Horticulture Innovation Australia

Final Report

Review of macadamia orchard nutrition

Timothy Smith
The Department of Agriculture and Fisheries (DAF)

Project Number: MC15012

MC15012

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Tel: (02) 8295 2300
Fax: (02) 8295 2399

Content

Summary

The AMS and Hort Innovation commissioned the current project to conduct a review of Macadamia orchard nutrition management and provide an initial presentation of the findings to the Annual Macadamia Consultants Workshop in Brisbane on the 8th June 2016. Various topics relating to soil and plant nutrition of Macadamias were discussed at length with the industry consultants. The comprehensive presentation covered: soil types; soil moisture; organic matter; soil health; soil pH; soil cation exchange capacity; soil cation ratios; Macadamia characteristics; root physiology; root uptake; tree nutrition; nutrient mobility; nutrient disorder symptoms; nutrient interactions; nutrient-disease interaction; boron, phosphorus, nitrogen and calcium nutrition; soil and leaf sampling for analysis; analytical methods; and average nutrient levels across industry. The success and complexity of this presentation highlighted the need for a series of regional workshops to provide further insights into nutritional management of Macadamias, provide a forum for more questions and answer time for greater understanding, and address specific nutritional constraints by region.

A series of six regional workshops were conducted from Bundaberg to the north and Macksville in the south. A draft report was provided to Macadamia nutrition consultants at the regional workshops to provide a process of review and assist in the clarification of nutritional issues. Comments and feedback were considered and relevant adjustments were made to the review report. The final version of the "Review of Macadamia orchard nutrition" is submitted as part of this final report to Hort Innovation.

The AMS and Macadamia consultants have requested further work on nutrition management for the Macadamia industry and this will be the subject of future funding submissions.

Keywords

Review, Nutrition, Macadamia, Integrated Orchard Nutrition, Integrated Orchard Management

Introduction

The Australian Macadamia Industry is aiming to refine nutrient management of orchards. To facilitate this, sampling methodology, nutrient analysis methods and interpretation of data needed greater refinement and clear guidelines for consultants and advisors to improve consistency of information provided to growers. Hence there was a need to review historical and current knowledge in nutrient management and to advise the integrated orchard steering committee and consultants on best nutrient management practices.

There were conflicting views with respect to soil and foliar sampling for interpretation of macadamia nutrition status, the use of a soil nutrient balance approach to cation management and analytical methods to use in Australia. This was creating confusion for industry consultants and inconsistent advice to Macadamia growers with respect to managing soil health and tree nutrition. Part of this confusion may derive from responses to nutrient inputs on a variety of soils with appreciably different adsorption characteristics e.g. phosphorous adsorption in Ferrosol soils compared to Kandosol soils as previously reported by Moody.

Orchard management of macadamia plantations in Australia tries to offset commercial imperatives with optimum growing conditions for the trees. This is encapsulated in the integrated orchard management (IOM) approach which aims to optimise orchard floor management, pollination, pest control, irrigation and nutrition (fertilisation) for maximal yield. In order to achieve optimum nutrient utilisation by the tree, it is imperative to focus on the quality of the root system and the soil constraints which may limit nutrient utilisation by the tree. The aim of the review is to critically evaluate all factors that affect nutrient uptake by macadamia trees in commercial Australian orchards.

This review focusses on three main areas of importance for macadamia culture. Firstly, understanding the soil types commonly used for macadamia plantations in Australia and the limitations of these soils to macadamia growth. Secondly, understanding the physiology of the macadamia tree with regards to growth and nutrient utilisation of the tree. Thirdly, this document discusses the implementation of fertiliser programs and the underpinning science.

Methodology

An extensive review of Macadamia Orchard Nutrition was conducted by Dr Tim Smith (DAF) and Dr Bernhard Wehr (UQ) and presented to a group of 100 Macadamia consultants and advisors at the 2016 Macadamia Consultants Workshop on the 9th June 2016. In addition, Dr Tim Smith was invited to do a "pollination and boron" presentation at the AMS Pollination Workshop, MFM orchard, 94 Pashleys Rd, Moore Park (Bundaberg) on the 16th June 2016 to an audience of growers, consultants, Hort Innovation staff and other researchers.

The review process included:

- A review of all available Macadamia nutrition reports, papers, books, and credible web pages;
- Consultation with retired and current Macadamia nutrition researchers;
- Consultation with industry consultants in the Sunshine Coast, Gympie, Bundaberg and Northern Rivers Regions;
- Statistical analysis of available nutritional data
- Preparation and delivery of presentations;
- Consideration of consultant feedback; and

- Completion of the written review of Macadamia orchard nutrition.

Robbie Commens from the Australian Macadamia Society confided that there were a large number of requests for copies of the presentation delivered at the 2016 Consultants Workshop and further training in soils and nutrition in response to the presentation. Hence Robbie requested an extension of the project to further the knowledge and understanding of soil and nutrition management of orchards amongst the consultant and advisor community servicing the Macadamia industry. A number of training workshops were requested to facilitate greater understanding soils and nutritional management to improve the accuracy and consistency of advice industry consultants provided to growers.

A total of six regional workshops were conducted in five of the major growing regions to target regional soil and nutrition issues to a greater extent than could be achieved through a single conference presentation. Regional Macadamia Orchard Nutrition Workshops were presented:

- Glasshouse Mountains Qld (3-4/04/17);
- Gympie Qld (5-6/04/17);
- Bundaberg Qld (20-21/04/17);
- Northern Rivers – Alstonville NSW (2-3/05/17);
- Northern Rivers – Wollongbar NSW (4-5/05/17); and
- Macksville NSW (29-30/05/17).

The workshops provided greater opportunities for participants to ask questions and work through issues relevant to their region. Thereby increasing the consultants understanding of complex nutritional factors and improve the nutritional advice provided to the Macadamia industry, resulting in increased and more consistent yields. The consultants were provided a draft copy of the review to provide comments and feedback to the project team to refine the outcomes of the final report.

Outputs

Macadamia Orchard Nutrition Review provided to industry nutritional consultants:

- Review of Macadamia orchard nutrition research to date;
- Provision of underlying principles of plant and soil nutrition;
- Advice on erroneous perceptions when interpreting soil analytical results;
- Demonstration of spatial variability of soil sampling and nutrient concentrations;
- Guidelines on preferred soil and foliar sampling to improve reliability and accuracy of soil and foliar analysis;
- Advanced understanding of the role of boron in nut set; and
- Final report as a reference for Macadamia orchard nutrition management.

Outcomes

Upskilling of the Macadamia industry's nutritional consultants:

- Greater understanding of soil nutrient variability;
- Realisation of differences between routine laboratory soil analyses and those required for low pH soils;
- Greater understanding of plant nutrient requirements as measured in foliar analyses verses perceived optimum nutrient balances in soils;
- Options for more consistent (and accurate) sampling for soil and foliar analyses that will enable processes such as nutritional benchmarking across the industry in the future; and
- Anecdotal reports of greater nut set in response to boron sprays at flowering to trees with low to marginal boron levels;

Evaluation and Discussion

The progress and achievements of the project were evaluated through a few mechanisms:

- Regular meetings with the project steering committee (15 Mar, 26 Apr and 30 Jul 2016, plus 8-9 Jun 2016 at consultants workshop);
- A survey of Macadamia consultants at the 2016 Consultants Workshop, conducted by AMS;
- Direct feedback from consultants at workshop presentations; and
- Milestone reporting to Hort Innovation.

The requirements of the review were formulated with the assistance of Robbie Commons (AMS), the steering committee and ongoing feedback from consultants (e.g. Ian Vimpany, Alan Coates, Tim O'Day, and Dr Chris Searle) and researchers (Dr Russ Stephenson and Paul O'Hare). This refined the outputs to ensure that the review and information was specifically targeted to industry issues. The review required intensive research, over a relatively short period of time, which was well received by the Macadamia industry consultants. Testament to this was the results of the consultant's survey of the nutrition review at 2016 Consultants Workshop. The survey of the integrated orchard nutrition workshop (Review of macadamia orchard nutrition presented by Tim Smith and Bernhard Wehr) indicated that:

- It met their expectations (84% positive);
- The information reinforced their current knowledge (89% positive);
- It resulted in plans to make changes after the ION workshop (78% positive);
- They would like to make direct contact with presenters to gain further detailed information (67% positive); and
- They were interested in attending another ION regional based workshop (89% positive).

In comparison to other horticultural tree crop industries (e.g. apple and avocado), there was very little information available that related nutritional data to gains in yield. Therefore it is hoped that the essential research can be conducted to determine the critical nutrient concentrations of essential tree nutrients to optimize nut yield and quality and further refine nutritional management in the Australian Macadamia industry.

Recommendations

AMS have requested an extension of the project to refine the consistency of analytical laboratory procedures, further address Macadamia orchard nutrition issues with industry consultants and then provide a series of Macadamia grower workshops.

The review has highlighted gaps in nutritional research knowledge that need to be addressed through detailed research. Thus it is recommended that postgraduate research projects are undertaken to determine critical concentrations of essential nutrients for optimum nut yield and quality.

Specific Macadamia orchard nutritional management recommendations from this project are detailed in the attached report: Review of Macadamia orchard nutrition by Dr Bernhard Wehr and Dr Tim Smith.

Scientific Refereed Publications

None to report

Intellectual Property/Commercialisation

No commercial IP generated

Acknowledgements

We would like to thank Dr Ian Vimpany and Alan Coates for access to their database with soil and foliar nutrient concentrations and to Drs Russ Stephenson and Paul O'Hare for discussion and access to unpublished research data. Thanks goes to Grant Bignell for his valuable contributions to the workshops. Special thanks to Robbie Commens and numerous consultants for their support and discussions. We gratefully acknowledge the funding from the Macadamia growers, Hort Innovation and our respective organisations DAF and UQ.

Appendices

The "Review of Macadamia Orchard Nutrition" is attached.

Review of macadamia orchard nutrition

Final report MC15012

J Bernhard Wehr. PhD.

School of Agriculture and Food Sciences. The University of Queensland, St Lucia

Tim E Smith, PhD.

Horticulture and Forestry Science. Qld Dept Agriculture and Fisheries

Contents

Abstract

Macadamia is a forest tree native to Queensland and NSW. It is adapted to nutrient-poor soils and forms fine roots and cluster roots to enable rapid nutrient recycling from decomposing organic matter. It responds positively to mulched soil and cooler temperatures, with photosynthesis inhibited when the leaf temperature exceeds 36 C.

It is grown on a variety of soils outside its natural habitat and those soils may constrain performance of the tree when inherent soil limitations are not addressed. While macadamia is adapted to acidic soil, aluminium (Al) toxicity may occur when the pH drops below pH 5 (measured in water). Soil pH is a master variable influencing availability of nutrients and the soil cation exchange capacity (CEC). Conversely, as pH is increased to pH 7 and above, nutrients such as zinc (Zn), iron (Fe) and manganese (Mn) and others become less available leading to visible nutrient deficiency symptoms. Thus, the recommended pH range is between pH 5-6 (in water) to optimise nutrient uptake of all essential tree nutrients.

Since macadamia comes from an environment with leaf litter on the surface, it is important to maintain high levels of organic matter (OM) in the soil and on the soil surface. This can be achieved by living groundcover, applying organic manures or high rates of mulch. Groundcover and mulch is essential to limit soil erosion, to lower the soil temperature, minimise temperature extremes for optimal microbial activity, maintain nutrient cycling through soil microbial activity, maintain water infiltration and water holding capacity, reduce surface crusting and maintain root function. Organic matter also acts as a slow release form of fertiliser and increases the nutrient holding capacity of the soil.

Water availability is important for nutrient uptake from soil (required for optimum utilisation of applied fertiliser), and essential during periods of nut set and nut filling. Irrigation may be needed in areas with unreliable rainfall.

Fertiliser, particularly nitrogen (N), should be applied as several split applications to avoid inducing excessive vegetative growth. For peak flowering and nut set, it is recommended that fertiliser containing boron(B) and Zn be applied by May since it takes up to 7 weeks for nutrients to be taken up, and later application of fertiliser may be impaired by lack of sufficient rainfall and low temperatures.

Foliar nutrient concentrations are a better indicator of nutrient availability than soil concentrations. Soil nutrient concentrations can vary up to 6 fold over a distance of 2 metres across the orchard floor, whereas tree roots explore a large volume of soil and integrate the nutrient availability across a larger area. To provide more consistent foliar and soil sampling results, it is recommended that fixed transect methods be adopted with a minimum of 20 tree samples and 20 soil cores bulked for each respective foliar and soil analytical sample. Foliar samples should be taken along the fixed transect over five rows, sampling at least 10 trees per transect and 10 soil samples evenly spaced along the transect. This transect should be repeated a second time per management block and individual samples combined, to yield a composite sample of 20 soil cores and foliage of 20 trees. The fixed transect method will greatly improve the reliability of soil and foliar results since it reduces variability. The fixed transect approach needs to be complemented for a few years by soil and foliar samples taken by the previously used approach to compare results and maintain continuity of interpretation of results.

Introduction

Orchard management of macadamia plantations in Australia tries to offset commercial imperatives with optimum growing conditions for the trees. This is encapsulated in the integrated orchard management (IOM) approach which aims to optimise orchard floor management, pollination, pest control, irrigation and nutrition (fertilisation) for maximal yield. In order to achieve optimum nutrient utilisation by the tree, it is imperative to focus on the quality of the root system and the soil constraints which may limit nutrient utilisation by the tree. The aim of the review is to critically evaluate all factors that affect nutrient uptake by macadamia trees in commercial Australian orchards.

This review focusses on three main areas of importance for macadamia culture. Firstly, understanding the soil types commonly used for macadamia plantations in Australia and the limitations of these soils to macadamia growth. Secondly, understanding the physiology of the macadamia tree with regards to growth and nutrient utilisation of the tree. Thirdly, this document discusses the implementation of fertiliser programs and the underpinning science.

Soils and their management for macadamia

Soil types for macadamia

Key points:

- Soil types differ in their inherent fertility and suitability for macadamia
- Different soils need to be managed differently
- Growers need to know and understand their soil types

Soil types are differentiated by their chemical and physical properties. Management of soil needs to take into account the strengths and weaknesses of the soil. Therefore, it is necessary to have some basic understanding of soil types and their main characteristics. The Australian Soil classification (see http://www.clw.csiro.au/aclep/asc_re_on_line/soilhome.htm) has 14 soil orders, of which 4-5 are commonly used for Macadamia culture and these are described below.

Ferrosol (Krasnozems)

The Ferrosols were the traditional soil type used for Macadamia culture, partly because Macadamia occur naturally on these soils. Further selection of cultivars on the basalt soils of Hawaii resulted in selection of cultivars adapted to this soil type. Ferrosols are derived from basalt rock and are characterised by a friable consistency and a reddish-brown colour and commonly occur in high rainfall regions in SEQ and NNSW. These soils are high in iron oxide (>5% Fe) and can contain manganese oxides. The metal oxides in Ferrosol impart some unusual properties to the soil, such has high phosphate fixation, high boron adsorption, high anion exchange capacity at low pH, risk of manganese (Mn) toxicity during waterlogging, and a variable organic matter content. The organic matter results in good aggregation and waterholding capacity, but poor management can result in loss of OM, crusting and compaction.

Image: B. Wehr (UQ)

Kandosol (Red and Yellow Earths)

The Red Kandosols may appear similar to a Ferrosol, having uniform to gradational textural changes with depth but contains less metal oxides and more quartz. The clay mineralogy is dominated by kaolinite and these soils have a massive structure with poor drainage and low CEC, resulting in low fertility.

Image: http://vro.agriculture.vic.gov.au/

dpi/vro/vrosite.nsf/pages/dairy_vic_soils-kandosol

Vertosol and Dermosol (Black and brown earths, Chocolate soils)

These soils are characterised by shrink-swell clays and are strongly aggregated. Due to the smectitic clays, these soils have a high CEC, high water holding capacity and high fertility. On the other hand, soils with high smectite content (Vertosols) can have very poor drainage when wet. These soils are typically found on flood plains, are often used for annual field crops, but less suited to tree crops due to water logging during high rainfall periods and root pruning as the soils dry out.

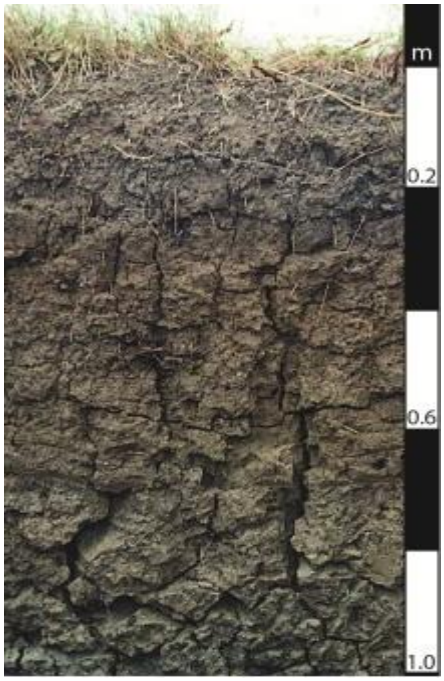
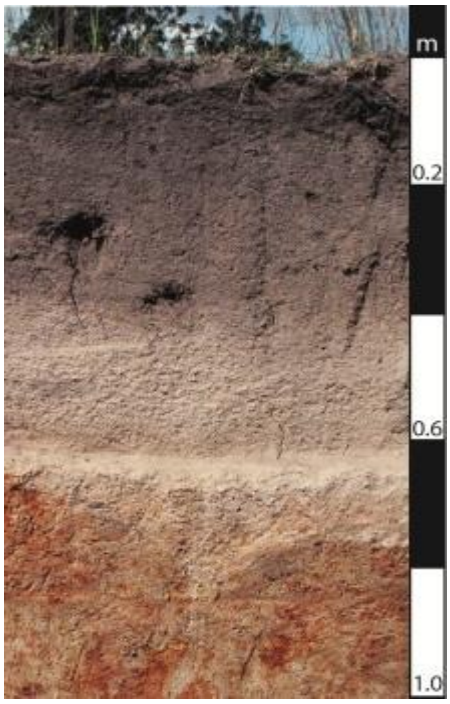


Image: https://www.qld.gov.au/environment/land/soil/soil-testing/types/

Chromosols, Sodosol, Kurosols (Duplex soils, Podzolics)

The duplex soils are characterised by a lighter-textured (i.e. more sandy) topsoil and a clayey subsoil, with the subsoil being either neutral, acidic or sodic. The subsoil constrains root growth which limits root exploration to the topsoil layer. Furthermore, the soil can become waterlogged on top of the subsoil due to low drainage of the subsoil. Duplex soils are often poorly fertile due to the low CEC.



