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Macadamia grower's guide 2023

NUTRITION AND SOIL HEALTH – PART 2: THE NEXT LEVEL

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Disclaimers

Image acknowledgements

Large cover photo: a newly established inter-row crop.

Smaller photos left to right: chipping and retaining pruned material in the orchard cycles biomass from the canopy to the orchard floor; liming at low rates can support nutrient uptake in acid-tending soils; when soil testing, divide the orchard divide the orchard into zones where conditions vary, such as different tree ages.

Unless otherwise stated, the images in this guide have been sourced from the NSW Department of Primary Industries.

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Nutrition and soil health – Part 2: The next level

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About this guide

Nutrition and soil health – Part 2: The next level, is a companion to *Nutrition and soil health – Part 1: The foundations*.

Good management of nutrition and soil health starts with *Part 1: The foundations*, which offers a framework for building and sustaining production that is beneficial in every orchard. The foundational approach uses soil and tree monitoring to support decision-making about:

- correcting pH
- building up organic matter
- implementing effective drainage
- replacing nutrients and correcting imbalances.

Part 2: The next level supports growers with:

- refining foundation practices
- making more use of monitoring information
- investigating the causes of nutrient disorders in trees
- positively managing nutrition and soil health
- increasing fertility and productivity over the life of the orchard.

The macadamia grower's guide project (2022–24) provides up-to-date resources on best management practices for macadamia growers. Online resources allow for updates incorporating new research findings and evolving macadamia management practices.

NSW DPI maintains current information for macadamia growers. More up-to-date information could be available online at https://www.dpi.nsw.gov.au/agriculture/horticulture/nuts

Contents

Good management – Part 1: The foundations

Macadamia trees need nutrients to grow and produce nuts. Good soil health makes nutrients available and supports the complex microbiology that healthy trees rely on. Soil conditions and nutrient profiles vary between and within orchards. Adding nutrients is necessary to replace losses and correct deficiencies.

First, prepare macadamia orchards for high productivity by implementing the nutrition and soil health foundations to:

- support soil and tree health
- ensure inputs contribute to orchard productivity
- minimise excess fertiliser use
- reduce nutrient losses to the environment.

The journey from good to optimal – Part 2: The next level

Having solid foundations means that management practices contributing to nutrition and soil health are part of routine farm activities. Many soil test results, particularly the available nutrients, are likely to improve after adopting the nutrition and soil health foundations.

Reasons to defer specific nutrient management until after the foundations are in place include:

- correct pH, which optimises the availability of the existing nutrients
- organic matter additions, which increase resources in the soil system
- fixing drainage issues so that the physical conditions for healthy roots are in place and fewer inputs are lost with erosion
- monitoring to provide the information needed to make informed, site-specific decisions.

Taking nutrition and soil health beyond *The foundations* (Figure 1) involves:

- reviewing and refining foundation practices
- balancing immediate crop needs with orchard resilience strategies
- refining nutrient additions using monitoring information to:
  - meet peak demand for specific nutrients
  - accommodate cultivar differences
  - respond to changing conditions
  - improve fertiliser efficiency
  - correct or prevent nutrient imbalances
  - support an increase in biomass
  - improve environmental performance
  - increase economic return on investment.

Nutrition and soil health management are complex and depend on soil characteristics. The foundations for macadamia nutrition and soil health are general and introduce key principles. We encourage growers to seek independent advice to enhance nutrition and soil health decisions.

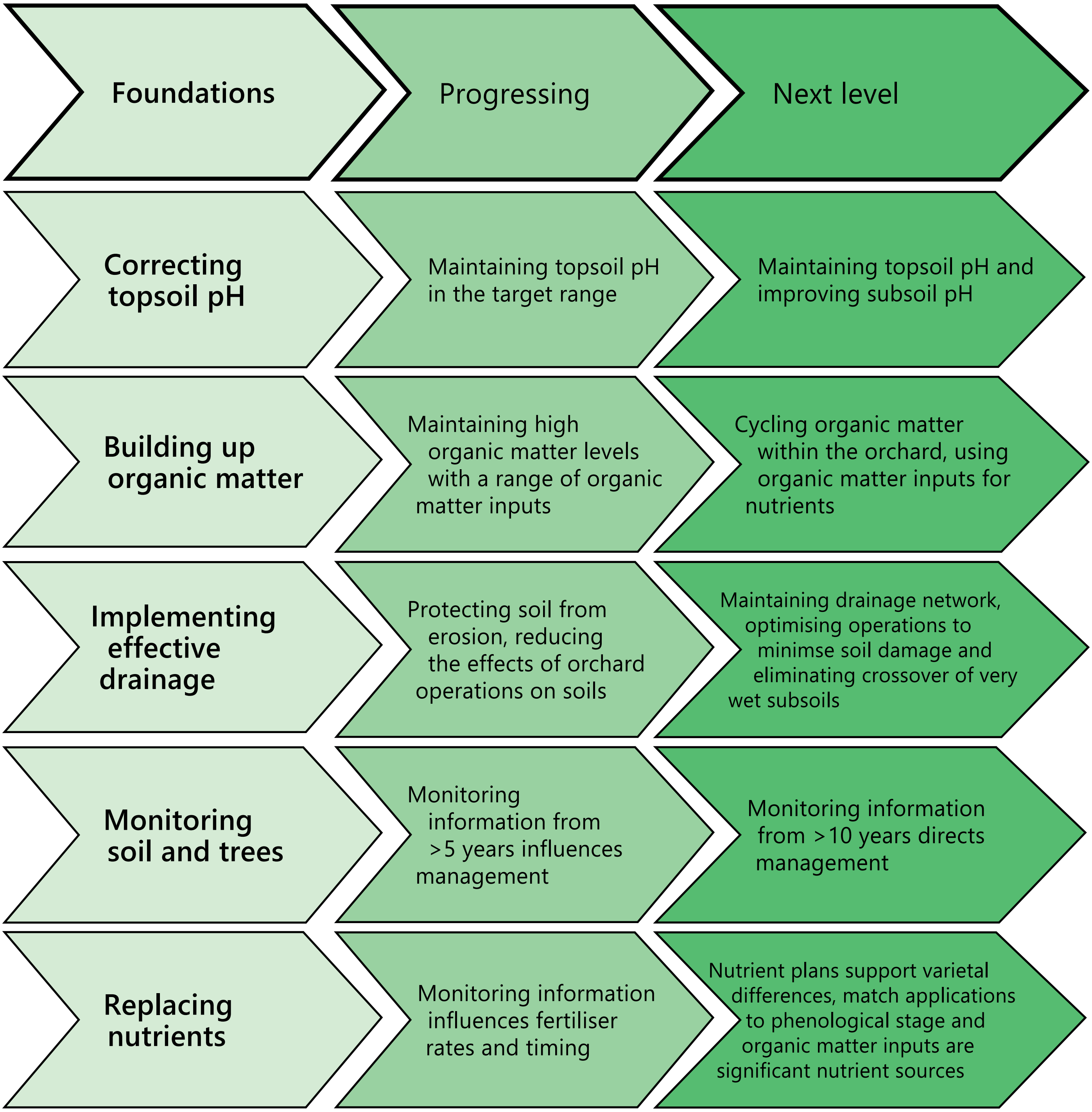


Figure 1. The foundations are the start of good practice in managing nutrition and soil health in macadamia. Growers with high-performing orchards implement key activities towards *The next level*.

Correcting soil pH

Soil pH is a valuable indicator of soil condition. Often it is the most limiting **manageable** soil factor for plant growth. Soil pH strongly influences soil chemistry by affecting the solubility of different minerals (Figure 2) and the cation exchange capacity (CEC). Sub-optimal pH means fewer desirable nutrients for trees and suppressed soil biology.

The target pH ranges for macadamia maximise nutrient availability and optimise conditions for root growth and soil biology. Monitoring soil pH and keeping it within the target range is critical to sustaining high productivity.

Soil pH is measured in water (pH_w) or calcium chloride (pH_{Ca}). Laboratory analyses usually report both measures. The target ranges are given in pH_{Ca} because they are more accurate (Figure 3) and less seasonally variable. The divergence between pH_w and pH_{Ca} tends to increase with increasing soil CEC.

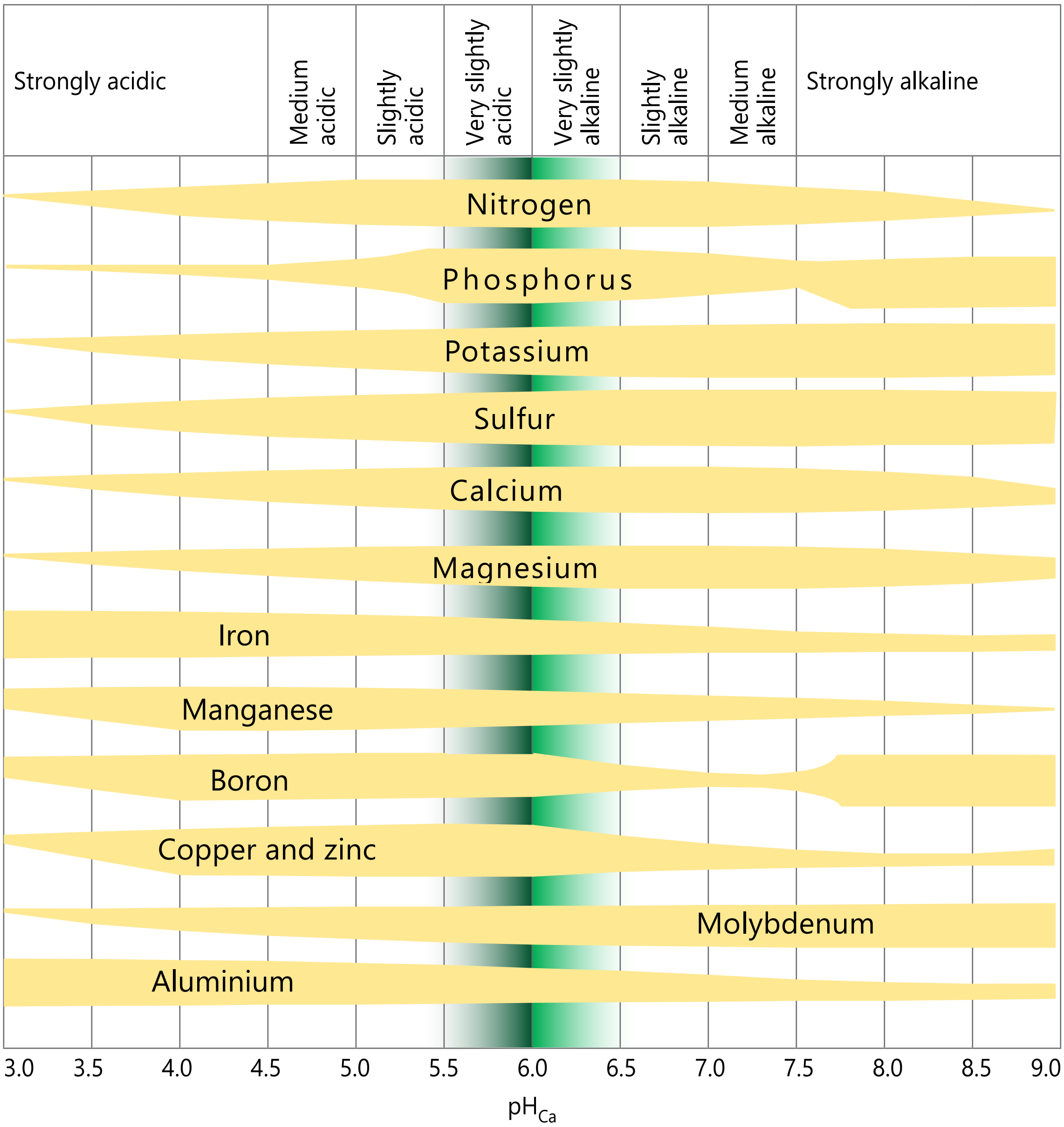


Figure 2. The availability of specific nutrients in soils changes with the pH. The thicker the yellow band, the more soluble the element is at that level of soil acidity or alkalinity. The target pH range for acidic soils is 5.5–6.0 pH_{Ca} (shaded in darker green) and for alkaline soils is 6.0–6.5 pH_{Ca} (in paler green). Source: adapted from Blake (2000).

The target soil pH_{Ca} ranges for macadamia are:

- 5.5–6.0 in naturally acidic soils
- 6.0–6.5 in naturally alkaline soils.

The recommended soil pH used to be 5.0 pH_w (<4.5 pH_{Ca}). The current pH target ranges are higher and promote maintaining pH within a range of 0.5 pH units, rather than at a specific point.

The **target range for acidic soils** keeps the availability of undesirable, toxic cations such as aluminium (Al) and manganese (Mn) at low levels. It maintains the CEC's role in providing plant-available, desirable cations. The pH of naturally acidic soils can fall below the target range without ongoing management.

The **target pH range for alkaline soils** promotes the availability of micronutrients such as boron (B), iron (Fe), copper (Cu) and zinc (Zn). The pH of naturally alkaline soils can rise above the target zone without ongoing management.

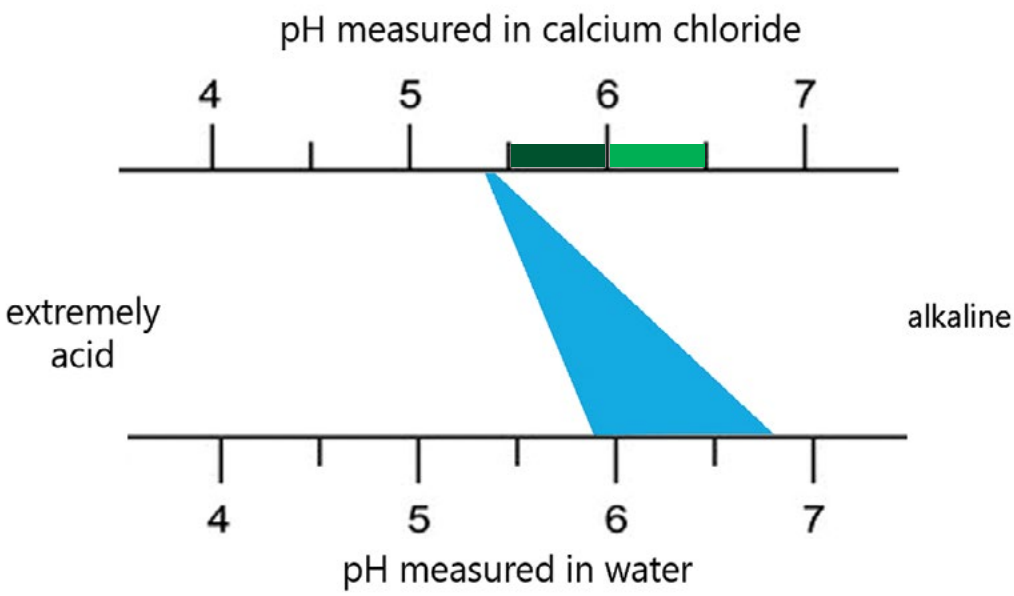


Figure 3. pH measured in water can be 0.5 to 1.3 pH units higher than when measured in calcium chloride (pH_{Ca}). The preferred range for acidic soils is 5.5–6.0 pH_{Ca} (shaded in darker green) and 6.0–6.5 pH_{Ca} for alkaline soils (in paler green). Source: adapted from Anon (2020).

