, studies might consider (i) rates and timing of nitrogen application, as has been done for ‘Hass’ in California, (ii) dynamic contributions of compost and mulch to short, medium and long term nitrogen supply, (iii) sustained-release inorganic fertilisers and (v) nitrification inhibitors.

5. **Compost and mulch application**
   Benefits of compost and mulch on root health and Phytophthora root rot suppression are well documented and have engendered their widespread use in Australian avocado orchards. However, the nature and composition of these organic materials is highly variable. As such, the magnitude and dynamics of their contribution to fruit nutrient status under Australian conditions is poorly understood. Important insight could be gained by comparing and contrasting different materials under specific conditions. Also, mulch and compost options, including ratios, should be explored in conjunction with other orchard management practices towards an informed integrated approach to improving fruit nutrient status, as proposed above for nitrogen management.

6. **Soil application of additional calcium at fruit set**
   Applying relatively expensive highly soluble forms of calcium (e.g., calcium thiosulphate, calcium nitrate) at fruit set is sometimes practiced in Australia. Current understanding around calcium uptake and transport by avocado trees casts doubt on the efficacy of such treatments when soil calcium concentrations are often adequate. Whether and to what degree fruit calcium concentrations may be enhanced by this relatively high cost practice awaits determination.

7. **Timing and type of fruit tissue sampling for nutrient analysis**
   Fruit tissue analysis is typically conducted at harvest maturity and involves analysis of either the peel or flesh tissue. Good correlations exist between avocado peel and flesh calcium concentrations. However, this is not necessarily the case for other nutrients. Also, tissue type which provides the best indicator of fruit nutrient status and robustness remains to be thoroughly investigated. Sampling reproductive tissue at an early phenological stages (e.g. the cauliflower stage of flowers) provides scope for timely intervention to address nutrient imbalance. Optimum nutrient concentration ranges need to be established for specific phenological stages.

8. **Rapid diagnostic tools for monitoring fruit nutrient status**
   Fruit nutrient analysis pertaining to critical imbalances (e.g. high nitrogen/calcium ratio) is currently costly, involving destructive sampling and typical turnaround times of a week or more. With calcium being a relatively reliable base measure of fruit robustness, merit lies in developing and optimising its cost effective rapid on-farm measurement, ideally along with the key co-determining nutrient nitrogen; viz., nitrogen/calcium ratio. More, and more timely assessments could fine tune orchard management practices.

9. **Plant growth regulators for canopy management**
   Plant growth regulator use to control vegetative vigour is 'common practice' in Australia and has been shown to promote calcium accumulation in avocado fruit when applied mid-anthesis as a single foliar spray. Anecdotal reports suggest that growers are applying plant growth regulators in multiple, low doses during the 12 weeks following fruit set. At present, effects of such applications on fruit nutrient status and ultimately fruit quality are unknown and so warrant investigation.

10. **Susceptibility to flesh bruising**
    Flesh bruising is a prevalent defect in Australian avocados at retail. However, its suspected relationship to fruit nutrient status is largely undefined. Preliminary research suggested bruise susceptibility in avocado fruit increases with decreasing flesh calcium concentration. Further investigation is, however, needed to confirm the role of calcium and determine whether boron is also involved, given its co-involvement in cell wall strengthening.

11. **Influence of the graft union on nutrient translocation**
    Preliminary studies have identified effects of grafting on nutrient translocation in avocado nursery trees. Further investigation to determine effects on mature trees would be valuable, particularly in the context of the apparent negative influence of Mexican race rootstocks on fruit quality in 'Hass'. Recent studies of the characteristics of xylem tissue in different avocado cultivars belonging to the three botanical races of avocado have highlighted important structural differences between the different races.

**Acknowledgements**

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Hort Innovation Strategic levy investment | AVOCADO FUND | Queensland Government

# Appendix C. Draft article for 'Talking Avocados' -

**REVIEW OF PREHARVEST MINERAL NUTRITION EFFECTS ON AVOCADO POSTHARVEST QUALITY IN AUSTRALIA**

**Project AV19004**

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Providing consumers with good quality avocados is essential for the Australian industry to retain and grow markets. However, around half of the thousand consumers surveyed in 2017 were dissatisfied with the quality of avocados available. Previous studies suggest that one avenue for improving fruit quality is to ensure that fruit have an optimal balance of nutrients by the time of harvest. This is more likely to result in robust fruit less disposed to developing decay and disorders in the supply chain. In light of this, project AV19004 was tasked with examining existing published evidence of the relationship between mineral composition and fruit quality in order to provide recommendations for orchard practices and/or further research.