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Tenosols/Rudosols (Alluvial soils)

Alluvial soils are formed on river terraces and are highly variable due to the nature of the parent material. Tenosols/Rudosols formed from sandy alluvial soils tend to be of low fertility, whereas silty and clayey soils will be more fertile. The depth to the water table may limit rooting depth. During periods of high rainfall, soils can become waterlogged and at risk of water erosion during riverine floods.

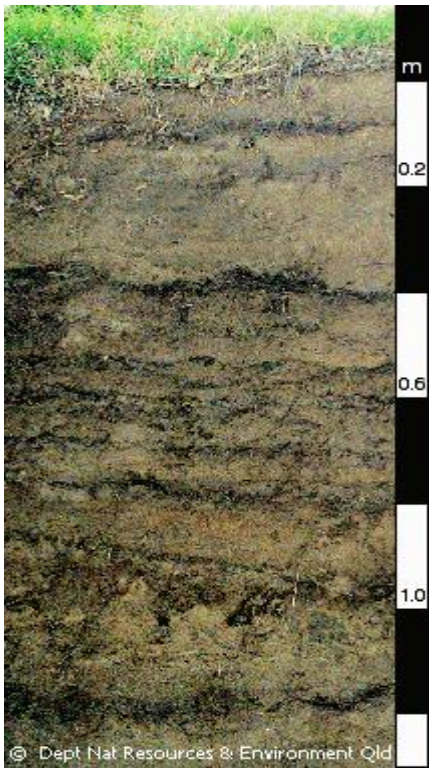


Image: http://www.clw.csiro.au/aclep/asc_re_on_line/ru/rudoprof.htm

Soil constraints and their effect on root growth

Key points:

- Soil pH affects solubility of P, B, Al and trace elements (particularly Fe, Zn and Mn)
- Soil pH affects CEC and AEC
- Macadamia have an optimum pH(water) of 5-6 or pH (CaCl2) 4.5-5.5
- OM is a source of nutrients
- OM differs in quality, there is a strong need to know the quality of the OM applied
- OM in the form of mulch protects soil surface from heat, drying and erosion
- OM is required to maintain soil quality
- Water is required for;
    - uptake of nutrients by roots
    - photosynthesis
    - leaf cooling
    - root growth
- Water stress decreases yield and nut quality

Soil pH

The pH (concentration of protons – hydrogen ions) of the soil is a master variable that affects chemical processes. Soils constituents have both positive charges and negative charges and the proportion of charges is controlled by pH. As soil pH decreases, the cation exchange capacity (CEC) decreases and the anion exchange capacity (AEC) increases; conversely, as the pH increases, the CEC increases and the AEC decreases (Brady and Weil 2008) (Figure 1). This clearly plays a role on the retention and availability of nutrients; at low pH cations (positive charge) are more likely to be leached and anions (negative charge) being retained.

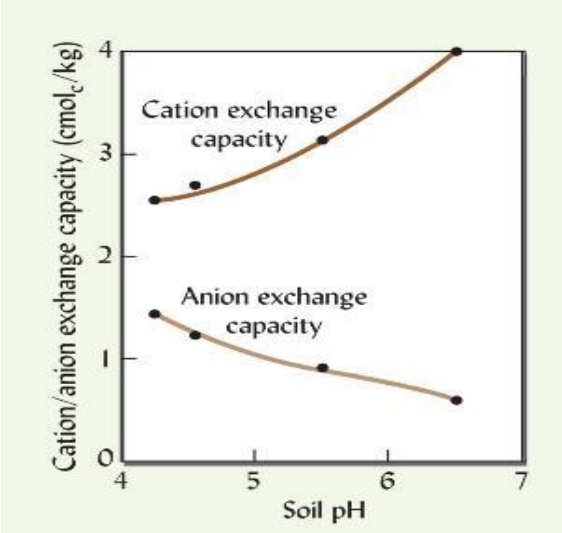


Figure 1 Generalised effect of soil pH on the cation and anion exchange capacity of a soil (Weil and Brady 2017).

Since pH is measured on a logarithmic scale, a one unit decrease in pH equates to a ten-fold increase in proton (H^+) concentration. The pH can be measured by different techniques, resulting in different numeric values. Most labs in Australia measure pH on a 1:5 soil suspension, using either deionised water (commonly denoted as pH water) or with 0.05 M $CaCl_2$ (commonly denoted as pH Ca). Samples suspended in 0.05 M $CaCl_2$ show a lower pH value (by approx. 0.7-0.8 units) than when suspended in water (Ahern et al. 1995; Aitken and Moody 1991) (Figure 2).

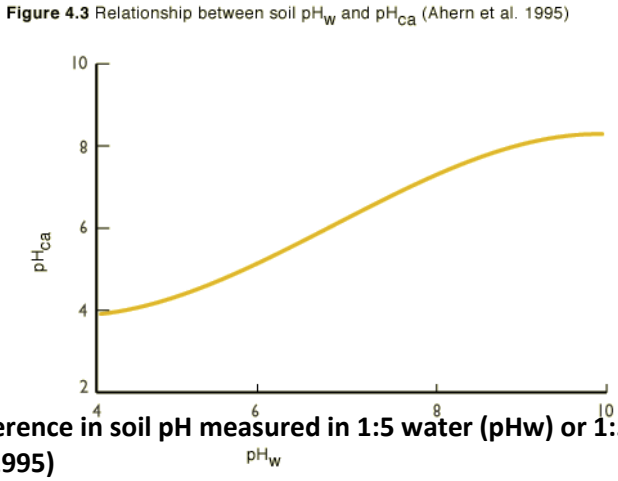


Figure 2. Difference in soil pH measured in 1:5 water (pHw) or 1:5 0.05M $CaCl_2$ (pHCa). After (Ahern et al. 1995)

The pH can affect the ability of plant roots to take up nutrients since the protons can compete with other cations such as potassium (K^+) for uptake (Marschner 1995). The pH below which adverse

effects can be expected is not clearly defined and depends on the susceptibility of the plant towards low pH, with macadamia being more tolerant to low pH than many other crop species (Stephenson et al. 1996).

At low pH, clay minerals dissolve, releasing aluminium (Al^{3+}) ions that are toxic to plant roots. The effect of pH on concentration of Al (due to dissolution of clay minerals) is pronounced at pHw < 5 (Figure 3) due to the fact that a one unit decrease in pH increases the Al concentration 1000-fold (Brady and Weil 2008). Thus, it is very important that the pH of the soil is not dropping below the critical value since even a "small" drop in pH can result in a large increase in Al. The main effect of Al ions is on the growth and root hair development (Blamey et al. 2015; Wehr et al. 2016). Root hairs increase the surface area of roots and are necessary for efficient uptake of nutrients. Plants subjected to Al toxicity have stunted root systems and lack root hairs, resulting in poor water and nutrient utilisation (Blamey et al. 2015; Wehr et al. 2016). In organic matter rich soils, Al can be immobilised, resulting in less Al toxicity than in soil at the same pH with low organic matter (Brady and Weil 2008).

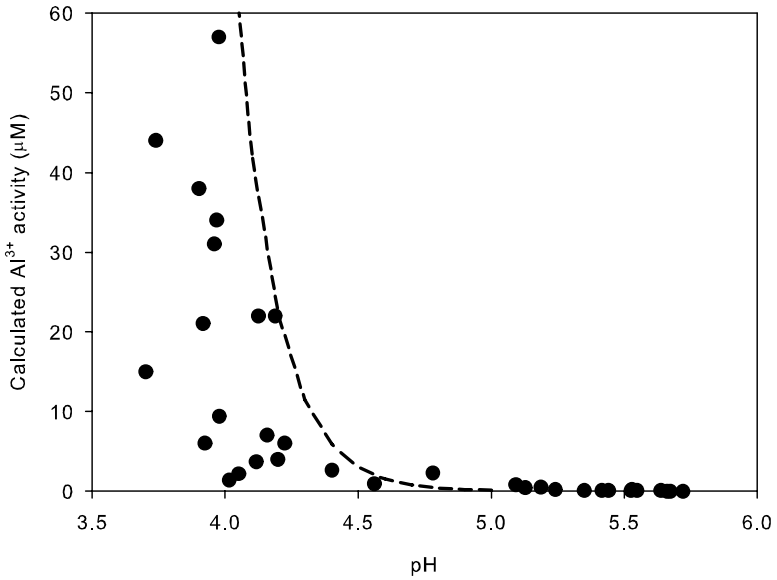


Figure 3. Change in Al availability (solubility) with soil solution pH (in water) in a Ferrosol. Taken from (Wehr et al. 2017)

The pH also affects the availability of phosphate and boron. Maximum P availability is around pH 6-6.5. At low pH, Al-phosphates precipitate and at higher pH, Ca-phosphates precipitate (Brady and Weil 2008) (Figure 4).

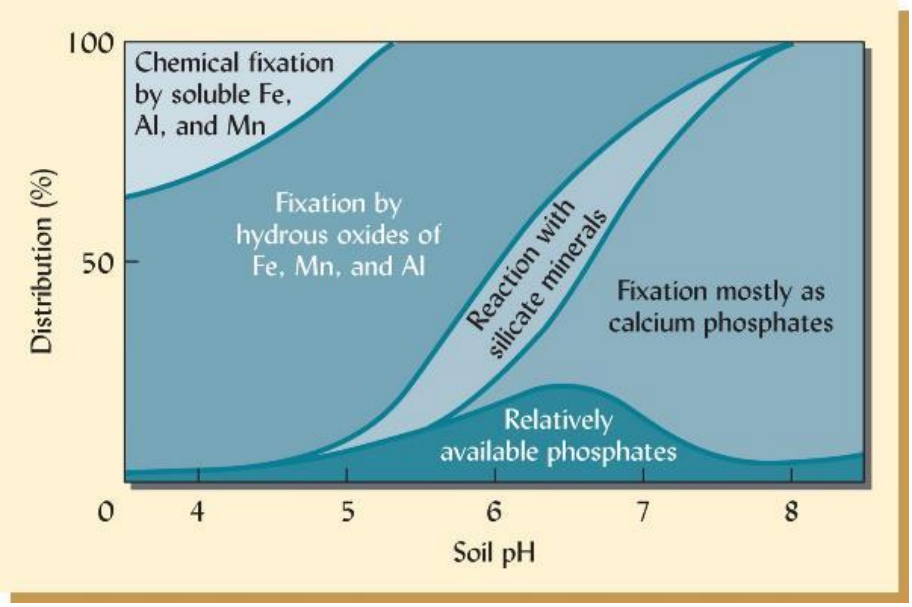


Figure 4. Effect of soil pH on the availability of phosphate and the various pools of fixed phosphates (from (Weil and Brady 2017))

Similar pH effects on availability of boron (B) is known (Figure 5). Adsorption of boron decreases as the pH becomes more acidic, thus availability increases at lower pH (Brady and Weil 2008).

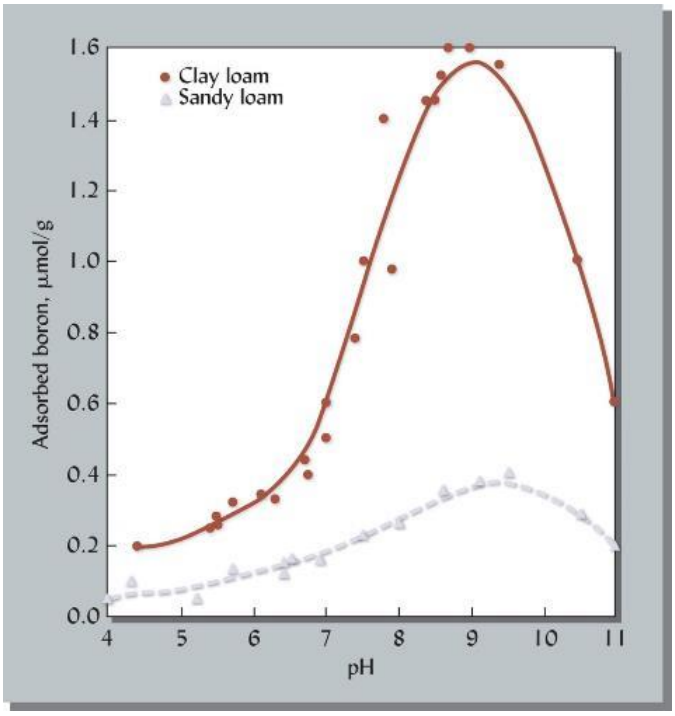


Figure 5. Effect of soil pH on the adsorption of boron in a clay loam and a sandy loam (Weil and Brady 2017)

Most other trace elements (apart from Mo) show a similar behaviour, i.e. solubility and plant availability increases with lower pH (Figure 6).

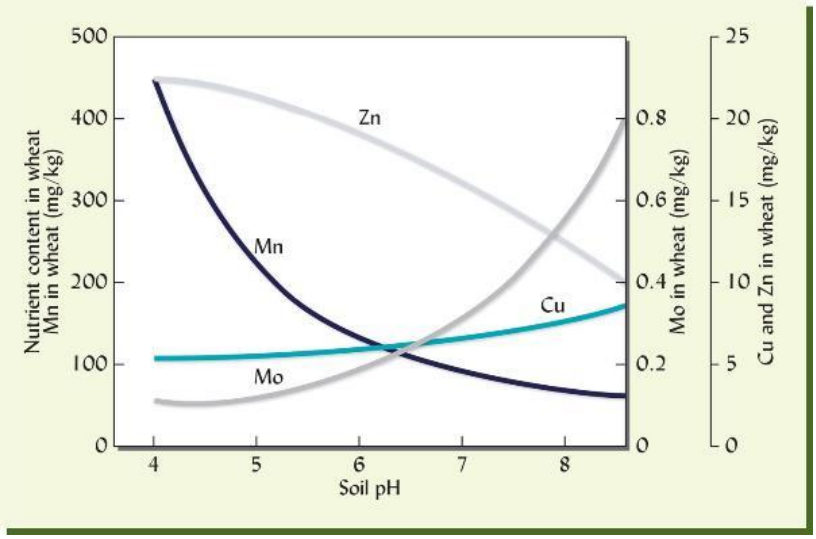


Figure 6. Effect of pH on the availability and uptake of trace elements, shown here for wheat (Weil and Brady 2017)

An effect of pH on soil microbial processes is also likely since microbes have their own pH optima. Fungi are generally more tolerant of low pH than bacteria and this shifts the potential for nutrient cycling in the soil. Litter-decomposing fungi are better at degrading wood and are responsible for nitrogen cycling from the woody debris at acidic soil pH whereas bacteria are inhibited (Weil and Brady 2017).

Soil pH naturally decreases over time in high rainfall regions. Rainfall is slightly acidic, resulting in soil acidification, but agricultural practices such as nitrogen fertilisation can also increase rates of soil acidification (Wehr et al. 2016). Since low pH (pHw <5) can increase risk of Al toxicity, liming is required to prevent acidification. Both calcitic limestone ($CaCO_3$) and dolomitic limestone ($CaCO_3/MgCO_3$) are commonly used liming materials, but movement of alkalinity (limestone) in soil is low when applied at low rates (Baigent and O'Brien 1987; Blamey et al. 2015; Stephenson et al. 1991) but organic matter may aid movement of lime into the subsoil (Firth and Loebel 1987). The pH adjustment of soil, and especially in the subsoil, needs to be performed during orchard preparation to ensure correct subsoil pH without affecting tree root growth. Soil tests will indicate when maintenance limestone rates are needed. Since macadamia trees are adapted to acidic soils, they have an optimum pH(water) of 5-6 or pH (CaCl2) 4.5-5.5 and heavy liming (to pH >6) will be detrimental to the root system of macadamia (Firth 1991; Shigeura et al. 1974).

Soil organic matter

Loss of organic matter from soil is common in macadamia orchards due to lack of ground cover under the trees. Organic matter is important to maintain soil structure and quality. A loss of organic matter often results in hard soil, forming a crust and having low water infiltration. Addition of mulch under the tree overcomes some of the problems, but surface applied organic mulch does not penetrate more than a few cm into the soil and requires physical incorporation. The presence of a "living mulch" such as a groundcover species is considered more beneficial to soil quality and decreases soil erosion (Cox et al. 2010; Dudgeon 2008; Reid 2002). The roots of the ground cover hold soil aggregates together and minimise raindrop impact. In contrast, a mulch layer only serves to minimise raindrop impact but does little to stabilise the soil (Cox et al. 2010) compared to a groundcover. A drawback of mulch or groundcover is that it may interfere with harvesting operations

and requires careful planning as to when mulch is placed under the trees. Finally, organic groundcover such a leaf litter, nut husk, manure or green cover contains a number of essential plant nutrients (Schafer 1987). When the groundcover slowly breaks down, the nutrients are released and taken up by the tree. Thus, organic mulch also acts as a slow release fertiliser for N, P and sulfur (S). In any case, the nutrients contained in the organic matter need to be accounted for in the fertiliser program to avoid over-fertilizing the trees.

Organic matter bought in as a form of manure, green mulch, wood chips, municipal compost requires quality control prior to placing in the orchard. Introduction of unwanted weed seeds is an obvious risk, but some organic matter sources may contain high concentrations of trace elements. In addition, the carbon : nitrogen ratio (C:N ratio) of the material needs to be determined to assess the risk of nitrogen drawdown and the rate with which the material degrades. Organic matter high in lignin will be more resistant to degradation, remain in the soil for longer but is also less beneficial for soil quality.

Soil organic matter is also important for soil microbes since they derive their energy from breakdown of organic matter (Cox et al. 2004). The microbes can have numerous beneficial effects in soil such as disease suppression, release of chelators that dissolve minerals, and release of phosphate compounds (Cox et al. 2004).

Finally, a layer of organic matter on the soil surface lowers the soil temperature, and the breakdown product of organic matter (humus) can increase soil structure, increase water infiltration and water holding capacity, increase the CEC and AEC and fertility. Indeed, several studies have shown that yield is greater under mulched trees than with bare soil (Firth and Loebel 1987; Newett 1987).

Soil erosion and soil compaction

Soil erosion is common on steep slopes and when the soil is bare. Soil erosion losses of up 20 t/ha have been suggested on steep slopes (Reid 2002). Steep slopes should best be avoided or a combination of wide tree spacing and tree height control options should be employed to allow living groundcovers to persist under the tree (Cox et al. 2010). Groundcovers are the most effective way in reducing soil erosion losses due to their root system. Soil erosion generally removes the topsoil layer of an orchard which is rich in nutrients (decomposing mulch and added fertiliser) and a loss of topsoil means a farming input is wasted. A clear sign of erosion soil losses are exposed structural roots under the tree (Cox et al. 2010) (Figure 7).

Figure 7. Sheet erosion in a macadamia orchard resulting in exposure of roots (R. Commens, AMS)

Soil compaction is likely to occur in the inter-rows due to farming machinery. Compacted soil has a higher bulk density and plant roots are often unable to penetrate soil with a bulk density of > 1.6 g/cm^3 (Shierlaw and Alston 1984). Therefore, compacted soil in the inter-row is likely to restrict root growth, limiting water and nutrient uptake from the inter-row. Soil compaction cannot be avoided in orchards but precautionary measures should be taken to minimise potential for compaction by using large tyres and minimise orchard operations when the soil is wet.