Correcting and stabilising soil pH is a cycle (Figure 4). If the soil is too acidic, apply liming materials and if the soil is too alkaline, apply acidifying materials. Liming materials are usually applied after nut set and before harvest because liming materials are dusty, especially superfine lime. Dust on new flowers could impede pollination. Applying lime after nut set allows the dust to settle and the lime to wash into the soil before harvest preparations begin.

Surface-applied lime moves into the soil with rainfall or irrigation. Avoid applying lime immediately before forecast high rainfall to minimise lime washing off the soil. Acidifying materials are usually also fertilisers, so the nutrition program determines the application timing.

Rapid pH change is a physiological stressor for living organisms. Before planting, there is an opportunity to make large pH corrections. Once the trees are growing, it is essential to minimise harm to tree roots and soil biology.

Safe incremental rates are the amounts of liming or acidifying materials that can be applied without harming trees or soil life and reduce the risk of losing recently applied materials. The safe incremental rate is limited by the soil's effective CEC (ECEC) and the need to place materials on the soil surface to avoid root disturbance.

The ECEC is an estimate of the CEC and is calculated from measuring individual exchangeable cations in the soil sample. It is the sum of the exchangeable cations calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), manganese (Mn) and aluminium (Al), measured in cmol(+)/kg (previously meq/100 g). Soils with higher ECEC can require and tolerate higher rates of liming or acidifying materials.

For more information, refer to the following sections on Acidity, Alkalinity and Safe incremental rates.

It can take several years to get the soil pH into the target range where a large shift is needed. Each application at a safe incremental rate moves the pH towards the target range. Organic matter inputs can reduce toxicities while the pH is out of the target range.

Once soil pH is within the target range, aim to keep it there. Measuring pH more often than annually could be helpful.

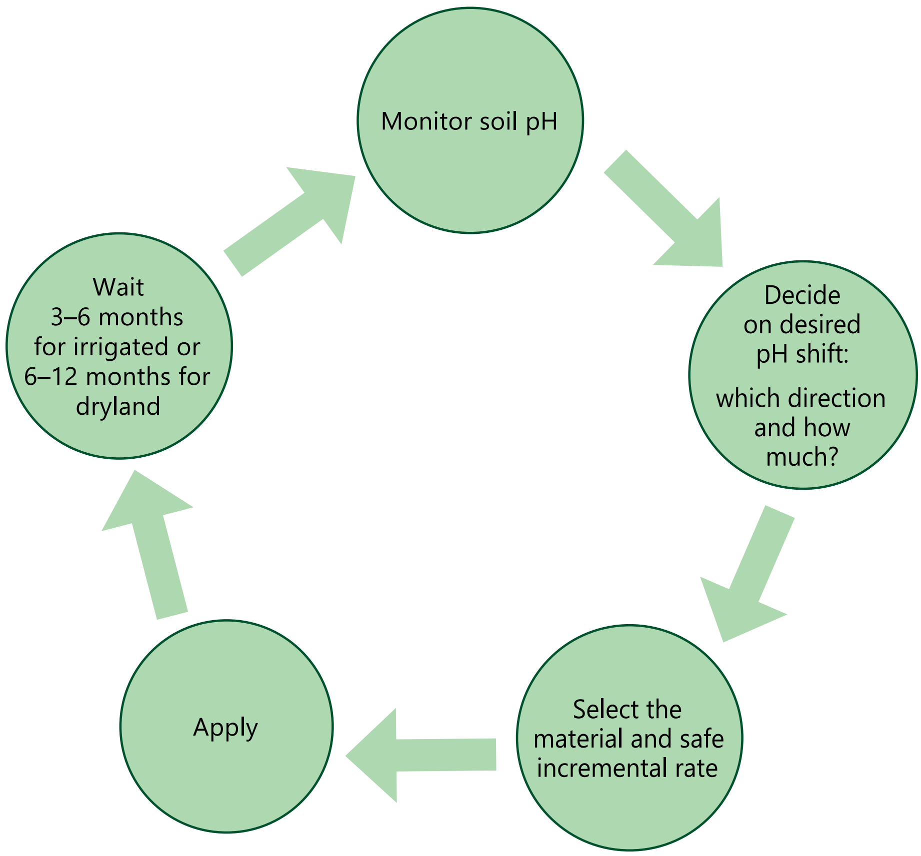


Figure 4. Monitoring and adjusting soil pH is a cycle.

Acidity

Acidity (low soil pH) is common in Australia where macadamias are grown. Soil acidification is a natural ongoing process in high rainfall areas. Many agricultural practices and some N fertilisers speed up soil acidification (Table 1). In soils with pH_{Ca}:

- **below 5.5**
  - tree growth is impaired, and younger macadamia trees (<5 years old) can slowly decline
  - older trees are more susceptible to pests and diseases such as bark beetle and phytophthora
  - soil microorganism activity reduces dramatically, impairing decomposition and nutrient recycling from organic sources
  - aluminium (Al) levels increase
- **below 4.8**
  - plants have stunted roots and a lack of root hairs
  - water and nutrient uptake are impaired
- **below 4.5**
  - aluminium and manganese (Mn) toxicities occur
  - calcium (Ca) and magnesium (Mg) availability fall.

Table 1. Fertiliser forms and the amount of lime required to offset acidification.

Nitrogen (N) source	Amount of lime (kg) required to offset each kilogram of fertiliser used
Potassium nitrate (13% N) Calcium nitrate (15.5% N) Composted poultry manure (3% N)	0
Urea (46% N) Ammonium nitrate (34% N)	2:
Diammonium phosphate (DAP) (18% N)	3.5:
Sulfate of ammonia (21% N) Mono-ammonium phosphate (MAP; 11.3% N)	5.5:

Source: adapted from Lines-Kelly (1992).

Liming materials to correct low pH

Nutrients

Select a liming material that will also provide the most needed nutrients for the soil. Liming materials usually contain significant amounts of Ca, Mg or both:

- agricultural **lime** supplies Ca
- **dolomite** supplies Mg and Ca
- **magnesite** supplies Mg.

Macadamia growers rarely use magnesite because Ca is often needed.

Particle size and neutralising value

Particle size, also called fineness, controls the neutralising reaction rate. Superfine limes with particle sizes as small as 0.07 mm (70 microns) are the best option for unincorporated surface applications. The smaller particles move more quickly into the soil.

A liming material's neutralising value (NV) is its capacity to neutralise compared with the standard, which is pure limestone (calcium carbonate) with an NV of 100. The NV of most commercial liming products is 96–98.

Effective NV (ENV) incorporates the range of particle sizes present. A lime with more small particles will have a higher ENV than a lime with more large particles. Macadamia growers rarely use liming products with an ENV >100 (e.g. hydrated or burnt lime) because they create a risk of pH shock that can harm tree roots and soil biology.

Safe incremental rates

Select a safe incremental rate for liming materials (Table 2) using the ECEC value from the most recent soil analysis.

Table 2. Safe incremental rates for liming materials at different soil effective cation exchange capacities (ECEC).

Soil test ECEC (cmol/kg)	Safe incremental rates for surface broadcast liming materials (t/ha)	Safe incremental rates for surface banded applications (2 m on each side of the tree trunk) (t/ha)
1	1	0.4
2	2	0.8
>3	3	1.2

Over-liming occurs when more lime is applied than was needed to reach the target pH range. The topsoil pH moves above the target range, usually temporarily. Over-liming can induce nutrient imbalances and availability issues. The risk of over-liming is highest in soils with a low ECEC, such as sandy soils with low levels of organic matter.

Liming rates over 3 t/ha for unincorporated surface applications are not ideal because of the amount of dust and the risk of losing the liming material during rain. Consider splitting into 2 applications, 3–6 months apart if applying >3 t lime/ha/year, even in high CEC soils.

Liming rates under 1 t/ha might be impractical to apply using a standard lime spreader. Some options, which growers can use in combination, are to:

- spread applications out over time (e.g. every 2 or 3 years instead of every year)
- use a prilled (pelletised) lime product that can be applied at lower rates with a fertiliser spinner (and can be blended with other inputs)
- use organic matter inputs to increase the soil's buffering capacity.

Proactive liming (Figure 5) at low rates can support nutrient uptake – even when the pH is in the target range for acidic soils. The early stages of acidification do not show up as pH change because hydrogen cations attach to CEC sites. This changes the nutrient supply from the CEC because the hydrogen cations occupy sites that could be holding useful nutrients. Liming neutralises hydrogen cations, removing them from the CEC and freeing up CEC sites to hold more nutrients.

Figure 5. Liming at low rates can support nutrient uptake. Photo: Graham Wessling, CL Macs.

In a soil test, sub-optimal nutrient supply caused by hydrogen cations occupying sites in the CEC would appear as low **base saturation**; a calculation based on the same measurements used to calculate ECEC. It is the sum of the exchangeable basic (non-acidic) cations (Ca, Mg, K and Na) divided by the total ECEC. The base saturation shows how much of the CEC is occupied by basic cations as a percentage of the total ECEC. Consider liming or adding Ca from another source to raise the base saturation if it is less than 80%. Liming to maintain the nutrient supply is most likely to be important in naturally acidic soils with high ECEC (>20 cmol/kg).

Subsoil acidity

Treat subsoil acidity by applying lime at a safe incremental rate or less. The lime starts to move down in the soil once the topsoil (0–100 mm) pH_{Ca} is >5.5. Some unreacted liming material builds up in the topsoil and moves slowly (around 10–30 mm/year) down into the subsoil with rain. It is impractical to expect any positive effect on subsoil acidity from liming until the topsoil pH is maintained in the target range for acidic soils.

Alkalinity

When soil pH is >6.5 pH_{Ca} many nutrients become unavailable. For example, boron (B), copper (Cu), iron (Fe) and zinc (Zn) can all become deficient.

Acidifying materials to correct high pH

Acidifying materials react chemically within the soil to produce acid. They are often fertilisers that supply nutrients. The main consideration when selecting acidifying materials is the nutrient contribution and how this complements the nutrient program. Avoid over-applying nutrients by subtracting those applied to acidify soils from other planned fertiliser rates.

The acidifying value of fertilisers is not clear-cut. The chemical reactions within the soil are more complex than liming reactions and vary in different soils. Less advice is available because the need to correct high pH in Australia is much less common than the need to correct low pH. One approach is to consider the inverse of the liming requirement (amount of lime recommended to offset the use of these fertilisers in acidic soils) for each fertiliser in Table 1.

All acidifying fertilisers are highly soluble in water. Therefore, their effects in the soil are rapid and present a risk of overcorrecting pH. Once the pH is close to the target range, and the aim is for small pH shifts (<0.5 pH units), consider using organic matter inputs instead of acidifying fertilisers. Organic matter decomposition slowly creates small amounts of acid and benefits soil health.

Building organic matter

Organic matter is a highly desirable constituent of the soil. Soil organic matter (SOM) is any living or non-living microbe, plant, fungi or animal material. About 40% of SOM is organic carbon. To convert SOM to soil organic carbon (SOC), divide the SOM by 1.75. Soil organic carbon values greater than 4% are considered high, 2–4% as medium, and 1–2% as low. Clay soils can support higher SOC than sandy soils.

Aim to have SOC levels greater than:

- 3.0% in clay soils
- 2.5% in clay loams
- 2.0% in loams
- 1.5% loamy sands.

Increasing organic matter levels in the soil:

- improves soil structure, drainage and water retention
- assists with disease suppression
- increases available nutrients such as nitrogen (N) and phosphorus (P)
- increases the CEC
- favours root growth.

High SOC (at or over the levels listed above) and active microbial cycling of organic materials can reduce the need for chemical fertilisers and contribute to the orchard's capacity to resist drought stress. Once organic matter and soil carbon levels are high, further inputs of organic materials will not substantially increase SOC. Continue to add organic matter to feed soil life and maintain a steady supply of nutrients from decomposition processes.

Applying organic inputs

Organic materials vary in their nutrient contents and rates of decomposition (Table 3). Broadly, organic inputs can be classed as mulches, manures or composts. Composting organic materials before spreading reduces:

- the weight and volume of material to spread by about half
- nutrient root burn from uncomposted manures
- nutrient drawdown (immobilisation) from microbial demand in decomposing carbon-rich materials
- pathogens present in the material.

Macadamia feeder roots are most dense close to the trunk. Spread organic materials close to the trees to protect the material from traffic and apply them in thick layers to create more space for feeder root development.

Cycling biomass

Cycling biomass is the mainstay of nutrient supply in natural forests. In their natural setting, macadamias feed primarily from the complex forest litter (leaves, branches, animal wastes and dead organisms) as it decomposes. However, a complex and deep forest litter is not compatible with orchard operations.

A macadamia orchard is a simplified forest. Growers aim to create an orchard floor system that allows orchard operations and provides suitable conditions for feeder roots and biological nutrient cycling. Living ground covers enable stable orchard floors. Ongoing canopy management maintains sunlight to ground cover plants.

Large quantities of woodchip from orchard renovations (Figure 6) are an essential part of reinvigorating the soil in run-down orchards. Frequent contributions of chipped tree prunings and mowed ground covers contribute fresh organic matter to the soil surface. They contribute to ground cover that protects the soil and decompose at different rates to provide nutrients to trees.

Mulching with materials from within the orchard adds more organic matter than an equivalent amount of mulch from another source. Plants balance the loss of above-ground biomass with proportional die-off in their root biomass. This root pruning occurs naturally after above-ground plant parts are pruned or mowed. The organic matter from root residues is already inside the soil and directly improves soil structure. Annual plants in the inter-row contribute root residues at the end of their life cycle.

Figure 6. Chipping and retaining pruned material in the orchard cycles biomass from the canopy to the orchard floor.

Table 3. Comparison of some organic matter inputs. Source: adapted from Hardy et al. (2017).

Amendment	Type	Typical nutrient value (%) N:P:K (guide only)	Particle size range	Useful features	Cautions
Grass clippings	Mulch	N 2.7–4.0 P 1.0 K 2.0	Fine	The high N value helps to break down carbon-rich residues.	Avoid piling excessively deep around young trees.
Chipped prunings or woodchip	Mulch	N 0.01 P 0.001 K 0.01	Coarse	From within the orchard: recycling nutrients and organic material, non-living ground cover.	The orchard might need additional N to balance the needs of trees and soil microbes. Try to double-grind if possible.
				External source: adding organic matter and non-living ground cover; can be used to bulk up other organic matter inputs.	Large woodchip pieces can float off in heavy rain or take years to break down. Try to double-grind if possible. If using municipal waste, it might contain weeds or other contaminants.
Sawdust	Mulch	N 0.048 P 0.007 K 0.017	Fine	Provides ground cover during harvest that is not picked up by harvesters.	Slow to break down. It can immobilise nutrients and form a less permeable surface crust.
Poultry manure	Manure	N 1.6–3.0 P 1.3 K 1.7	Fine	It can be blended with other materials.	Only apply uncomposted manure at least 4 months before mature nut drop starts. After that, composted manures can be applied more freely. See the *Australian Macadamia Industry Code of Sound Orchard Practices* (COSOP) for more information. Be careful not to overshoot the target for phosphorus levels in the soil.
Cow manure	Manure	N 0.5–2.0 P 0.1–0.7 K 0.3–1.5	Fine if composted before delivery	It adds nutrients and builds organic matter. It is standard as part of some organic matter mixes.	Uncomposted raw material is difficult to spread. If sourced from a feedlot, be wary of unwanted matter, e.g. stones in the product.
Municipal compost	Compost	N 1.4–3.5 P 0.3–1.0 K 0.4–2.0	Request fine/ screened material	It builds organic matter.	Inspect the compost before committing to an order. Some municipal composts contain plastics, and weed propagules.
Mill mud	Compost	N 0.30 P 0.24 K 0.08	Fine	It has some liming effect.	It blends well with manures.
Husk	Compost	N 0.38 P 0.06 K 0.70	Coarse	It can be blended with other material and builds organic matter.	Best applied as a blend with other products such as manure.

