Department of Employment, Economic Development and Innovation

Soil health for vegetable production in Australia

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and the Department of Employment, Economic Development and Innovation

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Part 1: Introduction to soil health

What is 'soil health'?

Some people think of 'soil health' as the biological capacity of soil (i.e. its function as a vital living system that sustains plants, animals and humans). Others treat soil simply as a medium to hold up a plant while we apply fertilisers, water and crop protection products to obtain maximum yield.

This manual takes a holistic view of soil health by considering the interaction of physical, chemical and biological soil properties (see below). The balance and stability of these components are what make a healthy soil.

In Australia, vegetables are grown on a wide range of soil types, so it is important to understand the characteristics and constraints of each of these soils—only then can we get the best from the soil for crop production.

Understanding your soil type and how to manage it will help you maintain long-term soil health and minimise soil loss and degradation.

Physical, chemical and biological soil properties

Physical soil properties relate to the size and arrangement of soil particles and the movement of air and water in the soil. 'Soil texture' and 'soil structure' are two important physical properties that influence many other soil characteristics.

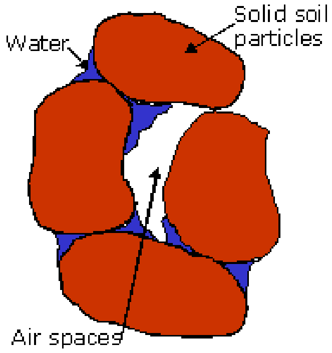
Chemical soil properties relate to nutrients held on soil particles, contained in soil organic matter and dissolved in the soil water.

A standard soil analysis measures a range of chemical soil properties including pH, electrical conductivity (EC), cation exchange capacity (CEC), organic carbon, organic and mineral forms of nitrogen, extractable phosphorus, exchangeable potassium, calcium and magnesium and extractable micronutrients.

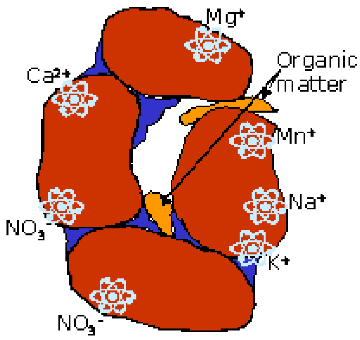
Biological soil properties relate to living soil organisms and their relationships with each other and with their main food source—soil organic matter. Organisms living in the soil include microbes such as bacteria and fungi, nematodes, insects and larger burrowing animals such as earthworms.

A healthy soil contains huge populations of microbes, with estimates typically being 100 million bacteria and 7 m of fungal strands per 1 g of soil. A few of these organisms attack plant roots and these have traditionally received the most attention from farmers and researchers—often to the detriment of the soil's other beneficial living organisms.

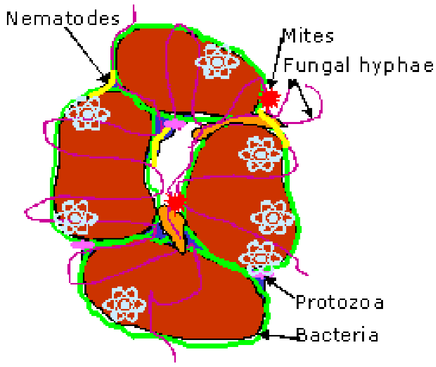
Physical soil properties



Chemical soil properties



Biological soil properties



About this manual

This manual aims to take the mystery out of managing soils to keep them healthy.

It includes:

- a guide to identify the types of soil you are working with, a review of their common constraints and suggestions on how to manage these constraints
- new ways to assess standard soil analysis results (what information are you already collecting that can help assess and improve the health of your soil?)
- suggestions for additional soil measurements that could help track changes in soil health.

Part 2: Know your soil and its constraints

The first step for successfully managing your soil is to know what type of soil you are dealing with. There are three main ways to identify your soil type:

1. Use 'do-it-yourself' (DIY) soil classification.
2. Use formal soil classification.
3. Use soil maps.[1]

Do-it-yourself (DIY) soil classification

The DIY method gives you a rough classification based on four soil characteristics:

1. soil texture
2. soil pH
3. dispersion and slaking characteristics
4. soil colour.

The four soil characteristics of texture, pH, dispersion and slaking, and colour can be determined for the top 30 cm of your soil, but checking deeper will let you look at more of the soil profile and highlight subsoil characteristics such as mottling (indicates waterlogging), clay layers and plough pans that have important effects on root development.

We also recommend getting a standard soil analysis test done by a reputable laboratory. It will provide information on the nutrient status of your soils and allow you to better manage your fertiliser program. Soil testing laboratories accredited by the Australasian Soil and Plant Testing Council (ASPAC) are listed at www.aspac-australasia.com

Before you can determine each of these soil characteristics, you will need to select a sampling site on your farm. You may need several sampling sites to cover the range of soils on your property. Perform the following steps:

- **Select a representative site for each soil type on your property.** Avoid areas such as row ends that may be compacted from turning vehicles. Clues for identifying different soils are changes in surface colour and/or texture and position in the landscape (e.g. ridge, mid-slope, lower slope or creek flat position).
- **Record the location of your representative site(s).** This allows you to return to that spot to check changes in soil health over time. Recording the location with a GPS unit is an ideal way of achieving this.
- **Take a soil sample.** A spade is a useful tool for exposing the soil to a depth of 30 cm—the rooting depth of many vegetable crops. To check to a depth of 50 cm or more you will need a soil auger or, better still, a backhoe or excavator to dig a pit. Don't run the machinery over the area you want to test and make sure there are no underground cables and pipes where you plan to dig.