Soil water availability

Water availability in soil affects the growth of plant roots and nutrient uptake. Nutrient uptake requires a (very thin) water film between the root surface and soil particles. In dry soil, the movement of nutrients from the soil to the plant root and into the plant root is impaired. In drier soil, the length of the path of diffusion of nutrients is increased, uptake of nutrients such as K and P is decreased (Brady and Weil 2008). On the other hand, excess of water is also detrimental. During waterlogging, the soil can become anaerobic, resulting is dissolution of iron and manganese mineral and toxicities of these metals, which is especially pronounced on Ferrosols.

Soil moisture is also important for photosynthesis and leaf cooling. Lack of water results in stomatal closure, decreased photosynthesis and increased leaf temperature. This will decrease available photosynthates, resulting in decreased shoot and root growth and may impair flowering, nut set and nut filling (Stephenson and Gallagher 1986; Stephenson and Gallagher 1987b; Stephenson et al. 2003; Trochoulias and Lahav 1983). Therefore, water stress during critical periods needs to be avoided (Figure 8).

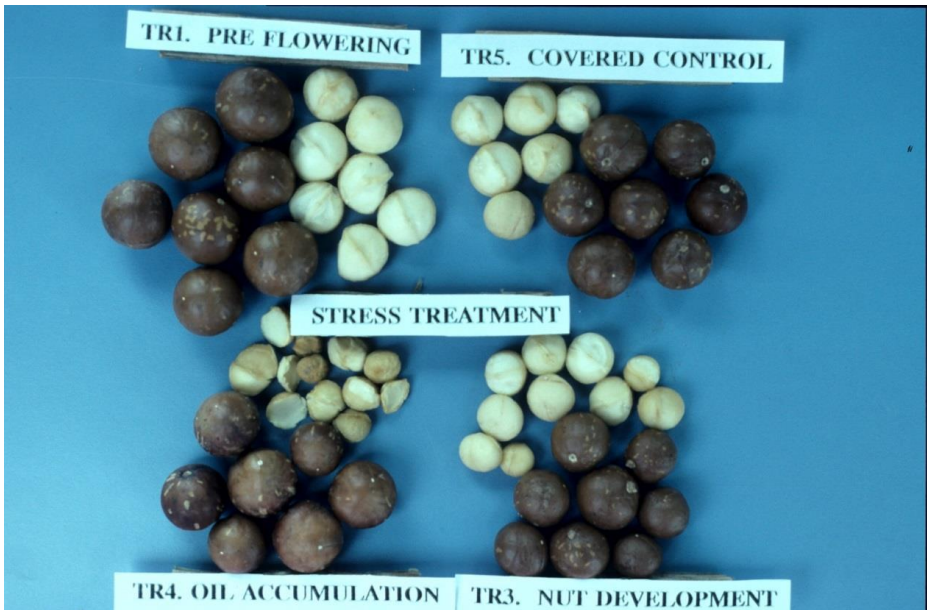


Figure 8. Effect of water stress during various periods of nut development on the size and quality of macadamia nuts (R. Stephenson, DPI)

Soil water availability can be ensured by irrigation but the quality of the wetting area needs to be considered. The wetted area should be large enough to encourage roots to extract nutrients and water from the soil. Sprinkler irrigation systems are preferable since they have a greater area of coverage than drip emitters (Figure 9).

Figure 9. Wetted area under macadamia trees with drip irrigation and sprinkler irrigation (Images: B.Wehr)

The physiology of macadamia trees

Key points:

- Macadamia is a rainforest tree adapted to acidic soil
- High temperature (>36°C leaf temperature) is detrimental to macadamia growth
- Adapted to low fertility soils by specialised root system

The macadamia is a member of the family Proteaceae with seven species of this genus native to Queensland and northern NSW (Gross 1995). Two species (*Macadamia integrifolia* and *Macadamia tetraphylla*) and several hybrids and cultivars of these species are used for commercial production of macadamia kernel. The native habitat of the tress is in subtropical sclerophyll and remnant rainforests at low altitudes (Gross 1995; Stanley et al. 1983) and prefers partially open areas such as rainforest edges (Ryan 2006). High nutrient alluvial and volcanic soils predominate, often with considerable exposure of rock fragments or substrate, mostly basalt and diorite. The surface soils are uniformly dark, slightly acid (pH 5.5–6.5), well drained and varying in texture from clayey-sand through various loams to silty-clay (Anonymous 2017). Vegetation communities in which macadamia is found range from complex notophyll mixed forest, extremely tall closed forest, simple notophyll mixed very tall closed forest to simple microphyll-notophyll mixed mid-high closed forest with *Araucaria* and *Argyrodendron* emergents Anonymous (2017).

Its habitat helps elucidate some of the requirements for cultivation. It is a tree that is growing in cooler, partly shaded conditions in areas with frequent rainfall and leaf litter on the ground in soils rich in organic matter. As such macadamia can tolerate low phosphorus (P), acidic soil and overcomes the risk of nutrients leaching from soil by storage of nutrients in the tree structure, in common with typical rainforest ecosystems. Research has shown that macadamia can utilise both ammonium (NH_4^+) and nitrate (NO_3^-) nitrogen forms (Fletcher et al. 2010), typical of acid tolerant plant species. Macadamias have a shallow root system, are adapted to rapid nutrient cycling from decomposing litter and can take up low concentrations of nutrients.

A further characteristic of its habitat is that photosynthesis is severely impaired if air and leaf temperatures are >36°C (Huett 2004; Stephenson and Gallagher 1986; Trochoulias and Lahav 1983), in keeping with its evolution in subtropical rainforests. Thus, macadamia plantations established in hotter and drier areas may suffer during heatwaves and under conditions of water stress. Stress results in lower nut set, nut size or quality, when photosynthesis is impaired during critical stages of nut formation.

The importance of the root system quality and root volume to macadamia

growth

Key points:

- Quality of root system is very important for water and nutrient uptake
- Most cluster roots and fine roots found from the surface to 15 cm below the soil surface
- Cluster roots are inhibited by high P and N fertilisation
- Cluster roots are not an indicator of tree or root health
- The presence of fine roots and the absence of exposed structural roots at the soil surface are more suitable indicators of tree and root health

An adaptation of Macadamia to poor soil is the development of cluster roots (also known as proteoid roots) (Figure 10). These are short, very dense root masses, produced laterally on the normal roots and heavily invested with root hairs (Lambers et al. 2008). They are formed mainly in the leaf litter layer during seasonal growth flushes, usually shrivelling at the end of the season to be replaced again next year (Schafer 1987).

Figure 10. Fine roots (left) and cluster (proteoid) roots of macadamia (Images: B.Wehr, R. Stephenson). The cluster root on the right is backlit.

The fine roots and cluster roots aid the uptake of scarce nutrients from low-fertility soil and intercept nutrients from the decomposing litter. The fine roots and cluster roots are short lived (several days) and the large root surface area and release of citric acids aids in mobilisation of P from soil (Shane and Lambers 2005). The signal for cluster root formation comes from the leaf in response to a deficiency of phosphorus (P) and nitrogen (N). Thus, a macadamia tree well supplied with N and P may not form cluster roots (Aitken et al. 1993; Hue 2009a; Shane and Lambers 2005). On the other hand, a severely stressed tree may not have enough energy reserves to develop an extensive root system, which then leads to tree decline (Landsberg 1987). Therefore, a good root system is imperative for a healthy and productive tree. Indicators of a healthy root system are the presence of fine roots and the lack of exposed structural roots.

The majority of plant nutrients are taken up actively from soil via plant roots. Roots need to grow continually to explore the root zone for nutrients since most nutrients are too immobile to be transported to the root by water flow (more detail later). Therefore, roots need to grow towards to the source of nutrients. Plants which develop an extensive (and thus highly branched) root system can explore a greater volume of soil for water and nutrients. A decrease in the soil volume (either by soil drying, diseases, compaction, or erosion) will decrease availability of nutrients to the plant.

The roots of macadamia trees are spatially inhomogeneous (Firth et al. 2003; Stephenson 2004) and fine roots (<1 mm diameter) are found in greatest numbers close to the stem and decrease exponentially with distance from the stem (Figure 11).

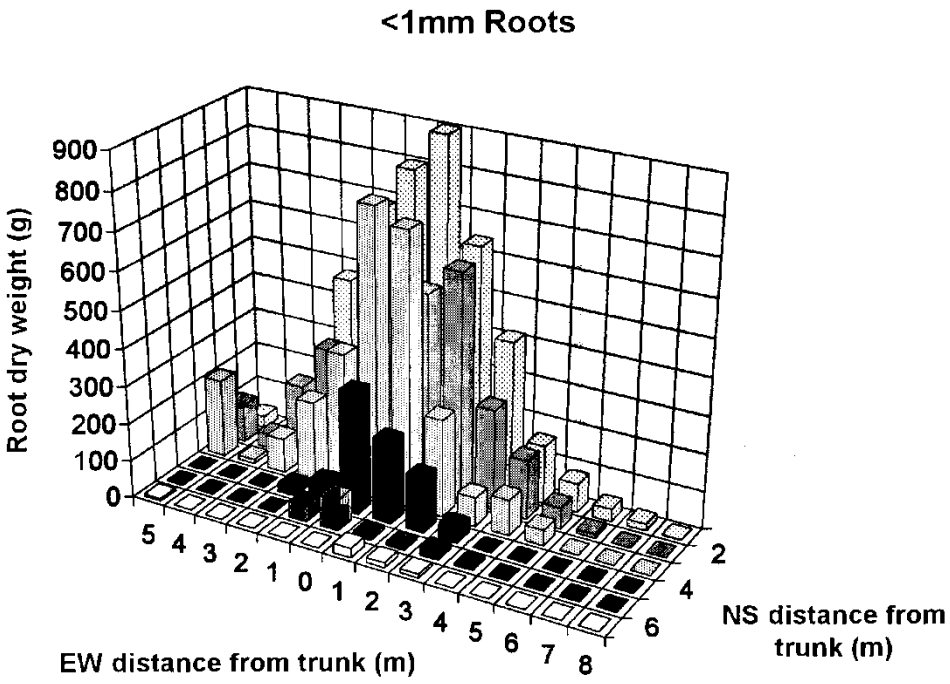


Figure 11. Distribution of fine roots around the stem of an orchard grown macadamia tree (R. Stephenson, DPI, unpublished)

Likewise, fine roots are found mainly in the top 30 cm and decrease with depth. Interestingly, one study found that unhealthy orchards have more cluster roots in the topsoil layer than healthy orchards (Figure 12). Thus, cluster root distribution in the surface soil alone should not be used as an indicator for soil /orchard health. Cluster roots in the topsoil may in early stages indicate soil constraints in the subsoil and/or a nutrient deficient tree, which will eventually lead to tree decline and lack of roots.

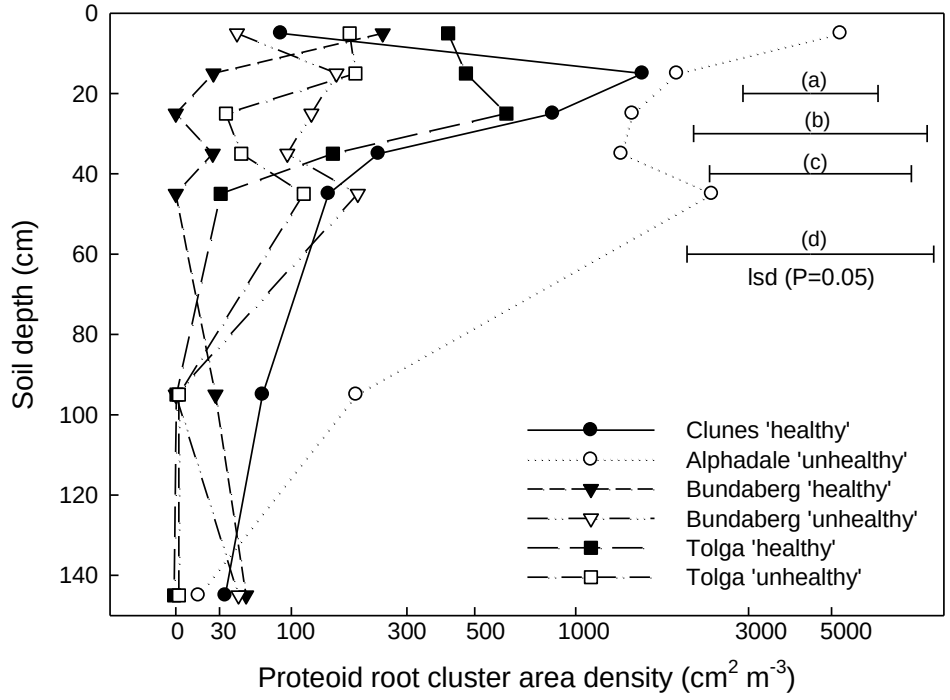


Figure 12 Proteoid root cluster area density from macadamia, cultivar HAES 344, trees at paired healthy and unhealthy sites in New South Wales (Clunes 'healthy' and Alphadale 'unhealthy'), Bundaberg, and Tolga at 10cm increments down the soil profile. lsd (P=0,05) for comparing: (a) means within Alphadale, (b) means within any other site, (c) Alphadale mean compared with mean of any other site, (d) means from any two sites other than Alphadale (Image: R. Stephenson, DPI, unpublished)

Aspects of mineral nutrition of macadamia

Key points:

- Uptake of nutrients is an active process, i.e. requires energy and is controlled by the plant
- Phosphate is immobile in soil and is taken up by diffusion, requiring a large root system
- Foliar tissue concentrations change over seasons

The mobility of nutrients in soil and the uptake by roots

Plant nutrients can be classified as cations (positively charged) or anions (negatively charged). Essential cations include calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and ammonia (NH_4^{+}), whereas sulfate (SO_4^{2-}), nitrate (NO_3^{-}), and phosphate (PO_4^{3-}) are anions. Depending of the chemical properties of the nutrients, they are either weakly adsorbed by soil minerals (SO_4^{2-}, Mg^{2+}, NO_3^{-}) or strongly adsorbed (PO_4^{3-}, Ca^{2+}, Al^{3+}) (Marschner 1995).

Ions that are weakly held can move to the plant root by mass flow (e.g. Mg^{2+}), that is movement in water as it flows to the root. Strongly held ions are not moving with mass flow but rely on diffusion (e.g. K^{+}, PO_4^{3-}) (Figure 13). The relative contribution of mass flow and diffusion to nutrient uptake is species dependent, and has not been researched in macadamia. Extrapolating from other species, it can be assumed that K^{+} and PO_4^{3-} will be transported to the root by diffusion. Ions relying on mass flow (NH_4^{+}, Ca^{2+}, Mg^{2+}) are taken up when water availability is greater, but ions taken up by diffusion (K^{+}, PO_4^{3-}) are favoured by root systems with a large surface area (i.e. branched and with root hairs) (Table 1).

Uptake of nutrients requires energy expenditure by the plant root. Thus, nutrient uptake is also impaired in cold or waterlogged conditions since these conditions affect the ability of the root to generate energy required for nutrient uptake (Lambers et al. 2008).

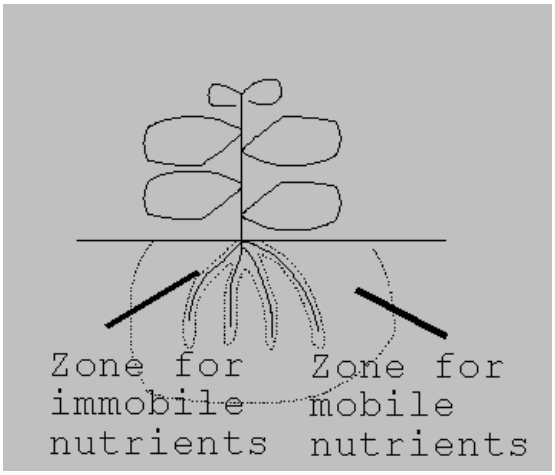


Figure 13. Schematic presentation of nutrient uptake zones for immobile and mobile nutrients (M. Goss, Uni Guelph)).

Table 1. Approximate proportion of nutrients taken by various pathways (Lambers et al. 2008). Two ticks denote that the majority of the nutrient is taken up by the pathway, one tick denotes that less than half of the nutrient is taken up by the pathway and no tick implies that an insignificant amount is taken up by the pathway.

Nutrient	taken up by interception	taken up by mass flow	taken up by diffusion
Nitrogen		✓✓	✓
Phosphorus			✓✓
Potassium		✓	✓✓
Calcium	✓✓	✓✓	
Magnesium	✓	✓✓	
Sulfur		✓✓	
Copper		✓✓	
Zinc		✓	✓✓
Boron		✓✓	
Iron		✓	
Manganese		✓✓	

Interaction between nutrients for uptake

The similarities between certain ions can result in competition at the plasma membrane for uptake (ion antagonism). Thus, high concentrations of ammonium ions can inhibit uptake of K^+, Ca^{2+} and Mg^{2+}; K^+ and Ca^{2+} can inhibit Mg^{2+} uptake; and Mn^{2+} inhibits Mg^{2+} uptake (Marschner 1995). Furthermore, high PO_4^{3-} rates can affect Fe^{2+} and Zn^{2+} uptake by precipitation of the elements in the vacuole of the plant. The possible interaction between nutrients is represented in the Mulder diagram (Figure 14).

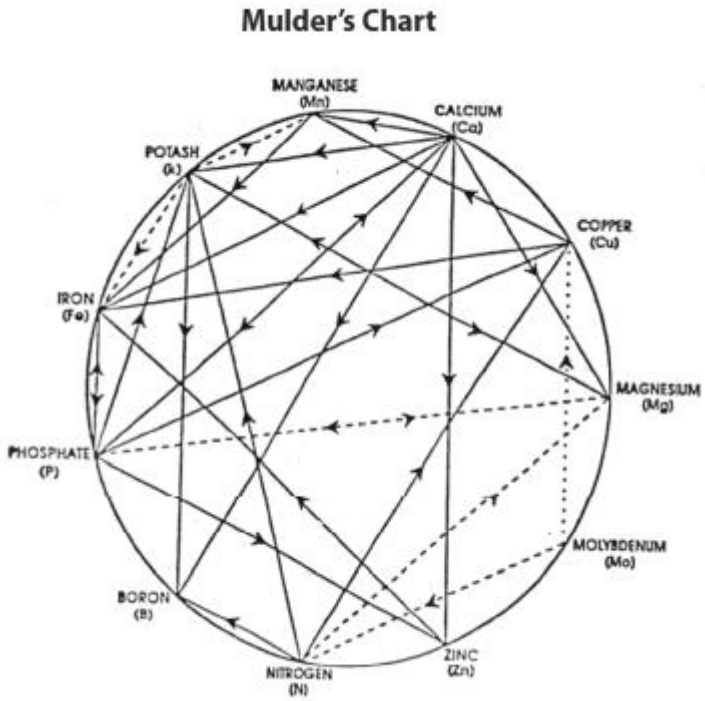


Figure 14. Mulder diagram showing interaction between nutrients for uptake in hydroponic solutions. Elements connected by solid lines represent inhibition of uptake (antagonism), dotted lines represent stimulation of uptake (synergism).