Inter-row crops

Cover crops or permanent sward in the inter-rows provide additional organic matter for the orchard and:

- protect the soil from erosion
- improve soil structure
- increase microbial activity and diversity
- can be critical habitat for beneficial insects
- keep soils cooler in summer and warmer in winter.

Green manure crops (Table 4) provide organic material to incorporate into the soil. They improve soil structure, health, fertility, organic matter and biological activity. Green manure options include legumes (e.g. beans, field peas and lupins) and cereals (e.g. barley, millet, oats and rye). Bio-fumigant crops, such as brassicas (e.g. forage rape and Indian mustard), can help reduce pest nematode populations.

Legumes can contribute extra N. The quantity depends on the nutrient status of the soil, successful nodulation, type and variety, soil moisture at the time of incorporation and temperature. Soil acidity (≤5.5 pH_{Ca}) and high levels of Al inhibit legume nodulation. The amount of N fixed varies between 0–300 kg/N/ha. Soil nitrate levels can peak about 5 weeks after incorporating the crop into the soil, but allow for the irregular release of this available N. Incorporating the crop is often only practical in young orchards with smaller trees. Cut the inter-row crop (Figure 7) with a slasher/mower and side-throw the material under mature trees.

Table 4. A guide to the nitrogen (N) content and carbon:nitrogen (C:N) ratio of some cover and green manure crops. Source: Hardy et al. (2017).

Crop type	Species	N (% dry matter)	C:N ratio
Legumes	Faba bean (*Vicia faba*)	3.4	13:1
	Field pea (*Pisum sativum*)	2.3	19:1
	Sandplain lupin (*Lupinus cosentinii*)	2.4	18:1
Medics	Barrel medic (*Medicago truncatula*)	3.9	11:1
	Burr medic (*Medicago denticulata*)	2.8	17:1
	Paraggio medic (*Medicago truncatula*)	2.9	15:1
	Prostrate lucerne (*Medicago sativa*)	3.6	12:1
Cereals	Oats (*Avena sativa*)	0.9	49:1
	Perennial ryegrass (*Lolium perenne*)	0.6	78:1
	Triticale (*Triticum aestivum* × *Secale cereale*)	1.1	41:1
	Wheat (*Triticum aestivum*)	0.8	52:1
Brassicas	Indian mustard cv. Nemfix (*Brassica* spp.)	4.3	9:1
	Weedcheck (*Raphanus* spp. × *Brassica* spp.)	3.0	13:1

Figure 7. An inter-row crop. Photo: Bob Maier, Macadamia Consultant.

Root exudates

Root exudates are secretions from roots, comprised mostly of dissolved sugars delivered directly to the soil through the feeder roots. They are the optimal biostimulant as they are applied with more effective placement than anything from the soil surface.

Diverse microorganisms feed on the exudates. Their activity boosts the nutrient supply close to the roots. The tree influences the populations of specific microorganisms in the root zone through variations in the exudate. Macadamias also secrete citric acid within their root exudates, contributing to local P solubility and uptake.

Root exudates can be up to a third of the sugars produced by the tree. Other plants in the orchard will deliver extra root exudates into the soil (Figure 8).

Troubleshooting

Soil slaking and surface crusting are signs of poor long-term management. They indicate very low organic matter and possibly other constraints. Resolve these problems by working on *Nutrition and soil health – Part 1: The foundations*, increasing living ground covers and reviewing harvest practices.

Figure 8. Establishing an inter-row crop is a good way to deliver root exudates into the soil.

Implementing effective drainage

Drainage refers to water movement across the surface and within the soil. Soil erosion is the leading process in orchard decline.

To prevent erosion from surface water movement:

- control run-on water into the orchard
- safely move concentrated water flows via grassed watercourses
- apply slope-specific management throughout the orchard.

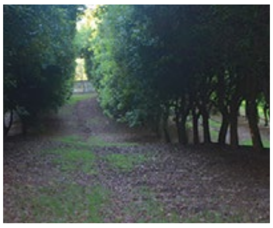
Slope-specific management involves maintaining minimum levels of ground cover to protect soil from being mobilised by raindrop impact. Steeper slopes require higher proportions of living ground cover. The best option is to use LiDAR mapping to define slope class areas to guide the ground cover targets through the orchard.

Integrated orchard management slope-specific management

The integrated orchard management (IOM) slope-specific management guidelines (Table 5) consider the slope's contribution to erosion potential by managing the density and type of ground cover. All ground cover is helpful. Living ground covers with roots in the soil have more capacity to resist the energy of moving water compared with non-living ground covers.

Living ground cover depends on sunlight getting to the orchard floor. Therefore, close attention to canopy management to allow sufficient light to the orchard floor is essential on moderate and steep slopes.

Table 5. Integrated orchard management slope-specific guidelines. Source: *Macadamia integrated orchard management guide* (2022).

Slope range	**Flat to gentle**	**Moderate**	**Steep**	**Too steep**
				
	A flat to gentle slope in a macadamia orchard.	A moderate slope in a macadamia orchard.	A steep slope in a macadamia orchard.	A too steep slope in a macadamia orchard.
Suitability	Preferred.	Workable with higher management costs.	Do not plant on these slopes. If already planted, manage the canopy to promote living ground cover.	Do not plant. Consider decommissioning blocks on these slopes.
Slope as percentage	0–12%	13–21%	22–30%	>31%
Slope as ratio	0:10 to 1:8	1:9 to 1:4.5	1:5 to 1:3	>1:3
Slope in degrees	0–7.5º	7.6–12.5º	12.6–17.5º	>17.5º
Minimum ground cover (living and non-living)	80%	90%	95%	Not suitable for macadamias.
Maximum proportion as non-living ground cover	100%	40%	5%	
				
	Mulch cover >80%.	Mixed living and non-living ground cover >90%.	Living ground cover >95%.	
Orchard floor priority	Building soil organic matter.	Dense living ground cover in the inter-rows.	Living ground cover up to the tree trunks.	

Mitigating poorly drained soils

Impaired sub-surface drainage can significantly reduce tree performance. Identify poorly drained soils by:

- detailed elevation mapping
- low elevation relative to the surrounding landscape
- wetland plants such as rushes or sedges
- a change of soil type across the slope
- a soil survey
- macadamia trees with impaired growth (Figure 9).

To investigate the soil condition, dig soil pits in the problem areas.

Figure 9. The trees at the end of the rows were in poor condition from the poorly drained soil and have since been removed.

Avoid areas with poorly drained soils when planning a new orchard or remediate the area before planting. Sub-surface drainage problems in existing orchards can be improved by:

- ameliorating soil compaction
- installing sub-surface drains
- removing trees from severely affected areas
- profiling to reshape the orchard floor to increase the mounding in tree rows (if the final profile is practical for harvesting and the work will not disturb unsuitable subsoil material).

The *Macadamia integrated orchard management drainage guide* (2022) contains detailed information on how to apply drainage strategies.

Understanding limiting issues

Soil physics

The soil's physical properties affect the soil conditions for plants. Different soil types benefit from different management approaches and also influence the results of those management practices. Soil physical properties influence:

- water infiltration and the effective use of rainfall and irrigation
- erodibility
- soil aeration and root growth
- hardpan layers and surface crusting developing
- nutrient management
- root growth.

Together, soil texture and structure set the amount of water and nutrients a soil can hold. Other physical properties, such as bulk density, porosity and plasticity, are controlled by soil texture and structure.

Soil texture

Soil texture (Figure 10) describes the relative proportions of different-sized particles (e.g. sands, loams, silts and clays):

- sandy soils have more large particles
- clay soils have more fine particles.

Soil texture is a permanent factor in soil management. The only way to change soil texture is by bringing in enormous amounts of material with a different texture. Being aware of soil texture helps to better select, schedule and adapt practices to benefit the orchard.

Sandy soils are generally well-drained and aerated, but have a low capacity to store water and nutrients. Building organic matter is the main way to improve sandy soils.

Clay soils are more fertile, having a greater capacity to hold and store water and nutrients. Their soil structure is more variable than sandy soils. They are more vulnerable to compaction, poor aeration and waterlogging; these effects are long-lasting. Managing orchard operations to prevent damage (such as compaction) is important in clay soils.

Soil structure

Soil structure describes the shape, size and arrangement of soil particles or aggregates and the pore spaces between them. Management can influence soil structure (Figure 11) but not soil texture.

Compaction reduces the air spaces within the soil and crushes the aggregates that provide better soil structure. The result is impaired water infiltration and drainage, as well as reduced oxygen supply to roots and soil organisms. Compaction is assessed onsite with a penetrometer and in the laboratory by measuring the bulk density of the soil. Roots might be unable to push into the soil where bulk density is >1.6 kg/m^3. Lower bulk density values are desirable.

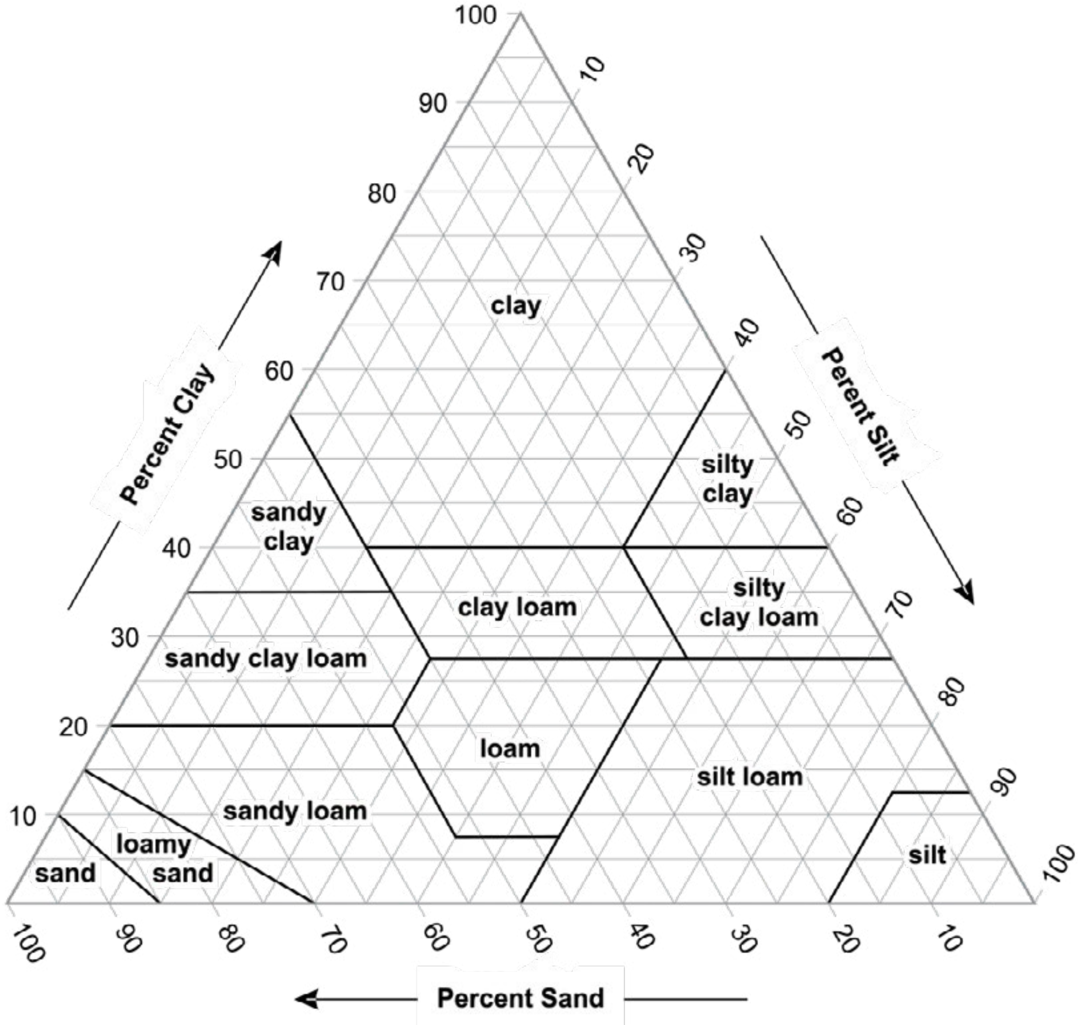


Figure 10. Soil texture is based on the proportion of clay, silt and sand present. Source: United States Department of Agriculture (1951).

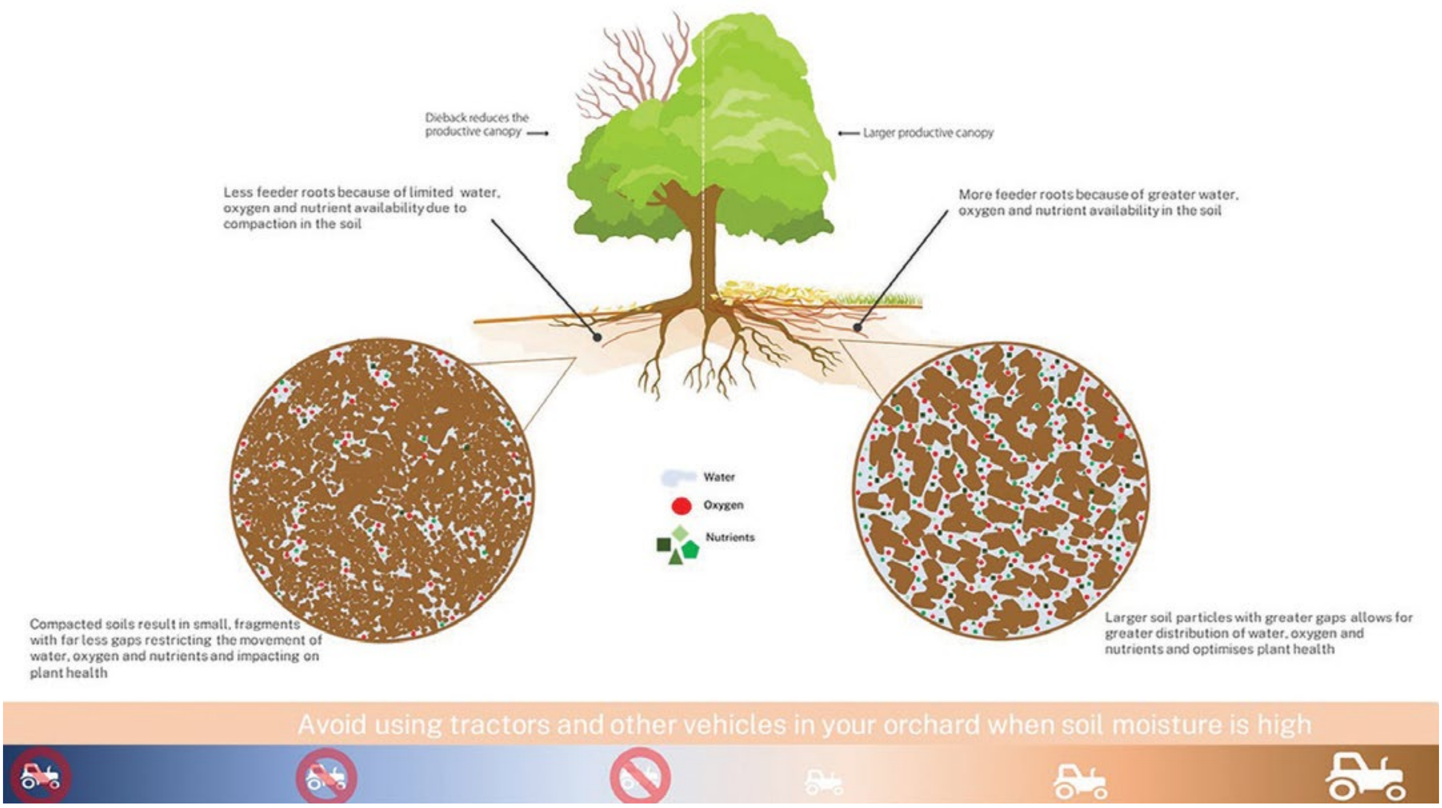


Figure 11. Soil compaction changes soil structure, reducing the size and connectivity of soil pores.