Note: Selecting a representative site to determine the soil type is different to taking a soil sample for pH and nutrient analysis. The latter requires taking several soil samples across a production block of the same soil type and bulking these together to give an 'average' surface soil sample.

Warning

Check the location of underground telephone and electric cables, and water pipes before digging a pit.

Dial 1100 or visit www.dialbeforeyoudig.com.au

1. Soil texture

Soil texture describes the relative amounts of sand (large particles), silt (medium particles) and clay (small particles) in the soil (see Table 1).

Texture is an important soil property because it affects nutrient- and water-holding capacity, porosity, aeration, water movement through the soil profile, structure, likelihood of compaction and resistance to root penetration and acidification.

Table 1. Soil texture

Sandy soils	90–100% sand particles by weight
Loams	Similar amounts of sand, silt and clay particles, but can range from sandy loams (with a higher proportion of sand particles) to clay loams (with a higher proportion of clay particles)
Clays	More than 35% clay particles by weight, with medium to heavy clays containing over 40% clay by weight

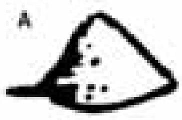
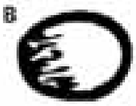
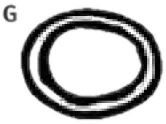
1 Some regional government offices may have soil maps for your region; however, these can sometimes be limited. Only the first two ways to identify your soil type are described in this manual.

To determine soil texture:

- Take a spoonful of soil in one hand and add water slowly while working the soil until it becomes sticky.
- Try to roll the soil into a ball.
- If you can make a ball, try to make a cylinder (or rod).
- If you can make a long cylinder (or rod), try to bend the soil into a 'U' shape without forcing it.
- If you can make a 'U' shape, try to make a ring.

Table 2 indicates soil texture based on the result.[2]

Table 2. Using shapes to determine soil texture (includes common soil constraints)[3]

Soil texture	Description	Shape	Constraints
Sand	The soil stays loose and separated and can only be accumulated in the form of a pyramid.	A 	• low water-holding capacity; seedlings can wilt because of a rapidly drying soil surface • low nutrient retention; excessive leaching of nutrients (particularly nitrate, potassium and sulphate) • acidity • extremely low phosphorus fixation • low organic matter content.
Sandy loam	The soil contains enough silt and clay to become sticky and can be shaped into a fragile ball.	B 	
Silty loam	Similar to the sandy loam, but the soil can be shaped by rolling it into a small, short cylinder. Soil has a 'silky' feel.	C 	• hard-setting/surface sealing if texture is fine sandy loam or silty loam • prone to compaction.
Loam	Can be rolled into a 15 cm long (approx.) cylinder that breaks when bent.	D 	
Clay loam	Similar to loam, although the cylinder can be bent into a 'U' shape (without forcing it) and does not break.	E 	
Fine clay	The soil cylinder can be shaped into a circle, but shows some cracks.	F 	• excessive/prolonged wetness • prone to compaction.
Heavy clay	The soil cylinder can be shaped into a circle without showing any cracks.	G 	

[2] Alternatively, you could include texture as a test in your next laboratory soil analysis.

[3] Adapted from EUROCONSULT (1989).

Table 3. Soil constraints associated with soil texture

Soil texture type	Common constraints
Sandy soil	• low water-holding capacity. Seedlings can wilt because of a rapidly drying soil surface • low nutrient retention. Excessive leaching of nutrients (particularly nitrate, potassium and sulphate) • acidity • extremely low phosphorus fixation • low organic matter content.
Loam/clay loam soil	• hard-setting/surface sealing if texture is fine sandy loam or silty loam • prone to compaction.
Clayey soil	• excessive/prolonged wetness • prone to compaction.

Note: If your soil profile has an abrupt increase in clay content in the subsoil (duplex soils) then the common constraints are:

- excessive/prolonged wetness in the surface soil due to the impermeable clay subsoil
- hard-setting/surface sealing if surface soil texture is fine sandy loam or silty loam
- low plant-available water-holding capacity if surface soil texture is sandy
- low nutrient retention if surface soil texture is sandy.

2. Soil pH

The pH is a measure of a soil's acidity or alkalinity on a scale from 0–14, with 7 being neutral. Soils with a pH greater than 7 are alkaline, while those with a pH less than 7 are acidic. Measuring pH determines the concentration of hydrogen ions (H^+) in the soil solution.

Soil pH is a standard measurement that is generally reported in standard soil nutrient analyses from reputable laboratories. Laboratories determine soil pH using either water or calcium chloride as the solution with soil, which may give different pH readings. Be sure you know which method has been used for your pH test. The result will be indicated as either pH^{water} or pH^{CaCl2}

You can do your own soil pH measurement in the field using a portable pH meter.

Choosing the right equipment

If you plan to do your own soil pH measurement, it is wise to invest in a good quality pH meter. Remember to calibrate your meter before each use by testing with supplied buffer standards of pH 4.0 and pH 7.0.

Each pH meter may have slightly different calibration methods, so check the manufacturer's instructions carefully.

If you intend to do a lot of pH samples it may be worth investing in a pH meter that has been specifically designed to work with soils, as soil solutions can be abrasive to some components in pH meters.

Collecting your soil sample

To collect a representative soil sample for pH measurement:

- Take a handful of soil to a depth of 10 cm from several sites of the same soil type across a paddock in a random 'Z' pattern. In a clean plastic bucket, thoroughly mix the samples together.
- Take your sample for testing from this mixed batch.
- Prepare a mixed sample for each different soil type.