Uptake of charged ions by plant roots would impart a charge to the plant. Therefore, the charge of the take-up ion needs to be balanced or off-set. This can be achieved by the plant root by releasing protons (H^+) or hydroxyl ions (OH^-), e.g. NH_4^+ uptake induces release of H^+, and uptake of NO_3^- releases OH^- ions (Marschner 1995). Positive interactions (ion synergism) between ions for uptake have also been observed, e.g. for Mg^{2+} stimulation of PO_4^{3-} uptake or Ca^{2+} stimulation of K^+ uptake (Marschner 1995). Apart from direct interactions between ions at the plasma membrane, indirect interactions can also take place due to changes in nutritional status (e.g. NO_3^- inhibition of Cl^- uptake) and NO_3^- suppression of NH_4^+ uptake (Lambers et al. 2008). The details of these interactions are beyond the scope of this review and are often species specific.

Role of nutrients for growth and yield in macadamia

The nutrients most important for tree growth and nut yield are N, P, K, and B and Zn. While other nutrients are also essential for macadamia trees, they are rarely deficient in well managed orchards in eastern Australia. Foliar nutrients change with both leaf age and during the season (Figure 15). Furthermore, leaf nutrients are affected by irradiation of the leaf - sun-exposed leaves have higher transpiration (and uptake of nutrients) than shade-exposed leaves.

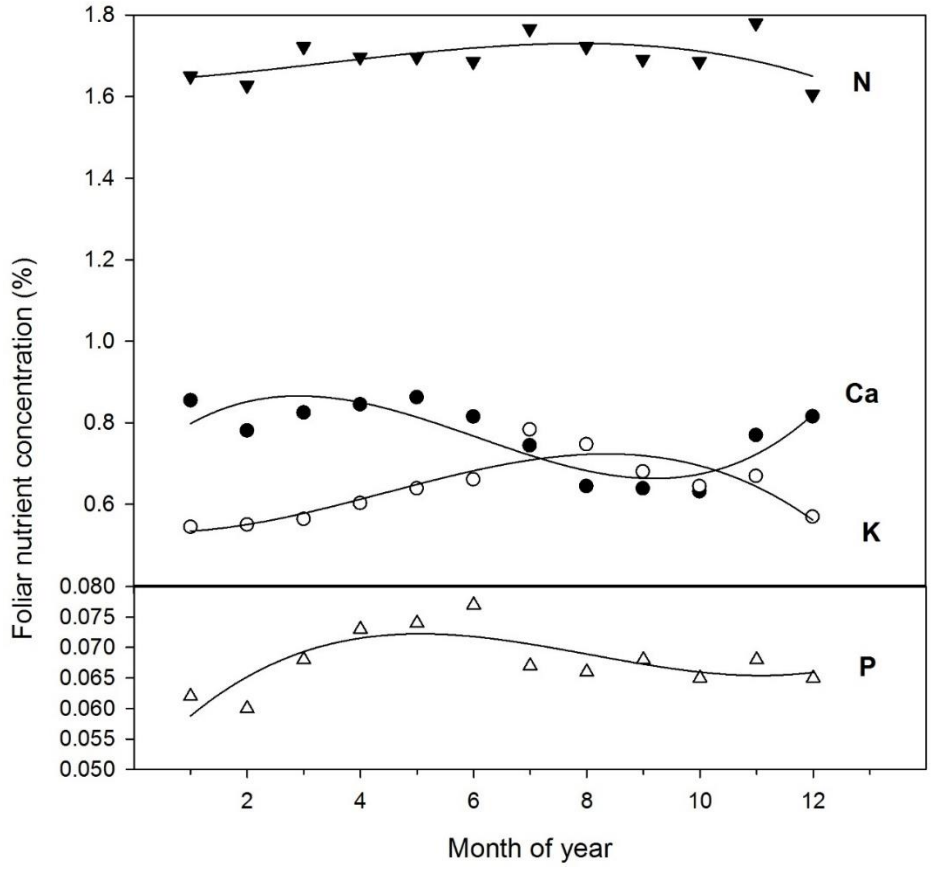


Figure 15. Monthly changes in foliar concentrations of nitrogen (N), calcium (Ca), potassium (K) and phosphorus (P) in macadamia foliage. Values are means of several cultivars grown in several regions and over three years and are taken from Huett and Vimpany (2007) for N, Ca and K, and from Stephenson and Cull (1986) for P.

Nitrogen is required for the production of enzymes and the photosynthetic apparatus. Nitrogen is highly mobile in the plant and concentrations are higher in young leaves than in old leaves and peak in spring time (Figure 15). High N levels encourage vegetative growth in trees (Nagao and Hirae 1992), which can be overcome by applying N in small frequent applications. Macadamia take up NH_4^+, NO_3^- and organic nitrogen forms (Fletcher et al. 2010; Nasholm et al. 2008). Nitrate utilisation by the trees requires energy to reduce NO_3^- to NH_4^+ (Lambers et al. 2008). Nitrogen should be applied in late spring prior to nut growth and in autumn to produce a healthy leaf flush which is required for carbohydrate production during winter (O'Hare et al. 2004). Increased N fertilisation does not increase nut set (Fletcher et al. 2010), whereas Perdona et al (2013) found that split application of N (total 150 kg N/ha) increased nut yield. Optimum levels of foliar N should be around 1.3% (Stephenson et al. 1997) to 1.4% (Perdona et al. 2013), while Huett and Vimpany (2007) recommended 1.4-1.7%. Cultivar specific differences in optimum leaf N were suggested with cultivar 660 having a higher tissue N (1.5%) (Pire et al. 2002) and cultivar 344 having an optimum foliar N of 1.6-2.0% (Huett and Vimpany 2007).

Phosphorus is required for cellular energy production and cell division. The requirement for P in macadamia is comparably low and decreases with leaf age and varies through the growing season with the highest foliar concentration observed in autumn (Stephenson and Cull 1986) (Figure 15). For older leaves, tissue concentration of 0.08% are considered sufficient (Huett and Vimpany 2007;

Stephenson and Cull 1986). High rates of P fertiliser can induce deficiency of Zn and Fe since Zn-P and Fe-P can precipitate in the cell (Aitken et al. 1992; Hue 2009a; Newett 1987; Warner and Fox 1972). Furthermore, high P rates inhibit formation of proteoid roots (Hue 2009b) and the suppression of cluster root formation comes from a leaf-derived signal in P-sufficient trees (>0.1% P) (Shane and Lambers 2005). Phosphorus is strongly bound in soil, especially Ferrosols, requiring application of P in bands in the soil to minimise P fixation (Hue et al. 1988) and applied P slowly becomes unavailable in soil.

Potassium is required as an osmoticum (regulates water content) in cells and is involved in many enzymatic processes as enzyme activator. Foliar K shows a maximum concentration in winter in Qld (0.8%) and a minimum of around 0.5% in February (Stephenson and Cull 1986; Stephenson et al. 1986) (Figure 15). Potassium can be transported from old leaves to young leaves, resulting in deficiency symptoms being shown mainly on older leaves as necrosis (dead tissue) of leaf edges and interveinal regions. Macadamia husks are high in K (Nagao and Hirae 1992) and can meet some of the K demand of the trees.

Boron is a trace element required for cell wall binding (pectin binding in the primary cell wall of all shoots and roots) (Ishii et al., 1999), pollen germination and germ tube growth (high pectin content), and is also required for seed development (Smith 1997a). In B-deficient orchards, seed set is severely decreased since pollen tube formation is blocked and overcoming B efficiency increased NIS yield, kernel weight and first grade kernel in cultivar 246 (Stephenson and Cull 1986; Stephenson and Gallagher 1987a). However, B toxicity is not uncommon and can result from excessive B application either through foliar sprays or from high B irrigation water. Foliar concentrations > 100 ppm in YFEL can lead to tree defoliation and death, and shoot and root growth starts to decline. The optimum foliar B levels were considered to be around 40-100 ppm in macadamia seedlings (Fox and Hue 1989), but research is required to determine the optimum range for nut yield and quality. By comparison avocados have a critical YFEL B of 46 ppm for fruit size (Smith 1997b) and an optimum range of 40-60 ppm for shoot growth.

Zinc is an immobile trace element which is required for photosynthesis and phytohormone (auxin) metabolism. Therefore, foliar Zn levels depend on the leaf age, with Zn being low in youngest expanding leaves, indicative of Zn uptake in the youngest fully expanded leaves (approximately 8 weeks old), and accumulating in older leaves. The recommended optimum Zn levels vary, with 6-15 ppm Zn in 3 month old leaves in spring considered adequate (Workshop 6, 2004; (Huett and Vimpany 2007)). Huett and Vimpany (2006) found that little soil applied Zn is taken up by the tree compared to foliar applications. Like P, Zn can also be strongly bound in soil, and banded (concentrated) soil applications are preferable to broadcast applications. Plants deficient in zinc will have small leaves and short internodes on the youngest growth, while old leaves are unaffected since Zn cannot be exported from old leaves to the shoot tip (Huett and Vimpany 2006; Marschner 1995). Zinc deficient trees also have a mottled interveinal chlorosis of younger leaves due to the Zn requirement for photosynthesis.

Nutrition of macadamia orchards

Key points:

- Foliar sampling is more valuable than soil sampling – direct indication of nutrient uptake by tree roots
- Foliar samples should be collected in the upper 1/3 of canopy from sun-lit leaves from the 2nd or 3rd whorl.
- Foliage needs to be thoroughly rinsed to remove dust and pesticide residue
- Soil should be sampled to 0-10 and 10-20 cm depth initially to compare results.
- Occasional soil sampling to >20 cm is needed for identification of developing soil constraints
- Soil and foliar samples should be collected along a fixed transect, with 20 soil samples and foliage from 20 trees making up one combined soil or foliar sample for the block.
- Soil nutrient concentrations vary between soils and cannot be compared between orchards
- Soil cation ratios should not be relied upon, growth may be affected by toxicities or deficiencies of a nutrient rather than a perceived imbalance of the cation ratios
- Foliar nutrient concentrations vary slightly between soil types but this may rather reflect differences in management (fertiliser applications) between soil types.
- Foliar nutrient concentrations vary slightly between cultivars
- Fertiliser applications of N should be applied in several split applications, and placed under the dripline of the tree.

Importance of sampling strategies for fertiliser recommendations

Recommendations for fertiliser applications can be based on available nutrients in soil, and/or nutrients in the plant foliage. Foliar nutrient analysis is more commonly used for perennial crops and is based on the interpretation of nutrient concentrations in certain plant parts. Since foliar nutrient concentrations are determined by the plant nutrient demand, i.e. under control of active plant uptake, foliar nutrient concentrations vary only slightly for trees grown on different soil types. Since roots spread over a considerable distance, nutrients are taken up over the whole root zone and thus foliar nutrients integrate the nutrient availability of the whole root zone and give a very good indication of nutrient availability, but are a poor predictor of future nutrient supply ability. Critical deficiency concentrations are known for some nutrients for macadamia and a large body of information is available for adequate foliar nutrient concentrations. Therefore, foliar nutrient analyses are the best method to determine plant nutrient status and fertiliser applications. Foliar nutrient concentrations vary with age of the leaf, and the phenology of the tree. Therefore, it is necessary to standardise the time of sampling in terms of age or phenology (i.e. after flowering, after flushing, etc.). For the correct identification of foliar nutrient levels, past research has identified that:

Foliage should be collected from the upper sun-lit part of the canopy

> Since sunlit foliage will transpire more water than shade-leaves, it is important to collect only sunlit leaves, otherwise, foliar nutrient concentrations cannot be compared to standard values.

Foliage should be collected from the youngest fully expanded mature whorl (Second or third whorl from the tip), i.e. around 8 weeks old

> Leaf nutrient concentrations change with leaf age (e.g. K and P decrease with age, Ca and Si will increase with age). Therefore, it is important that leaves of the correct age are collected and compared to standard values of the same leaf age.

Foliage should be consistently collected after nut maturity (i.e. after nut growth and oil accumulation) and prior to bud initiation (between Feb and April in most regions).

> The timing of the year needs to be standardised for foliage collection. Since macadamias grow in flushes, whole-tree nutrients may decrease during a growth flush or during nut formation and increase during the recovery period. Figure 15 shows the change in foliar nutrient levels with month of the year and requires that foliar concentrations are adjusted when using other sampling times.

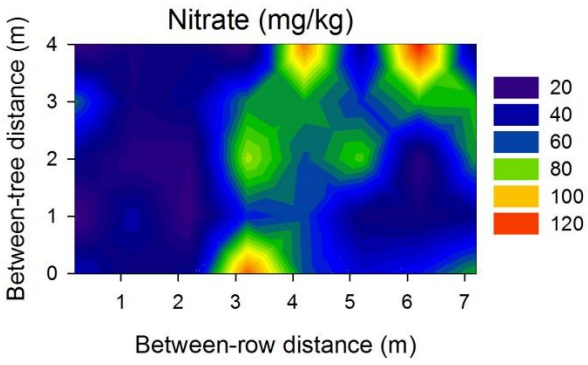
Foliage should be free from insect damage or other abnormalities

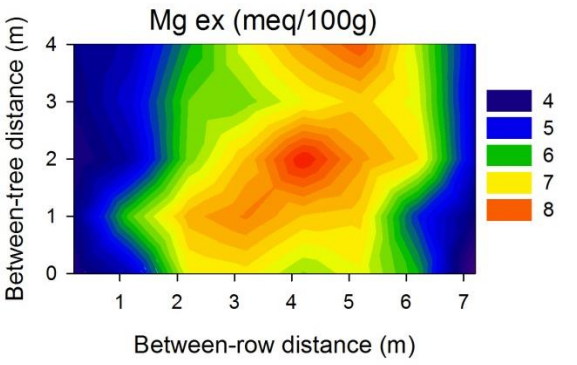
> Leaves with visible damage should be avoided. Insect damage may affect foliar nutrient levels and environmental damage (e.g. sunburn) will affect nutrient levels.

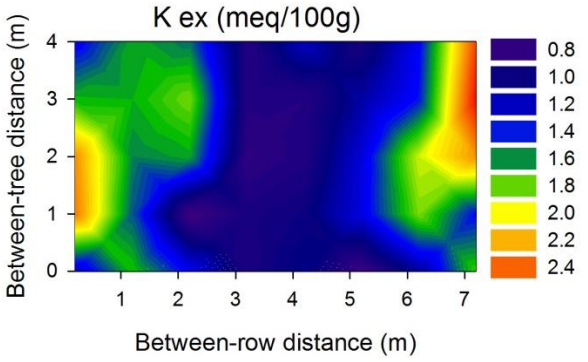
Foliage needs to be thoroughly rinsed in deionised water

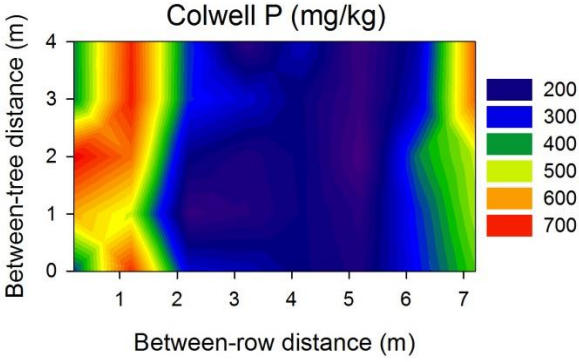
> Foliage contaminated with dust or agricultural chemicals will affect measurements. Dust can be raised during orchard operations (blowers, sweepers), and agricultural chemicals (e.g. fungicides) can contain nutrients. These contaminants will increase measured nutrient levels of leaves, but since these nutrients are attached to the outside of the leaf, they are not plant available.

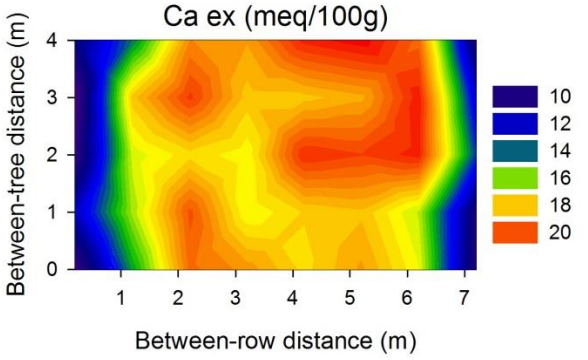
Soil analyses can also be used for fertiliser recommendations. Soil analyses will indicate the future supply of nutrients to the plant, but will not indicate if the nutrients are available for plant uptake. For instance, Krasnozem soils (Ferrosols) will have high concentrations of Fe minerals, but these minerals are not plant available. Therefore, it is necessary to have field calibration data that can be used to relate soil nutrients to plant nutrient uptake. The field calibrations need to be conducted for each soil type and this information is not available for Australian macadamia orchards. Additional concerns are that nutrients are not evenly distributed in orchards. Due to strip application of fertiliser and mulch, and changes in nutrients with soil depth, no standardised approach (standard sampling points, e.g. dripline) to soil sampling can be recommended (Figure 16). The high spatial variability in soil nutrients explains the often observed lack of relationship between soil and foliar nutrient levels and poor response between soil and foliar nutrients and fertiliser applications. Therefore, growers should base their fertiliser programs on foliar rather than soil analyses, but use soil analyses to identify soil constraints such as nutrient build-up, nutrient run-down, and trends in pH.