Managing the effects of orchard operations

Some orchard operations damage soils. The two most significant operational issues are soil disturbance at harvest (leading to increased soil erosion) and compaction from vehicles.

Soil disturbance at harvest can be reduced by:

- having as much living ground cover as possible
- using double-ground mulch (i.e. mulch with particle sizes <10 mm) that stays in place during harvest operations that use sweepers and finger wheels
- avoiding high-powered or poorly designed blowers to move nuts out of the tree rows
- being less aggressive with sweepers (check if brushes need replacing and cover exposed roots that trap nuts).

Ongoing compaction can be lessened by:

- increasing living ground covers in the inter-row
- reducing the weight of orchard machinery
- only driving in designated areas
- reducing traffic in wet conditions (Figure 11).

Soil compaction is a more significant issue in NSW than in Queensland because of heavier clay soils and the frequency of rainfall during harvest. In recent years, many NSW growers have moved to smaller, lighter harvesters as they reduce soil compaction. They also allow harvesting sooner after rain.

A simple test can help detect when to reduce traffic to avoid compaction. Squeeze a small lump of soil into a ball and try to roll it into a rod about 3 mm in diameter (Figure 12). If the rod forms easily, the soil is too wet and will compact if it is worked or has machinery on it. If a crumbly rod forms, the soil should cope with traffic and cultivation without compaction.

Figure 12. If a rod can easily be formed from a small soil sample, it is at risk of compaction.

Existing compaction can be improved by:

- mechanical aeration
- building SOM and mulch cover to support larger soil animals such as earthworms and burrowing insects
- growing deep-rooted inter-row cover crops such as perennial grasses, lucerne, medic and hickory (once sunlight reaches the orchard floor).

Nutrient uptake

Trees control their nutrient uptake through 3 processes: mass flow, diffusion and interception. All 3 processes rely on adequate soil moisture. Understanding nutrient uptake processes helps correct uptake restrictions and makes fertiliser treatments more efficient.

Consider nutrient uptake issues where:

- soil tests do not suggest a lack of nutrients in the soil
- tissue testing has confirmed symptoms of nutrient deficiency
- trees might have impaired root development.

There is little research on how these pathways contribute to the uptake of specific nutrients in macadamia. The following information on Mass flow, Diffusion and Interception is from research on other plants.

Nutrient uptake is suppressed in cold or waterlogged conditions and becomes impossible in very dry soils.

Mass flow

Mass flow is water being drawn through the soil towards the roots, driven by evaporation from the leaves pulling water towards the top of the tree (transpiration pull). Weakly held ions move into the root with this water flow. Water availability and sunshine control mass flow nutrient uptake, which slows as soils dry.

Mass flow is considered the main pathway for **nitrogen** (N), **calcium** (Ca), **magnesium** (Mg), **sulfur** (S), **copper** (Cu), **boron** (B) and **manganese** (Mn) uptake. It is also involved in potassium (K), zinc (Zn) and iron (Fe) uptake.

Deficiencies of mass flow nutrients seen in leaf tissue, without low soil nutrient levels, could be water limited. Investigate and correct:

- compaction
- low ground cover percentage
- low soil organic matter
- irrigation performance.

Diffusion

Diffusion draws nutrients from the surrounding soil into the root zone as tree uptake depletes the nutrients from the root zone. Access to nutrients taken up through diffusion is improved by large, intricate root systems with complex branching and root hairs.

Diffusion is important in the uptake of P, Zn and, to a lesser extent, N.

Deficiencies of diffusion nutrients in leaf tissue, without low soil nutrient levels, could be because the root mass is limited. Investigate and correct:

- erosion near trees and root exposure
- compaction
- low ground cover percentage.

Interception

Interception occurs when growing roots contact new soil material. Active root growth promotes interception.

Interception is important in Ca uptake and, to a lesser extent, Mg.

Deficiencies of interception nutrients in leaf tissue, without low soil nutrient levels, might indicate recent root growth inhibition. Investigate and correct:

- toxicities
- low ground cover percentage
- active soil erosion
- irrigation performance.

Nutrient interactions

High concentrations of some nutrients can reduce the uptake of other nutrients (called inhibition or antagonism), which might affect tree health (Table 6). There are also situations where the concentration of one element increases the uptake of another (called stimulation or synergism). Relationships between nutrients are displayed in the Mulders chart (Figure 13).

Investigate nutrient interaction issues where:

- soil test information does not suggest a lack of the nutrient/s in the soil
- tissue testing confirms the deficiency
- root systems are healthy (where compromised root systems exist, improving them is a far higher priority than a potential nutrient interaction).

Interpreting and acting on suspected nutrient interactions is speculative because there is no specific evidence in macadamia. The following information is based on general horticultural principles in other plants. The best approach is to:

- have a logically sound hypothesis for why a specific problem might be occurring
- have evidence from orchard monitoring that supports suspected nutrient interactions (Table 6)
- use treatments that align with other desirable outcomes.

Table 6. Some nutrient inhibitions that might affect tree health.

Cause	Nutrients affected	What to do	Why
High ammonium (NH_4^+)	Potassium, calcium, magnesium, boron and copper	• apply organic matter • reduce ammonium fertiliser use • monitor pH.	Ammonium fertiliser or manure applied in excess induces this problem. Low CEC soils are at higher risk. Applying carbon-rich organic material promotes the temporary immobilisation and later slow release of nitrogen through microbial biomass flux.
High potassium and calcium	Magnesium	Apply magnesium.	To increase the amount of magnesium relative to the calcium and potassium present.
High manganese	Iron	Correct pH.	To make manganese less available.
High phosphate (PO_4^{-3})	Iron, manganese, zinc and copper	Apply iron to the soil.	Excess phosphate reacts with iron, manganese or copper to form insoluble solids. When these form in the plant cells, they prevent zinc from moving within the plant. Soil-applied iron helps insoluble compounds to form in the soil, immobilising some soil phosphorus, slowing its uptake and reducing the problems in the tree.
High chloride	Nitrate (NO_3)	See Table 7 for management options for high chloride.	Chloride ions can compete with nitrate ions in plant uptake processes.

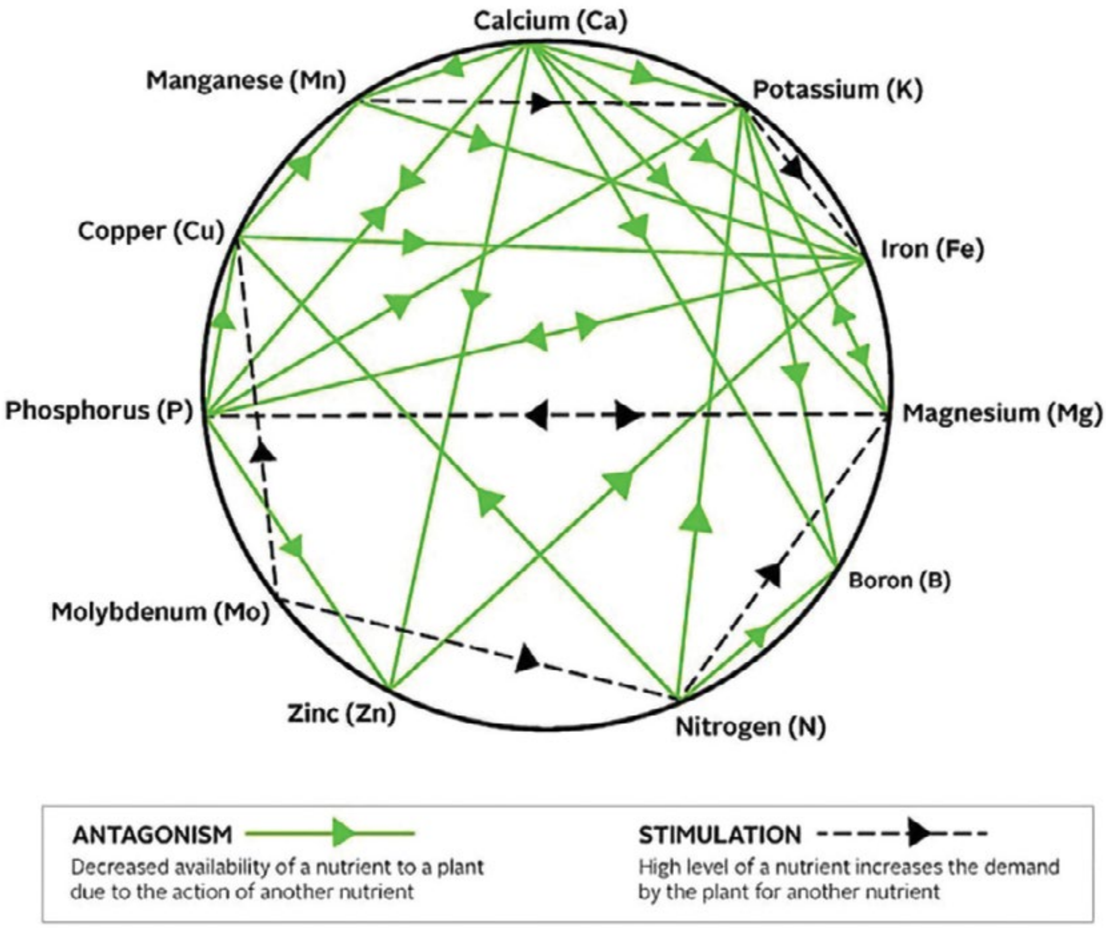


Figure 13. Mulders chart showing antagonism (green arrows) and stimulation (black arrows) links between nutrients. Source: https://m.apkpure.com/crop-nutrient-interactions/com.weel.tns#com.weel.tns-4

Monitoring soil and trees

Soil health

Investigating soil health helps to understand how well the soil is performing. Regularly checking soil health can show specific functional limitations that might not be obvious in laboratory tests.

Focus on correcting soil health issues to improve soil condition and productivity. Ignoring soil health problems can lead to wasted effort on ineffective actions and money on inputs that the trees cannot use.

Macadamia soil health card

Soil health cards (SHCs) guide growers through observing and assessing their soils. The macadamia SHC (Anon 2008) examines these 10 characteristics:

1. diversity of soil life
2. ground cover
3. soil hardness
4. infiltration (the speed water soaks in)
5. root development
6. soil structure
7. depth of the organic layers
8. earthworms (Figure 14)
9. soil pH
10. plant vigour.

Figure 14. Earthworms are one of many indicators of good soil function.

Annual monitoring with the macadamia SHC will reveal if soil function is improving or declining.

Biological testing

Healthy soils are biologically balanced. They help to suppress soil-borne pathogens such as phytophthora and maintain a stable ecological balance in the soil. Microorganisms play vital roles in releasing nutrients from organic matter and soil minerals.

New tests are emerging to monitor aspects of soil biology. The management implications of these test results are not yet clear. Soil respiration is measured onsite and indicates the total biological activity in the soil at the time of measurement. Laboratory measurements to assess soil biology include:

- microbial biomass
- bacterial and fungal biodiversity
- the ratio of free-living to plant-parasitic nematodes.

Soil chemistry tests

There are 3 main reasons to test soils:

1. **Baseline** – is a starting point for measuring soil pH and fertility and anticipating nutrient requirements.
2. **Monitoring** – an annual check-up, creating records of the pH, organic matter and nutrients to understand trends in the soil.

3. **Troubleshooting** – looking for nutrient issues as a reason for poor crop health or potential deficiency or toxicity symptoms in the plant.

It is often convenient to do soil tests with leaf tests. Avoid soil testing for at least:

- 3–6 months (irrigated) or 6–12 months (dryland) after liming
- 2 months after fertiliser application.

Soil sampling

Soil samples must represent the area in which decisions will be made. If conditions vary, consider dividing the orchard or block into zones and sampling each separately. For example, if:

- the soil texture changes, e.g. from clay to loam or sand
- tree age or variety varies (Figure 15)
- there are high- and low-yielding areas.

Having information from the different parts of blocks helps growers make informed decisions about whether the application rates target the needs of average, low- or high-performing areas.

Decide whether to focus on the macadamia feeder root area (tree row) or cover the whole block (tree row and inter-row). Monitoring the inter-row, as well as the tree row, can be informative and assist with ground cover nutrition.

The zone of maximum root growth (and usually fertilisation) extends from the tree trunk to 300 mm beyond the tree drip zone. The centre of the inter-row is a crucial area because dense living ground cover is needed to prevent soil erosion on steep slopes. If under-tree sprinklers are in use, take samples from the wetted zone at a minimum and consider sampling outside the wetted zone for comparison.

Figure 15. Divide the orchard into zones where conditions vary, such as different tree ages.

Decide on the soil sample pattern before collecting the samples. Sampling across a block in a transect (i.e. a line) in a W or V pattern is the most common approach. Unless multiple transects are being used within each area, use the same transect for re-testing to monitor trends in fertility over time. Other methods to consider are:

- clustering samples around typical trees that become the 'sentinel trees' for the block (Figure 16); re-test at the same trees
- grid sampling to achieve more random coverage.

Avoid areas such as old fence lines, dam sites and headlands. Do not include surface material such as leaf or mulch in the sample sent for analysis, and do not mix the topsoil and subsoil samples; keep a separate bucket for topsoil and subsoil.

- For each topsoil sample (0–100 mm), collect at least 25–30 soil cores, crumble and mix them thoroughly in a bucket (this is the composite or 'bulked' sample).
- For each subsoil sample (100–300 mm or deeper), collect 8–10 cores. Subsoils typically show less variability than surface soils.

Place at least 500 g of the topsoil sample and 500 g of the subsoil sample in separate laboratory submission bags or containers, label them, fill out the soil sample submission form and send them to the laboratory as soon as possible. Store soil samples in a fridge until dispatch or keep them in the freezer if they need to be stored for longer than a couple of days.