Testing your soil sample for pH

<table>
<tr><th>What you need</th><th>Steps to follow</th></tr>
<tr><td>

- digital balance to weigh soil (accurate to 0.1 gram)
- screw top jars
- deionised (distilled) water
- pH meter
- soil collected from across the paddock mixed together.


</td><td>

- Before starting, calibrate the pH meter according to the manufacturer's instructions.
- Weigh a screw top jar and record the weight.
- Weigh 30 g of soil into the jar.
- Add 150 mL by volume or 150 g by weight of distilled or deionised water to the jar and screw on the lid. Shake the jar vigorously for 1 minute.
- Allow the water to settle for 30 seconds. Take a reading from the upper half of the suspension with the pH meter and write the results in a recording sheet.
- Rinse the pH meter with distilled water between measurements. When you have completed your final measurements, store the meter as directed by the manufacturer.

If you do not have a balance to weigh soil, then use just enough water to make a saturated paste of the soil sample. Carefully insert the pH meter into the paste and take a pH reading. This pH value will be lower (by up to 0.5 of a pH unit) than pH determined by the method described above, but can be used as a guide to the soil's pH.

Note: Soil paste is abrasive and may damage the bulb of the pH meter.
</td></tr>
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Soil pH has significant effects on the availability of many nutrients. Low or high pH makes some nutrients unavailable and causes others to be released from soil particles in toxic quantities. Typical constraints associated with soil pH are shown in Table 4.

Table 4. Constraints and implications associated with soil pH

Diagnostic range (soil pH_{water})	Constraint	Implications
Less than 5.5	Acidity	• Soil pH values markedly less than 4 – will be found in peat and acid sulfate soils – may occur in extremely weathered mineral soils of low fertility – may occur in sandy textured soils subjected to highly acidifying agricultural practices, such as high application rates of ammonium-based nitrogen fertilisers, removal of large amounts of harvested product or mineralisation of nitrate from decomposing leguminous plant residues. • Aluminium or manganese toxicity is probable. • Can have deficiencies of molybdenum (because of decreased availability at low pH) and calcium, magnesium, and potassium (due to leaching losses). • May be reduced activity of some soil microbes (especially nitrifiers).
8.5 to 9.0	Alkalinity	• Zinc, iron and manganese become less available as the pH increases, whereas molybdenum becomes more available.
Greater than 9.0	Sodicity	• In this pH range, soils are strongly alkaline and dominated by sodium and magnesium carbonates. • Copper, zinc, iron, manganese, potassium and phosphorus can be deficient. • Boron can be toxic. • The soil is likely to have very poor structure and be low in available nutrients.

3. Dispersion and slaking characteristics

Dispersion is the release of clay particles into water, causing the water to become cloudy. Slaking is the spontaneous disintegration ('slumping') of soil aggregates when placed in water.

Dispersion indicates that the soil is probably sodic (sodium-rich), whereas slaking indicates that forces holding aggregates together are weak—both are signs that the soil will be susceptible to compaction and surface sealing.

Emerson dispersion test

The Emerson dispersion test is commonly used to measure the slaking and dispersion characteristics of a soil.

Note: This test is not appropriate for sandy soils as they rarely form aggregates.

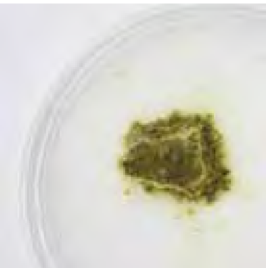
What you need	Steps to follow
• flat dish • deionised (distilled) water or the water being used to irrigate the soil • two or three pea-sized aggregates of the soil being tested • timer.	• Take two or three pea-sized aggregates and place in a dish with deionised (distilled) water or the water used to irrigate the soil. • After 5 minutes observe their appearance. • If the aggregates stay together then the soil has good aggregate stability. • If the aggregates fall apart, but the water remains clear, the aggregates have slaked. • If the aggregates fall apart and the water is cloudy, the soil is dispersive.
Dispersed soil  Slightly dispersed  Moderately dispersed  Highly dispersed	Slaked soil  Stable soil aggregate  Slaked aggregate

Table 5. Soil constraints associated with slaking and/or dispersion characteristics

Characteristic	Constraints	
Slaking	• excessive/prolonged wetness • hard-setting/surface sealing	• compaction • low organic matter content.
Dispersion	• excessive/prolonged wetness • hard-setting/surface sealing • sodicity.	• compaction • low organic matter content

4. Soil colour

Soil colour will be influenced by the minerals in the soil, the weathering of the soil, the aeration of the soil and the amount of organic matter in the soil. For example, red indicates high iron levels; darker soils tend to have more organic matter.

Some soils will have a change in the colour down the soil profile. If the colour change is abrupt the soil is known as a 'duplex soil'. A marked change in colour is often also associated with a marked change in another soil property (e.g. texture or pH).

We have grouped the major soil colours as:

- black to grey
- brown
- red
- yellow
- white (or bleached).

See Table 6 below. We have also included some comments on mottled and waterlogged colourations, along with common constraints that can be inferred from soil colour.