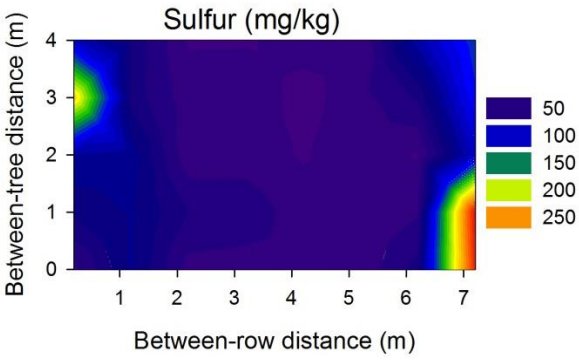

Nitrate (mg/kg)
Between-tree distance (m)
Between-row distance (m)
20
40
60
80
100
120

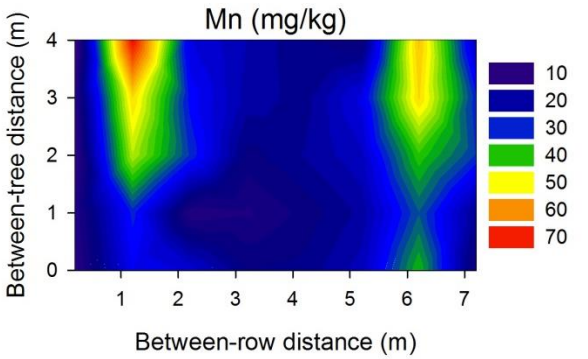

Mg ex (meq/100g)
Between-tree distance (m)
Between-row distance (m)
4
5
6
7
8

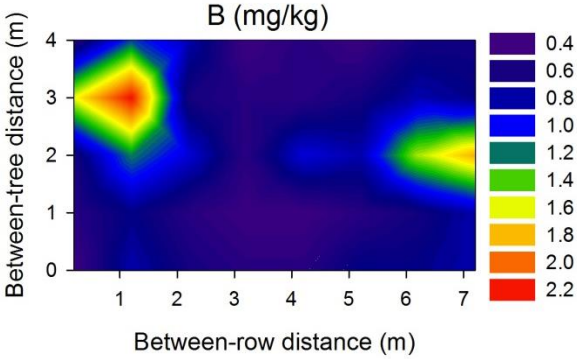

K ex (meq/100g)
Between-tree distance (m)
Between-row distance (m)
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4


Colwell P (mg/kg)
Between-tree distance (m)
Between-row distance (m)
200
300
400
500
600
700


Ca ex (meq/100g)
Between-tree distance (m)
Between-row distance (m)
10
12
14
16
18
20


Sulfur (mg/kg)
Between-tree distance (m)
Between-row distance (m)
50
100
150
200
250


Mn (mg/kg)
Between-tree distance (m)
Between-row distance (m)
10
20
30
40
50
60
70


B (mg/kg)
Between-tree distance (m)
Between-row distance (m)
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2

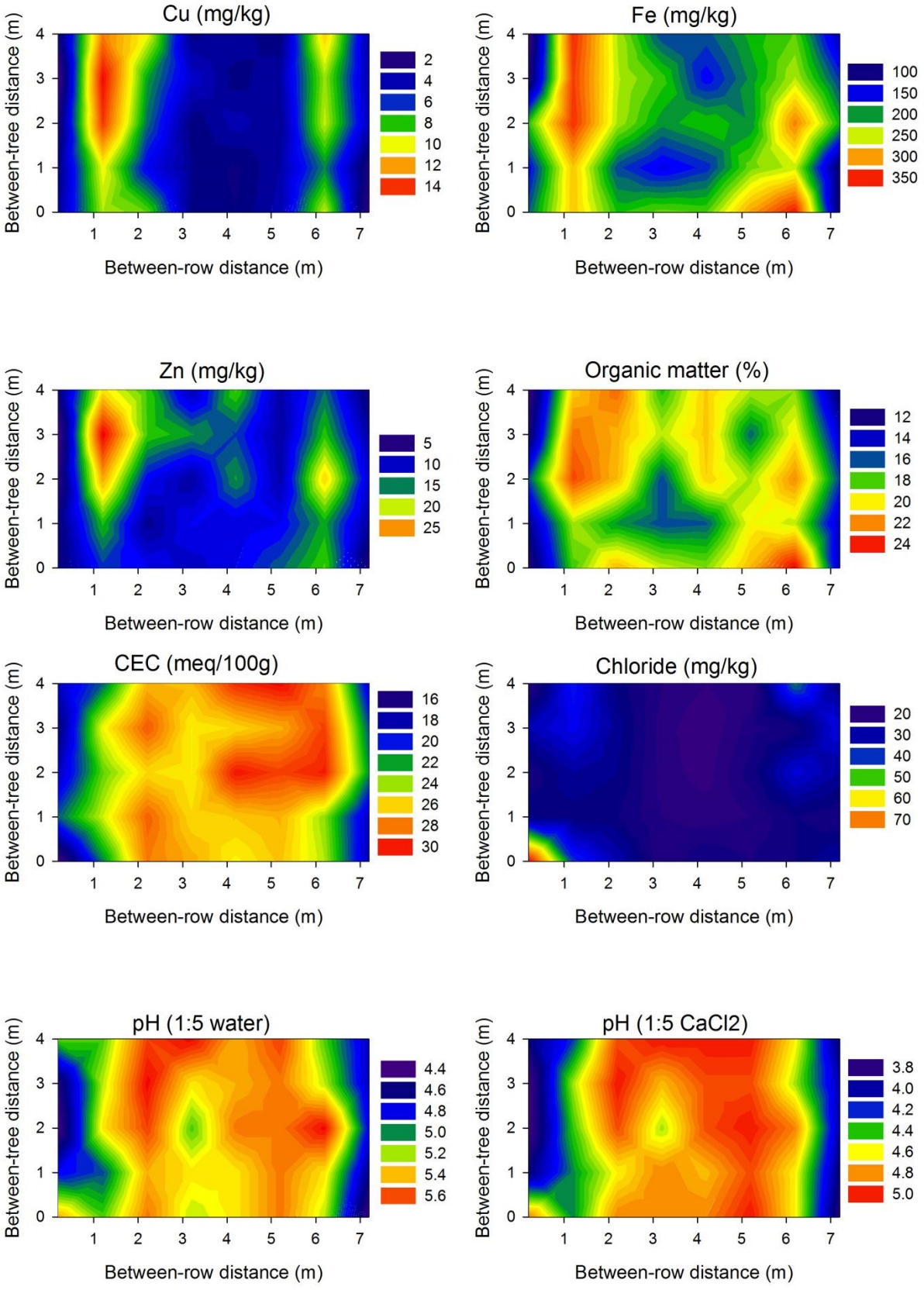


Figure 16. Spatial variation in soil nutrient characteristics in a macadamia orchard in Maleny QLD. Sampling was conducted on a square-metre grid with the four corners representing single trees. The orchard was 17 year old, and planted with 4 x 8 metre spacing on a Ferrosol. Samples were taken from the topsoil layer (0-10 cm depth) of an orchard last fertilised four months before sampling.

Sampling sites and recommended protocol

The selection of sites for soil and foliar sampling across an orchard is subject to intense debate. Nutrient inputs in orchards are localised and concentrated in certain areas of the orchard (e.g. under the tree, or near dripline in fertigated orchards, fertiliser bands, and low inputs in the interrow). This affects the location of soil samples more than foliar sampling. The oil-palm industry was facing a similar dilemma to the macadamia industry with localised inputs, and has suggested a sampling routine using fixed transects (Nelson et al. 2015) that could be adapted to macadamia orchards (Figure 17a). By using a fixed transect across four rows, with ten samples taken per transect, it is possible to reduce variability in sample composition. At least two transects i.e. 20 samples (leaf and soil), are pooled per management unit (orchard/variety/soil type) to produce one composite leaf or soil sample for analysis. This approach will slightly increase the time required to take samples, but will not increase analytical costs, but greatly increase the reliability of the results. Furthermore, the fixed transect overcomes possible changes due to the trees increasing in size, canopy closure, changes in inter-row management since the whole orchard floor is sampled randomly (Figure 17b). Soil should be sampled initially in 0-10 and 10-20 cm increments to obtain comparable results with the commonly used 0-10 cm sampling. Once sufficient data have been collected for 10-20 cm layer, correlations can be made between soil and foliar levels to further refine the optimum sample depth, given that feeder roots are prolific throughout the 0-20 cm depth. Sampling to greater depth (e.g 30 cm) is more time consuming and adds little information for routine nutrient management, but may help to identify developing subsoil constraints. Foliar sampling will also be conducted along the same transect (Figure 17 a).

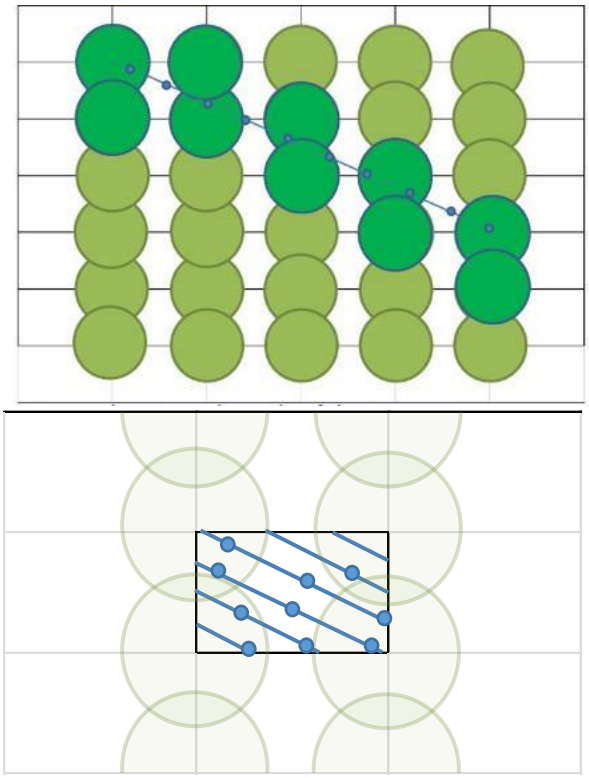


Figure 17 (a). Suggested soil and foliar sampling strategy for macadamia orchards. It is recommended to follow a theoretical transect across four rows at an oblique angle. Along the transect, ten soil samples (small blue circles) and ten trees are sampled (dark green circles) and pooled. This is repeated for a second transect in the same block. (b) schematic presentation of the orchard floor coverage with the proposed fixed transect sampling. Dark blue circles are the sampling locations, which cover the under-tree, between-tree, dripline and inter-row areas of the orchard. Border rows and border trees should not be sampled to avoid edge effects.

The convenience of the fixed transect method has been demonstrated in the field (Figure 18), and the fixed transect method gave the same results as the intensive grid sampling (Table 2).

Figure 18. Example of a fixed transect sampling in a macadamia orchard. Two trees (shown with orange circles) are selected 4 rows apart. A hypothetical transect placed between the two trees (orange line), avoiding transects either directly along the row, across the row and diagonally (shown as dashed lines). At least 10 samples are taken evenly spaced along the transect (shown as orange dots). The length of the transect can be calculated from the tree and row spacing as follows: transect = square root ((number of rows x row spacing)^2 + (tree offset x tree spacing)^2). In this example: transect = square root ((4x9)^2+(3x5)^2) = 39 metres. Sampling locations can then be calculated by diving the transect length by the number of samples plus one, thus 39/(10+1) = 3.25 metres, i.e. every 6 paces .

Table 2. Selected soil characteristics in a macadamia orchard when sampled either intensively or along an 11-sample fixed transect.

		NO3-N (ppm)	Colwell P (ppm)	Potassium (meq/100g)	Boron (ppm)	Zinc (ppm)	Organic Matter (%)	CEC (meq/100g)	pH [1:5 H2O]
Whole	**Avg**	**48.3**	**344.4**	**1.4**	**0.8**	**12.1**	**17.9**	**24.3**	**5.2**
orchard	Stdev	27.3	187.9	0.5	0.4	5.8	3.5	4.1	0.4
(n=40)	CV (%)	56.5	54.6	35.9	53.5	47.8	19.4	16.9	6.9
transect	**Avg**	**59.2**	**436.6**	**1.6**	**0.6**	**12.2**	**17.7**	**24.9**	**5.1**
(n=11)	Stdev	41.9	208.8	0.6	0.1	6.9	3.3	3.6	0.3
	CV (%)	70.8	47.8	41.3	21.9	56.9	18.8	14.4	5.4
Probability (t-test)*		**0.3038**	**0.1651**	**0.4129**	**0.1194**	**0.9575**	**0.8942**	**0.7025**	**0.3153**

* Probability figures >0.05 indicate that the data is not significantly different

Foliar nutrient levels

Firstly, we compared recommended foliar tissue concentrations for Australia with those published for overseas plantations (Table 4). Foliar nutrient levels in Australia differ little from values established overseas considering that soil types and climatic conditions differ. This indicates that foliar nutrient levels are mainly determined by the plant requirements and not by environmental factors if the orchards are healthy and well-grown.

Secondly, we reviewed tissue nutrient levels for Australian orchards using databases established by consultants to the Macadamia industry. These datasets cover many growing years, all major growing regions in Australia, nine soil types and 20 commercially grown cultivars (Table 7). As fertiliser inputs and yield data were not available, it was not possible to suggest minimum nutrient levels for optimum yield. However, comparison of foliar nutrients between average yield orchards (3-5 t/ha) to higher-yielding orchards (5-6 t/ha) revealed no significant difference in foliar nutrient concentrations (compare Table 6 to Table 7). However, research would be needed to determine if nutrient application levels are optimal for yield on different soil types.

Statistical analyses reveal that foliar concentrations of N, P, K, Ca, and Mg were affected by an interaction between soil type and cultivar. Therefore, no generalised recommendation per cultivar can be made without knowledge of the soil type. It is possible that cultivars were fertilised differently on different soil types, resulting in differences in foliar concentrations recorded in the database (no fertiliser application rates were recorded). This would require a field trial to resolve if foliar nutrient concentrations are affected by soil type.

Foliar concentrations for several cultivars for each soil type are shown in Table 7.

Soil nutrient levels

Soil types differ in their elemental composition and availability of nutrients (Table 8). Therefore, soil nutrient levels cannot be compared between soil types since availability depends on pH, texture, organic matter etc. The Olsen P concentration in the loam and clay loam soils is much lower than in the heavier textures and this is likely due to lower adsorption (fixation) of P in these soils, resulting in lower P rates being applied. There was often a significant interaction between soil nutrients and cultivars (Table 8). This interaction is likely due to different fertiliser regimes on different soils, with some cultivars likely to be fertilised differently as well. Furthermore, sampling depths may differ and this has a large effect on measured nutrient levels; the values shown in Table 8 are for 0-10 cm

depths only.

In soils, nutrient cycling through leaf litter results in higher nutrient concentrations measured in the topsoil relative to the subsoil. Macadamia orchards are routinely sampled to 10 cm depth, but it is known that roots extend to well below 10 cm depth (see Figure 12). Therefore, we suggest that soil samples are taken to 20 cm depth (as separate 0-10 cm and 10-20 cm intervals initially to obtain comparable results, which will also inform of changes in subsoil pH and other constraints developing in the subsoil.

It is recommended that the sampling strategies above are combined with the old sampling strategies for at least a number of years so that results can be compared between sampling approaches and a knowledge base generated.

Interpretation of soil analyses

There are a large number of assays used to measure quantity and availability of nutrients. In this section, we will focus on P assays, CEC determination and exchangeable ions.

The P in soils is held in various pools, such as exchangeable P, fixed P, organic P and insoluble mineral P. These pools can be distinguished to some extent by different extraction methods. The commonly used P extraction methods are Colwell, Olsen, Bray and BSES.

The Olsen method uses 0.5M bicarbonate extraction for 30 minutes. This method is considered to measure exchangeable P (P intensity) (Rayment and Higginson 1992).

The Colwell method also uses 0.5 M bicarbonate extraction but extends the duration for 16h. This method is considered to measure exchangeable and fixed P (P quantity) and the results with the Colwell method are generally higher than those obtained with the Olsen method (Rayment and Higginson 1992).

The Bray method uses ammonium fluoride to extract soil P and this method is considered to measure exchangeable P, soluble P and some mineral P (Rayment and Higginson 1992).

The BSES method was developed for sugarcane soils and uses dilute sulfuric acid extraction. This method measures the exchangeable, fixed and mineral P pools and often yields higher values than the Colwell or Bray method and can overestimate plant P availability (Rayment and Higginson 1992).

In pot trials using macadamia seedlings, it was found that optimum concentration of extractable P was 50 ppm when measured by the Colwell method, 23 ppm for the Olsen method and 29 ppm for the Bray method (Aitken et al. 1992). Therefore, results for extractable P differ considerably between methods and P methods cannot be used interchangeably. Comparable median P values for a range of macadamia orchards were 78, 52 and 160 mg/kg P with the Bray1, Olsen and Colwell methods, respectively (Moody 2009). O'Hare (2004) recommended that 85 mg/kg Colwell P is optimal for most orchard soils, but the optimum soil levels depend on the extent of P fixation, and thus soil type.

There are several methods for the determination of the CEC in soil. The selection of the appropriate method depends primarily on the soil pH and salinity (Gillman et al. 1983; Soil Science Australia Queensland branch 2013). Most methods rely on the displacement of exchangeable cations (Ca, Mg, Na, K, and Al) and quantification of the exchanged cations. Evidently, the presence of free salts (as indicated by elevated electrical conductivity >300 µS/cm) will overestimate the CEC since free salts are present in the soil which are not held on the exchange. Similarly, recently limed or fertilised soil will show higher CEC. For this reason, soil samples should not be taken after recent liming or fertilisation of the soil and in soils with elevated electrical conductivity, a prewashing step or other

corrections are required (Gillman 1981; Soil Science Australia Queensland branch 2013).

At low pH, it is often considered that hydrogen ions occupy exchange sites. This is incorrect and a result of an experimental artefact. There is little exchangeable H held on the exchange in mineral soils since Al ions will bind much stronger than H and displaces H from the exchange (Menzies et al. 2011). The cation exchange sites on soil minerals will be saturated by cations (Ca, Mg, Na, K, Al), only soils high in organic matter will contain some measureable quantity of exchangeable H. The correct method to estimate CEC is by adding up exchangeable cations at the pH of the soil. The basic cations are extracted with 1M NH_4Cl or NH_4 acetate solution (pH 7) (Methods 15A1 or 15B1; (Rayment and Higginson 1992) and the acidic cations (Al, some H) by 1 M KCl (Method 15G1; (Rayment and Higginson 1992). The sum of cations is the effective CEC of the soil. This method is referred to as 15J1 in the Australian Laboratory handbook of soil and water analyses (Rayment and Higginson 1992; Soil Science Australia Queensland branch 2013) and the effect of different methods on the determination of the CEC is shown in Table 3, with methods determining the CEC at pH 7 or 8.5 resulting in a large overestimation of the CEC.

Results for exchangeable cations and the CEC can be reported as either SI units of centimol per kg (cmol/kg) or in the old units of milliequivalents per 100g (meq/100g). The former unit needs to be clear if the results are referring to concentrations of ions, or to concentrations of charges, e.g. 5 cmol Ca/kg = 10 cmol (+)/kg since calcium is a divalent cation. The concentration of charges is denoted by (+). Results reported as cmol(+)/kg are numerically the same as meq/100g, thus, a CEC given as 10 cmol(+)/kg is the same as 10 meq/100g.