Taking topsoil and subsoil samples can show if and how quickly pH change is moving down the profile. Re-test subsoils every 5 years.

Figure 16. Sentinel trees will allow consistency with trends in nutrient levels. Note the yellow dot indicating a sentinel tree for soil sampling.

Soil test interpretation

A lot of information can be gleaned from a typical soil test. One method for prioritising decisions from the soil test information is shown in Table 7.

The likely short-term actions are a guide and not the only possibilities. The long-term direction often lies in refinements to the foundation practices (correcting pH, building organic matter, implementing effective drainage and replacing nutrients). In some areas, referring to the leaf test analysis and tree health is necessary to interpret the soil test results. Be aware if the issue is new or has been consistent for a period of monitoring, as this might influence the timing, type and scale of the action required to improve the issue. An established trend is a more persuasive reason to act than an initial change that might be a temporary fluctuation. Growers are advised to seek independent advice to enhance nutrition and soil health decisions.

Table 7. A step-by-step method for interpreting soil test results.

Step	Look at	Implications	Likely short-term action	Long-term direction
1	pH_{Ca}	Correct towards the target ranges of pH_{Ca} 5.5–6.0 (acidic soils) or 6.0–6.5 (alkaline soils)	Apply liming or acidifying material at a safe incremental rate. If liming, select the material based on calcium and magnesium levels. For example, in ferrosol: • use lime if calcium is <5.0 ppm and exchangeable calcium is <65% • use dolomite if magnesium is <1.6 ppm or exchangeable magnesium is 10–20% • if ECEC is <10, add organic matter to boost CEC.	• Continue to monitor and stabilise pH in the target range. • Review drainage every 5 years to ensure liming material is not washing away.
2	Toxic exchangeable cations – low pH	High aluminium and manganese inhibit root growth and function.	Lime to correct pH (as above) and add organic matter, even if ECEC is >10, to immobilise some toxic cations.	Continue to monitor and correct pH towards the target range. Expect the amount of each toxic cation available to decrease with pH correction and organic matter additions. Continue organic matter additions annually.
	Toxic exchangeable cations – high pH	High boron and/or molybdenum.	Apply acidifying material to correct pH and add organic matter to immobilise some toxic cations.	Monitor and correct pH towards the target range. Expect toxic cations to drop with pH correction and organic matter additions. Continue organic matter additions annually.
3	Sodium % of ECEC	Desirable: <2% of ECEC. If >1, check the quality of irrigation water.	Improve areas with poor sub-surface drainage. Apply gypsum. Avoid using high salt index fertilisers.	Build organic matter. Improve irrigation water quality.
4	Chloride (mg/kg)	Desirable: <200. High chloride is not a naturally occurring problem. Identify which management actions are the cause.	>200, check irrigation water quality and the height of the water table, avoid chloride-containing fertilisers and use sulfate forms of potassium fertiliser.	Monitor chloride levels and do not repeat the management practice that caused the high levels.

Step	Look at	Implications	Likely short-term action	Long-term direction
5	Conductivity (EC dS/m)	Desirable: <3 dS/m	>3, apply leaching quantities of water (volumes sufficient to move dissolved nutrients down through the soil profile out of the active root zone). Check the sodium content of irrigation water and consider pre-treatment if this could contribute to rising sodium levels in the soil.	Monitor conductivity levels and do not repeat the management that caused the high conductivity.
6	PBI* and phosphorus in leaf	High PBI in soil and low phosphorus in leaf tissue analysis.	Correct pH and apply extra phosphorus with organic matter inputs (e.g. poultry manure, blood and bone), as this phosphorus is fixed more slowly than from chemical fertilisers.	Monitor and stabilise pH in the target range and build organic matter.
7	Soil organic matter (SOM) or soil organic carbon (SOC). SOC is 40% of SOM. SOC = SOM ÷ 1.75	Approximate healthy values for ECEC: • sands: ECEC 1–5, SOC 1.25% • sandy clay loams: ECEC 10, SOC 1.5% • clay loams: ECEC 14, SOC 2.5% • heavy clays: ECEC 20, SOC 3%	Add organic matter each season until SOC and ECEC are equal or exceed the approximate healthy values for texture.	Maintain correct pH, build organic matter and increase organic matter cycling within productive orchards. SOC values higher than healthy values are advantageous.
8	Micronutrients	Correct the pH before acting on specific micronutrient levels. Compare with leaf tissue analysis if pH is in the target range.	Use foliar feeding if concerned about specific deficiencies and the pH is not in the target range	Be aware that uptake from foliar feeding is variable, so use leaf analysis to confirm the result of foliar applications.
	Boron (mg/kg)	Desirable 1–2 mg/kg in soil; 40–75 mg/kg in leaf analysis.	Foliar application pre-flowering. Apply carefully to the soil near trees and at low rates.	Monitor and stabilise pH in the target range and build organic matter. Consider applying boron to the soil.
	Copper (mg/kg)	Generally, sufficient availability exists from fungicide sprays for husk spot. Young macadamia growing on northern NSW floodplains have shown deficiency.	<3, apply copper sulfate to the soil and use a foliar copper-containing fungicide for husk spot or an alternative copper foliar feed for young trees.	Monitor and expect the soil application to stabilise copper levels for some time. Maintain correct pH and build organic matter.
9	Nitrogen	Consider total N and leaf tissue analysis for perspective. Note that nitrate-nitrogen (1:5 water extract) tests are unreliable. Nitrate-nitrogen also fluctuates with seasonal conditions in both soil and leaves.	• >15 ppm, maintain current nutrient program • >30 ppm, apply less than the current nutrient program • add organic matter.	Keep organic matter levels high to gain available N from decomposition. Prioritise tree health as an indicator over the soil test.
10	Phosphorus (mg/kg)	Favour Colwell P test in alkaline to slightly acidic soils. Use Bray I test in acidic soils with pH_{Ca} <5.5.	• <60, apply at the rate of 25 kg/ha phosphorus • 60–85, apply at replacement rate • >100, no application • seek specialist advice for high PBI soils • add organic matter.	Maintain correct pH and build organic matter. Prioritise tree health as an indicator over the soil test.

Step	Look at	Implications	Likely short-term action	Long-term direction
11	Potassium (% of ECEC)	Desirable: 2–10% of ECEC	• <0.5, apply at replacement rate + 20% • 0.5–1.0, apply at replacement rate • >1.0, no application.	Split applications to match phenological demand. Maintain correct pH and build up organic matter.
12	Calcium (% of ECEC)	Desirable: 65–80% of ECEC	• <5 and pH_{Ca} <5.5, apply lime or dolomite if levels of Mg are also low • <5 and pH_{Ca} 5.5–6.0, continue the routine liming program • <5 and soil pH_{Ca} >6.0, apply gypsum • >5 and pH_{Ca} >6.5, treat to reduce soil pH.	Maintain correct pH, build organic matter and apply further gypsum as required.
13	Magnesium (% of ECEC)	Desirable: 10–20% of ECEC	• <1.6 and pH_{Ca} <6.0, apply dolomite • <1.6 and pH_{Ca} >6.0, apply magnesium oxide.	Maintain correct pH and build organic matter.

ECEC – effective cation exchange capacity, CEC – cation exchange capacity, PBI – phosphorus buffering index, SOC – soil organic carbon, SOM – soil organic matter.

*PBI measures the soil's tendency to adsorb phosphorus (P) chemically. The higher the PBI, the quicker and more strongly P binds to soil particles. Stronger soil binding means that there is less P available to plant roots.

Leaf tissue tests

Annual leaf analysis helps fine-tune nutrition programs. Looking at leaf tissue tests alongside soil test results helps distinguish between soil deficiencies and plant uptake problems.

Collect leaf samples from the spring flush after hardening off (change from light to darker colour). Take mature, undamaged leaves from the second whorl of sunlit terminals (Figure 17). Collect 50–100 leaves from 10–20 trees of the same variety for each sample. Be aware that on tall old trees with a 7 × 4 m spacing, you might need an extended pole to reach the 'sunlit' leaves required for sampling (Figure 18).

Figure 17. Select the second whorl (red circle) of a hardened, new-flush limb. The leaf should be undamaged and in full sunlight. Diagram: K Griffin, Southern Cross University.

Leaf tissue testing is the best way to investigate the micronutrient status of B, Zn and Cu. When micronutrients are below acceptable levels (Table 8), a foliar spray can be useful. The long-term approach to correcting micronutrient levels involves improving soil condition, fertility and plant nutrient uptake.

The broad possibilities are:

- **Acceptable nutrient levels in the soil and leaves** – this supports a nutrient replacement approach to maintain nutrient levels.
- **Adequate nutrient level in the soil and low level in the leaves** – this shows that the tree has trouble accessing enough of that nutrient. There could be a soil constraint, a tree health problem, an uptake problem, a nutrient interaction issue or a combination of contributing effects.
- **Low nutrient levels in the soil and leaves** – this indicates a true deficiency to correct with nutrient inputs.
- **Low nutrient levels in the soil and acceptable levels in the leaves** – this signals a possible future nutrient deficiency as the nutrient might soon become more difficult for the trees to access.

Figure 18. An extended pole might be required to reach the 'sunlit' leaves for sampling.

Table 8. A guide to leaf tissue nutrient levels* in macadamia. Source: O'Hare et al. (2004).

Nutrient	Deficient	Low	Acceptable	High	Excess/toxic
Nitrogen (% N)	<1.20	1.20–1.30	1.40–1.80	>1.80	–
Phosphorus (% P)	<0.05	0.05–0.07	0.08–0.10	0.09–0.15	>0.15
Potassium (% K)	<0.40	0.40–0.50	0.60–0.70	>0.70	–
Sulfur (% S)	<0.10	0.10–0.17	0.18–0.25	>0.25	–
Calcium (% Ca)	<0.40	0.40–0.50	0.60–0.90	>0.90	–
Magnesium (% Mg)	<0.06	0.06–0.07	0.08–0.10	>0.10	–
Boron (mg/kg B)	<20	20–39	40–74	75–100	>100
Zinc (mg/kg Zn)	<10	10–14	15–50	>50	–
Copper (mg/kg Cu)	<3	3.00–4.40	4.50–10	20–70	–
Iron (mg/kg Fe)	–	–	40–200	–	–
Manganese (mg/kg Mn)	<20	20–90	100–1,000	1,600–3,000	3,000–5,500
Chloride (% Cl^-)	–	–	0.00–0.20	0.30–0.60	0.70–1.50
Sodium (% Na)	–	–	0.01–0.10	0.20–0.30	>0.40

* Leaves analysed by the dried tissue technique. Levels do not apply to results obtained from sap analysis techniques. These leaf nutrient standards are based on surveys and field observations, not calibrated yield responses. Local monitoring of yield responses to leaf nutrient levels could refine these recommendations.

Implications for each nutrient

Nitrogen (N)

- If N is within the desired range, use the nutrient replacement approach to determine application rates.
- If N is below the desired range, apply N.
- 'A' varieties tend to have higher N requirements than Hawaiian varieties. Some surveys indicate higher leaf N levels (1.6–1.8%) in high-yielding orchards. In some settings, the adequate range might include these levels. Be wary of high levels (>1.8%N; Table 8) of N in leaves, as this will encourage new leaf growth at the expense of productivity.

Phosphorus (P)

- It is hard to increase mature tree leaf P above 0.08%, and P applications (soil or foliar) have little effect on leaf P levels.
- If P is above or below the desired range and soil pH is in the target range, use soil analysis results and nutrient replacement to determine application rates.
- If within the desired range, no action is necessary.

Potassium (K)

- If K is below the desired level, there might be either insufficient K or competition for uptake from high levels of Ca and Mg. Use soil analysis results to determine application rates. Remember that K levels fall as the crop load increases on the tree, so the sample timing is important when interpreting results.
- If K is within or above the desired range, use soil analysis results and nutrient replacement to determine application rates.

Sulfur (S)

- Rarely out of range, although Hidden Valley A varieties can have lower levels.

Calcium (Ca)

- Calcium accumulates as leaves age, so younger leaves have lower levels.
- Drought conditions can influence Ca levels.
- If below the desired range, distinguish between insufficient Ca, low soil pH, or an imbalance with K or Mg before selecting a corrective action.
- If within or above the desired range, no action is necessary.

Magnesium (Mg)

- If below the desired range, distinguish between insufficient Mg, low soil pH, or an imbalance with K or Ca before selecting a corrective action.
- If within or above the desired range, no action is necessary.

Boron (B)

- If below the desired range, apply up to 4 foliar sprays of disodium octaborate tetrahydrate (e.g. Solubor®) between September and March (B is immobile in the plant, so repeat sprays are necessary) and spread 3 g of borax or 1.5 g of disodium octaborate tetrahydrate per square metre of soil surface evenly beneath the trees.
- Boron levels can become toxic, so check leaf levels after 2 months before further applications.
- If within or above the desired range, no action is necessary.

Zinc (Zn)

- If below the desired range, check for high soil pH and excessive P or N. Some evidence suggests that macadamias might not effectively take up soil-applied Zn, particularly in ferrosol soils. Apply a foliar spray of zinc sulfate heptahydrate at Zn kg/1,000 L/ha (1.5% solution) plus 1 kg of urea to the summer growth flush.
- Where a deficiency is severe, re-apply the foliar spray to the winter–spring flush. In soils other than ferrosols, band zinc sulfate monohydrate at a rate of 3 g/m^2 of canopy cover in a band 300 mm wide around the tree's dripline.
- If within or above the desired range, no action is necessary.

Copper (Cu)

- Copper is rarely out of range where Cu fungicide sprays are used. Where leaf symptoms indicate a Cu deficiency, use foliar sprays.

Iron (Fe)

- Iron is rarely out of the desired range except where heavy applications of lime, dolomite or P have been used.

Manganese (Mn)

- Macadamia is only likely to be manganese-deficient in white sands. If below the desired range, apply a foliar spray of manganese sulfate at 100 g/100 L to the spring flush.

Chloride (Cl^-)

- If above the desired range, check irrigation water quality and soil analysis results.

Sodium (Na)

- If above the desired range, check irrigation water quality and soil analysis results.

Improving nutrient management

Nutrition and soil health – Part 1: The foundations includes the general recommendations for macadamia fertiliser. Adaptations to the general recommendations should:

- be based on monitoring information
- aim to improve the nutrition plan's performance by using the 4Rs, which are the right source, right rate, right place and right time (Roberts 2007).

Right source

The right source is cost-effective, does not create other problems and could have other benefits. When selecting nutrients, consider:

- what is available
- the cost of the options
- the immediate and long-term benefits of a particular source.

There are ways of incorporating good levels of nutrients while building organic matter and soil health. Often a mix of sources is a good compromise.

Right rate

Monitoring soils, trees and yields provides information to adjust general recommendations for a block. Higher or lower rates of individual nutrients could be appropriate. Be aware of nutrient source release rates. Most chemical fertilisers provide nutrients quickly. Prilled, chemically protected products and organic matter sources release nutrients more slowly. When more nutrients are available than the plants need, there is a risk of:

- losing some nutrients to the environment
- excessive tree growth
- nutrient imbalances.