Table 6. Major soil colours, soil types and common constraints associated with soil colour

Soil colour	Characteristics	Constraints
Black	Soils high in organic matter. Examples: • vertosols* (cracking clays) • peat or organic soils.	• excessive/prolonged wetness • compaction • salinity • sodicity • alkalinity.
White, pale or bleached surface soil	Sandy soils. Example: podosol*.	• low water-holding capacity. • low nutrient retention. • acidity • extremely low phosphorus fixation • low organic matter content.
Red	Well-drained soils with high content of iron oxides. Example: ferrosol*.	• compaction • low water-holding capacity • low nutrient retention • acidity • high phosphorus fixation.
Yellow or Yellow-brown	Imperfectly drained to moderately well-drained soils with high content of iron oxides. Example: tenosol*.	• excessive/prolonged wetness • compaction • low water-holding capacity • low nutrient retention • acidity.
Brown	Moderate soil organic matter levels and some iron oxides. Example: dermosol*.	• no specific constraints.
Gleyed, grey or blue-grey	Nearly permanent waterlogging; anaerobic (reduced) conditions. Example: hydrosol*.	• excessive/prolonged wetness.
Mottles	Intermittent waterlogging; intermittent anaerobic (reduced) conditions.	• excessive/prolonged wetness.

* *The Australian soil classification* (Isbell 1996)

Soil orders—classifications and soil constraints

The system for classifying soils in Australia is known as the Australian soil classification. This information is available from soil maps, the CSIRO Australian soil classification website (www.clw.csiro.au/aclep/asc_re_on_line/soilhome.htm) or the Australian Soil Resources Information System website (www.asris.csiro.au/index_ie.html).

Soil classification information is mainly used by soil scientists who distinguish different soils to produce soil maps. They often assign local names to specific regional soil types.

The main soil orders used in vegetable production are shown in Table 7, along with their main attributes and horizon development.

Soils belonging to the same soil order have similar constraints that vegetable growers should be aware of. The soil constraints for the different soil orders are given in Table 8.

Table 7. Soil orders of *The Australian soil classification* (Isbell 1996) used for vegetable production in Australia

Soil order	Vertosol	Calcarosol	Ferrosol	Sodosol	Dermosol	Chromosol	Kandosol	Tenosol	Podosol
Typical colour	Black-grey	Grey	Red	Grey	Brown	Red	Brown	Yellow	White
Horizons	No texture change in horizons	No texture change in horizons	No texture change in horizons	Strong change in texture between horizons	No texture change in horizons	Strong texture change in horizons; B horizon pH >5.5	No texture change in horizons	No texture change in horizons	Strong colour change in horizons
Diagnostic features	Clay soils; strong cracking when dry; slick sides when wet; >35% clay	White calcium carbonate in soil; pH >8.5	Clay rich soils with high iron giving red colour	Change in texture with depth; highly dispersive	No textural contrast; well structured B horizon	Strong textural contrast; not dispersive; pH >5.5 in B horizon	No textural contrast; weakly structured B horizon	Weakly developed and typically very sandy	B horizon dominated by organic matter, iron or aluminium; highly sandy and acidic

Source: <http://www.clw.csiro.au/aclep/asc_re_on_line/soilhome.htm

Table 8. Common constraints of the soil orders of *The Australian soil classification*[A] (Isbell 1996) and the corresponding great soil group[B] in the superseded classification of Stace et al. (1968)

Soil order[A]	Great soil group[B]	Common constraints
Vertosol	Black earth, black cracking clay, grey clay	• excessive/prolonged wetness • compaction • salinity • sodicity • alkalinity.
Calcarosol	Solonised brown soil, grey-brown and red calcareous soils	• low water-holding capacity • sodicity • alkalinity.
Sodosol	Solodised solenetz, solodic soils	• excessive/prolonged wetness • compaction • hard-setting/surface sealing • salinity • sodicity • alkalinity.
Chromosol	Red brown earth, non-calcic brown soil, red podzolic, lateritic podzolic, red and brown duplex soils	• excessive/prolonged wetness • compaction • hard-setting/surface sealing.
Ferrosol	Krasnozem, euchrozem	• compaction • low water-holding capacity • low nutrient retention • acidity • high phosphorus fixation.
Kandosol	Red and yellow earths	• hard-setting/surface sealing • low water-holding capacity • low nutrient retention • acidity.
Kurosol	Red podzolic, grey-brown podzolic, soloth	• excessive/prolonged wetness • compaction • acidity.
Podosol	Podzol	• excessive/prolonged wetness • low water-holding capacity • low nutrient retention • acidity • extremely low phosphorus retention.
Dermosol	Red podzolic	• hard-setting/surface sealing • acidity.
Tenosol	Earthy sand	• low water-holding capacity • low nutrient retention • extremely low phosphorus retention.
Hydrosol	Grey podzolic	• excessive/prolonged wetness • compaction • acidity.
Organosol	Peat	• excessive/prolonged wetness • acidity.

Part 3: Managing soil constraints

Sustainable agricultural systems are based on managing soils according to their capabilities and constraints.

The productive capacity of a soil is determined by soil properties; some (such as texture) are inherent and cannot be changed easily, while others (such as pH) can be manipulated by management.

Once you know your soils and their inherent constraints, you can then make an informed decision on how to maximise productivity, sustainability and soil health.

Management options are provided for the following.

Physical constraints

- waterlogging and excessive/prolonged wetness
- low water-holding capacity
- hard-setting/surface sealing
- compaction.

Chemical constraints

- low nutrient retention
- acidity
- salinity
- sodicity
- alkalinity
- high phosphorus fixation
- extremely low phosphorus retention
- low organic matter content.

Biological constraints

- soil-borne diseases
- soil insect pests.

Physical constraints

Waterlogging and excessive/prolonged wetness

Excessive or prolonged soil wetness indicates limited water movement through the soil profile. This can be a result of compaction or sealing at the soil surface, subsoil compaction or a clay subsoil horizon.