*Table 1. Fruit mineral nutrients in the peel or flesh associated with increased (+) or decreased (-) expression of postharvest quality defects in avocado fruit. Blank spaces indicate no association or no information available.*

| Defect name | Mineral nutrient | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | B | Mn | Si | Zn | N/Ca | (Ca+Mg)/K |
| Body rots | + | + | +/- | - | +/- | - | | - | | + | - |
| Stem end rot | + | | + | - | +/- | | | - | | + | - |
| Diffuse discolouration | +/- | +/- | + | - | - | - | - | | | | +/- |
| Vascular browning | + | | | - | | - | | | | | - |
| Vascular leaching | + | | +/- | - | - | | | | | + | - |
| Pulp spot | | + | - | - | | | | | - | | |
| Discrete patches | + | | + | | + | | | | | | - |
| Endocarp black spot | | | | | | - | | | | | |

**Minerals associated with postharvest quality and their management**

*Calcium*

Elevated levels of calcium in avocado flesh have been linked to delayed ripening, greater firmness after storage and a reduction in quality defects (including rots) and physiological disorders. However, concentrations of calcium in flesh and skin tissues vary widely. Even within the same tree there can be a three-fold difference between individual fruit. The development of postharvest body rots in 'Hass' fruit has been more consistently correlated with the nitrogen/calcium ratio than to calcium concentration alone. 'Hass' has shown substantial development of postharvest body rots with flesh nitrogen/calcium ratios of 40-45 at harvest as compared to little or none when ratios were 33 or lower.

Calcium uptake and transport in plants occurs via a transpiration driven process. Solution in the transpiration stream travels from roots via the water conducting xylem vessels to leaves, flowers and fruit that are actively transpiring. Uptake is greatest at the root tip, which is also the first point of attack of Phytophthora root rot. This is a particularly important factor to consider in Australia, where Phytophthora root rot is rife. Also, other mineral ions, such as sodium ($Na^+$), potassium ($K^+$) and magnesium ($Mg^{2+}$), compete with calcium ($Ca^{2+}$) for uptake at the root tip.

Calcium is deposited where the water exits the plant. For the first eight or so weeks after fruit set, the avocado fruit possesses functional stomata. Water will transpire though these, leaving calcium behind in the fruit. However, after this period, stomata on the fruit become dysfunctional and form lenticels. Thereupon, the principal way in which calcium can accumulate in the fruit is finished. Since this mineral is relatively immobile in the plant, it is virtually "game over" for increasing fruit calcium levels.

Transpiration rate is driven by Vapour Pressure Deficit (VPD). The drier, hotter and windier it is, the higher is the VPD and transpiration potential. Accordingly, humid, cool and still conditions during the eight week period after fruit set means less calcium deposition in fruit. However, contrasting conditions do not necessarily guarantee high calcium. This is because as the VPD increases, so too does the likelihood that the plant will close stomata to conserve moisture.

During this critical time period after fruit set, there must be: (i) sufficient calcium in the soil solution, (ii) balance between soil nutrients, (iii) good soil moisture, (iv) healthy root systems, (v) adequate transpiration, and (vi) absence of strong vegetative growth which could divert xylem flow away from fruit.

Increasing rates of soil-applied calcium in various forms have been shown to provide little or no increase in avocado fruit calcium levels. Foliar calcium application has been investigated, but results have been inconsistent. Moreover, calcium absorption by leaves is unlikely to have any bearing on fruit levels due to the poor mobility of calcium between plant organs.