Crop replacement approach

A plan to balance nutrients for building soil fertility will match fertiliser rates to the nutrients that go out with every tonne of nut-in-shell (NIS) harvested from the orchard. Other inputs and losses in the nutrient balance include biomass changes, organic matter inputs and losses to the environment (Figure 19).

Nutrition and soil health – Part 1: The foundations (Page 21) recommends using fertilisers based on yield and adjusted crop replacement values from recent research in 8 macadamia varieties. The nutrient content of nut-in-husk (NIH) was investigated over 2 years years (which included both a drought affected and a wet year) in 2020-21, as part of a NSW DPI Clean Coastal Catchments research project funded through the NSW Government's Marine Estate Management Strategy.

As well as quantifying nutrient values in husk, shell and kernel, the study found that:

- regardless of seasonal conditions, the crop will generally take what it requires
- seasonal conditions, dry or wet, do not appear to influence the amount of nutrients per tonne of NIH
- the differences between varieties are small but become more relevant as yields increase
- minimal values for micronutrients such as B and Zn mean soil and leaf analyses are important to ensure micronutrient levels are satisfactory

- having adequate CEC improves nutrient availability for the plant
- keeping pH_{Ca} >5.5 allows the most efficient microbial activity to cycle nutrients.

The approach used to get from the recorded values from husk, shell and kernel to adjusted rates for crop replacement is similar to the previous *Macadamia grower guide* (2004), continuing to increase N by 30%, K by 20%, Ca by 10% and Mg by 25%. The 100% increase in P was removed, as this was intended for ferrosols with a high phosphorus buffering index (PBI), and macadamia are now grown on a broad range of soil types.

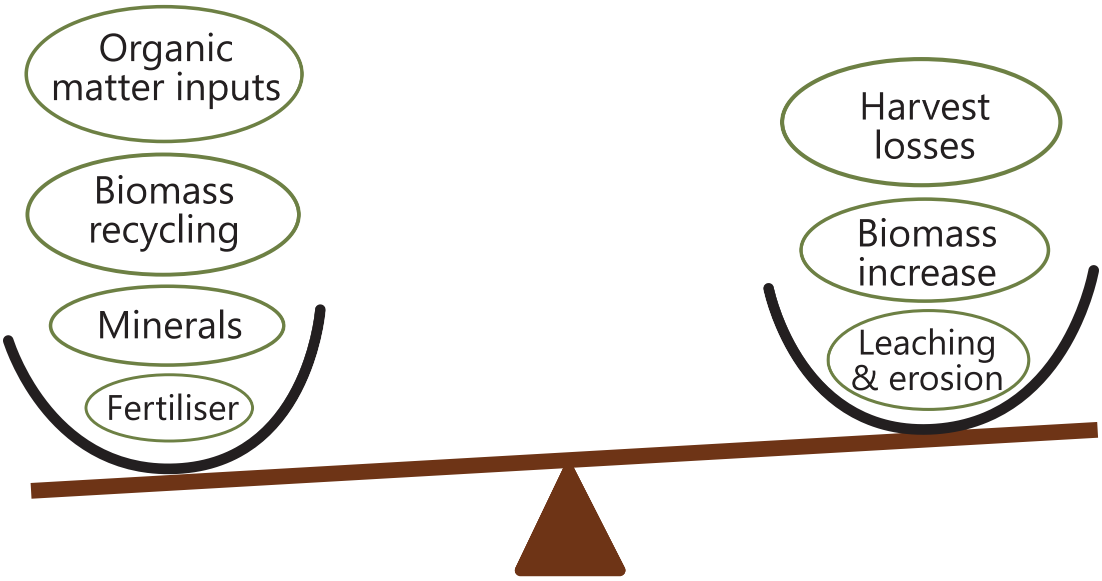


Figure 19. The nutrient balance of the orchard moves in response to the accumulated inputs and losses.

The nutrient values in NIH for each of the selected macadamia varieties averaged over 2 years are in Table 9. This information can be used to create variety-specific nutrient plans where variable rate applications are practical. Monitor on a variety basis (for soil and leaf analysis) to review and refine variety-specific nutrition plans.

Table 9. Nut-in-husk (NIH) nutrient replacement values, adjusted, for 8 macadamia varieties.

Variety	Nitrogen	Phosphorus	Potassium	Sulfur	Calcium	Magnesium
	Kilograms per tonne (NIS @ 10% moisture content)				Grams per tonne (NIS @ 10% moisture content)	
A16	14.4	1.2	9.4	1.4	1.1	1.2
A4	12.9	1.1	9.6	1.2	0.9	1.0
A38	12.6	1.0	8.4	1.3	0.6	1.0
A203	11.6	0.8	8.8	1.3	0.7	0.8
G	16.0	1.0	11.4	1.3	0.9	1.0
246	15.8	1.0	10.1	1.4	0.6	0.9
816	15.1	1.2	12.2	1.4	0.7	1.0
741	15.3	0.9	11.2	1.5	0.7	0.9

Reasons to do more than crop replacement

Keep a detailed record of the nutrient-rate refinements, why those changes were made and continue monitoring. Some of the more common reasons are described below.

To support the tree at specific times

Tree demand for specific nutrients varies at different growth phases. Unmet nutrient demands can limit nut yield. Strategically timed nutrient inputs can support the trees when the existing soil and feeder root systems are unlikely to meet those needs.

To build up nutrient resources in the soil

Organic matter inputs are generally the best way to build soil resources. Soil testing can reveal if specific nutrient levels are low or if there is an imbalance with other nutrients. Adding nutrients that are at lower than optimal levels in fertilisers or other amendments can build up reserves and prevent deficiencies.

To replace environmental losses

Leaching washes dissolved nutrients through the soil profile, removing them from the active root zone, mostly in very wet conditions. Depending on soil test results, replacing leached nutrients after very wet seasons might be required. For example, applying up to 20% extra N in very sandy soils.

Nutrients are also lost in eroded soil. Having effective drainage will reduce nutrient losses. Managing erosion must be a priority when high nutrient rates are used to support the crop. This starts with identifying and understanding where and how much erosion there is. Modelling with LiDAR mapping and using the revised universal soil loss equation (RUSLE) can show areas at high risk for erosion. Make changes to drainage systems to reduce erosion and prevent further losses before adding more nutrients. See *Macadamia integrated orchard management drainage* (2022) for more details.

To correct a nutrient deficiency

Some deficiencies, confirmed by leaf tissue testing, can be partially corrected with foliar feeding. This is possibly a quick fix to bypass the tree's problem with accessing the nutrients in the soil. Long term, correct the underlying problem, whether it be an uptake issue, a lack of nutrients in the soil or limited nutrient availability.

To compensate for nutrient immobilisation

Nutrients become unavailable when microbes or inter-row plants incorporate them into their biomass. The nutrients are still in the orchard, but while those organisms survive, the nutrients in their tissues are immobilised and not accessible to macadamia roots. Extra nutrients might be required when there is high nutrient demand from microbes that are decomposing organic matter additions or inter-row crops.

To support an increase in biomass

Nutrients are incorporated into new tissues as trees grow. During orchard development, when it is desirable for the trees to increase in size, or after heavy pruning or row removal, nutrient programs need to support growth as well as replace nutrients in the harvested crop.

Once trees reach the desired size for the orchard design, balance applying nutrients to support growth with pruning to recycle organic material and nutrients within the orchard. Excess canopy and tree height are not conducive to the orchard's long-term productivity and contribute to:

- a dark orchard that pests prefer
- poor ventilation and fungal issues
- problems with spray coverage
- reduced ground cover on the orchard floor
- erosion due to loss of ground cover
- root exposure
- unproductive dead centres in the tree leading to bark beetle issues.

Right place

Consider focusing nutrient application to where the feeder roots are (concentrated close to the tree trunk) or across whole orchard blocks, including the inter-rows (Figure 20). Soil and leaf analyses will help guide soil and foliar application choices.

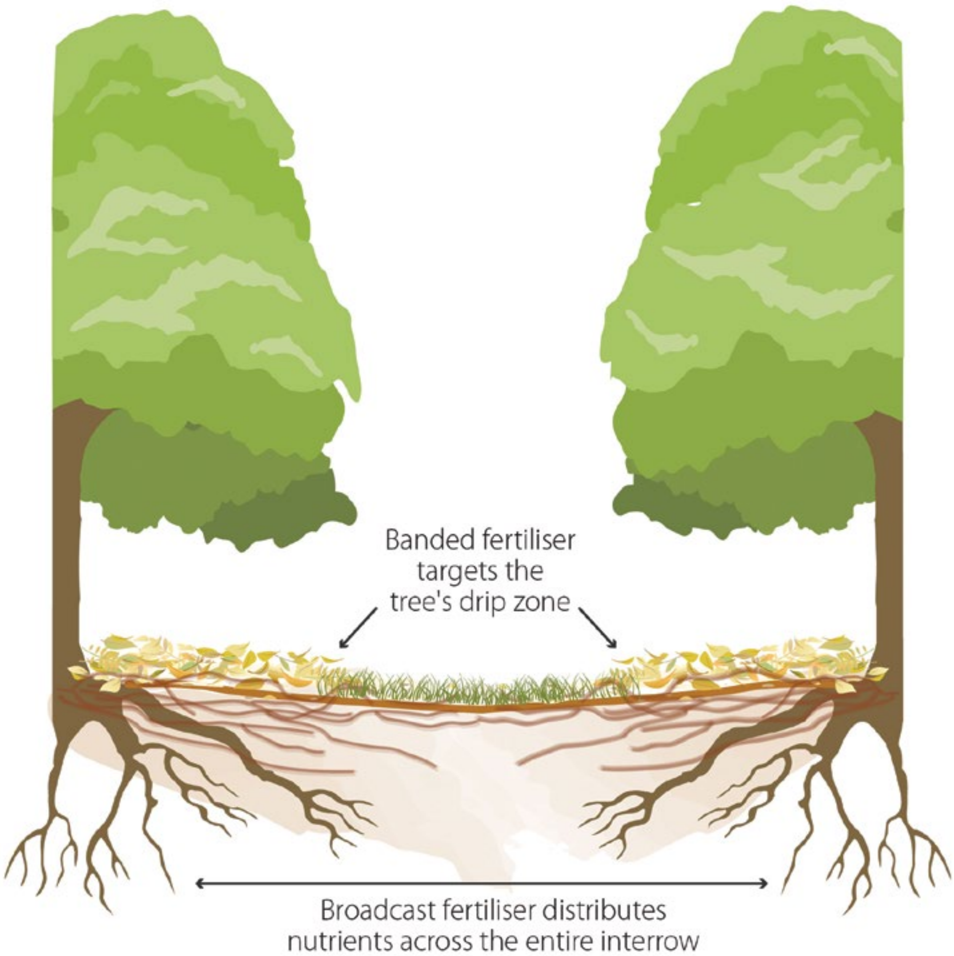


Figure 20. Sample sites will depend on where fertilisers are placed and what is being identified: nutrition for the tree or ground cover.

Focus on ground application

Improvements in soil condition and fertility could reduce reliance on foliar applications. Refer to *Nutrition and soil health – Part 1: The foundations*. Avoid reliance on foliar feeding. There is limited evidence that foliar treatments are reliably effective in achieving the target nutrient levels in the plant.

Right time

Avoiding periods with a risk of high rainfall

Apply nutrients to moist soil but delay applications when there is a risk of rain being received at a rate higher than the infiltration rate in the 2 weeks following nutrient application. Much of the value is lost if the products wash away and become pollutants downstream. Do not apply nutrients to saturated soils. It is better to apply small amounts of nutrients often than to make large applications a few times a year.

Matching supply to seasonal crop demand

Macadamia trees have distinct growth stages (phenological phases) throughout the year. Matching nutrient supply to these phases can enhance production (Table 10). Consider improving the timing of split fertiliser applications to better match the growth stage.

Table 10. Suggested breakdown of nutrient applications during the year as a percentage of the annual total.

Growth stage	Time (depending on location)	N	P	K	Ca
		Percentage of the annual application			
Pre-flower to nut set	April to August	25%*	0%	20%	20%
Nut set to oil accumulation	September to December	25%*	0%	60%	30%
Oil accumulation to harvest	January to March	50%*	100%	20%	50%

*Nitrogen can be applied in small, split applications within each growth stage to ensure the nutrient has more chance of reaching the roots. This reduces losses and increases uptake.

Nutrients

There are 16 essential elements for plant growth: most come from the soil, and a few from air and water.

Nutrients from the soil and sometimes through the foliage

- Macronutrients required in large amounts (kg/ha):
  - nitrogen
  - phosphorus
  - potassium
  - calcium
  - magnesium
  - sulfur.
- Micronutrients required in small amounts (g/ha):
  - manganese
  - iron
  - copper
  - boron
  - zinc
  - molybdenum
  - chloride.

Nutrients from air and water: carbon, hydrogen and oxygen.

Nutrient uptake requires dissolved mineral ions to enter the plant roots and move up to the leaves and nuts. Mobile nutrients such as N, P and S can move within the tree to other sites, such as new growth. Deficiency symptoms appear in older leaves as the tree relocates nutrients to the new growth.

Mobile nutrients in the plant = older leaves show deficiency

Immobile nutrients such as Ca and most micronutrients cannot move to different parts of the tree. Tree health relies on a steady supply of these nutrients from the soil. Symptoms of deficiency appear in the older leaves.

Immobile nutrients in the plant = new flush shows deficiency

The critical nutrients to monitor and manage are nitrogen, phosphorus, potassium, calcium, magnesium, boron and zinc. Deficiencies of other nutrients are rare in well-managed orchards.

Macronutrients

Nitrogen (N)

Function

Nitrogen is the most crucial nutrient for tree growth. It is needed in all enzymes and proteins, including chlorophyll (the green pigment in leaves). Nitrogen-deficient trees can have light green or yellow leaves (Figure 21). Nitrogen is also required to synthesise plant hormones, which control tree growth.

Figure 21. Nitrogen-deficient trees with light green or yellow leaves. Photo: Andrew Sheard, Mayo Macs.

Behaviour in soil and plants

- Australian soils are generally low in N. It is mainly in SOM. Soils with high clay content typically have higher reserves.

- Nitrogen is very mobile in the soil and leaches readily, particularly in high rainfall areas. It might need topping up with small applications after extended rain.
- Nitrogen is very mobile within the tree. New vegetative growth has a strong demand for N, and it is moved from the old leaves to young leaves during rapid growth when demand for N exceeds root uptake.
- Deficiency symptoms appear on older leaves (Figure 22).
- Too little N reduces photosynthesis and growth, causes early leaf fall, and reduces fruit set and yield.
- Too much N promotes excessive leaf production and reduces flowering.
- Macadamia can take up N as ammonium (NH_4^+) and nitrate (NO_3).
- Organic N is not immediately available to macadamia and must be decomposed and transformed by microbes into nitrate-nitrogen or ammonium-nitrogen.
- The tree supplies energy to convert nitrate to ammonium.
- Crop uptake might only be 40–70% of applied N. The remainder is immobilised or lost via ammonium volatilisation, denitrification, leaching and erosion.
- Organic matter additives with a C:N ratio of 20:1 or less provide more available N.

Figure 22. Older and younger leaves all show general yellowing from nitrogen deficiency. As nitrogen is mobile within the plant, the yellowing is observed on older leaves first. Photo: Andrew Sheard, Mayo Macs.

