


Soil Wealth
NURTURING CROPS









Soil Testing and Interpretation for Vegetable Crops

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Introduction

This guide has been prepared with funding from Horticulture Innovation Australia using the vegetable levy and funds from the Australian Government as part of VG13076 Soil condition extension and capacity building. Technical experts and practitioners reviewed this guide and provided valuable inputs.

The purpose of this guide is to help growers and agronomists interpreting conventional 'chemical' soil tests and identify soil chemical constraints for commercial vegetable production in Australia. It can be used to guide site specific decisions on nutrition management. It does NOT provide prescriptive information on how much of a certain nutrient or fertiliser to apply to various vegetable crops. A recipe approach is not recommended because results in crop performance would be unreliable.

Conventional soil tests give information about potentially available nutrients and nutrient uptake conditions in the root zone. A given nutrient level in the soil does not necessarily mean that a crop can access the nutrients when needed. Fertiliser programs should be fine-tuned using yield targets and nutrient removal with harvest data. These can be calculated using results from plant dry tissue tests and yield data. Examples are given in Appendix 1.

A soil test, combined with a visual soil assessment, and knowledge about paddock history and production plans, provides a sound basis for a nutrition program. A conventional soil test can provide some information about biological and physical soil properties.

A complete soil condition assessment covers physical, biological and chemical soil properties of the topsoil and subsoil. It includes assessments of the soil profile and soil variations and management zones within a paddock. If detailed information about the biological or physical condition of a soil is required, separate soil samples must be taken. Sampling methods depend on the required information and analyses to be conducted.

Why soil test?

The purpose of soil testing must be clear i.e. predictive testing to check soil fertility and better predict nutrient requirements, monitoring to assess the suitability of current management practices and adjust existing fertiliser programs as required, or diagnostic testing to help determine the reason for poor growth. Asking this question helps to determine timing of sampling, where to sample, sampling depth(s) and the type of analyses to get done.

In summary, there are several reasons why to tests soils:

1. To check general fertility indicators that influence nutrient availability and uptake such as organic matter, pH, electric conductivity, cation exchange capacity.

2. To determine the level and ratios of nutrients in the root zone.

3. To determine priorities for intervention if low or excess levels have been found considering the nutrient budget, climatic and economic factors.

4. To prepare a nutrient budget and management plan based on the yield target and predicted crop removal.

5. To monitor changes and trends in soil properties and nutrient levels over time so that management inputs can be adjusted.

For intensive crops like vegetables, annual soil testing is recommended as a minimum. In some instances, more frequent testing could be beneficial especially checking nutrients that can leach and especially if they can cause environmental harm, such as nitrogen (N) and phosphorus (P). Plant testing should be used as an additional monitoring tool to ensure nutrient uptake meets expectations.

Detailed technical information on soil testing and interpretation for Australia can be found in:

• Interpreting Soil Test Results: What Do All the Numbers Mean? by Pam Hazelton and Brian Murphy, CSIRO Publishing, 2016.

• Soil Analysis: An Interpretation Manual; by K. I. Peverill, Leigh A. Sparrow and Douglas J. Reuter, CSIRO Publishing 1999.

• Soil Chemical Methods – Australasia; by George E. Rayment and David J. Lyons, CSIRO Publishing, 2011.

The International Plant Nutrition Institute (IPNI www.ipni.net) and International Fertiliser Industry Association (IFA http://www.fertilizer.org) are useful information sources.

Choosing the right soil testing service

Soil testing laboratories (labs) offer a range of soil analyses for specific production systems. In addition, some labs can undertake specialist testing for contamination (e.g. heavy metals, pesticides). The choice of test to use and the sampling depths should be made based on:

- the reason for soil testing, i.e. what the information is going to be used for
- soil type
- soil texture (proportions of sand, clay and silt)
- soil pH
- crop(s) and rooting depth(s)
- previous soil testing history, especially when looking at trends
- which test methods have calibrated interpretation data for a crop.

If unsure, get advice to determine the most appropriate analyses for your needs. It is recommended to test all fertility indicators and nutrients discussed in this document because all influence the crops, and multiple interactions need to be considered. The money you would save on 'quick/basic' soil test can become very expensive if important information is missing and crops suffer deficiencies as a result.

The right choice of test can be discussed with a certified laboratory or a trained crop nutrition adviser.

The following points are important for all soil analyses:

1. The lab should be member of the Australasian Soil and Plant Analysis Council Inc (ASPAC) , participate in the ASPAC proficiency program and be proficient in the test methods requested.

2. The lab should ideally operate under a quality assurance system such as NATA or ISO/IEC17025-2005

3. Sampling must be done correctly for the required testing service; the laboratory can provide information

4. Ensure you know how to best get the sample(s) to the chosen lab before you sample. Remember that if a sample arrives just before the weekend, it will be stored. Sending samples on a Friday is not recommended; it will be stuck in the mail for a while. Call the lab if you need to know details.

5. Sample early enough to get results in time to determine a fertiliser program or application; some labs have a longer turnaround time than others; factor in time needed to interpret the test results and to organise the fertiliser.

ASPAC provides further advice on selecting the right testing service on its public web site.

Interpreting conventional agricultural soil tests

This document contains comprehensive information to assist with understanding of soil test information and basic nutrient management approaches.

General Considerations

Looking at trends over time will provide more information than looking at single soil test results.

Conventional agricultural soil tests are used to check soil fertility; they focus on examining potential nutrient availability to crops (i.e. nutrients supposedly available to the chosen soil sampling depth, and soils chemical properties that influence nutrient availability and uptake by roots). Generally, conventional soil tests are topsoil tests (0-10, 0-15 or 0-20 cm, sometimes to 30 cm). They may not represent the entire root zone. Subsoil testing is recommended to investigate any subsoil constraints. Sampling the main root zone depth is recommended for minimum or no till systems because nutrient or pH stratification can lead to misleading information with shallow sampling (0-15 cm) if no subsoil samples are taken. A consistent soil sampling depth permits the monitoring of changes to soil fertility over time.

Fertcare training material suggests a minimum of 25 cores for topsoil sampling and at least 8-10 cores for sub soil sampling (www.fertilizer.org.au/Fertcare). Most laboratories also provide detailed sampling instructions.

It is important to avoid sample contamination e.g. by cigarette ash, oxidized zinc from galvanized buckets or fencing materials, hands, food, manure or other items which may touch or end up in the sample.

Nutrients and soil properties that are most commonly analysed for vegetable crops are listed in a soil test interpretation table in this document. A complete reference on testing methods for Australia is: Soil Chemical Methods – Australasia; by George E. Rayment and David J. Lyons, CSIRO Publishing, 2011.