A soil that previously drained well but now has a waterlogging problem may have a compacted 'hard pan' as a result of tillage and/or machinery traffic.

Waterlogging causes anaerobic (oxygen-depleted) soil conditions, which lead to denitrification (loss of nitrogen to the atmosphere as the gas nitrous oxide—a contributor to global warming), death of plant roots and favourable conditions for root pathogens.

Indicators

Things to look for that may indicate the constraint:

- low-lying position in the landscape
- clayey texture
- mottles or bleaches in the soil profile
- pale-coloured or bleached subsoil.

Measurement methods

Measurements that may indicate the constraint:

- high bulk density
- high soil resistance (see 'Drop penetrometer to measure soil resistance' on p. 33).

Management

Practices that combat hard pans and water infiltration problems will help improve internal soil drainage and reduce the risk of excessive or prolonged soil wetness. These include:

- deep ripping to break the hard pans
- changing to minimum tillage practices
- mounding of crop beds
- rotating with crops that are deep-rooted, such as forage sorghum and lucerne
- avoiding driving heavy vehicles and machinery over wet ground
- adding organic material—needs to be continued for many years. This is only a remedy in loam and clay soils where aggregation can be improved (see 'Case study 1' on p. 12).

Increasing the efficiency with which surface water is removed from paddocks will also help. This can be achieved using ground works such as:

- laser levelling
- stabilised surface drains
- subsurface drainage.

Case study 1: Dealing with waterlogging


Mario is still smiling despite the wet weather

Over the past eight years, Mario Muscat has been working hard to improve soil health and soil structure at his Windsor farm in New South Wales. He has been using organic fertilisers to increase his inputs of soil carbon and reducing his tillage with the aim of finding a better way to farm.

The result has been a steady improvement in his soil structure. This was apparent when his farm experienced wet weather in December 2007. Mario's sweet corn crop did not suffer as much as a neighbouring sweet corn crop. This could be attributed largely to good soil structure, which allowed water to move through the soil profile and allowed air back into the soil.

Testing of Mario's soil showed a lower soil bulk density, which meant there were more pore spaces in the soil, and increased aggregate stability, which meant that soil pores were not being clogged with disintegrating soil particles. Mario's soil also had a higher soil nitrate reading compared to the farm next door, suggesting he may not have lost as much nitrogen during the wet weather.

Through good soil management Mario was able to offset the impacts of prolonged wet weather and maintain yield. By reducing tillage and using organic fertilisers, Mario can continue to improve the porosity of his soil. Mario knows that his efforts at maintaining a healthy soil will pay off next time he gets wet weather.

Indicator	Mario's farm	Nearby
Soil	Clay loam	Clay loam
Bulk density (g/cm^3)	1.31	1.42
Aggregate stability (%)	11	3
Organic carbon (%) (Walkley–Black method)	1.3	1.6
Labile carbon (mg/kg)	613	580
Nitrate-nitrogen (mg/kg)	12.5	3.5
Soil structure from drop test three days after heavy rain (see Soil drop test on p. 35)		

Low water-holding capacity

Low water-holding capacity indicates a sandy textured soil with low organic matter content or a clay loam soil with a high content of iron oxides (e.g. a ferrosol soil). Soils with low water-holding capacity are drought-prone and require frequent irrigation to maintain crop growth.

Indicators

Things to look for that may indicate the constraint:

- light-coloured soil with a sandy texture
- red clay loam soil (ferrosol)
- crop wilts only a short time after rain or irrigation
- high water infiltration rate.

Measurement methods

Measurements that may indicate the constraint:

- low soil organic carbon (SOC) level (see 'Soil organic carbon (SOC) and labile carbon' on p. 24).

Management

Increasing soil organic matter content will improve the water-holding capacity of the soil (see 'Low organic matter content' on p. 20). Applying clay minerals or water-retaining compounds is also possible, although the economics of these options need to be carefully assessed.

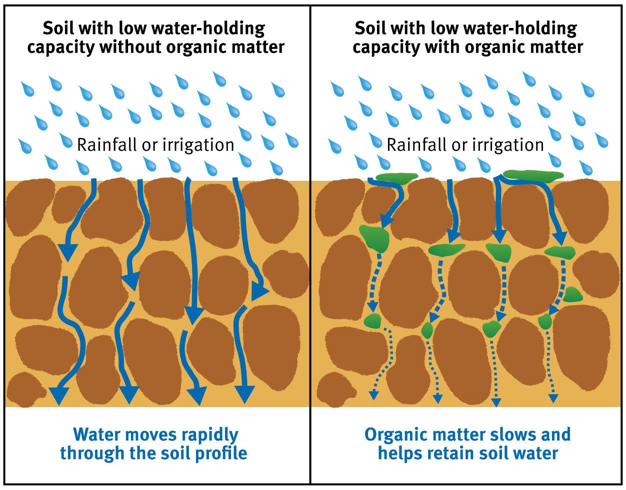


Figure 1. Water moves quickly through soils with low water-holding capacity. With higher organic matter levels, water movement is slowed and soils retain more moisture

Hard-setting/surface sealing

A hard-setting soil or a soil that has a surface seal is often the result of dispersed clay particles and indicates poor soil structure and/or possible sodicity problems (see 'Sodicity' on p. 18).

Another cause of surface sealing is raindrop impact on weak soil aggregates, causing them to disintegrate and allowing small particles to seal off soil pores. Too much cultivation, reduced soil carbon levels or a bare soil surface increases the risk of surface sealing problems.