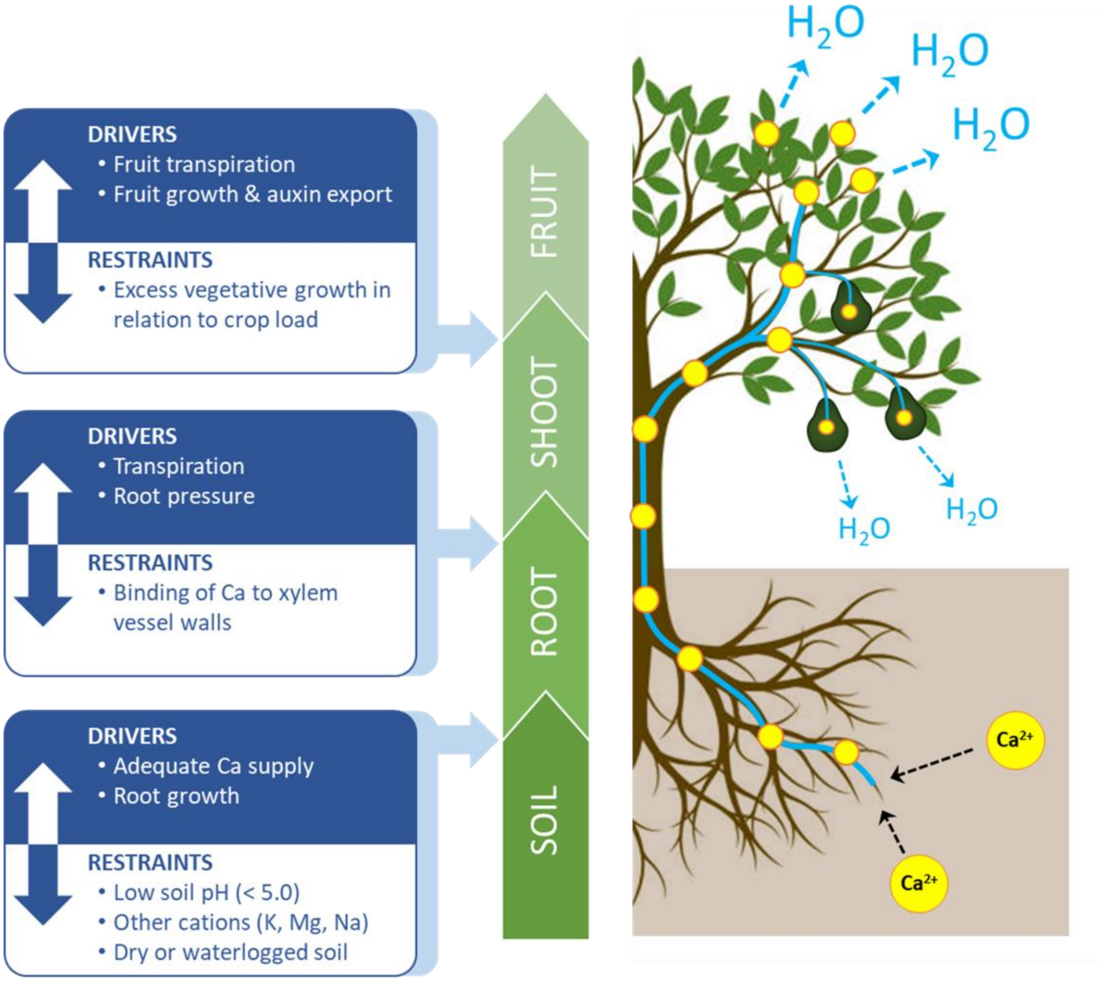


*Figure 1. Processes of calcium accumulation in avocado fruit.*

*Nitrogen, tree vigour, canopy management and the use of plant growth regulators*

Together with calcium, nitrogen plays a crucial role in determining fruit quality. Hence, management of these two minerals is inextricably linked. Nitrogen is key to managing vegetative vigour. Moreover, whilst nitrogen is needed to feed flowering, fruit set and fruit retention, high levels in avocado fruit have been linked to greater susceptibility to postharvest rots, vascular browning and diffuse flesh discolouration.

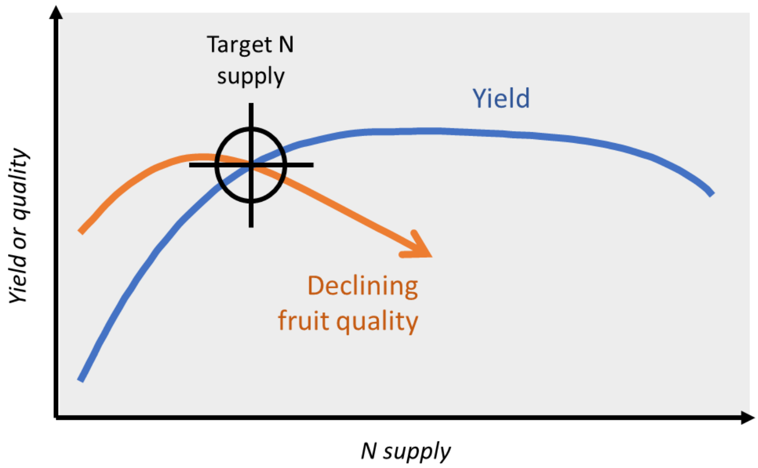


*Figure 2. Nitrogen supply management for balance between avocado fruit yield and quality.*