Fertiliser forms

Consider the effect of N forms (e.g. urea vs calcium nitrate vs mono ammonium phosphate (Table 1). Nitrogen in nitrates is non-acidifying, while N in ammonium forms acidifies the soil.

The N content of some commonly used fertilisers is:

- urea (46% N)
- ammonium sulfate (sulfate of ammonia, 21% N)
- potassium nitrate (13% N, 38% K)
- calcium nitrate (15% N, 18–19% Ca)

- calcium ammonium nitrate (CAN, 27% N, 8% Ca)
- diammonium phosphate (DAP 18% N, 20% P, 2% S)
- mono-ammonium phosphate (MAP 10–12% N, 48–61% P).

Management

Split applications through the season produce higher yields. The best strategy is to apply small amounts of N in as many applications as practical throughout the year. In young trees, apply N regularly to develop the leaf canopy. Nitrogen rates for bearing trees should be related to production history (nutrient replacement approach). Excess N interferes with K, Ca and Mg uptake. It can also accelerate organic material decomposition and deplete SOM.

During summer, small N applications meet the high demand during nut development and oil accumulation. Avoid heavy N applications to bearing trees during nut development to reduce the risk of leafy growth flushes. These can compete with the developing nutlets, reducing nut yield and quality. The most at-risk time for leaves competing with nut development is up to 10 weeks after flowering.

Applying N to trees with exposed roots will rarely benefit the tree. As few feeder roots are present, erosion and washouts often move the N away from the tree.

Phosphorus (P)

Function

Phosphorus helps transfer energy from sunlight during photosynthesis. Phosphorus is used in root growth, flower initiation and nut set.

Behaviour in soil and plants

- Phosphorus-deficient macadamia plants will have large amounts of leaf drop, poorly developed new growth and reduced yields. Other P deficiency symptoms can include dieback in new shoot growth.
- Only a tiny proportion of soil P is available for tree uptake. In some soils, such as ferrosols, P is fixed (held with strong chemical bonds and is inaccessible to plants). Soil-fixing applied P near the surface reduces its availability to the tree and predisposes it to losses from soil erosion.
- Phosphorus availability is linked to soil pH and is most readily available when the pH_{Ca} is between 6 and 7. When pH_{Ca} is:
  - >6.5, soil P is increasingly fixed into less soluble forms by excess Ca
  - <5.5, soil P is increasingly fixed into less soluble forms by excess Al.
- Phosphorus is relatively immobile in the soil and not readily leached. Therefore, roots must be able to grow into new sources of P. Compaction, inadequate aeration, and waterlogging lead to low P uptake, even in high P soils. Impaired root growth (Figure 23) in bare, eroded soil is associated with P uptake problems.
- Phosphorus is very mobile in the plant, moving readily upwards and downwards.
- Excessive soil P levels can induce Fe and Zn deficiencies. Iron deficiency is common in soils where sugar cane has previously been grown. The Fe to P ratio (Fe:P) in leaves is a reliable indicator of tree health. An Fe:P ratio of <0.070:1.00 is often associated with phosphorus-induced Fe deficiency (chlorosis).
- Proteoid or cluster roots are specialised feeder roots that form in low soil P conditions. These roots are adapted to enhance the sparingly available P uptake by increasing the root surface area available for absorption and producing special root exudates that make P more available to the tree. Proteoid roots require ground cover to form, and deep mulches favour their development.

Fertiliser form

The P content of some commonly used fertilisers is:

- superphosphate (9% P, 11% S, 20% Ca)
- triple superphosphate (19% P, 2% S, 18.5% Ca)
- diammonium phosphate (DAP, 18% N, 20% P, 2% S)
- monoammonium phosphate (MAP 11 % N, 52 % P)
- guano (P content varies according to source; check P content before calculating application rates)
- poultry manure (P content varies according to source; check P content before calculating application rates)
- rock phosphate (P content varies according to source; check P content before calculating application rates). The availability of P from rock phosphate is hard to predict, and it cannot be relied on for a quick supply. Most rock phosphate sources are essentially insoluble within practical time frames.

Figure 23. Exposed structural roots and no feeder roots create an environment less able to absorb phosphorus. Photo: Andrew Sheard, Mayo Macs.

Management

Maintain soil pH in the target range. As P is crucial for all growth, including photosynthesis and root development, it should be available at adequate levels all year round.

Monitor soil and leaf levels regularly and apply P fertilisers only as required. Leaf P levels often fall rapidly as the tree starts to crop and can be hard to maintain in older bearing trees.

The optimum level for macadamias in most soils is about 50–85 mg/kg (using the Colwell soil test), based on field trials calibrated to yield and pot trials with various soils to support seedling growth. Many productive orchards fall in this range.

Phosphorus moves very slowly through the soil profile, except in sands. Banding P into the subsoil during orchard establishment might be helpful for long-term P supply.

Potassium (K)

Function

Potassium regulates water balance by influencing water movement and controlling stomata (water pores on leaves) opening and closing. Potassium directly affects nut yield and quality through its involvement in the synthesis and movement of starches, sugars and oils.

Behaviour in soil and plants

- Potassium is very mobile in the soil and readily leached, particularly in sandy soils. Potassium is available for plant uptake via the soil's CEC.
- Potassium is very mobile in the plant, readily moving in all directions. New growth flushes do not draw much K away from developing nuts because leaves do not require large amounts.
- Deficiency appears as light brown necrotic areas between veins and along the leaf margins (Figure 24).

Figure 24. Necrotic areas between the veins and along leaf margins are signs of potassium deficiency. Photo: Andrew Sheard, Mayo Macs.

Fertiliser forms

The K content of some commonly used fertilisers is:

- potassium sulfate (sulfate of potash, 41% K, 16.5% S)
- potassium chloride (muriate of potash, 50% K, 50% chlorine)
- potassium nitrate (nitrate of potash, 38% K, 13% N).

Management

Peak K demand occurs during nut growth and oil accumulation. Potassium availability is supported by maintaining soil pH in the target range and building CEC with organic matter inputs. Excessive K fertiliser applications can induce a Mg deficiency.

Sulfur (S)

Function

Sulfur is a component of proteins and chlorophyll. It is often applied as a constituent of other fertilisers where there is an advantage to reducing the amount of chloride applied.

Behaviour in soil and plants

Sulfur is relatively mobile in the soil. Movement in the tree is mainly upwards. Sulfur cannot move to other tree parts once incorporated into proteins.

Fertiliser forms

The S content of some commonly used fertilisers is:

- ammonium sulfate (sulfate of ammonia, 24% S)
- elemental sulfur (98% S).
- gypsum (14–18% S)
- single superphosphate with sulfur (26.1% S)
- superphosphate (11% S)

Management

There is little effect from other nutrients on S uptake and movement. There are no specific management strategies for S in macadamias. Commonly used fertilisers contain enough S to meet tree requirements. If leaf S levels are low, select sulfur-containing fertilisers. Heavy application rates of elemental S reduce soil pH.

Calcium (Ca)

Function

Calcium plays a vital role in cell division and the development of new leaves, nuts and root tips.

Behaviour in soil and plants

- Calcium is relatively immobile in the soil.
- Calcium is mobile within the tree upwards, towards the leaf tips, with little remobilisation downwards.
- Low Ca causes abnormal development in new leaves (Figure 25), which might become yellow at the leaf tips (Figure 26). Nuts and root tips can also become yellow.

Fertiliser forms

The Ca content of some commonly used fertilisers is:

- calcium sulfate (gypsum, 18–20% Ca, 14–18% S)
- calcium carbonate (lime, 35–40% Ca)
- calcium and magnesium carbonates (dolomite, 12–15% Ca, 8–12.5% Mg)
- calcium ammonium nitrate (CAN, 8% Ca, 27% N)
- calcium nitrate (18–19% Ca, 15% N).

Figure 25. Calcium deficient leaves. Photo: Andrew Sheard, Mayo Macs.

Figure 26. Yellowing leaf tips is a symptom of calcium deficiency. Photo: Theunis Smit, Carbon Friendly – Sustainable Agriculture

Management

Calcium is available in liming materials. Use fine material with 98–100% fines (particles <0.25 mm in diameter) where the aim is to increase Ca levels. Use higher rates for coarse materials such as lime sands in Western Australia. Apply before the wet season so rain can move the nutrient deeper into the soil.

Use lime when soil pH and Ca levels are both low; dolomite when soil pH, Ca and Mg levels are low; and gypsum when pH is within the target range but the soil Ca level is low. Gypsum is also used on soils with high Na levels to displace Na on the soil colloids and improve soil structure. Excessively high Ca soil levels can reduce Fe, Mn, Zn, B, Cu and P uptake.

Magnesium (Mg)

Function

Magnesium is a component of chlorophyll and is vital for photosynthesis. In addition, it regulates the uptake of other plant nutrients and is essential for many biochemical functions in cells.

Behaviour in soil and plant

- Magnesium is relatively mobile in the soil. Uptake is mainly through mass flow.
- Magnesium is very mobile within the tree, moving readily from old to new leaves. Symptoms of deficiency appear in older leaves (Figure 27) and mainly occur in high rainfall areas with low soil pH.
- High soil concentrations of ammonium, K and Ca might compete with Mg for uptake, leading to Mg deficiency.

Fertiliser forms

The Mg content of some commonly used fertilisers is:

- magnesium sulfate (Epsom salts, 9.5% Mg)
- calcium and magnesium carbonates (dolomite, 8–12.5% Mg, 12–15% Ca)
- magnesite (27% Mg)
- magnesium oxide (Granomag®, 54% Mg).

Figure 27. Interveinal yellowing from leaf tips to midrib is a symptom of magnesium deficiency. Note the leaf base area remains green. Photo: Andrew Sheard, Mayo Macs.

Management

Review Mg availability relative to other nutrient cations, such as Ca and K. An excess of one can reduce the availability of others. For example, heavy applications of K can induce Mg deficiency. Base decisions on rates and nutrient application timing on leaf and soil analyses due to the links between pH, ECEC, and the potential for nutrient interactions. Aim to keep soil pH within the target ranges.

Apply liming materials in autumn:

- Use dolomite when soil pH, Ca and Mg levels are all low.
- Use magnesite when pH and Mg are low but Ca is not.

If pH adjustment is not needed, use magnesium sulfate when additional S is also beneficial.

Corrective Mg application is usually only necessary once every few years.

Where soil pH is outside the target range, a foliar spray of magnesium sulfate, mixed with calcium nitrate to aid uptake, might help where deficiency symptoms are present, as a soil application might be slow to control symptoms.

Micronutrients (trace elements)

Macadamias only need small quantities of micronutrients. Boron (B), copper (Cu), zinc (Zn) and iron (Fe) are the most likely to be deficient. Oversupplying micronutrient applications can retard tree growth.

Boron (B)

Function

Boron is involved in cell division. It is needed to grow new roots, shoots, flowers and nuts.

Behaviour in soil and plants

- Boron is very mobile in the soil and leaches readily from acidic soils. It becomes unavailable in alkaline soils in very wet or dry conditions.
- Boron is not very mobile in the plant; its movement is solely upwards.
- Boron deficiency decreases nut set because pollen tubes do not form, blocking fertilisation. Other symptoms include leathery young leaves with split veins, leaf burn (Figure 28) along the margins, poor internodal growth and leaf dieback (Figure 29).

Figure 28. Leaf burn along the margins from boron toxicity. Photo: Andrew Sheard, Mayo Macs.

Figure 29. Boron deficiency showing poor internode growth and leaf dieback. Photo: Andrew Sheard, Mayo Macs.

Fertiliser forms

The B content of some commonly used fertilisers is:

- sodium borate decahydrate or sodium borate (Borax, 11% B)
- disodium octaborate tetrahydrate (e.g. Solubor®, 20.5% B)
- boric acid (17% B).

Boron is often incorporated into N:P:K mixes, e.g. North Coast Macadamia Mix.

Management

Use leaf and soil analyses to monitor B. There is a narrow range between deficiency and toxicity. Therefore, most Australian growing environments need small, frequent B applications.

Uneven B fertiliser application can cause areas of B toxicity in the soil. Spraying dissolved fertiliser onto the ground or applying it via fertigation can even out the application. Poor drainage or irrigation practices can cause B deficiency by creating poor conditions for roots, which limits their growth, metabolic activity and nutrient uptake. Uptake of other nutrients is also limited. Boron deficiency symptoms might appear before others, but not always.

Where B is deficient, foliar sprays have increased nut-in-shell and kernel recovery yields. Foliar concentrations >100 ppm in young, fully expanded leaves can cause defoliation and tree death or, if less severe, reduced root and shoot growth.

Follow up foliar sprays with soil applications, but do not apply in dry conditions.

Copper (Cu)

Function

Copper is involved in energy transfer in metabolic processes. It is needed to produce lignin, which strengthens branches.

Behaviour in soil and plants

- Copper is immobile in the soil and not readily mobile in the tree. It can, however, be transferred from older to younger leaves when levels are sufficient.
- Anything that inhibits new root growth can impair Cu uptake. Copper deficiency most commonly occurs in sandy soils receiving high N or where soil P is very high. The most obvious symptom of Cu deficiency is angled branches (Figure 30) in new flush growth.
- High Cu can induce Fe deficiency and suppress soil biology. Copper can build up in the soil from heavy or frequent Cu applications. Foliar Cu sprays once a year to control husk spot should not lead to problematic Cu accumulation.

Fertiliser forms

The Cu content of some commonly used fertilisers is:

- copper sulfate pentahydrate (25% Cu)
- copper sulfate monohydrate (35% Cu)
- copper hydroxide (57–65% Cu)
- copper oxides (75% Cu)
- copper chelates (8–13% Cu).

Management

When using Cu fungicides, Cu deficiency is rarely an issue. If Cu fungicides are not used, monitor for deficiency.

Figure 30. A 90-degree branch angle of new flush is a typical sign of copper deficiency. Photo: Andrew Sheard, Mayo Macs.

Zinc (Zn)

Function

Zinc is essential for photosynthesis and auxin hormone metabolism. In addition, Zn is necessary for chlorophyll and carbohydrate formation.

Behaviour in soil and plant

- Zinc is not very mobile in the soil. Mycorrhizae fungi (those with a symbiotic relationship with plant roots) assist with Zn uptake.
- Zinc is not very mobile in the tree. It tends to accumulate in the roots. Movement in the tree is mainly upwards. Once incorporated into proteins, it cannot move to other plant parts.
- Zinc-deficient plants have small leaves, short internodes and mottled chlorosis (Figure 31 and Figure 32) on the youngest growth, while older leaves might appear unaffected.

Figure 31. Distinct intercellular chlorosis, which is typical with zinc deficiency. 'Little leaf' or rosetting is also present. Photo: Andrew Sheard, Mayo Macs.

Figure 32. Intercellular chlorosis caused by zinc deficiency.
Photo: Andrew Sheard, Mayo Macs.

Fertiliser forms

The Zn content of some commonly used fertilisers is:

- zinc sulfate heptahydrate (23% Zn)
- zinc sulfate monohydrate (36% Zn)
- zinc oxide (80% Zn)

Zinc is often incorporated into N:P:K mixes, e.g. North Coast Macadamia Mix.