[1] http://www.aspac-australasia.com/
[2] http://www.nata.com.au or
[3] AS ISO/IEC 17025-2005 'General requirements for the competence of testing and calibration

Soil Testing and Interpretation for Vegetable Crops

Soil test reports usually show a desirable range for each indicator. The indicators typically apply to topsoil tests only and represent the desirable 'best case scenario'. Some nutrient analyses can be conducted via different methods depending on soil texture or pH (e.g. for phosphorus and potassium) or following tradition in an industry or region. The desirable ranges provided with the soil test report are usually adjusted to the respective analysis, soil and crop type. Remember that the desirable ranges and any automated interpretations (e.g. low, optimum, high) cannot consider multiple nutrient interactions or the impact of physical and biological soil conditions on nutrient availability, e.g. compaction, the potential effect of irrigation management, water quality, organic matter, and other management factors. Automated interpretations can take testing results into account that affect nutrient availability e.g. texture, cation exchange capacity, pH or phosphorus levels and the phosphorus buffer index (PBI).

Soil test interpretations (for top soils), automatically included with laboratory reports, should therefore not be the sole source of information used to make decisions about soil and nutrition management. Interpretation of soil test reports requires specialised knowledge of yield targets for the crop, local conditions, specific crop needs and their management as well as limitations to nutrient applications e.g. irrigation systems used, pesticide programs or spreader capability.

It is important to consider the lab testing method when interpreting a soil test and discussing management options. Consult a trained adviser with adequate local knowledge to interpret soil test results if unsure.

Getting the best out of soil tests

Conventional soil tests from representative samples and conducted by reputable laboratories are essential for making decisions about fertiliser inputs to vegetable crops. Still, soil test data may not alert adequately to limiting factors for a crop if they are not nutritional. Other factors such as soil structure decline (compaction), subsoil restrictions, drainage issues, water quality, irrigation, root damage from insects or diseases or climatic factors can all be major limiting factors.

Structural, biological or climatic limitations may be much more difficult to identify and fix than a nutrient shortage. These limitations or unsuitable crop management approaches may be major factors for root growth and nutrient uptake. Recognising non-nutritional limiting factors can make a big difference to nutrient use efficiencies of applied fertilisers.

When collecting soil samples and interpreting tests, the following site specific conditions should be noted to aid with decisions about the types of fertilisers to use, as well as fertiliser application rates, timings and placement:

- Paddock history, crop rotation, previous inputs, issues with previous crops, drainage issues
- Paddock uniformity
- Condition of the soil surface (crumbly, compacted, mossy, slumped and silted up, cloddy etc.)
- Whether the soil is hard or easy to dig into; a penetrometer may be used to measure soil strength
- Depth of the topsoil and potential rooting depth [cm]
- Structure of the soil in the root zone and below (crumbly, cloddy)
- Existence, depth and firmness of a hardpan (compaction layer)
- Any sign of soil life (worms or other organisms and their holes in the soil)
- Amount and condition of plant roots (during in-crop sampling)
- The soil texture (clay, loam, sand, or a combination of these, such as sandy loam or clay loam)
- Irrigation management.

Many methods of visual soil assessment (VSA) have been published and can be used as a guide. Refer to: Visual soil examination techniques as part of a soil appraisal framework for farm evaluation in Australia. by David C. McKenzie. Soil and Tillage Research Volume 127, March 2013, Pages 26–33.

Observations and visual assessments should be considered when interpreting soil test results and preparing fertiliser programs or reviewing automated fertiliser recommendations.

Quick guide to soil test interpretation

Suggested nutrient levels in the below tables may be somewhat high if applied to dryland crops and pastures. Some high yielding vegetable crops may yield best at the high end of the given nutrient range, if healthy planting stock is used, nutrition is balanced, physical and biological conditions are good, and irrigation and crop protection are managed well.
NB: [mg/kg] is the same as [ppm].

MEASUREMENT	WHAT IS IT? WHAT DOES IT TELL US?	WHAT IS A GOOD LEVEL OR RANGE?	WHAT DOES IT MEAN IF RESULTS ARE NOT IN THE DESIRED RANGE?	HOW TO CHANGE OR MANAGE IT?
Soil texture	Soil texture reveals the soils sand, silt and clay proportions	Soil texture is commonly assessed ‘by feel’; laboratory methods are available but time consuming. The lighter the texture (sandier the soil) the lower the nutrient holding capacity; smaller quantities of nutrients should be applied more frequently. Texture also relates to many physical and biological indicators. Critical nutrient ranges for some tests will vary with soil texture. The soil cation exchange capacity (CEC) provides an indication of soil texture (low CEC, light, sandy soil; high CEC, heavier, more clay based soil).		
pH - measured in a 1:5 soil:water and/ or 1:5 soil:$CaCl_2$ (calcium chloride) solution	pH reveals whether a soil is acid (pH <6.9), neutral (pH 7) or alkaline (pH >7.1). It informs about potential chemical, physical and biological soil properties. The pH (water) value may vary by as much as 0.6 units throughout the year. It is lower in dry soils. Soil salinity increases the pH (CaCl2) reading. pH (CaCl2) is more consistent throughout the year and usually about 1 pH unit lower than pH (water).	Most agricultural crops perform best in a range between pH (CaCl2) of 5.5 and 7. Different species and varieties have different tolerances. Acid loving crops (blueberries) prefer a pH CaCl2 between 4 and 5.	Availability, uptake and or balance of nutrients is affected (Appendix 1); populations of soil organisms change, organic matter breakdown may be hampered leading to accumulation on the soil surface. Soil borne disease pressure may increase. NB. The seasonal or salinity variation of pH (water) can affect automated recommendations for fertilisers, particularly lime.	pH can be increased by using lime (calcium carbonate) or dolomite (magnesium carbonate). In both products, it is the carbonate that changes the pH not the Ca or Mg. The effectiveness of agricultural lime is a combination of “fineness” and “purity” (termed neutralisation value). pH can be lowered by elemental sulphur. Some fertilisers such as urea or ammonium (e.g. in ammonium sulphate or MAP) reduce the soil pH. Gypsum does not change the pH.