A balanced ratio of vegetative to reproductive growth is credited with enhancing fruit quality. Avocado trees with low vegetative vigour and/or high crop load tend to bear fruit with high calcium levels and fewer postharvest diseases and disorders. Pruning that limits vegetative growth at the critical time of fruit set and early fruit development has been shown to generate larger fruit with relatively higher fruit calcium levels and fewer postharvest body rots, whilst producing similar total yield to unpruned trees. However, pruning that stimulates vegetative regrowth at this critical time can have a negative impact on fruit quality because it diverts resources, including calcium, away from developing fruit.

In warmer climates, flowering commences after the previous season's fruit have been harvested. However, trees grown in cooler climates often have overlapping crop cycles and managing the demands of both can be challenging. Differing nitrogen requirements of trees during 'on' and 'off' flowering years also need to be managed.

The plant growth regulator paclobutrazol applied as a foliar spray suppresses vegetative growth. In concert, it has been shown to increase fruit calcium levels and reduce body rot severity, without sacrificing yield. However, this plant growth regulator should only be used on vigorous healthy trees, with well managed nitrogen levels.

*Potassium*

Oversupply of potassium in the soil has been shown to limit calcium and magnesium uptake and reduce the concentrations of these nutrients in the fruit flesh, which can lead to quality problems.

Work with 'Hass' in Californian orchards found that optimum leaf potassium for high-yielding trees is 0.8% and that yield is suppressed above 1% leaf potassium. This finding suggests scope to reduce the upper limit of 2% currently recommended in Australia with a view to improving fruit quality.

The antagonistic effect of potassium on calcium uptake and the fact that most potassium accumulation in avocado fruit occurs during the later stages of development, implies that potassium fertilisation should be delayed to later stages of fruit development.

*Boron*

Higher flesh boron levels in 'Hass' fruit have been linked with lower incidence and severity of diffuse flesh discolouration and vascular browning, absence of a postharvest flesh browning disorder near the stem end of the seed cavity and lower severity of body rots. However, growers need to be mindful of the narrow window between boron deficiency and toxicity. In this regard, it is advisable to seek expert advice.

**Other factors influencing fruit mineral status**

*Variety*

Lower nitrogen/calcium ratios were measured in 'Shepard' fruit as compared with 'Hass' harvested from the same site. 'Shepard' is typically a relatively smaller tree with a compact growth habit and tends to flower when the spring vegetative flush is well advanced. Hence, the ability of this variety to readily accumulate fruit calcium may be a result of relatively low calcium demand from vegetative tissues during early fruit development.

*Rootstock*

In Australia fruit harvested from 'Hass' and 'Shepard' trees grafted to Mexican race rootstocks (e.g. 'Duke 6', 'Duke 7' and 'Thomas') had generally inferior quality and nutrient status than those grafted to Guatemalan (e.g. 'Anderson 10' and 'SHSR-03') or West Indian x Guatemalan (e.g. 'Velvick') race rootstocks.

*Soil*

Avocado trees are sensitive to soils that are both too wet and too dry. They initially respond to both conditions by closing their stomata. The functionality of stomata can be slow to recover after drought stress. Moreover, extended water deficit can cause trees to produce permanent plugs, called tyloses, in their xylem. Both responses restrict water flow and therefore reduce nutrient supply through the tree. Waterlogging aids the spread of Phytophthora root rot and asphyxiates feeder roots, again resulting in impeded nutrient uptake.

In Australia, free draining soils that help manage Phytophthora root rot tend to have inherently low nutrient holding capacity and high potential for the leaching of soil-applied nutrients. Addition of compost and mulch engenders higher soil organic matter. In turn, this enhances soil moisture availability and improves the soil's ability to hold nutrients. Both outcomes lead to better retention and availability of nutrients. Moreover, enhancement of a soil environment where soil biology (microorganisms) can flourish also has beneficial outcomes in suppression of pests and diseases.