Table 3. Effect of different methods on the determination of exchangeable cations and the CEC. The soil was a Ferrosol (Krasnozem) topsoil (0-10 cm) with pH 5.4 and 3.9 % organic carbon. Data from (Soil Science Australia Queensland branch 2013)

Method	Ca	Mg	K	Na	Sum cations	CEC
	cmol(+)/kg					
NH4OAC, pH 7	2.4	1.7	0.2	0.2	4	17
NH4Cl, pH 7	2.7	1.6	0.1	0.2	5	16
NH4Cl, pH 8.5	1.1	1.0	0.2	0.2	2	30
Compulsive exchange	3.2	1.8	0.1	0.2	5	6
ECEC (method 15J1)						6

Micronutrients in Australian soils are extracted with DTPA and soil tests are fairly well calibrated (Method 12A1) (Rayment and Higginson 1992). The Mehlich 3 method uses a combination of extractants (acetic acid, ammonium fluoride, ammonium nitrate, nitric acid, EDTA) and can extract not only micronutrients, but also exchangeable cations, aluminium and P (Walton and Alle 2004). Thus, the Mehlich 3 is an attractive extractant that can result in significant cost-savings. However, this test is not widely used in Australia and is not calibrated to Australian soils and not calibrated for Macadamia. Therefore, more research would be needed before the Mehlich 3 method can be endorsed. Micronutrients can be reported as either SI unit (mg/kg soil) or in the old unit of parts per million (ppm), both units are interchangeable, i.e. 5 mg/kg = 5 ppm.

The concept of optimum cation ratios in soils have been proposed almost a century ago and were widely promoted by Albrechts in the US during the 1940's. The concept that soils should have an optimum ratio of cations has since been repeatedly proven wrong (Edmeades 2011; Kopittke and Menzies 2007; Schulte and Kelling 1993). Plants can grow in wide range of soil cation concentrations and at extremes of cation concentrations (i.e. an imbalance on cation ratios), growth may be affected by toxicities or deficiencies of the nutrient rather than an imbalance itself. Therefore, focus should be on overcoming soil constraints rather than trying to achieve some non-existent optimum cation ratios. Adequate soil cation levels are shown in Table 4 and Table 8, and serve as a reliable baseline for soil nutrients.

Table 4. Suggested analytical methods for soil analyses and the optimum soil levels for macadamia (O'Hare et al. 2004) on Ferrosol soils

Element (extraction procedure shown in brackets)	Optimum soil levels
pH (1:5 water)	5.0 – 5.5
pH (1:5 $CaCl_2$)	4.5 – 5.0
Organic carbon (Walkley-Black)	more than 2.0%C
Nitrate nitrogen (1:5 aqueous extract)	more than 15 mg/kg
Sulphate sulphur (phosphate)	more than 20 mg/kg
Phosphorus (Colwell)	85 mg/kg P
Potassium (exchangeable)	more than 0.5 meq/100 g K
Calcium (exchangeable)	more than 5 meq/100 g Ca
Magnesium (exchangeable)	more than 1.6 meq/100 g Mg
Sodium (exchangeable)	less than 2% exchangeable cations
Aluminium (exchangeable)	less than 5% exchangeable cations
Chloride (1:5 aqueous extract)	less than 200 mg/kg Cl
Conductivity (1:5 aqueous extract)	less than 3 dS/m
Boron (hot calcium chloride)	1 – 2 mg/kg B
Total cation exchange capacity	preferably more than 7
Cation balance (%)	calcium 50 – 80 magnesium 10 – 50 potassium 2 – 10 sodium less than 2 aluminium less than 5

Fertiliser regime

The habitat of the macadamia tree (rainforest) indicates that the tree benefits from frequent small applications of fertiliser rather than single large applications of N (Stephenson and Gallagher 1989; Stephenson et al. 1992). Indeed, it has been shown that single large applications can induce vegetative flushes, lead to yield losses and poor nut quality (Stephenson et al. 2002) (Figure 19), and can impair root growth (Hue 2009b). Therefore, it is recommended that trees are fertilised frequently (>3 times per year) with small quantities of nutrients, or fertigated.

We suggest applying fertiliser for flowering/nut set (i.e. fertilisers containing Zn and boron) in May.

This is the latest when reliable rainfalls can be expected to dissolve the fertiliser and plants may be able to take it up. Applying fertiliser later may delay uptake due to low soil temperatures and lack of rainfall. For nitrogen, it is known that N uptake occurs after three weeks and peak tissue concentrations are reached after 7 weeks (Fletcher et al. 2010); while it is not known how rapidly other nutrients are taken up, we assume a response similar to N. Thus, a May fertiliser application will reach maximum tissue concentration around July, in time for peak flowering and nut set in August (O'Hare et al. 2004).

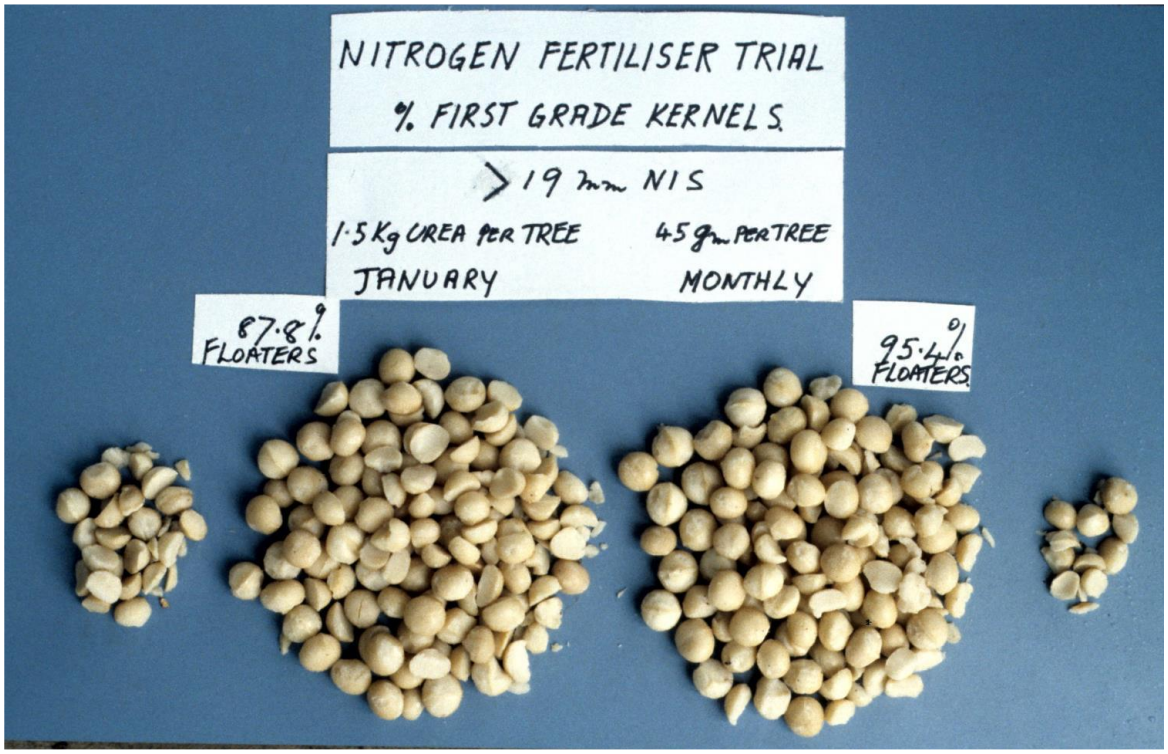


Figure 19. Effect of split nutrient application versus a single large application on nut quality (R. Stephenson).

Organic manures

Organic fertilisers or addition of manure and compost is beneficial to macadamia growth. In shaded orchards, loss of vegetative ground cover decreases the input of organic matter into the soil. Thus, organic matter or organic fertilisers (manures) need to be added to maintain soil carbon and minimise soil erosion.

Placement

The optimal placement of nutrients is still debated and no consensus has been reached. Root distribution decreases with distance from stem (Figure 11), suggesting that placement of nutrients should occur within the drip line. Furthermore, soils with high adsorption potential for nutrients (e.g. Ferrosol), require placement of nutrients such as Zn and P in bands to minimise adsorption losses of the nutrients, but the effectiveness of P banding on foliar P levels in macadamia is debated (Firth 1995).

Summary of Key points

The key points that advisors and growers should be aware of are highlighted below

Key points for soils and their management:

- Soil types differ in their inherent fertility and suitability for macadamia
- Different soils need to be managed differently
- Growers need to know and understand their soil types
- Soil pH affects solubility of P, Al and trace elements (Zn, Fe, Mn, B)
- Soil pH affects CEC and AEC
- Macadamia have an optimum pH(water) of 5-6 or pH (CaCl2) 4.5-5.5
- OM is a source of nutrients
- OM differs in quality, there is a strong need to know the quality of the OM applied
- OM protects soil surface from heat, drying and erosion
- OM is required to maintain soil quality
- Water is required for;
    - uptake of nutrients by roots
    - photosynthesis
    - leaf cooling
    - root growth
- Water stress decreases yield and nut quality

Key points for the physiology of macadamia trees:

- Macadamia is a rainforest tree adapted to acidic soil
- High temperature (>36C leaf temperature) is detrimental to macadamia growth
- Adapted to low fertility soils by specialised root system
- Quality of root system is very important for water and nutrient uptake
- Most cluster roots and fine roots found from the surface to 15 cm below the soil surface
- Cluster roots are inhibited by high P and N fertilisation
- Cluster roots are not an indicator of tree or root health
- The presence of fine roots and the absence of exposed surface roots are more suitable indicators of tree and root health

Key points sampling and nutrition of macadamia orchards:

- Foliar sampling is more valuable than soil sampling – direct indication of nutrient uptake by tree roots
- Foliar samples should be collected in the upper 1/3 of canopy from sun-lit leaves from the 2nd or 3rd whorl.
- Foliage needs to be thoroughly rinsed to remove dust and pesticide residue
- Soil should be sampled to 0-10 and 10-20 cm depth initially to compare results.
- Occasional soil sampling to >20 cm is needed for identification of developing soil constraints
- Soil and foliar samples should be collected along a fixed transect, with 20 soil samples and foliage from 20 trees making up one combined soil or foliar sample for the block.
- Soil nutrient concentrations vary between soil types and cannot be compared between orchards
- Soil cation ratios should not be relied upon
- Foliar nutrient concentrations vary slightly between soil types but this may rather reflect differences in management (fertiliser applications) between soil types.
- Foliar nutrient concentrations vary slightly between cultivars
- Fertiliser should be applied in several split, and placed under the dripline of the tree.

Conclusion and key recommendations

It is important to understand that maximising yield in macadamia orchards requires that all environmental and physiological drivers of yield are optimised. This implies that canopy management, orchard floor management, and drainage are optimised as embodied by the three pillars of integrated orchard management (Figure 20).

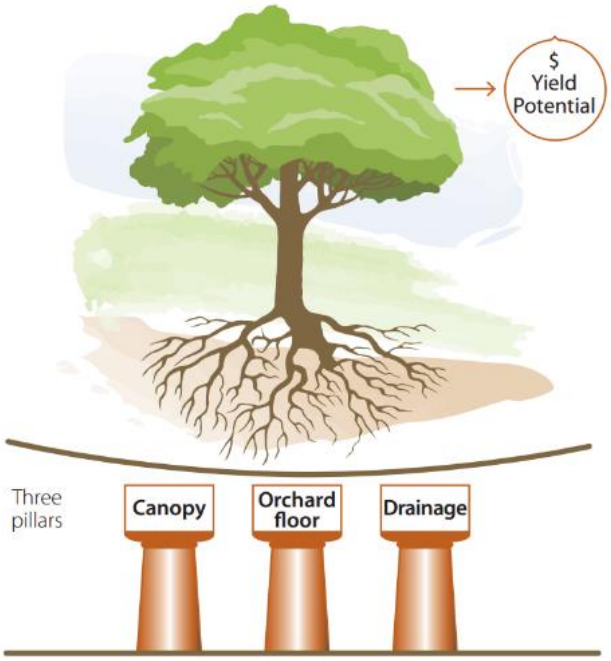


Figure 20. Schematic presentation of the concept of integrated orchard management for macadamia, with tree yield being underpinned by canopy management, orchard floor management and drainage/erosion control (Bright et al. 2015).

In addition, factors that may limit yield need to be addresses such as insufficient pollination, subsoil constraints, temperature extremes, water stress and tree nutrition, and this concept is often presented by "Liebig's barrel" (Figure 21). Investing money in fertiliser may not increase yield if nutrients are not limiting yield. For instance, poor pollination may limit the yield potential and increasing fertiliser will overcome yield limitations.

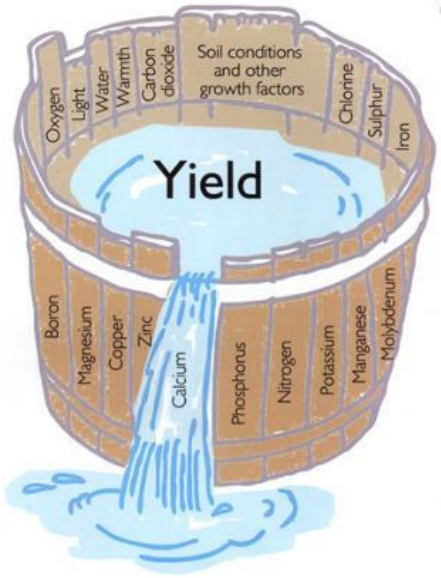


Figure 21. Schematic presentation of the Liebig-Sprengel barrel showing the effect of environmental factors on plant yield, with the most limiting factor controlling yield. Taken from http://www.aglime.org.uk/tech/lime_is_a_fertiliser.php

Acknowledgments

We thank Dr Ian Vimpany and Alan Coates for access to their database with soil and foliar nutrient concentrations and to Drs Russ Stephenson and Paul O'Hare for discussion and access to unpublished research data. Special thanks to Robbie Commens and numerous consultants for their support and discussions.

Table 5. Foliar nutrient concentration reported in various studies for healthy productive macadamia orchards in Australia and other countries

		O'Hare Fertman.pdf	Huett and Vimpany	Tamimi	Stephenson QLD	Stephenson Aus	Van Niekerk	O'Farrell	Nagao Hirae	Perdona	Pire	Reuter	Manson
N	%	1.4-1.5	1.4-1.7	1.67	1.3	1.4-1.5	1.2-1.6	1.6	1.45-2	1.4-1.8	1.3-1.7	1.3-1.4	1.3-1.5
P	%	0.08-0.1	0.07-0.1	0.07	0.07	0.08-0.1	0.08-0.1	0.09	0.07-0.11	0.09	0.07-0.09	0.08-0.11	0.08-0.1
K	%	0.6-0.7	0.4-0.8	0.53	0.63	0.6-0.7	0.6-0.7	0.7	0.45-0.6	0.8	0.5-0.6	0.66-0.8	0.5-0.79
Ca	%	0.6-0.9	0.6-0.9	0.48	0.76	0.6-0.9	0.6-0.9	0.8	0.55-1.0	0.7	0.6-1.1	0.65-0.9	0.5-0.8
Mg	%	0.08-0.1	0.08-0.12	0.08	0.1	0.1	0.08-0.1	0.10	0.08-0.1	0.07	0.08-0.1	0.09-0.11	0.08-0.12
S	%	0.18-0.25	0.15-0.21	0.14	0.18	0.18	0.18-0.25	0.16	0.24	0.1		0.17-0.25	0.18-0.25
Fe	ppm	40-200	30-100	50	94		40-200	63.4	50	82	70-150	20-200	25-200
Zn	ppm	15-50	6-15	6.3	30	15	15-50	11.2	15-20	11	10-14	15-20	15-50
B	ppm	40-75	40-80	26	39	40-75	40-75	69.3	40-100	31		50-80	20-50
Cu	ppm	4.5-10	5-10	2.8	39	4.5	4.5-10	36.4	4	13	5-6	5-10	5-12
Mn	ppm	100-1000	250-1850	415	860	100	100-1000	457.5	50-1500	330	150-250	100-1000	100-1500
Al				17				65.3	<200				

A) (O'Hare 1993)
B) (Huett and Vimpany 2007), 6-7 month old leaves, in spring
C) (Tamimi et al. 1992) for Hawaii, YFEL
D) Values for Queensland (Stephenson and Cull 1986), 6-7 month old, in spring
E) Values for Australia (Stephenson and Cull 1986), 6-7 month old, in spring
F) (van Niekerk 2002) for South Africa
G) (O'Farrell 2011) non AVG orchards, Australia
H) (Nagao and Hirae 1992) for Hawaii
I) (Perdona et al. 2013), 3rd from YFEL for Brazil
J) (Pire et al. 2002) leaf from second whorl, for Venezuela
K) (Reuter and Robinson 1997) for Australia
L) (Manson and Sheard 2007) 4th leaf from YFEL for South Africa

Table 6. Foliar nutrient concentrations s in high yielding (4.5-5 t/ha NIS) orchards in QLD (data from A. Coates and Dorey (Lorna))

Element	Range
Nitrogen (%)	1.52-1.67
Phosphorus (%)	0.08-0.09
Potassium (%)	0.64-0.73
Sulfur (%)	0.21-0.23
Calcium (%)	0.60-0.80
Magnesium (%)	0.09-0.11
Sodium (%)	0.02-0.02
Copper (mg/kg)	5.8-8.6
Zinc (mg/kg)	8.3-11.6
Manganese (mg/kg)	1053-1500
Iron (mg/kg)	54-82
Boron (mg/kg)	42-46

Table 7. Foliar nutrient concentrations of Macadamia varieties grown on several soil types. Concentrations for N, S, P, K, Ca, and Mg are shown in %. Concentrations of micronutrients (Cu, Zn, Mn, B, Fe) are shown in mg/kg dry matter. Values in rows for each variety followed by the same letter are not significantly different (Tukey HSD, P =0.05). Values shown are median values obtained from at least 5 datasets per cultivar and soil type.