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Electrical conductivity (EC) – measured in a 1:5 soil:water solution or as "saturated paste extract" (ECse)	Measurement of electric current – indirect measure of soil salinity It tells us how quickly an electric current would travel through the soil. Some labs multiply EC 1:5 by a factor between 6 and 13, depending on texture to report ECse (Appendix 2).	Soils with ECSE above 1.5 [dS/m] are high in soluble salts. < 1.5 [dS/m] = [mS/cm] = 1500 [µS/cm] = 960 [ppm] Crops can grow well at higher EC levels if managed right.	Plant water uptake is impeded with increasing salinity; plants take up toxic levels of sodium (Na) and chloride (Cl) if salt is the EC issue. Potassium uptake is repressed by sodium; Calcium (Ca), Phosphorus (P) and Boron (B) uptake may be reduced.	Drainage, taking water off the paddock, strategic, deep rooted plantings, growing different varieties or species, carefully managing irrigation, adapting plant nutrition programs (monitor and get advice), increase soil calcium levels, increase organic matter levels. A catchment wide approach may be needed to lower water tables.
Chloride – Cl [mg/kg] Soluble Cl is extracted from a 1:5 soil:water solution	Cl adds to soil ionic strength and thus salinity; plants require very small amounts of Cl.	Critical levels for salinity are: <120 [mg/kg] sands to sandy loam <180 [mg/kg] loam to clay loam <300 [mg/kg] clays	Elevated levels of soil Cl (1:5 soil/water extract) can enhance the propensity of sensitive crops (e.g. carrots, lettuce, spinach) to absorb cadmium (Cd), a toxic, regulated, heavy metal.	Avoid fertilisers containing high levels of chloride (Cl) such as Muriate of Potash (MOP) or some gypsum sources. Check the salt index of fertilisers, especially for sensitive crops such as lettuce or spinach.
Electrochemical Stability Index (ESI) The ratio of the EC 1:5 [dS/m] and ESP	Information about potential: • water infiltration rates • water holding capacity • oxygen supply to roots and soil life • nutrient use efficiency • structural stability (erosion and compaction risks)	> 0.05	A low ESI can mean poor: • water infiltration rates • water holding capacity • oxygen supply to roots and soil life • nutrient use efficiency • structural stability (erosion and compaction risks)	An economically viable response to gypsum and/or lime can be expected where ESI values are at or below 0.05. The best results will be achieved if the gypsum is dissolved prior to application

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Organic carbon (OC) % Organic matter (OM) % (OC x 1.72 = OM)	OC or OM give information about soil function: soil chemical, physical and biological conditions, disease suppression potential and buffering against toxic elements or substances. OM is an essential food source for soil organisms; soils with high OM / OC usually have higher soil microbial populations and good nutrient holding and cycling ability.	A good approach is to keep soil as close as possible to levels that are typical for comparable soil types (or texture) and climate in the area. For horticultural crops (Appendix 3)	Lower organic carbon than typical for the soil type and climate means reduced water and nutrient holding capacity, lower diversity of soil organisms and less disease suppression, poorer drainage, poorer root growth and potentially a higher risk of erosion and compaction.	Keep soil covered with plants, grow and retain as much plant biomass as possible, minimise tillage and erosion; spread or incorporate organic materials such as composts, manures and crop residues; use cover crops, do not burn stubble. Use methods recommended by carbon farming (CFI) methodologies and especially for your region and crops. Refer to EPA and food safety regulations when using soil amendments containing manures; do not use biosolids without EPA permit.
Carbon / Nitrogen (C/N) ratio = Total Carbon / Total Nitrogen	Indicates whether nitrogen will be fixed or released when microorganisms break down organic matter, organic matter contains around 45-50% Carbon (C); it contains Nitrogen (N), (also Phosphorus (P) and Sulphur (S)).	High C/N ratio = >25 **Medium C/N ratio = 11-24** Low C/N ratio = <10	If the C/N ratio is too high (excess carbon), nutrient cycling slows down; microbes will compete with the crop for nitrogen (nitrogen fixing or draw down). If the C/N ratio is low the soil contains excess nitrogen, which may be lost from the root zone through leaching, or as nitrous oxide gas (greenhouse gas).	If C/N is too high, add nitrogen fertilisers of the right type and amount, at the right time to reduce N drawn down by microbes; If C/N is low, reduce N fertilisers or use small amount more often and retain crop residues; high carbon amendments may be added to the soil so that microbes ‘fix’ excess N when breaking these down (wood or bark, straw)

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Total Nitrogen (N) % (used to calculate the C/N ratio) also, often abbreviated as TN	A measure of the total amount of N in the soil in all forms, not just what is available to plants. Indication of a soil's long-term nitrogen supplying capacity (potentially mineralisable nitrogen). About 5% of TN (0-10 cm depth) is mineralised per year. This fluctuates depending on soil type, soil health and climatic conditions.	Less than 0.10% is regarded as low, while over 0.25% is high Ideally, TN should be > 0.15	Low levels of TN mean that the soil will not provide much free nitrogen via mineralisation; fertiliser applications need to provide most of the nitrogen plants require (i.e. fertiliser N inputs = crop N removal rates). High TN levels mean that the N mineralisation potential is high and nitrogen fertiliser inputs can be cut down esp. when mineralisation conditions are good (good soil moisture, soil temperatures between 15 and 28°C).	Adjust fertiliser programs so that supplied N from soil and fertilisers match N needs of crops at different growth stages. Monitor available N in the root zone (N-check or 'deep soil N) and crop N uptake to make good decisions on nitrogen management. When applying N fertilisers, ensure you understand which type will give the best results in your specific situation to avoid gaseous losses, leaching and runoff as well as soil acidification.
Available nitrogen: nitrate (NO3) and ammonium (NH4) – 'deep soil N' [mg/kg] or 'N-check' [kg/ha]	Readily available root zone nitrogen that needs to be included in nitrogen budgets Levels are either reported as NO3-N and NH4-N or as NO3 and NH4 N x 4.42 = NO3 N x 1.29 = NH4 NO3 x 0.226 = NO3 - N NH4 x 0.777 = NH4 - N	Depends on crop and situation, <25 [kg N/ha] may be low, > 100 [kg N/ha] maybe high	If available nitrogen is lower than needed, topping up with nitrogen fertiliser is required; types, amounts, number of applications and timing vary with crop type and situation.	Available nitrogen reserves should be checked using the right test(s) before planting and or before a crop grows rapidly. A nitrogen budget should be used to determine applications; plant testing should be used to monitor.
Nitrate (NO3) [mg/kg] dry soil extract of topsoil	Indicates available nitrate to sampling depth, poor indicator compared to deeper testing.	40-50 [mg/kg] NO3-N (nitrate N) 175-220 [mg/kg] NO3 (nitrate)	The topsoil may be low in organic carbon if levels are low; if they are high, fertiliser may just have been applied or OM levels and mineralisation conditions are good.	See above re using the best tests for checking on available nitrate or total nitrogen and managing N. Calculating nitrogen use efficiency (NUE%) is one way of checking whether N is used well.