**Monitoring mineral status**

Leaf analysis is a useful indication of fruit mineral levels for nitrogen, potassium and boron, because these are relatively mobile in the plant. However, leaf analysis is not a good indicator of fruit calcium because calcium is relatively immobile in the plant and the period during which it can accumulate in fruit is finite, whereas in leaves it continues to accrue. High leaf calcium is more a reflection of greater leaf age than it is of nutrient status.

Soil analysis is a useful indicator of soil calcium availability and can also alert growers to imbalances among calcium, magnesium and potassium, changes in soil pH, salt build up and toxic levels of boron, all of which can adversely affect fruit quality.

Mineral analysis of fruit flesh provides direct information on levels of individual nutrients, the nitrogen/calcium ratio and the balance between calcium, potassium and magnesium. This information can inform the prediction of fruit robustness and potentially be used to channel fruit into short, medium or long supply chains to market.

In California, research has indicated that mineral nutrient levels in the cauliflower stage of flowers are a better predictor of yield than are leaf nutrient levels. This stage is easy to identify and so carries less risk of sampling the wrong tissue at the wrong time. Moreover, it may allow sufficient time to take corrective action that will benefit the imminent crop.

**Conclusion and recommendations**

High fruit calcium, adequate boron and modest levels of nitrogen and potassium have consistently been linked to better fruit quality. Figure 3 depicts orchard practices that will help achieve fruit mineral status conducive to robust fruit.

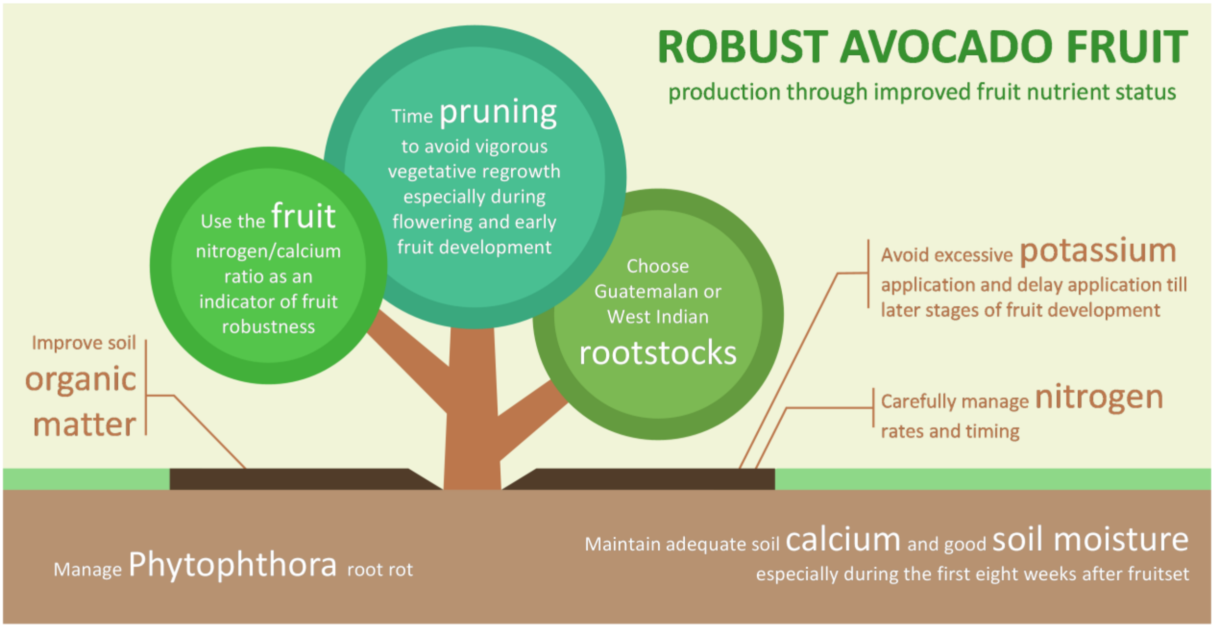


*Figure 3. Orchard practices for improving avocado fruit quality through mineral nutrition.*

A more detailed report called "AV19004 Technical Grower Summary . . . " can be found in the Best Practice Resource.


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