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Light	**A203**	1.53 a	0.19 a	0.07 a	0.80 a	0.52 b	0.15 b	8.1 a	6.2 a	637 a	78 a	71 a
Loam/ clay loam	**A203**	1.49 a	0.17 a	0.08 a	0.72 a	0.58 b	0.16 b	4.0 a	6.0 a	505 a	57 b	56 a
Sandy	**A203**	1.30 a	0.16 a	0.07 a	0.77 a	0.79 a	0.17 a	9.2 a	6.6 a	366 a	60 b	62 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**205**	1.60	0.22	0.07	0.71	0.72	0.09	17.5	8.8	730	40	55

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Vertosol	**246**	1.59 a	0.19 a	0.08 ab	0.56 b	0.63 a	0.11 a	31.5 a	8.2 ab	347 b	44 b	73 a
Ferrosol	**246**	1.58 a	0.22 a	0.07 b	0.65 b	0.75 a	0.09 a	18.2 a	7.7 a	1216 a	50 b	55 a
Loam/ clay loam	**246**	1.70 a	0.22 a	0.08 ab	0.77 a	0.59 a	0.10 a	11.8 a	6.6 ab	313 b	52 b	48 a
Sandy	**246**	1.38 b	0.21 a	0.08 a	0.71 a	0.73 a	0.08 a	12.1 a	6.7 b	327 b	83 a	50 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Light	**A268**	1.30 a	0.17 a	0.10 a	0.75 a	0.66 a	0.16 a	3.8 a	8.0 a	193 a	32 b	58 a
Loam/ clay loam	**A268**	1.40 a	0.18 a	0.08 a	0.73 a	0.57 a	0.17 a	2.6 a	6.0 bc	450 a	57 a	38 a
Chromosol	**A268**	1.34 a	0.17 a	0.07 a	0.71 a	0.55 a	0.13 a	2.3 a	5.4 c	336 a	35 b	46 a
Sandy	**A268**	1.38 a	0.20 a	0.08 a	0.77 a	0.68 a	0.16 a	3.1 a	7.0 ab	203 a	55 a	39 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**333**	1.65	0.24	0.07	0.66	0.79	0.10	40.2	8.1	1346	54	85

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Vertosol	**344**	1.67 ab	0.16 a	0.08 ab	0.62 a	0.66 a	0.12 ab	20.5 a	7.9 a	503 bc	48 b	66 a
Ferrosol	**344**	1.72 a	0.20 b	0.08 b	0.67 a	0.68 a	0.10 b	16.1 a	8.1 a	937 a	52 b	56 a
Light	**344**	1.80 ab	0.19 ab	0.10 ab	0.64 a	0.64 a	0.11 ab	10.3 a	8.5 a	120 c	85 a	42 ab
Loam/ clay loam	**344**	1.70 ab	0.22 ab	0.08 ab	0.76 a	0.75 a	0.11 ab	19.0 a	6.9 a	299 abc	49 ab	55 ab
Chromosol	**344**	1.78 ab	0.20 b	0.09 ab	0.74 a	0.66 a	0.10 b	10.5 a	7.8 a	738 ab	71 a	50 ab
Sandy	**344**	1.66 b	0.19 b	0.09 a	0.69 a	0.70 a	0.13 a	9.3 a	7.9 a	427 bc	79 a	43 b

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**508**	1.58 a	0.20 b	0.07 b	0.69 a	0.72 a	0.08 b	15.0 a	9.2 a	1041 a	44 b	58 a
Loam/ clay loam	**508**	1.62 a	0.24 a	0.08 b	0.76 a	0.64 a	0.11 a	24.3 a	8.0 a	380 b	66 a	48 a
Sandy	**508**	1.56 a	0.24 a	0.12 a	0.77 a	0.61 a	0.11 a	3.9 a	8.6 a	364 b	68 a	42 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**660**	1.64 a	0.20 b	0.08 a	0.69 b	0.71 a	0.08 b	26.2 a	7.4 b	992 a	48 b	60 a
Loam/ clay loam	**660**	1.65 a	0.21 b	0.08 a	0.77 a	0.63 b	0.11 a	9.4 a	7.0 b	387 b	58 b	51 a
Sandy	**660**	1.60 a	0.24 a	0.09 a	0.76 ab	0.70 ab	0.09 ab	5.0 a	8.5 a	465 b	89 a	48 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Vertosol	**741**	1.65 ab	0.18 b	0.11 ab	0.50 c	0.59 abc	0.11 b	8.4 a	7.4 a	300 b	52 b	60 a
Ferrosol	**741**	1.69 b	0.19 b	0.08 b	0.66 c	0.66 ab	0.10 b	11.2 a	8.2 a	832 a	51 c	60 a
Light	**741**	1.63 ab	0.20 ab	0.07 b	0.87 a	0.46 abc	0.11 b	3.0 a	7.2 a	392 ab	43 b	51 a
Loam/ clay loam	**741**	1.82 a	0.22 a	0.12 a	0.82 ab	0.68 a	0.15 a	7.9 a	8.7 a	292 b	94 a	63 a
Loamy sand	**741**	1.79 ab	0.19 b	0.08 b	0.83 ab	0.55 abc	0.11 b	6.5 a	8.0 a	59 b	69 a	57 a
Chromosol	**741**	1.70 ab	0.19 ab	0.09 ab	0.86 ab	0.57 abc	0.12 b	1.8 a	7.2 a	247 b	54 b	56 a
Sandy	**741**	1.69 b	0.19 b	0.08 b	0.80 ab	0.55 c	0.11 b	6.3 a	7.5 a	243 b	70 b	55 a
Sandy loam	**741**	1.70 ab	0.15 b	0.09 ab	0.53 c	0.45 abc	0.12 ab	3.6 a	7.2 a	210 ab	61 a	38 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**800**	1.65	0.19	0.08	0.65	0.62	0.10	7.1	7.8	1100	41	57

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**816**	1.55 a	0.17 a	0.07 a	0.61 a	0.56 a	0.10 a	6.2 a	6.8 a	797 a	44 a	50 a
Light	**816**	1.50 a	0.18 a	0.07 a	0.70 a	0.53 a	0.12 a	5.4 a	7.5 a	335 a	52 a	43 a
Loam/ clay loam	**816**	1.60 a	0.18 a	0.07 a	0.84 a	0.51 a	0.11 a	3.5 a	6.4 a	275 a	53 a	60 a
Chromosol	**816**	1.63 a	0.19 a	0.09 a	0.68 a	0.55 a	0.10 a	2.4 a	6.3 a	503 a	53 a	53 a
Sandy	**816**	1.52 a	0.17 a	0.08 a	0.70 a	0.49 a	0.10 a	2.6 a	7.5 a	351 a	83 a	53 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Vertosol	**842**	1.50 a	0.16 a	0.08 a	0.65 abc	0.67 a	0.09 a	4.2 a	7.3 a	910 a	34 a	55 a
Ferrosol	**842**	1.65 a	0.17 a	0.08 a	0.75 abc	0.40 a	0.09 a	3.5 a	7.2 a	425 a	29 a	45 a
Light	**842**	1.60 a	0.19 a	0.08 a	0.72 b	0.60 a	0.15 a	6.0 a	6.7 a	270 a	65 a	45 a
Loam/ clay loam	**842**	1.75 a	0.20 a	0.08 a	0.93 a	0.52 a	0.11 a	3.0 a	6.9 a	155 a	53 a	70 a
Chromosol	**842**	1.60 a	0.17 a	0.09 a	0.66 c	0.68 a	0.12 a	2.7 a	6.8 a	533 a	55 a	54 a
Sandy	**842**	1.54 a	0.18 a	0.08 a	0.86 a	0.50 a	0.11 a	3.6 a	6.8 a	124 a	67 a	47 a
Sandy loam	**842**	1.50 a	0.15 a	0.10 a	0.64 abc	0.56 a	0.14 a	3.9 a	6.4 a	100 a	48 a	52 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Dermosol	**849**	1.20 a	0.14 c	0.07 a	0.55 c	0.56 a	0.08 b	2.7 a	5.5 a	885 ab	26 a	39 a
Ferrosol	**849**	1.58 a	0.18 bc	0.07 a	0.60 c	0.59 a	0.10 b	7.9 a	7.0 a	1053 a	46 a	57 a
Light	**849**	1.53 a	0.20 ab	0.10 a	0.79 ab	0.50 a	0.13 a	4.9 a	6.8 a	191 b	59 a	46 a
Chromosol	**849**	1.60 a	0.24 a	0.09 a	0.89 a	0.69 a	0.10 ab	2.2 a	6.5 a	600 ab	58 a	58 a
Sandy	**849**	1.49 a	0.17 bc	0.09 a	0.72 b	0.51 a	0.12 a	4.0 a	6.8 a	313 b	67 a	41 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Dermosol	**A16**	1.60 ab	0.18 a	0.09 a	0.68 ab	0.69 ab	0.17 a	5.2 a	8.1 ab	1850 a	52 ab	64 a
Ferrosol	**A16**	1.57 ab	0.16 a	0.08 a	0.55 b	0.75 ab	0.11 b	36.1 a	8.9 a	1456 a	54 b	66 a
Loam/ clay loam	**A16**	1.66 a	0.18 a	0.08 a	0.77 a	0.61 b	0.12 b	6.2 a	7.9 ab	359 b	99 a	75 a
Chromosol	**A16**	1.60 ab	0.18 a	0.10 a	0.69 a	0.74 ab	0.14 ab	5.4 a	7.6 ab	1180 ab	53 b	56 a
Sandy	**A16**	1.51 b	0.17 a	0.08 a	0.68 a	0.85 a	0.15 a	16.7 a	7.7 b	555 b	70 b	58 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**A29**	1.40	0.19	0.07	0.56	0.79	0.12	50.0	6.9	1600	55	60

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**A38**	1.48 a	0.16 a	0.07 b	0.49 b	0.70 a	0.11 a	18.04a	6.8 ab	1675 a	45 a	62 a
Chromosol	**A38**	1.60 a	0.15 a	0.09 a	0.72 ab	0.54 a	0.12 a	3.6 a	5.2 b	400 b	38 a	41 a
Sandy	**A38**	1.63 a	0.16 a	0.10 a	0.71 a	0.64 a	0.13 a	29.3 a	7.3 a	145 b	54 a	60 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**A4**	1.48 a	0.16 ab	0.07 a	0.64 c	0.69 a	0.11 a	21.9 a	7.5 a	1390 a	50 b	60 ab
Light	**A4**	1.40 a	0.18 ab	0.07 a	0.82 abc	0.41 c	0.14 a	5.8 a	6.5 a	400 ab	66 ab	51 ab
Loam/ clay loam	**A4**	1.50 a	0.19 a	0.08 a	0.90 abc	0.77 ab	0.14 a	9.4 a	8.0 a	685 ab	92 a	73 ab
Chromosol	**A4**	1.42 a	0.13 c	0.07 a	0.77 ab	0.77 a	0.11 a	24.7 a	7.8 a	671 b	63 ab	51 b
Sandy	**A4**	1.53 a	0.14 bc	0.09 a	0.83 ab	0.56 bc	0.12 a	11.7 a	7.0 a	121 b	64 ab	77 a

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**D4**	1.20	0.15	0.07	0.46	0.85	0.09	38.5	6.5	865	29	44

Soil	Variety	N	S	P	K	Ca	Mg	Cu	Zn	Mn	B	Fe
Ferrosol	**Daddow**	1.60 a	0.16 a	0.07 a	0.39 b	0.55 a	0.08 a	5.1 a	8.5 a	980 ab	45 a	45 a

Loam/ clay loam	**Daddow**	1.67 a	0.17 a	0.07 a	0.67 a	0.41 a	0.09 a	3.0 b	6.3 a	214 b	43 a	59 a
Chromosol	**Daddow**	1.70 a	0.19 a	0.07 a	0.53 ab	0.57 a	0.09 a	2.4 b	7.8 a	1700 a	32 a	59 a

Soil	**Variety**	**N**	**S**	**P**	**K**	**Ca**	**Mg**	**Cu**	**Zn**	**Mn**	**B**	**Fe**
Ferrosol	**H2**	1.48 a	0.20 a	0.08 b	0.53 a	0.88 a	0.09 a	24.9 b	6.5 a	1213 a	46 b	65 a
Sandy	**H2**	1.40 a	0.19 a	0.11 a	0.57 a	1.00 a	0.12 a	68.0 a	6.0 a	550 a	76 a	85 a

Table 8. Soil nutrient concentrations of under various macadamia cultivars on several soil types. The pH was measured as 1:5 slurry in water (pH w) or 0.05 M CaCl2 (pH Ca), Olsen P is in units of mg P/kg soil and exchangeable concentrations of cations are shown in cmol/kg and the effective CEC has been calculated from the sum of exchangeable basic and acid cations and is expressed as cmol/kg. Values are shown as mean of several dozen data sets and means followed by the same letter are not significantly different (Tukey HSD, P =0.05).

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Vertosol	**246**	6.15 a	5.63 a	239.8 a	1.1 a	20.3 a	6.6 a	0.0 a	0.2 a	28.8 a
Vertosol	**344**	5.85 ab	5.29 a	307.0 a	1.0 a	17.8 a	5.9 a	0.1 a	0.2 a	25.0 a
Vertosol	**741**	5.35 b	4.68 b	245.0 a	0.9 a	11.1 a	2.9 a	1.2 a	0.3 a	16.2 a
Vertosol	**842**	6.00 ab	5.10 ab	71.0 a	0.8 a	15.0 a	5.4 a	0.1 a	0.2 a	22.0 a

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Dermosol	**849**	5.85	5.10	170.0	1.0	10.5	4.1	0.1	0.2	16.2
Dermosol	**A16**	5.25	4.55	115.0	1.0	6.0	2.3	1.0	0.1	10.5

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Ferrosol	**205**	5.40 ab	4.80 a	290.0 abc	0. 7 a	8.5 ab	1.5 a	0.3 ab	0.1 a	11.3 ab
Ferrosol	**246**	5.55 ab	4.92 a	289.7 ab	0.7 a	8.1 ab	1.7 a	0.3 ab	0.1 a	10.9 ab
Ferrosol	**333**	5.80 ab	5.30 a	435.0 abc	0.7 a	9.5 ab	1.8 a	0.1 ab	0.1 a	12.6 ab
Ferrosol	**344**	5.57 ab	4.98 a	259.6 c	0.6 a	8.3 a	1.8 a	0.3 b	0.1 a	11.2 a
Ferrosol	**508**	5.44 b	4.82 a	273.2 abc	0.7 a	7.6 ab	1.5 a	0.4 ab	0.1 a	10.2 ab
Ferrosol	**660**	5.61 ab	4.98 a	285.8 abc	0.6 a	7.8 ab	1.5 a	0.3 ab	0.1 a	10.4 ab
Ferrosol	**741**	5.64 ab	4.99 a	257.1 abc	0.6 a	8.0 ab	1.8 a	0.2 ab	0.1 a	10.9 ab
Ferrosol	**800**	5.48 ab	4.95 a	175.0 abc	0.7 a	8.2 ab	1.9 a	0.2 ab	0.1 a	11.3 ab
Ferrosol	**816**	5.63 ab	4.88 a	135.0 abc	0.7 a	8.0 ab	2.9 a	0.3 ab	0.1 a	12.2 ab

Ferrosol	**842**	6.50 a	5.80 a	210.0 abc	0.7 a	10.0 ab	2.6 a	0.0 ab	0.1 a	13.1 ab
Ferrosol	**849**	5.45 ab	4.80 a	178.3 abc	0.6 a	6.6 ab	1.8 a	0.4 ab	0.1 a	9.4 ab
Ferrosol	**A16**	5.48 ab	4.88 a	221.1 b	0.6 a	7.5 ab	1.6 a	0.5 ab	0.1 a	10.5 ab
Ferrosol	**A29**	5.40 ab	4.90 a	320.0 abc	0.9 a	10.0 ab	2.1 a	0.2 ab	0.1 a	13.5 ab
Ferrosol	**A38**	5.32 b	4.77 a	144.3 c	0.6 a	6.2 ab	1.7 a	0.6 ab	0.1 a	9.1 ab
Ferrosol	**A4**	5.41 b	4.79 a	220.2 b	0.6 a	6.3 b	1.5 a	0.6 a	0.1 a	9.2 b
Ferrosol	**Daddow**	5.60 ab	4.85 a	150.0abc	0.5 a	7.0 ab	2.5 a	0.3 ab	0.1 a	10.6 ab
Ferrosol	**H2**	5.43 b	4.81	355.8 a	0.7 a	7.9 ab	1.5 a	0.4 ab	0.1 a	10.8 ab

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Light	**203**	6.70 ab	6.00 ab	53.7 ab	0.2 a	3.4 a	2.0 a	0.1 a	0.2 a	6.1 a
Light	**268**	5.90 ab	5.20 ab	99.0 ab	0.3 a	3.8 a	0.7 a	0.0 a	0.1 a	5.0 a
Light	**344**	5.45 b	4.80 b	103.5 a	0.2 a	2.9 a	0.5 a	0.2 a	0.2 a	3.9 a
Light	**741**	7.00 ab	6.33 ab	41.0 ab	0.2 a	4.7 a	2.9 a	0.0 a	0.3 a	8.6 a
Light	**816**	7.18 a	6.35 a	37.8 b	0.2 a	3.1 a	1.5 a	0.0 a	0.1 a	5.0 a
Light	**842**	6.70 ab	5.90 ab	35.0 ab	0.1 a	3.0 a	1.6 a	0.1 a	0.2 a	5.2 a
Light	**849**	6.38 ab	5.60 ab	66.0 ab	0.3 a	3.1 a	1.2 a	0.1 a	0.2 a	4.9 a
Light	**A4**	6.40 ab	5.50 ab	48.0 ab	0.2 a	2.5 a	1.2 a	0.0 a	0.2 a	4.2 a

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Loam / clay loam	**203**	6.35 a	5.45 ab	39.5 a	0.4 a	5.8 abc	4.3 a	0.1 ab	0.2 ab	10.9 ab
Loam / clay loam	**246**	6.05 a	5.61 ab	122.0 a	0.7 a	8.4 abc	2.8 a	0.0 b	0.3 ab	12.3 a
Loam / clay loam	**268**	6.70 a	5.90 ab	39.0 a	0.3 a	5.5 abc	4.2 a	0.0 ab	0.3 ab	10.9 ab
Loam / clay loam	**344**	5.85 a	5.10 ab	129.0 a	0.6 a	6.9 abc	2.2 a	0.0 ab	0.3 ab	10.0 ab
Loam / clay loam	**508**	5.82 a	5.05 ab	121.3 a	0.6 a	6.1 abc	2.0 a	0.1 ab	0.2 ab	9.2 abc

Loam / clay loam	**660**	6.32 a	5.56 ab	102.7 a	0.5 a	7.0 ab	2.7 a	0.0 b	0.3 a	10.6 ab
Loam / clay loam	**741**	6.92 a	6.21 a	54.8 a	0.6 a	7.6 a	2.4 a	0.0 b	0.3 ab	10.7 ab
Loam / clay loam	**816**	6.00 a	5.00 ab	77.0 a	0.1 a	3.2 abc	1.2 a	0.1 ab	0.2 ab	4.8 abc
Loam / clay loam	**842**	5.75 a	4.80 ab	68.0 a	0.1 a	2.8 abc	0.9 a	0.1 ab	0.1 ab	4.3 ab
Loam / clay loam	**A16**	5.91 a	4.86 b	56.8 a	0.2 a	3.0 c	0.8 a	0.1 ab	0.1 b	4.3 c
Loam / clay loam	**A4**	6.05 a	5.20 ab	97.5 a	0.8 a	5.5 abc	1.7 a	0.1 ab	0.2 ab	8.9 abc
Loam / clay loam	**Daddow**	5.80 a	4.85 b	60.0 a	0.2 a	3.4 abc	1.0 a	0.1 a	0.1 b	4.9 c