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Phosphorus (P) [mg/kg]	"Extractable" phosphorus in the soil, loosely indicating potential P availability, however, actual available P will depend on soil type and root distribution (P is mostly immobile). Several tests are offered, some estimate P availability better than others[4].	Varies with soil type, levels < 30 [mg/kg] is usually marginal or low, levels 70 - 100 [mg/kg] are generally adequate to high; Colwell P levels should be higher in heavier soils and or high yielding crops with high removal.	No matter which test is used, inadequate P supply leads to reduced plant function, poor root growth, increased risk of pest and disease attack. P is important for early establishment.	In all cases, the application of fertilisers and or manures is used to increase soil P levels. Frequent or heavy use of manures can lead to elevated soil P levels and eventually leaching and or run-off. The risk can be assessed using the Phosphorus environmental risk index (PERI) or the Mehlich 3 P saturation ratio (M3 PSR) (Appendices 4 - 6). High P applications reduce Zinc uptake.
Colwell P [mg/kg] – most commonly used test	Soils high in free lime (calcareous soils pH >7) generally "lock up" most of the soil P; this reduces the accuracy of this test. A recent review rated the much-used test as inferior to others[5].	Varies with soil type, levels < 30 [mg/kg] is usually marginal or low, levels 70 - 100 [mg/kg] are generally adequate to high; Colwell P levels should be higher in heavier soils and or high yielding crops with high removal.		
Olsen P [mg/kg] – use above pH 6, definitely > pH 7, correlates with water P test	Soils high in free aluminium and iron (e.g. Ferrosol soils pH < 5.5) generally "lock up" most of the soil P, this reduces the accuracy of this test.	For vegetables, < 20 [mg/kg] is usually low, > 50 [mg/kg] is often considered high		

[4] Holford I.C.R, 2015; Reply to 'Comments on papers relating to soil phosphorus testing in 'Making better fertiliser decisions for cropping systems in Australia' by. P. W. Moody, C. B. Dyson, S. D. Speirs, B. J. Scott and R. Bell. CSIRO Crop & Pasture Science.

[5] Holford I.C.R, 2015; Reply to 'Comments on papers relating to soil phosphorus testing in 'Making better fertiliser decisions for cropping systems in Australia' by. P. W. Moody, C. B. Dyson, S. D. Speirs, B. J. Scott and R. Bell. CSIRO Crop & Pasture Science.

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Mehlich 3 (M3) P [mg/kg] – use below pH 7.5	Used over a wider pH range; The M3 multi-element soil test has gained popularity nationally and internationally. Moreover, its measurement performance for P has improved rapidly across the past 7 years, more so than the other soil P tests mentioned here.	< 30 is usually low, > 70 is usually high (Appendix 4)	No matter which test is used, inadequate P supply leads to reduced plant function, poor root growth, increased risk of pest and disease attack. P is important for early establishment.	In all cases, the application of fertilisers and or manures is used to increase soil P levels. It takes an input or removal of 3.5 [kg] per hectare of phosphorus to change the soil test level by 1 [kg] per hectare. Frequent or heavy use of manures can lead to elevated soil P levels and eventually leaching and or run-off. High P applications reduce Zinc uptake.
Bray P [mg/kg] - use below pH 7.2	Bray P has most use in NSW. Its measurement performance in ASPAC inter-laboratory proficiency programs across two decades has been poor and inconsistent; it cannot be recommended, even with acidic soils.	< 20 [mg/kg] is usually low, > 60 [mg/kg] is usually high		
DGT and resin tests - under development	Potentially available P	No data for vegetables yet		
Phosphorus buffering / fixing capacity (PBI = P buffer index	How much P may be fixed by the soil and how much should be supplied via fertilisers or manures	Good PBI: < 140 (with rising PBI, P fixation potential increases, (Appendix 5)	Reduced plant availability even if P is fixed by Ca at high pH > 7 or Fe and Al at low pH < 5.5.	Adjust fertiliser or manure rates according to the soils P fixing capacity.
Phosphorus buffering / fixing capacity PSR = P saturation ratio)	How much P may be fixed by the soil and how much should be supplied via fertilisers or manures, leaching risk	Good PSR: 0.062 - 0.2 (Appendix 4)	PSR < 0.062: decreasing P availability to the crop > 0.2 indicates leaching risk.	Adjust fertiliser or manure rates according to the soils P fixing capacity to stay the agronomic and environmental optimum.
Phosphorus Environmental Risk Index (PERI)	P leaching risk calculated from the available P (Colwell) and PBI	Critical ration value: 2 (Appendix 6)	> 2 the risk of P movement in the soil increases.	Reduce fertiliser or manure inputs.

[6] IPNI Crop Nutrient Removal Calculator - http://www.ipni.net

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Sulphur (S) [mg/kg] – several methods in use	Potentially available S	10 – 20 [mg/kg] is generally adequate, < 10 [mg/kg] is low, > 40 [mg/kg] is high	S is an important building block of proteins, so overall plant function is reduced if S uptake is low.	Use the sulphate form of fertilisers to build S in soils. Can use Single Super as a phosphorus (SSP) as it also supplies SO4-S and Ca. If using SSP, monitor soil and crop cadmium (Cd) levels.
Available potassium (K) [mg/kg] Different methods (e.g. Colwell, Skene, Mehlich 3) give similar but not identical results.	Potentially available K Heavier soils usually have and require higher K levels; they also hold onto K better than lighter soils (clay > clay loam > sandy loam > sand).	As a guide < 110 [mg/kg] is low, > 250 [mg/kg] is usually high. NB: most crops remove as much or more K from the soil as nitrogen.	K is especially important for regulating transpiration; low K can mean that plants lose water quickly. High Sodium (Na) and or Magnesium (Mg) uptake depresses K uptake in plants (leading to cation imbalance).	In heavier soils K can be applied pre-planting as per a K removal budget. K may leach from the root zone in lighter soils depending on water movement. Foliar applications or fertigation work well. Some crops have a high K demand, especially during rapid growth, and even though soils have adequate levels, additional K at that time may be beneficial.
Exchangeable cations and Cation Exchange Capacity (CEC) (major exchangeable cations: Ca, Mg, K, Na and Al; hydrogen H and trace metals can also be counted as cations)	The CEC and cation proportions (%) give information about soil structure, nutrient availability and storage capacity, the soil pH and the potential soil response to fertiliser. Cations have a positive charge.	CEC increases with the soil's clay and organic matter content. Low CEC < 5 [cmol/kg] High CEC > 20 [cmol/kg] Desirable levels for individual cations vary for crops and soil type – see below for general guidance. [cmol/kg = meq/100g = meq%] Refer to Appendix 7 for cation balances	Low CEC means that the soil does not hold nutrients well. The soil usually has a sandy texture with little clay and or organic matter. Nutrients, especially nitrogen, sulphur, boron and potassium can leach. These soils need smaller quantities of nutrients applied more frequently than heavier soils. A high CEC usually indicates a higher fertility; the soil holds nutrients well and OM accumulation can be greater than in low CEC, lighter soils.	Given organic matter has a higher CEC than clay, adding organic matter is a good way of increasing or maintaining CEC. Some growers have added clay to sandy soils to increase nutrient (and water) holding capacity. All cations compete for uptake by plants, therefore an oversupply of one can reduce uptake of another (cation imbalance). Elevated levels of ammonium ions (NH4+) in soil solution compete for uptake with other nutrient cations, particularly Ca. This tendency is enhanced when plants are forced to meet much of their mineral-N requirements from NH4-N rather than NO3_N. Low plant Ca concentrations are often a result.