Surface seals (or surface crusts) impede seedling emergence and increase run-off from rainfall or irrigation, thus increasing the potential for erosion. Silty soils and sandy soils with a high proportion of fine sand are prone to hard-setting.

Indicators

Things to look for that may indicate the constraint:

- visible surface crust or clay 'skin'.

Measurement methods

Measurements that may indicate the constraint:

- high penetrometer resistance (see 'Drop penetrometer to measure soil resistance' on p. 33)
- dispersion and/or slaking (see 'Emerson dispersion test' on p. 6).

Management

By increasing soil organic matter content and reducing tillage, soil surface crusting can be minimised. The most important factor is to maintain some surface cover on the soil at all times. This reduces the force with which raindrops hit the soil surface and keeps the soil surface open, allowing water and air to enter the soil profile.

Short-term remedial practices such as tillage are able to physically loosen the soil surface but this is only temporary—the next rainfall or irrigation event will again result in surface crusting. In the long term, reduced tillage, controlled traffic, maintaining soil surface cover and adding organic matter will all help to reduce soil surface crusting.

Practices that reduce the risk of compaction, such as increasing soil organic matter content and reducing tillage, are useful for managing hard-setting soils.

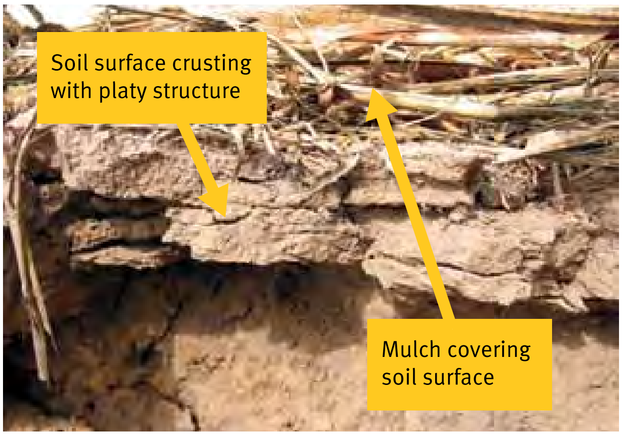


Figure 2. This soil with surface crusting shows a 'platey' structure (the soil compacted into layers), which slows the movement of air and water into the soil. Surface mulch retains moisture and reduces the impact of the surface crusting on plant growth

Compaction

Compaction is caused by applying stress to a soil with a moisture content wetter than its plastic limit (see 'Determining the plastic limit' breakout box below). This stress causes the soil to deform (or smear in the case of tillage) and form a layer with very few pore spaces (i.e. it has a high bulk density). Both aggressive tillage and wheeled traffic apply stress to a soil and can result in compaction if the soil is wet. The soil can become compacted on the soil surface or in the subsoil just below the cultivation depth (a 'plough pan').

Compacted soils are less permeable to air and water. When water is unable to infiltrate into the soil it will run off the soil surface, causing erosion problems. Compacted subsoils restrict water movement through the profile, resulting in a perched watertable and anaerobic conditions.

The volume of soil that plant roots are able to explore is also reduced in compacted soil, making it harder for plants to take up water and nutrients. The pore spaces are smaller in compacted soil and plants have more difficulty extracting water from small pore spaces than large ones. Therefore, compacted soils have lower plant-available water even when they have more total water compared to non-compacted soils. Compacted soils also offer greater resistance to tillage implements, thus requiring greater horsepower and higher fuel consumption for tillage operations.

Determining the plastic limit

How to assess if a soil is wetter or drier than its plastic limit:

- Collect some soil (about the size of a golf ball) from at least 10 cm below the proposed depth of cultivation.
- Roll the soil between the palms of the hands and attempt to form a rod or cylinder about 50 mm long and 4 mm thick.
- If cracks appear in the cylinder, the soil is drier than its plastic limit and is therefore suitable for cultivation.
- If the cylinder stays intact, then the soil is wetter than its plastic limit and cultivation will cause compaction.

This technique is very useful for assessing your soil's readiness for cultivation, thus reducing the risk of compaction.

Indicators

Things to look for that may indicate the constraint:

- silty soil texture or a soil with a high content of fine sand
- a soil layer exhibiting 'platey' structure, especially at the usual depth of tillage
- plants showing sudden water stress.

Measurement methods

Measurements that may indicate the constraint:

- Bulk density will identify generalised soil compaction but not specific compaction layers.
- Abrupt increase in penetrometer resistance with depth identifies compaction layers (see 'Drop penetrometer to measure soil resistance' on p. 33).

Management

Deep ripping is the first option to correct subsoil compaction as it can break the plough layer, but this is only a temporary solution. Once the soil receives rainfall, and with normal irrigation and cropping practices, it will return to a compacted state.

Rotating crops between plants with a fine, fibrous root system and deep tap roots can help to break apart compacted soil, allowing air and water to move down the old root channels into the soil profile.

Tillage of wet soils will lead to subsurface compaction due to compression and smearing caused by implements. Therefore, the soil should only be tilled when it is drier than its plastic limit just below the depth of cultivation (see 'Determining the plastic limit' breakout box). Rotary hoes, mouldboard ploughs and disked implements are more likely to cause compaction than tyned implements because they are more disruptive to the soil.

Tillage and its impact on soil health are discussed in more detail in Part 5.