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Sandy loam	**741**	7.10	5.90	48.0	0.2	1.5	0.8	0.0	0.1	2.5
Sandy loam	**842**	6.70	5.70	70.0	0.1	2.3	0.8	0.0	0.1	3.0

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Chromosol	**268**	5.82 bc	4.94 bc	242.0 a	0.4 b	3.3 b	0.8 a	0.2 ab	0.0 c	4.8 b
Chromosol	**344**	6.29 ab	5.63 ab	139.3 a	0.6 ab	8.5 ab	1.6 a	0.1 b	0.2 a	11.1 ab
Chromosol	**741**	6.03 abc	5.10 abc	176.7 a	0.3 b	2.4 b	0.8 a	0.1 ab	0.0 bc	3.6 b
Chromosol	**816**	5.27 c	4.50 c	306.7 a	0.4 b	2.2 b	0.5 a	0.4 ab	0.0 bc	3.6 b
Chromosol	**842**	5.80 abc	4.87 bc	143.7 a	0.3 b	3.4 b	1.3 a	0.1 ab	0.1 bc	5.2 b
Chromosol	**849**	5.70 abc	4.90 abc	270.0 a	0.4 ab	2.6 ab	0.7 a	0.1 ab	0.0 bc	4.0 abc
Chromosol	**A16**	5.40 c	4.50 c	195.0 a	0.5 ab	2.5 b	1.0 a	0.9 a	0.1 bc	4.9 abc
Chromosol	**A38**	5.80 abc	5.00 abc	400.0 a	0.5 ab	4.9 ab	0.8 a	0.1 ab	0.0 abc	6.5 ab
Chromosol	**A4**	5.47 c	4.84 c	217.9 a	0.8 ab	7.2 ab	1.5 a	0.5 ab	0.1 ab	10.0 ab
Chromosol	**Daddow**	6.65 a	6.20 a	106.8 a	1.2 a	13.5 a	1.8 a	0.0 ab	0.1 ab	16.6 a

soil	variety	pH w	pH ca	Olsen P	K ex	Ca ex	Mg ex	Al ex	Na ex	CEC
Sandy	**203**	5.70 abc	5.03 abc	81.5 bcde	0.2 abc	2.2 a	0.4 a	0.2 bc	0.1 ab	2.9 ab
Sandy	**246**	5.52 c	4.72 c	175.6 ab	0.3 a	3.4 a	0.9 a	0.6 ab	0.1 b	5.4 a
Sandy	**268**	5.70 abc	4.90 abc	85.3 bcde	0.2 abc	2.1 a	0.5 a	0.2 bc	0.1 ab	3.0 ab
Sandy	**344**	6.28 a	5.55 a	61.2 de	0.2 b	2.9 a	0.8 a	0.1 c	0.1 b	4.1 ab
Sandy	**508**	5.95 abc	5.10 abc	48.8 de	0.1 b	1.9 a	0.5 a	0.1 bc	0.0 b	2.6 ab
Sandy	**660**	5.80 abc	4.93 abc	59.9 de	0.2 abc	2.6 a	0.6 a	0.1 bc	0.1 b	3.6 ab
Sandy	**741**	5.88 bc	5.03 bc	99.9 e	0.2 bc	2.7 a	0.5 a	0.1 c	0.1 b	3.6 b
Sandy	**816**	5.72 abc	4.77 bc	77.9 de	0.1 b	1.5 a	0.6 a	0.5 abc	0.1 b	2.8 ab
Sandy	**842**	5.77 abc	5.00 abc	35.7 de	0.1 ab	2.8 a	0.5 a	0.1 bc	0.3 a	3.8 ab
Sandy	**849**	5.78 abc	4.93 abc	79.6 de	0.2 b	1.9 a	0.5 a	0.4 bc	0.1 b	3.1 ab
Sandy	**A16**	6.04 ab	5.34 ab	99.1 cde	0.3 ab	3.4 a	0.9 a	0.1 c	0.1 b	4.8 ab
Sandy	**A38**	5.55 abc	5.00 abc	212.5 abc	0.3 abc	2.7 a	0.5 a	0.1 bc	0.0 b	3.6 ab
Sandy	**A4**	5.81 abc	5.18 abc	223.8 a	0.2 abc	3.1 a	0.6 a	0.1 bc	0.0 b	4.0 ab
Sandy	**H2**	5.30 abc	4.40 abc	200 abcde	0.2 abc	2.0 a	0.3 a	0.7 abc	0.0 ab	3.2 ab

References

Ahern CR, Baker DE, Aitken RL (1995) Models for relating pH measurements in water and clacium chloride for a wide range of pH, soil types and depths. Plant Soil 171: 47-52.

Aitken RL, Moody PW (1991) Interrelations between soil pH measurements in various electrolytes and soil solution pH in acidic soils. Aust J Soil Res 29: 483-491.

Aitken RL, Moody PW, Compton BL, Gallagher EC (1992) Pland and soil diagnostic tests for assessing the phosphorus status of seedling *Macadamia integrifolia*. Aust J Agric Res 43: 191-201. doi: 10.1071/ar9920191.

Aitken RL, Moody PW, Stephenson RA, Gallagher EC, Pignata AJ (1993) Phosphorus fertilizer requirements for macadamia - Final report MC017. Australian Macadamia Society.

Anonymous (2017) Macadamia. Species profile and threats database. Australian Government. Dept of the Environment and Energy, Canberra.

Baigent DR, O'Brien K (1987) Effects of lime/dolomite application on macadamia productivity. In: T Trochoulias, I Skinner (eds) Second Australian Macadamia Research Workshop, Bangalow, NSW.

Blamey FPC, Kopittke PM, Wehr JB, Menzies N (2015) Aluminum. In: AV Barker, DJ Pilbeam (eds) Handbook of Plant Nutrition. CRC Press, Boca Raton.

Brady NC, Weil RR (2008) The nature and properties of soils. Pearson, Delhi.

Bright J, Alt S, Commens R (2015) Macadamia integrated orchard management guide. NSW Dept Industry, Skills and REgional Development.

Cox J, Dalby T, Morris S, Keen B, Slavich P (2010) Improving soil and orchard floor management in macadamias - Final report MC05001. Horticulture Australia Sydney, NSW.

Cox J, Van Zwieten L, Ayres M, Morris S (2004) Macadamia husk compost improves soil health in sub-tropical horticulture. SuperSoil 2004: 3rd Australian and New Zealand Soils conference, Sydney, NSW.

Dudgeon M (2008) Smothergrass management - benefits and drawbacks. Australian Macadamia society - Annual conference. Australian MAcadamia society, Lismore, NSW.

Edmeades DC (2011) Base saturation ratios - why they are nonsense. The Fertiliser review No 26. agKnowledge, Hamilton, New Zealand.

Firth DJ (1991) The effect of regular heavy aplications of lime and dolomite on macadamias. AgNote. NSW Agriculture.

Firth DJ (1995) Deep placement of phosphorus in macadamia: final report. HRDC.

Firth DJ, Loebel MR (1987) Effect of calcareous amendments and mulch on macadamia trees with decline symptoms. In: T Trochoulias, I Skinner (eds) Proceedings of the Second Australian Macadamia Research Workshop, Bnagalow, NSW.

Firth DJ, Whalley RDB, Johns GG (2003) Distribution and density of the root system of macadamia on krasnozem soil and some effects of legume groundcovers on fibrous root density. Aus J Exp Agric 43: 503-514. doi: 10.1071/ea02108.

Fletcher A, Rennenberg H, Schmidt S (2010) Nitrogen partitioning in orchard-grown Macadamia integrifolia. Tree Physiol 30: 244-256. doi: 10.1093/treephys/tpp107.

Fox RL, Hue NV (1989) Boron requirement of macadamia seedlings. J Plant Nutr 12: 207-217. doi: 10.1080/01904168909363946.

Gillman G, Bruce R, Davey B, Kimble J, Searle P, Skjemstad J (1983) A comparison of methods used for the determination of cation exchange capacity. Commun Soil Sci Plant Anal 14: 1005-1014.

Gillman GP (1981) Effects of pH and ionic strength on the cation exchange capacity of soils with variable charge. Aust J Soil Res 19: 93-96.

Gross CL (1995) Macadamia. In: AE Orchard, PM McCarty (eds) Flora of Australia. CSIRO, Canberra.

Hue NV (2009a) Iron and phosphorus fertilizations and the development of proteoid roots in macadamia (Macadamia integrifolia). Plant Soil 318: 93-100. doi: 10.1007/s11104-008-9820-0.
Hue NV (2009b) Iron and phosphorus fertilizations and the development of proteoid roots in macadamia (*Macadamia integrifolia)* Plant Soil 318: 93-100.
Hue NV, Fox RL, McCall WW (1988) Chlorosis in macadamia as affected by phosphate fertilisation and soil properties. J Plant Nutr 11: 161-173. doi: 10.1080/01904168809363793.
Huett DO (2004) Macadamia physiology review: a canopy light response study and literature review. Aust J Agric Res 55: 609-624. doi: 10.1071/ar03180.
Huett DO, Vimpany I (2006) An evaluation of foliar nitrogen and zinc applications to macadamia. Aus J Exp Agric 46: 1373-1378. doi: 10.1071/ea05165.
Huett DO, Vimpany I (2007) Revised diagnostic leaf nutrient standards for macadamia growing in Australia. Aus J Exp Agric 47: 869-876. doi: 10.1071/ea06133.
Ishii T, Matsunaga T, Pellerin P, O'Neill MA, Darvill A and Albersheim P (1999) The plant cell wall polysaccharide rhamnogalacturanon II self-assembles into a covalently cross-linked dimer. The Journal of Biological Chemistry. 274: 13098-13104
Kopittke PM, Menzies NW (2007) A review of the use of the basic cation saturation ratio and the "Ideal" soil. Soil Sci Soc Amer J 71: 259-265.
Lambers H, Chapin FSI, Pons TL (2008) Plant Physiological Ecology. Springer, New York.
Landsberg JJ (1987) Macadamia decline: disorder or a matter of resource allocation? In: T Trochoulias, I Skinner (eds) Second Australian Macadamia research workshop, Bangalow, NSW.
Manson AD, Sheard A (2007) Macadamia fertilization in KwaZulu-Natal. KZN Agri-report No N/A/2007/10. KwaZulu-Natal Dept of Agriculture and Environment.
Marschner H (1995) Mineral nutrition of higher plants. Academic Press, London.
Menzies NW, Harbison D, Dart P (2011) Soil chemistry – facts and fiction and their influence on the fertiliser decision making process. Proceedings of the 26th Annual Conference of The Grassland Society of NSW. The Grassland Society of NSW, Bathhurst, NSW.
Moody PW (2009) Indicative critical soil phosphorus tests - Final Report MC7019. AMS-HAL-DERM.
Nagao MA, Hirae HH (1992) Macadamia - cultivation and physiology. Crit Rev Plant Sci 10: 441-470. doi: 10.1080/07352689209382321.
Nasholm T, Kielland K, Canereg U (2008) Uptake of organic nitrogen by plants. New Phytol 182: 31-48.
Nelson PN, Banabas M, Goodrick I, Webb MJ, Huth NI, O'Grady D (2015) Soil sampling in oil palm plantations: a practical design that accounts for lateral variability at the tree scale. Plant Soil 394: 421-429.
Newett SDE (1987) Some data supporting the need for higher phosphorus levels for macadamia in Australia. In: T Trochoulias, I Skinner (eds) Proceedings of the Second Australian Macadamia Research Workshop. Australian Macadamia Society, Bangalow, NSW.
O'Farrell (2011) Developing corrective treatments for maintaining macadamia nut production and normal growth. Final report MC3012. HAL-AMS-DEEDI.
O'Hare PJ (1993) Fertiliser management. Macadamia grower quality training program 1993.
O'Hare PJ, Stephenson R, Quinlan K, Vock N (2004) Macadamia Grower's Handbook. Department of Primary Industries and Fisheries in collaboration with New South Wales Department of Primary Industries and the Australian Macadamia Society, Nambour, Qld.
Perdona MJ, Martins AN, Suguino E, Soratto RP (2013) Nutrition and yield of macadamia nut as affected by nitrogen doses. Pesquisa Agropecuaria Brasileira 48: 395-402. doi: 10.1590/s0100-204x2013000400007.
Pire R, Arizaleta M, Melendez O (2002) Mineral nutrition of four cultivars of bearing and non-bearing macadamia trees in Villanueva, Lara State, Venezuela, and its variation in time. In: M

Tagliavini, M Toselli, L Bertschinger, D Neilsen, M Thalheimer (eds) Proceedings of the International Symposium on Foliar Nutrition of Perennial Fruit Plants.
Rayment GE, Higginson FR (1992) Australian laboratory handbook of soil and water chemical methods. Inkata Press, Melbourne.
Reid G (2002) Soil and nutrient loss in macadamia lands: a pilot study. Horticulture Australia HRDC project AA0001, Sydney.
Reuter D, Robinson JB (1997) Plant analysis: an interpretation manual. CSIRO, Collingwood, VIC.
Schafer BM (1987) Aspects of soil fertility management for macadamia production. In: T Trochoulias, I Skinner (eds) Second Australian Macadamia Research Workshop, Bangalow, NSW.
Schulte EE, Kelling KA (1993) Soil calcium to magnesium ratios - should you be concerned? University of Wisconsin, Wisconsin, USA.
Shane MW, Lambers H (2005) Cluster roots: A curiosity in context. Plant Soil 274: 101-125. doi: 10.1007/s11104-004-2725-7.
Shierlaw J, Alston AM (1984) Effect of soil compaction on root growth and uptake of phosphorus. Plant Soil 77: 15-28. doi: 10.1007/bf02182808.
Shigeura GT, Silva JA, Bullock RM, Sumida DM (1974) The effects of phosphate fertilizer in macadamia nut tree nutrition. Hawaii Macadamia Producers Association 14th Annual Proceedings, Kainaliu, Kona.
Smith TE, Stephenson RA, Asher CJ, and Hetherington SE (1997a) Boron deficiency of avocado 1. Effects on pollen viability and fruit set. In Boron in Soils and Plants. R.W. Bell and B. Rerkasem (eds.). Kluwer Academic Publishers, Netherlands. p 131–133
Smith TE, Asher CJ, Stephenson RA, and Hetherington SE (1997b) Boron deficiency of avocado 2. Effects on fruit size and ripening. In Boron in Soils and Plants. R.W. Bell and B. Rerkasem (eds.). Kluwer Academic Publishers, Netherlands. p 135–137
Soil Science Australia Queensland branch (2013) Measuring soil cation exchange and exchangeable cations. Australian Society of Soil Science Incorp., Warragul, Vic.
Stanley TD, Ross EM, Jessup LW (1983) Flora of south-eastern Queensland / T.D. Stanley and E.M. Ross. Brisbane : Queensland Department of Primary Industries, Brisbane.
Stephenson R (2004) Develop a benchmark for soil health in macadamia orchards. Horticulture Australia Ltd, Sydney.
Stephenson RA, Aitken RL, Gallagher EC, Moody PW (1996) Amelioration of coarse textured acidic soils used for macadamia production .1. Tree growth, yield and leaf nutrient composition. Aust J Agric Res 47: A97-A107.
Stephenson RA, Cull BW (1986) Standard leaf nutrient levels for bearing macadamia trees in Southeast Queensland. Scientia Hort 30: 73-82. doi: 10.1016/0304-4238(86)90083-x.
Stephenson RA, Cull BW, Mayer DG, Price G, Stock J (1986) Seasonal patterns of macadamia leaf nutrient levels in Southeast Queensland. Scientia Hort 30: 63-71. doi: 10.1016/0304-4238(86)90082-8.
Stephenson RA, Gallagher EC (1986) Effects of temperature during latter stages of nut development on growth and quality of macadamia nuts. Scientia Hort 30: 219-225. doi: 10.1016/0304-4238(86)90100-7.
Stephenson RA, Gallagher EC (1987a) Effects of foliar boron sprays on yield and quality of macadamia nuts. Scientia Hort 32: 97-103. doi: 10.1016/0304-4238(87)90020-3.
Stephenson RA, Gallagher EC (1987b) Effects of temperature, tree water status and relative humidity on premature nut drop from macadamia. Scientia Hort 33: 113-121.
Stephenson RA, Gallagher EC (1989) Timing of nitrogen application to Macadamias. 3. Reproductive growth, yield and quality. Aus J Exp Agric 29: 581-585. doi: 10.1071/ea9890581.
Stephenson RA, Gallagher EC, Aitken RL (1991) The effects of lime applications to acid soils on tree growth and production.
Stephenson RA, Gallagher EC, Doogan VJ (1997) Leaf nitrogen as a guide for fertilising macadamia. Aus J Exp Agric 37: 599-604. doi: 10.1071/ea96143.

Stephenson RA, Gallagher EC, Doogan VJ (2003) Macadamia responses to mild water stress at different phenological stages. Aust J Agric Res 54: 67-75. doi: 10.1071/ar02108.
Stephenson RA, Gallagher EC, Gogel BJ (2002) Macadamia nut size and maturity influenced by lime and nitrogen applications. Aust J Agric Res 53: 677-680. doi: 10.1071/ar01146.
Stephenson RA, Gallagher EC, Pignata AJ (1992) Nitrogen strategies for maximizing macadmia yield. Proceedings of the First International Macadamia Research Conference, Kailua-Kona, Hawaii.
Tamimi YN, Matsuyama DT, Sako G, Okazaki E (1992) Mineral distribution in macadamia trees. Proceedings of the First International Macadamia Research Conference, Kailua-Kona, Hawaii.
Trochoulias T, Lahav E (1983) The effect of temperature on growth and dry-matter production of macadamia. Scientia Hort 19: 167-176. doi: 10.1016/0304-4238(83)90058-4.
van Niekerk K (2002) Fertilisation of macadamia nut trees. South African Macadamia Growers Association Newsletter January: 2-10.
Walton K, Alle D (2004) Mehlich No. 3 Soil Test - The Western Australian Experience. SuperSoil 2004: 3rd Australian New Zealand Soils Conference, Sydney, NSW.
Warner RM, Fox RL (1972) Concentration and distribution of S, Mg, and five mincronutrients in macadamia in relation to yields. Hawaii Macadamia Producers Association Twelfth Annual Meeting Proceedings, Hilo.
Wehr JB, Blamey FPC, Menzies NW (2016) Aluminum. In: R Lal (ed) Encyclopedia of Soil Science. 3rd edn. Taylor and Francis, New York.
Wehr JB, Blamey FPC, Smith TE, Menzies NW (2017) Growth and physiological responses of teak (*Tectona grandis*) clones to Ca, H and Al stresses in solution and acid soils. New Forests 48: 137-152.
Weil RR, Brady NC (2017) The nature and properties of soils. Pearson Higher Ed., Boston.