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Exchangeable magnesium (Mg) [mg/kg], [cmol/kg], % CEC	Potentially available Mg CEC proportion (%), considering Al and H as part of CEC	200 – 400 [mg/kg] 1.6 – 2.0 [cmol/kg] 10 – 20 % of total eCEC or CEC	Soils high in Mg are usually hard setting when dry and sticky when wet; this is made worse if Na levels are also high (e.g. due to salinity or sodicity). Low Mg means that plants will suffer from Mg deficiency and nutrient imbalance.	Low Mg levels can be corrected via a range of Mg fertilisers applied to soils or as foliar products. Dolomite contains Mg and can be used if a pH increase is needed as well. Applying Calcium fertilisers or Gypsum can counteract high Mg levels. Make sure potassium availability and uptake are adequate when using Mg fertilisers.
Exchangeable potassium (K) [cmol/kg], % CEC	CEC proportion (%), considering Al and H as part of CEC Potentially available K [mg/kg] is explained separately above	Soil type related differences need to be considered, below is an overall rough guide: 0.5 – 0.7 [cmol/kg] 3 - 8 % of total eCEC or CEC	K is especially important for regulating transpiration; low K can mean that plants lose water quickly. High Sodium and or Magnesium uptake depresses K uptake in plants (leading to cation imbalance).	In heavier soils K can be applied pre-planting as per a K removal budget[6]. K may leach from the root zone in lighter soils depending on water movement. Foliar applications or fertigation work well. Some crops have a high K demand, especially during rapid growth, and even though soils have adequate levels, additional K at that time may be beneficial.
Exchangeable calcium (Ca) [mg/kg] [cmol/kg], % CEC	Potentially available Ca CEC proportion (%), considering Al and H as part of CEC	6.0 – 7.5 meq/100g 65 - 80% of total eCEC or CEC (Not all soil Ca methodology excludes solid- phase Ca from the apparent result so care is needed with choice of method and interpretation)	Ca strengthens plants (cell walls) and is needed for developing tissues (shoot tips, buds, roots). In the soil, it also helps to strengthen structure in many ways.	Plants need free Ca in the soil solution and rely on transpiration for uptake. Low soil solution Ca, dry or humid conditions hamper uptake. Ca can be applied via fertilisers with high soluble Ca content or applied as a foliar product. It does not move downwards in plants, only up with transpiration. To improve soil Ca, lime and gypsum can be applied.
Free Lime assessment via effervescence	Presence of free carbonate in the soil which can increase the pH	Nil to slight: Non-calcareous Moderate to high to very high: Calcareous	N/A	Use of acidifying fertilisers.

MEASUREMENT	WHAT IS IT? WHAT DOES IT TELL US?	WHAT IS A GOOD LEVEL OR RANGE?	WHAT DOES IT MEAN IF RESULTS ARE NOT IN THE DESIRED RANGE?	HOW TO CHANGE OR MANAGE IT?
Exchangeable sodium (Na) [mg/kg] % CEC or ESP	Potentially available, toxic Na CEC proportion (%), considering Al and H as part of CEC also called exchangeable sodium percentage ESP	< 80 [mg/kg] ESP < 4% of total eCEC or CEC or < 6% of total eCEC or CEC Maximum recommended levels vary depending on soil type	Na is not a plant nutrient! It interferes with plant water uptake and soil structure. High levels make the soil hard setting when dry and sticky when wet. Na competes with potassium (K) for plant uptake so plants become K deficient and need extra K input.	High soil Na can be managed by increasing soil calcium (Ca) via lime or gypsum depending on pH. Crops should get extra soluble Ca fertiliser and extra K fertilisers. Ammonium (NH4) based fertilisers should be avoided. Improving organic matter levels is helpful to buffer the sodium effect.
Exchangeable aluminium (Al) [mg/kg] % CEC	Potentially available, toxic Al Toxicity is usually associated with pH levels below 5.5 in soils which contain significant aluminium	< 1% CEC extractable Al is < 2 [mg/kg] for sensitive plants	High Al levels will reduce root growth and can lead to toxicity symptoms. Plant species that are adapted to low pH soils usually have a higher tolerance to Al.	Increase pH (e.g. via lime or dolomite). Increase levels of other cations, especially calcium (Ca).

Extraction procedures for trace elements can vary between laboratories, resulting in different figures. The most widely used trace element test for trace metals iron (Fe), copper (Cu), manganese (Mn) and zinc (Zn) across Australasia is the DTPA. EDTA extracted trace elements are considered more reliable on acid soils while DTPA is considered more reliable on alkaline soils (DTPA produces generally lower levels than EDTA). The Mehlich 3 (M3) extraction can be used over a relatively wide pH range.

Critical levels for trace elements vary with soil texture and crop. Adequate levels are lower in sandy soils than in loams or clays. Sands are often inherently low on trace elements. Soil testing for trace elements can only be a guide; further investigation through plant testing is recommended.

The very general guide for the preferred level of trace elements in soil is based on DTPA extraction (EDTA or M3 for neutral to slightly acid soils in brackets).

MEASUREMENT	WHAT IS IT? WHAT DOES IT TELL US?	WHAT IS A GOOD LEVEL OR RANGE?	WHAT DOES IT MEAN IF RESULTS ARE NOT IN THE DESIRED RANGE?	HOW TO CHANGE OR MANAGE IT?
Copper (Cu) [mg/kg] trace metal	Potentially available Cu	0.3-1 [mg/kg] (2-50 [mg/kg]) (less available / tied up in insoluble forms in high pH and calcareous soils, deficiencies can occur in dryer conditions)	Reduced protein synthesis, reduced nitrogen (N) fixing by legumes.	Cu can be applied to soil or plants. Trace metals compete for uptake if not in balance in the soil.