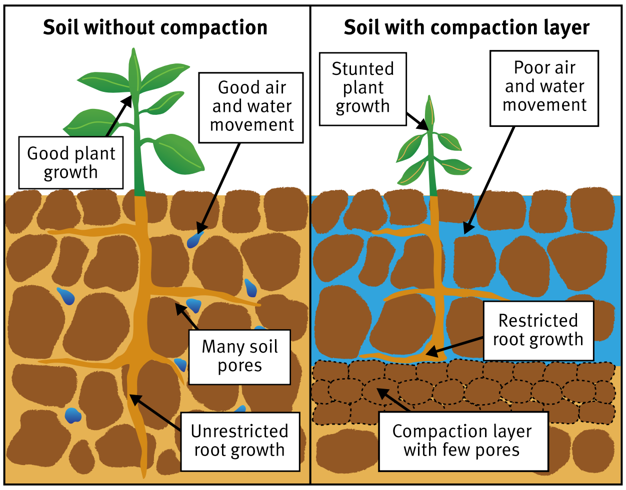


Figure 3. Excessive tillage or traffic when the soil is above its plastic limit can lead to a compaction layer, which limits root development and air and water movement through the soil

Chemical constraints

Low nutrient retention

Soils with a low cation exchange capacity (CEC less than 4 cmol(+)/kg) have a very limited ability to hold nutrient cations such as potassium (K^+), calcium (Ca^{++}) and magnesium (Mg^{++}).

Under such circumstances, these nutrients leach with the movement of water through the soil profile. Sandy soils typically have a low nutrient holding capacity because the soil particles are large, with a limited amount of charged surface area to attract and hold onto nutrient cations.

Indicators

Things to look for that may indicate the constraint:

- light-coloured soil with a sandy texture.

Measurement methods

Measurements that may indicate the constraint:

- low CEC value from standard nutrient soil test. Note that CEC can be expressed as cmol(+)/kg or as meq/100 g. For all practical purposes these units are the same.

Management

Management of soils with low nutrient retention must focus on increasing the CEC of the soil. CEC can be improved by increasing soil organic matter content (see 'Low organic matter content' on p. 20) or adding high-activity clay minerals (if economically feasible).

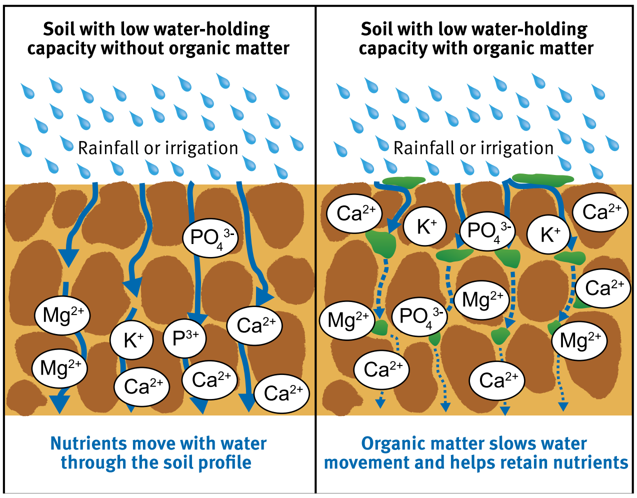


Figure 4. Adding organic matter to the soil can increase its CEC (a measure of the soil's ability to hold onto nutrients) and increase the water-holding capacity of the soil

Case study 2: Dealing with soils that have low nutrient retention

Two brothers started growing loose-leaf lettuce on adjacent blocks near Gingin, north of Perth, in the late 1990s. They adopted two different management approaches. At one site they focused on applying best fertiliser and irrigation management practices, while management at the other site focused on using organic amendments to improve soil performance. The organic amendments included regular use of manures and some use of compost.

As part of a national soil health project, areas of similar soil and crop rotations were selected and the soils tested to compare the impacts of the treatments on soil health.

These tests showed that regular use of organic amendments has increased soil organic carbon (SOC) almost three-fold and as a result, soil water-holding capacity and nutrient holding capacity have similarly increased. The amended soil has a higher phosphorus buffering capacity (a measure of the soil's ability to hold onto phosphorus) and improved nitrate retention. Soil pH has also increased. Best practice fertiliser and irrigation management would be expected to amend the very low pH on this site with lime or dolomite guided by a 'lime requirement' soil test.

As well as an increase in SOC, the use of organic amendments has increased the amount of labile carbon, which is the active form of carbon readily used by microbes in the soil. Adding organic matter has lowered the bulk density of the soil, probably due to improved soil aggregation. This results in increased porosity and aeration, making it easier for roots to explore the soil.

Sandy soils tend to have limited buffering capacity, meaning that they quickly run out of available nutrients. By regularly adding organic matter, the soil was better able to retain nutrients.

Indicator	With organic inputs	Without organic inputs
Texture	Loamy sand	Loamy sand
Organic carbon (%) (Walkley–Black method)	1.95	0.67
Labile carbon (mg/kg)	720	584
CEC (meq/100 g)	10.6	2.7
Nitrate-nitrogen (mg/kg)	31.2	12.0
Phosphorus buffer index	85	35
Soil pH	6.8	4.6
Bulk density (g/cm3)	1.11	1.40

Acidity

Excessive soil acidity means that there are too many hydrogen ions (H^+) in the soil solution. An excess of hydrogen ions reduces soil pH and causes nutrient imbalance.

Excessively acidic soils generally have low available levels of some of the major nutrients, such as phosphorus, potassium, calcium and magnesium. The availability of molybdenum is also reduced. Typically, aluminium and/or manganese may become toxic in excessively acidic soils.

Indicators

Things to look for that may indicate the constraint:

- poor crop performance
- visible symptoms of manganese toxicity or nutrient deficiencies.