Management

Zinc deficiency is reasonably common. It can occur with high pH or following heavy lime applications. Confirm Zn deficiency in the tree via leaf analysis. Foliar Zn is lowest in the youngest fully expanded leaf and accumulates in older leaves.

Correct mild deficiency with a foliar spray of Zn and urea to the summer flush and bring high soil pH into the target range. For severe deficiency, re-apply to winter and spring flushes, as well as developing nuts. Concentrate soil applications of Zn in a band near the tree's dripline.

High soil P can reduce Zn uptake. In ferrosols, macadamia takes up little soil-applied Zn, and trees might need ongoing foliar sprays.

Iron (Fe)

Function

Iron is a component of chlorophyll and is involved in plant respiration and metabolism. It plays a role in energy transfer within the plant.

Behaviour in soil and plants

- Iron is generally abundant and relatively mobile in soil but is not very mobile in the tree.

- Deficiency appears as interveinal chlorosis in younger leaves (Figure 33). In severe cases, young leaves can turn white with dieback at the leaf tip and shoot growing point; immature nut husks will lose their green lustre (Figure 34). Deficiency often occurs in nursery trees grown in soil-less mixes.
- Where the soil has a pH_{Ca} <5.5 and is saturated, compacted or poorly aerated, Fe availability can increase to the point of toxicity. Deficiencies of other nutrients, such as Zn, can mask Fe toxicity.

Figure 33. Yellowing of iron-deficient plants due to the lack of chlorophyll. Photo: Andrew Sheard, Mayo Macs.

Figure 34. Iron deficiency in macadamia nutlets showing chlorosis due to lack of chlorophyll. Photo: Andrew Sheard, Mayo Macs.

Fertiliser forms

The Fe content of some commonly used fertilisers is:

- iron sulfate (20% Fe)
- ferrous ammonium sulfate (14% Fe)
- iron DTPA chelate (10% Fe); use in soils with pH_{Ca} <6.5
- iron EDDHA (6 % Fe); use in soils with pH_{Ca} >6.5.

Management

Iron is best managed by correcting pH as high Fe is primarily related to low pH, and low Fe to high pH. Highly soluble P can inhibit Fe uptake. Foliar Fe can assist in high P soils.

Molybdenum (Mo)

Function

Molybdenum is necessary for plant use of nitrate-nitrogen and conversion to amino acids. It is essential to convert inorganic P into organic forms within the plant.

Behaviour in soil and plant

- Molybdenum is mobile within the plant, moving readily in the phloem and xylem conductive tissues.
- Molybdenum deficiency causes an accumulation of unused nitrate-nitrogen, causing irregular twisting in the leaves. The whole plant might be pale, and older leaves can show striped chlorosis and burnt leaf margins.
- Soil tests cannot reliably assess if a deficiency exists because the required amount of molybdenum is so low. Soil pH controls the availability of applied and naturally present molybdenum.

Fertiliser forms

The molybdenum content of some commonly used fertilisers is:

- Sodium molybdate (39% Mo) is toxic to rhizobia, the symbiotic bacteria that enable legumes to fix N. Avoid this form where living ground covers include legumes or they are used in inter-row cover crops
- Molybdenum trioxide (66% Mo)
- Ammonium molybdate (54% Mo)

Management

Correcting soil pH is essential to support molybdenum supply. Foliar molybdenum can assist in acute deficiencies.

Manganese (Mn)

Function

Manganese is needed to form chlorophyll and assimilate carbon dioxide in photosynthesis. It is essential in the plant enzyme system and is directly involved in Fe and ascorbic acid uptake. In addition, Mn assists in fruiting, nut growth and development.

Behaviour in soil and plants

- High soil pH induces Mn deficiency. Deficiency symptoms appear on the younger leaves as Mn is not very mobile in the plant. The most common symptom is interveinal chlorosis near the midrib (Figure 35). Leaves will be a distinct dark green along the veins and midribs.
- Low soil pH increases Mn availability, even to the point of toxicity. Toxicity symptoms include interveinal spots along the outside edge of older leaves (Figure 36), often called 'measles', and stunted root tips. Leaves might eventually brown off from the edges inwards and drop off. This symptom can sometimes be misdiagnosed as 'salt burn' in coastal macadamia. Increasing soil pH_{Ca} to >5.5 and increasing organic matter will alleviate Mn toxicity. Manganese can be easily stored in the CEC and immobilised in organic matter.
- When the soil is transitioning from flooded to average moisture content, a 'flush' of excess Mn can cause temporary toxicity, especially if soil pH is low.

Fertiliser forms

The Mn content of some commonly used fertilisers is:

- Manganese sulfate (23–28% Mn)
- Manganese oxide (41–68% Mn)
- Manganese chelate (5–12% Mn).

Management

Maintaining soils in the target pH range is the most practical way to avoid most problems with Mn. In high pH soils, applying acid-forming fertilisers in the tree row can increase Mn and other micronutrient uptake. Multiple foliar applications during the growing season are often needed to compensate for soil deficiencies.

Figure 35. Manganese deficiency shows as chlorosis with dark green along the midrib. Photo: Andrew Sheard, Mayo Macs.

Figure 36. Manganese toxicity appears as brown spots along the outer edges of the leaves. Photo: Andrew Sheard, Mayo Macs.

Chloride (Cl^-)

Function

Chloride (Cl^-) is a micronutrient, not to be confused with the toxic form chlorine (Cl). Chloride is involved in photosynthesis and transporting cations within the plant. Chloride, with K, is essential for the proper function of plant stomatal openings and control of internal water balances. Adequate levels might reduce the effects of fungal infections.

Behaviour in soil and plants

- Chloride is highly soluble and moves freely with soil water. It can leach from the soil profile in high rainfall areas with good drainage.
- Chloride accumulates in older leaves. Symptoms of deficiency appear on younger leaves, which can be small, yellow and drop early.
- Chloride toxicity can appear as scorched leaves with brown or dead tissue at the tips, margins, or between the veins. The damaged leaf tissue sometimes looks bleached instead of scorched.
- Chloride, nitrate, sulfate, B and molybdenum are all anions and are antagonistic to each other. An excess of one can decrease the availability of another.

Fertiliser forms

The chloride content of some commonly used fertilisers is:

- Sodium chloride (61% Cl^-)
- Potassium chloride (47% Cl^-)
- Calcium chloride (64% Cl^-).

Management

Chloride deficiencies are unlikely in coastal areas (where atmospheric deposition occurs) or where growers have used chloride-containing fertilisers. If chloride toxicity occurs, avoid chloride-containing fertilisers and investigate irrigation water quality.

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Glossary

Active root zone	The area of the soil where the main mass of roots is found, usually the top 400 mm.
Banded (fertiliser application)	When fertiliser is delivered to a defined area, commonly in a strip below the outer edge of the canopy.
Blower	A mechanical component on a macadamia harvester that blows high-velocity air from a funnel to move nuts from inaccessible areas to where the harvester can pick them up. Blowers move soil and nuts away from trees, contributing to soil erosion.
Bray 1	A measure of how much phosphorus is available in the soil. It is generally used for soils with a pH <7.5.
Broadcast (fertiliser application)	When fertiliser is spread evenly over the whole orchard soil surface.
C:N ratio	The carbon:nitrogen ratio is the mass of carbon to the mass of N. It is often reported in mulch and compost analyses.
Carbohydrate	A biological molecule consisting of carbon, hydrogen and oxygen. Plants produce carbohydrates and draw energy from them for metabolic processes.
Cation	A positively charged ion.
Cation exchange capacity (CEC)	The amount of positively charged nutrients (cations) a soil can hold and exchange. A useful indicator of soil fertility.
Colwell P	A measure of phosphorus in the soil that is available for plants. It is used with an associated phosphorus buffering index (PBI) to measure the soil's ability to bind phosphorus.
Compaction (soil)	Increasing soil density by packing soil particles closer together. It is commonly caused by heavy machinery traffic, particularly on wet soil.
Compound fertiliser	A fertiliser that contains two or more nutrients; also known as a multi-nutrient fertiliser.
Crop load	An estimate of the number of nuts per tree.
Crop replacement value	A value in kilograms of nutrients taken out of the orchard system with every tonne of nut-in-shell at 10% moisture content.
Cultivar	A plant variety that has been produced in cultivation by selective breeding.
Denitrification	The process that converts nitrate to N gas.
Diffusion	The movement of particles or a substance from an area of high concentration to an area of low concentration.
Dripline	An imaginary line on the ground corresponding to the outer perimeter of the canopy.
Erosion (soil)	The mobilisation and transport of soil material. Soil erosion is a natural geologic process that is often accelerated by human activities.
Exchangeable sodium percentage (ESP)	A measure of the amount of sodium held in the soil relative to other cations and an indicator of whether the soil is sodic.
Feeder roots	Small, thin roots that efficiently absorb water and minerals/nutrients from the soil. They can break easily but are replaced quickly in healthy soil conditions.
Ferrosols	Well-draining soils that are characterised by relatively high levels of free iron oxide in the subsoil, giving them a red or yellow-brown appearance. They are valued for intensive agricultural production because of their good structure, moderate to high chemical fertility and water-holding capacity, although these soils are susceptible to structural decline if not maintained.
Fertigation	Application of fer¯tiliser through the irrigation system.
Flush (leaf)	The mass production of new leaves on a tree.
Flush (roots)	The mass production of new roots on a tree. It is typically post-leaf flush.
Foliar	Relating to leaves. Where a product is sprayed directly onto the plant leaves, it will be referred to as a 'foliar spray'.

Gypsum	A soft mineral used as a fertiliser and soil ameliorant. Components include calcium and sulfate.
Hardened-off (leaves)	Used to describe when leaves have matured, they become darker and more rigid in structure. Often root flush happens after this phase.
Husk	The outer covering of a seed or fruit. It is generally green during fruit development and dries out at maturity. It is removed in the process of dehusking.
Inorganic fertiliser	A manufactured or synthetic fertiliser.
Interveinal chlorosis	When the veins of a leaf are green and the area between them is yellow due to lower-than-normal amounts of chlorophyll.
Leaching	The loss of water-soluble plant nutrients from the soil; or the application of excess irrigation to dilute and disperse soil salinity.
Light detection and ranging (LIDAR)	A remote sensing technique that provides a 3-D terrain and vegetation view of a property. A very useful tool for recognising drainage networks throughout the orchard.
Lime (Aglime)	A soil additive made from pulverised limestone or chalk, primarily composed of calcium carbonate.
Metabolic activity	Represents the rate at which chemical reactions change food into energy.
Microbial	Relating to microorganisms or microbes, usually unseen to the naked eye.
Micronutrients	Elements required by plants in very small amounts. These include boron (B), zinc (Zn), manganese (Mn), iron (Fe), copper (Cu), molybdenum (Mo) and chloride (Cl^-).
Microorganism	A living organism that cannot usually be seen with the naked eye.
Monitoring	A process of systematically checking the tree, flowers, and nuts (both attached and fallen) for pests and diseases and recording progress to make decisions on pest and disease management strategies.
Mycorrhizal fungi	A fungus that has a symbiotic relationship with an associated plant. The plant exudes sugars from photosynthesis and, in return, receives nutrients such as phosphorus from the fungus.
Necrotic	Dead or dying; when plants or plant cell cultures are subjected to abiotic stress, they initiate rapid cell death.
NIH	Nut-in-husk.
NIS	Nut-in-shell.
Nitrogen immobilisation	The process in which nitrate and ammonium are taken up by soil organisms and therefore become unavailable to crops.
Nitrogen mineralisation	The process by which the decomposition of dead organisms and degradation of organic nitrogenous compounds provide inorganic N that is available to crops.
Nutrient immobilisation	When microbes outcompete plants for nutrients and retain these nutrients, making the nutrients unavailable for plant uptake.
Nut set	i. The crop stage after flowering when the nut starts to develop. ii. Nuts that hold onto the raceme either after flowering or nut drop.
Nutrient availability	The nutrients available for plant growth.
Nutrient cycling	The movement and exchange of nutrients with and between microorganisms in the soil.
Oil accumulation	The final stage of crop development towards maturity, when the dominant process is sugars conver to oils in the kernel.
pH (power of hydrogen)	A quantitative measure of the concentration of hydrogen ions in a solution indicating acidity or alkalinity on a logarithmic scale between 0 and 14. On this scale, a pH value of 7 is neutral, which means it is neither acidic nor alkaline. A pH value of less than 7 means it is more acidic, and a pH value of more than 7 means it is more alkaline.

Phenology	The study of periodic events in biological life cycles and how these are influenced by seasonal and climatic variations such as temperature, humidity, and diurnal cycles.
Phloem vessels	Vascular cells that transport water, carbohydrates and minerals downward from the canopy to the roots of the plant.
Phosphorus buffering index (PBI)	An index that indicates a soil's capacity to fix applied phosphorus. A high PBI soil tightly binds phosphorus making it unavailable, whereas a low PBI soil leaves phosphorus freely available for plant uptake and potential leaching.
Photosynthesis	The biological process used by plants, algae and certain bacteria involving sunlight, carbon dioxide and water to produce the carbohydrates (including sugars) required for normal growth.
Physiological	Relates to the functions of living organisms and their parts.
Phytophthora	A soil-borne water mould (oomycete) that causes disease. *Phytophthora cinnamomi* is the most common species in macadamia in Australia. Initial symptoms usually occur in the root system but can spread throughout the tree and cause significant crop loss.
Propagule	The part of plant matter used to propagate a plant, e.g. weed seed.
Raceme	The compound macadamia flower consisting of a central stalk (called a rachis) carrying up to 400 individual flowers or flower buds ('bud' is the term applied to a flower before it opens; when it opens, it is referred to as a 'flower').
Root exudate	Secretions from the roots of a plant. For example, sugar secretions to feed microorganisms.
Salinity	The amount of salt dissolved in a body of water or soil.
Soil aggregate	The arrangement of primary soil particles (sand, silt and clay).
Soil crusting	A smooth, poorly structured top layer of soil that is usually more compacted than the underlying material.
Soil organic carbon (SOC)	A measure of the carbon component of the organic matter in the soil.
Soil organic matter (SOM)	Any living or dead animal and plant material. It includes living plant roots and animals, plant and animal remains at various stages of decomposition, and microorganisms and their excretions.
Soil pH	The measure of acidity or alkalinity in the soil.
Soil structure	Describes the arrangement of the soil and is determined by how individual granules clump, bind together or aggregate.
Soil texture	Refers to the proportion of sand, silt and clay-sized particles that comprise the soil. It is used as a basis for soil classification.
Stomata	Small pores on the leaf surface that control gas exchange and regulate the loss of water from the plant.
Sweeper	A mechanical component on many macadamia harvesters that consists of a rotating cylindrical brush that moves the nut into the path of collection systems.
Transect	A path along which one counts and records occurrences of the objects of study (e.g. plants or pests).
Transpiration	The process of water movement through a plant and its evaporation from aerial parts, such as leaves, stems and flowers.
Volatilisation	Where a substance is dispersed through vapour, e.g. N fertiliser such as urea, it will lose some of its N to the atmosphere as ammonia gas via volatilisation when placed on the soil.
Whorl	Also called a verticil is the arrangement of leaves, sepals, petals, stamens, or carpels that radiate from a single point and surround or wrap around the stem or stalk.
Xylem vessels	Vascular cells that transport water and minerals upward from the roots and into the stem and canopy.

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