MEASUREMENT	WHAT IS IT? WHAT DOES IT TELL US?	WHAT IS A GOOD LEVEL OR RANGE?	WHAT DOES IT MEAN IF RESULTS ARE NOT IN THE DESIRED RANGE?	HOW TO CHANGE OR MANAGE IT?
Iron (Fe) [mg/kg] trace metal	Potentially available Fe	10-70 [mg/kg] (10-200 [mg/kg]) (less available / tied up in insoluble forms in high pH and calcareous soils, can be worse in wet conditions)	Reduced photosynthesis, respiration and chlorophyll production.	Fe can be applied to soil or plants. Trace metals compete for uptake if not in balance in the soil.
Zinc (Zn) [mg/kg] trace metal	Potentially available Zn	0.5-1 [mg/kg] (1- 20 [mg/kg] (less available / tied up in insoluble forms in high pH and calcareous soils)	Carbohydrate metabolism and enzyme activation are affected (like manganese (Mn)).	Zn can be applied to soil or plants. Trace metals compete for uptake if not in balance in the soil. High P applications reduce Zn uptake.
Manganese (Mn) [mg/kg], trace metal	Potentially available Mn	1 – 10 ([mg/kg] Low: 5-10 [mg/kg], high: > 50 [mg/kg]) (less available / tied up in insoluble forms in high pH and calcareous soils, deficiencies can occur in dryer conditions)	Disturbed carbohydrate metabolism and energy transfer (like Zn). Some soils are naturally high in Mn, this can repress the uptake of other metals.	Mn can be applied to soil or plants. Trace metals compete for uptake if not in balance in the soil. If Mn uptake is too high, the other trace metal should be applied to correct the imbalance.
Boron (B) hot water extraction [mg/kg] or indicative test for “plant-available” B is hot CaCl2-extractable B	Potentially available Boron	0.5-4 [mg/kg] (1-2 [mg/kg]) (B toxicity may occur in sensitive crops when >5)	New tissues cannot develop normally and can die, roots and fruits crack.	Plants rely on transpiration for B uptake. It can be applied to soil or plants. Using too much B fertiliser can cause toxicity.
Molybdenum (Mo) - testing for extractable Mo is uncommon	Potentially available Mo, most Mo soil tests are not reliable, Rayment and Lyons (2011) published a method based on 0.01 M CaCl2	2 [mg/kg]	Reduced N assimilation and rhizobia function in legumes.	Mo can be applied to soil or plants.

Toxic Metals

It is important to check for toxic metals in all organic fertilisers and wastewater. Soils need monitoring for these metals, e.g. if recycled materials have been used. Phosphorus fertilisers can contain cadmium. Several common pesticides used extensively in agriculture and horticulture in the past contained substantial concentrations of metals and this may have led to high soil concentrations in some instances. Potentially toxic elements include Arsenic (As), Cadmium (Cd), Chromium (Cr), Lead (Pb), Mercury (Hg), Nickel (Ni). The trace elements Zinc (Zn) and Copper (Cu) can be toxic to humans and animals in high concentrations.

Toxic levels (to animals and humans) in edible parts of plants may occur if crops / pastures accumulate heavy metals in the proportion of plants that is consumed. Metal concentrations in these parts of plants should be monitored if a risk has been identified.

Australia developed a National Cadmium Minimisation Strategy and established a National Cadmium Management Committee (NCMC) in 2002. The NCMC ceased to operate in December 2006, having achieved all its aims. CSIRO continues to provide research and advice on issues related to cadmium in agriculture and continues to host the website www.cadmium-management.org.au.

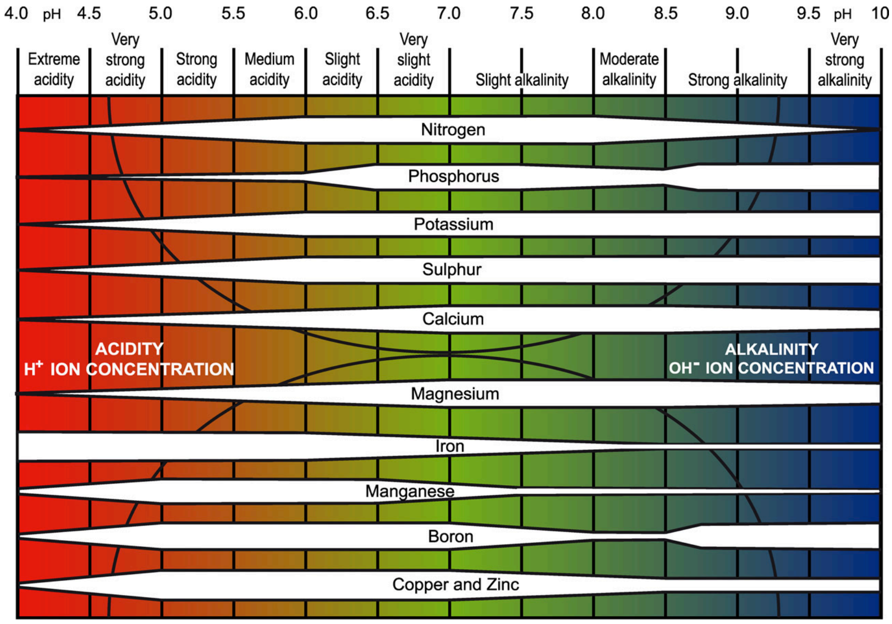
The Australia New Zealand Food Standards Code provides maximum levels in foods. Environmental Protection Authorities in each state (EPA) provide guidelines for maximum levels in recycled resources and soils. EPA also regulates the safe use of recycled resources. Still, residual contamination from times prior to regulation may occur in soils. If high levels of potentially toxic metals are detected in soils or plants, it is important to identify the contamination source and eliminate it or manage potential risks on a case by case basis, considering a range of soil properties. Specialist advice should be sought.

Appendix 8 explains the basic principles of preparing a fertiliser program.

Appendix 1

pH, Nutrient Availability and Adjusting Soil pH

pH and nutrient availability



Nutrient removal figures [kg/tonne]

CROP	N	P	K	S	Ca	Mg
Bean green	4.0	0.9	3.0	0.0	0.4	0.3
Broccoli	4.5	0.9	4.6	0.0	0.4	0.2
Cabbage Dutch	3.0	0.4	2.7	0.0	0.6	0.2
Capsicum	3.0	0.3	2.9	0.0	0.1	0.2
Carrot	2.0	0.4	3.7	0.0	0.6	0.5
Cauliflower	4.0	0.5	3.3	0.0	0.4	0.2
Celery	3.5	0.9	6.6	0.0	1.9	0.3
Cucumber	1.0	0.4	1.5			
Lettuce	3.0	0.4	3.3	0.0	0.7	0.2
Lettuce Oakleaf	2.5	0.3	3.2	0.0	0.6	0.2
Pea Green	5.0	0.7	3.3	0.0	0.6	0.4
Pumpkin	1.8	0.4	2.5	0.0	0.4	0.2
Spinach	4.2	0.6	0.6	0.0	1.3	0.6
Sweetcorn	4.0	0.9	4.4	0.0	0.1	0.4

Appendix 2

Salinity

Soil salinity is usually measured in a 1:5 soil:water solution. Data on the salt tolerance of plants is usually based on the electrical conductivity of a saturated extract ECSE (dS/m).

Most soil test reports show EC 1:5. they need to be converted to ECSE figures to check against salinity tolerance figures for crop. The conversion of the laboratory result from an EC 1:5 test to ECSE involves multiplying it by a factor that depends on your soil texture.

For example, an EC 1:5 of 0.4 dS/m on a clay loam soil (multiplication factor of 9) gives an ECe value of 0.4 dS/m x 9 = 3.6 dS/m.

If soil texture is not determined, laboratories may provide ECe data by multiplying EC 1:5 results by a factor of 10.

Conversion factor of various soil types for EC 1.5 to ECe

SOIL TEXTURE GROUP	MULTIPLICATION FACTOR	IF EC 1:5 = 0.2 THEN ECE = BELOW [DS/M)
Sands, loamy sands	13	2.6
Sandy loams, fine sandy loams	11	2.2
Loams, very fine sandy loams, silty loams, sandy clay loams	**10**	**2.0**
Clay loams, silty clay loams, very fine sandy clay loams, sandy clays, silty clays, light clays	9	1.8
Light medium clays	8	1.6
Medium clays	7	1.4
Heavy clays	6	1.2

Conversion factors for the most used units of measurement for salinity are given below

dS/M	mS/cm	S/cm	ppm	Milli mho/cm	Micro mho/com
1	1	1000	670	1	1000
0.001	0.001	1	6.7	0.001	1
0.00156	0.00156	1.56	1	0.00156	1.56

Appendix 3

Total Organic Carbon

Total organic carbon is a measure of the carbon contained within soil organic matter.

Organic carbon percentage over a range of conditions

ORGANIC CARBON (OC) %	LOW ANNUAL RAINFALL	HIGH ANNUAL RAINFALL
	CROPS INCLUDING VEGETABLES AND FRUIT	CROPS INCLUDING VEGETABLES AND FRUITS
	<300 [MM] PER GROWING SEASON	400 TO 600 [MM] PLUS
Low	Below 1.5	2.5
Desirable	1.5 to 2.5	2.5 to 5
High	Above 2.5	Above 5

Adapted from http://www.depi.vic.gov.au/

Organic Carbon (OC)[7] is the most important driver of nutrient storage, nutrient cycling, soil life and access of roots to nutrients. It improves water storage, soil air supply and feeds soil life.

Labile Carbon is the fraction of soil organic carbon with most rapid turnover times. Its oxidation drives the flux of CO2 between soils and atmosphere.

Soil type (clay content, minerals, density) determines the potential storage of organic carbon (OC)
The amount of OC stored in soils tends to increase with increasing clay content because the clay reduces access to organic matter (OM) by microorganisms. In sandy soil microorganisms are able to more easily access OC. This causes greater loss of OC by decomposition in lighter soils.

Climate determines the possible storage of organic carbon
Climate determines the possible storage of OC in soil by regulating plant biomass production. Under dryland agriculture for instance, rainfall is the climate factor that has most influence on plant productivity and therefore inputs of OC to soil. In regions with high rainfall or in irrigated crops, soils tend to have greater possible storage of OC than the same soil type in a lower rainfall region or without irrigation.

Management determines the actual storage of organic carbon in soil
Practices that can increase the amount of total OC stored in soil and decrease losses include:

- Increased plant growth generally increases inputs of OC to soil in shoot material, roots and root exudates, e.g. optimal nutrition, increasing water use efficiency, decreasing disease.
- Growing plants for longer periods each year generally increases inputs of OC to soil, e.g. shorter fallow, conversion from cropping to pasture, conversion from annual to perennial pasture.
- Improving soil structure can increase the amount of OC stored in soil by reducing losses of OC from soil by decomposition and erosion, e.g. retaining crop residues / stubble, maintaining ground cover and reducing compaction by vehicles and stock.
- Continuous pasture builds organic carbon quicker than other rotations.

Tillage, fallow periods and erosion lead to the greatest OC losses. Well managed nutrition and irrigation help to grow more OC; soil amendments can be used to import OC.

Microorganisms break down soil organic carbon as an energy source – this occurs faster when the soil is moist and warm. Tillage can enhance microbial breakdown as soil aggregates are disrupted, making protected organic matter available to microorganisms to decompose and because better soil aeration increases microbial activity.

[7] Adapted from http://www.soilquality.org.au/factsheets/how-much-carbon-can-soil-store

Appendix 4

The Mehlich Phosphorus Saturation Ratio (M3-PSR)

The Mehlich-3 Phosphorus saturation ratio (M3-PSR) is a combination of the agronomic Mehlich-3 P soil test and the environmental aspects of a soil P saturation test (Khiari et al., 2000; Sims et al., 2002; Maguire and Sims, 2002).

The M3-PSR has initially been developed as an environmental management tool and is, according to US research, better at identifying soils susceptible to soluble P losses by leaching than Mehlich-3 P alone. As a gauge for P solubility, it also has value as an agronomic indictor of potential P availability to plant roots (Maguire et al 2002).

In general, a PSR <0.062 is below the agronomic optimum based on US literature. According to Australian research (Bloesch and Rayment, 2006), a low potential for P losses from top-soils via runoff and/or leaching is expected when M3-PSR is < 0.2 to 0.25. At a PSR of above 0.2, P losses through leaching and run-off from vegetable production areas are likely occur. Depending on site conditions i.e. the likelihood of surface run-off, rapid drainage (e.g. lack of plant cover) and vicinity to waterways, a range of 0.15 M3-PSR may already indicate a risk of P losses to waterways.

Considering the influence of site conditions on risks, it is important to integrate soil P testing (for P concentration and P fixing/leaching potential) with other site risk assessments to avoid P effects on water quality. This is especially important for water reuse schemes effluent and manure use.

While environmental soil limits are useful in identifying potential problems, a more comprehensive approach, e.g. using a phosphorus site index, will be more accurate at identifying the relative risk of P losses than soil P testing, including M3-PSR and other P buffer capacity indicators, alone.

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Appendix 5

Phosphorus Buffering Index for the Colwell Phosphorus Test

The PBI is a measure of the soil's capacity to hold on to, or release, phosphorus and is closely related to soil texture. Light textured soils tend to have a relativelow PBI, whereas heavy soils have higher PBI values.

For Colwell P the critical soil test value also changes with soil texture. Together with PBI, it allows producers to modify fertiliser applications according to soil texture. Other P soil extractions such as Olsen, Bray or Mehlich 3 are more or less independent from soil texture.

In a practical sense, a high PBI soil will have a higher critical soil test value, compared to a low PBI soil to achieve production potential.

PBI	RATING OF P-FIXING ABILITY
<15	Extremely Low
15-35	Very Very Low
36-70	Very Low
71-140	Low
141-280	Moderate
281-840	High
>840	Very High

Burkitt L.L. et.al. 2002. A simple phosphorus buffering index for Australian soils. Australian Journal of Soil Research 40(3) 497 – 513

When soil P 'critical values' are known to be influenced by soil P fixation status, they may warrant downwards adjustment when PBI (or a similar index value) is low, and upwards movement when expected P sorption is high to very high.

Appendix 6

Phosphorus environmental risk index (PERI)

Movement of phosphorus (P) from the site of soil application generally occurs because of water movement of organic and mineral sediment to which the P is attached, or dissolved in moving water. The PERI is a calculation that provides some indication of the potential for P to move through the soil with water. It is calculated from the available Colwell P and the Phosphorus Buffer Index (PBI). As the available P to PBI ratio rises, the probability that the P buffer capacity of the soil is exceeded and leaching occurs increases. Once a critical value of 2 is exceeded the risk of movement of P in the soil increases.

Validation of the PERI is still in progress but sufficiently advanced to provide confidence that it will provide worthwhile comment to defining the line between sufficient P for high productivity and where environmental risk increases.

Adapted from: http://www.backpaddock.com.au/news/explaining-new-calculations-in-soilmate/

Appendix 7

The Soil Cation Ratio Concept

The optimum soil cation ratio concept also referred to as referred to as the ‘Base Saturation Ratio approach’, first proposed about 70 years ago, has been incorporated into many fertiliser recommendation philosophies in various ways. It is a soil-based concept that ignores plant requirements (indicated by sufficiency levels) and does not take account of differences between species in their adaptation to different soil conditions.

Recent field evaluations of this concept have shown that the ratio of cations has no impact on the response of crops to Ca, Mg, and K in fertiliser programs. Using the optimum cation ratio concept alone has a major disadvantage as, even if the ratio of cations in the soil is optimum, a nutrient deficiency may still exist. A sufficient supply of all available cations in the root zone is the most important consideration in making economic fertiliser recommendations.

Source:

Eckert, D.J. 1987. Soil test interpretations: Basic cation saturation ratios and sufficiency levels. In J.R. Brown (ed.) Soil Testing: Sampling, Correlation, Calibration, and Interpretation. Special Publication No. 21. Soil Science Society of America. Madison, WI.

Many Australian soils have ‘unbalanced’ cation ratios; sodium and magnesium levels can be high. These imbalances cannot be fixed in an economically viable manner to match the ‘soil cation ration concept’.

However, if calcium (Ca) uptake is low due to competition from other cations (Mg, Na, K), crops will benefit from provision of sufficient soluble calcium to the rootzone with fertilisers. Liming or adding gypsum will not provide sufficient soluble Ca because these products do not contain a lot of soluble Ca. They are still important soil conditioners.

Typical CEC ranges and soil texture are shown in the below table.

CEC	SOIL TEXTURE
0-8	Sand
9-12	Loamy Sand
13-20	Sandy / Silty Loam
21-28	Loam
29-40	Clay Loam
>40	Clay

Note: the CEC is often a calculated value reached via adding up the result of testing for the major cations (in meq).

This means that a soil rich in limestone may have a very high CEC value in a test report. However, a large proportion of the calcium measured is in solution on not on exchange sites. Then the CEC value does not represent CEC.

This situation may also occur if the soil test is taken after liming or adding gypsum or in sodic soils.

The typical order of adsorption strength on exchange sites (organic matter, clay) is:
$Al^{3+} > Ca^{2+} > Mg^{2+} > K^{+} = NH_4^{+} > Na^{+}$

Conversion of ppm to meq/100g

CATION	DIVIDE RESULT IN PPM BY
Calcium	200
Magnesium	120
Potassium	390
Sodium	230
Aluminium	90

Appendix 8

Basic principles of developing a fertiliser program

Determine the purpose of soil testing, select appropriate soil tests and a laboratory, and sample at appropriate time/s and depth/s. Results are used in conjunction with interpretative information, yield targets and removal rates to help guide decision on the need for, rates, timing and placement of fertilisers and amendments.

Fertiliser program considerations

- Adjust soil deficiencies and imbalances pre-plant as much as possible based on soil tests and trends
- Use yield potential [t/ha] and crop removal rates [kg/t] to determine the nutrients [kg/ha] you need for the crop.

Consider

- Mobility of different nutrients and nutrient interactions
- Specific nutrient needs of the crop at different growth stages
- Types of fertilisers and soil amendments to use and application methods
- Timing and placement
- Site-specific conditions / possible constraints
- Monitoring actual nutrient uptake during early growth using plant analysis.

The most important factor influencing plant nutrient uptake is root length density, not the quantity of fertilisers applied. Soil structure, crop type, age and density, temperatures, root health and irrigation management, amongst others influence root length density.

The Fertiliser Institute of Australia, through its Fertcare, Stewardship and Research Programs provides guidance on efficient fertiliser use.

Conversion from ppm or mg/kg to kg/ha

A 10 cm layer of soil over 1 ha has a volume of 1000m3 – the weight of the soil depends on its Bulk Density (BD)

- A soil with BD of 1.0 g/cm3 will weigh 1000 t to 10cm depth
  The nutrient content will be 10 kg/ha per mg/kg of nutrient to 10cm depth
- A soil with BD of 1.2 g/cm3 will weigh 1200 t to 10cm depth
  The nutrient content will be 12 kg/ha per mg/kg of nutrient

Plant roots explore soil volumes, not weights which are used for soil testing.

This means if a soil's Bulk Density is really high or low, the soil test result may be over or underestimating nutrient levels available to the root system.