Measurement methods

Measurements that may indicate the constraint:

- low field pH reading or pH result from standard nutrient soil test (pH_{water} less than 5.5). See 'Soil pH' on p. 4 for a detailed description of pH.

Management

Excessively acidic soils require amendment with agricultural lime (calcium carbonate) or dolomite (magnesium carbonate) if soil magnesium is considered marginal. A 'lime requirement' soil test is available through ASPAC accredited soil testing laboratories and this test allows lime rate recommendations to be made for a target soil pH_{water} of 5.5 or 6.0.

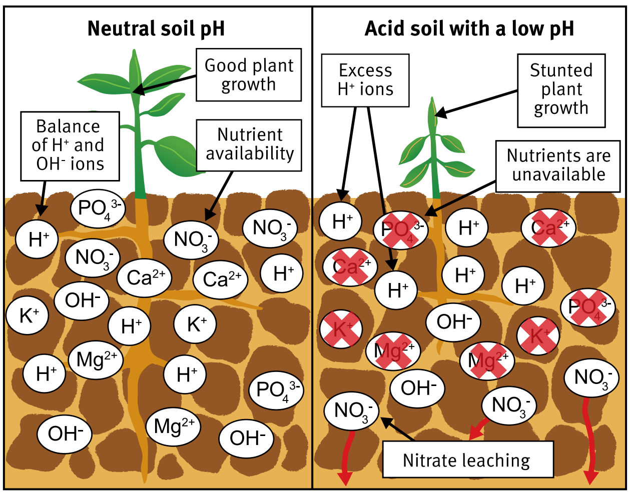


Figure 5. A soil with a neutral pH has a balance of hydrogen ions (H^+) and hydroxyl ions (OH^-). When a soil has an excess of H^+, which may result from nitrate (NO_3^-) leaching, the soil becomes acidic and some nutrients become less available while others may become toxic

Salinity

Excessive levels of soluble salts in the soil, particularly sodium chloride, cause poor plant growth. A build up of salts in the soil interferes with water and nutrient uptake by plants because of osmotic effects (i.e. high concentrations of salts in the soil make the soil water less available for plant uptake). Affected plants wilt or show salt burn symptoms on the older leaves. Crops vary in their tolerance to soil salinity and Table 9 provides soil salinity ratings based on field electrical conductivity (EC) measurements.

Indicators

Things to look for that may indicate the constraint:

- visible salt scalds on the soil surface
- crop wilting or salt burn on the leaves.

Measurement methods

Measurements that may indicate the constraint:

- high field EC reading
- high EC, chloride and sodium levels reported in a standard soil nutrient analysis.

Management

Ideally, the excess salts need to be leached out of the soil. This may take many years, and in severe cases requires some dramatic changes in farm layout to keep the salts below the root zone. Gypsum applied to manage a soil high in sodium will temporarily increase the salinity of the soil solution, which could adversely affect seed germination and plant growth. It may take several years and several applications of gypsum before soil salinity is noticeably lowered (also see 'Sodicity' on p. 18).

Table 9. Salt tolerance of crops grouped according to soil salinity criteria measured as $EC_{1:5}$ for different soil clay contents and field textures (Moody & Cong 2008)

Soil salinity rating	$EC_{1:5}$ based on soil clay content (dS/m)				Plant salt-tolerance grouping
	10–20% clay (loamy sand, sandy loam)	20–40% clay (loam, clay loam)	40–60% clay (clay)	60–80% clay (heavy clay)	
Very low	‹ 0.07	‹ 0.09	‹ 0.12	‹ 0.15	Sensitive crops
Low	0.07–0.15	0.09–0.19	0.12–0.24	0.15–0.3	Moderately sensitive crops
Medium	0.15–0.34	0.19–0.45	0.24–0.56	0.3–0.7	Moderately tolerant corps
High	0.34–0.63	0.45–0.76	0.56–0.96	0.7–1.18	Tolerant crops
Very high	0.63–0.93	0.76–1.21	0.96–1.53	1.18–1.87	Very tolerant crops
Extreme	› 0.93	› 1.21	› 1.53	› 1.87	Generally too saline for crops

$EC_{1:5}$ = electrical conductivity of a one part soil to five parts water solution

‹ = less than

› = greater than

Salt tolerance of vegetable crops can be found at:
www.dpi.nsw.gov.au (click on ‘Agriculture’ › ’Natural resources and climate’ › ’Soil health and fertility’ › ’Salinity’)

Sodicity

Sodicity refers to excessive levels of sodium ions (Na^+) in the soil. Sodicity causes physical problems in soil (such as dispersion) and also restricts rooting depth and plant growth.

Sodium tends to displace exchangeable cations, such as calcium, from the sites where they are attached to soil particles. Exchangeable calcium helps to keep soil particles bound together in aggregates, but in soils with excess sodium, the sodium causes clay particles to break away from soil aggregates and disperse. This has the effect of reducing pore spaces and reducing the movement of water through the soil profile. In sodic topsoils, a hard crust may form when the soil surface dries out.

Indicators

Things to look for that may indicate the constraint:

- surface crusting
- clay ‘skins’ on the soil surface.

Measurement methods

Measurements that may indicate the constraint:

- exchangeable sodium percentage (ESP) greater than 5% (from standard soil test)
- high field pH reading (pH greater than 9)
- dispersion using the Emerson dispersion test (see p. 6)
- low aggregate stability using the aggregate stability test (see p. 32).

Management

Applying gypsum (calcium sulphate) can improve the structure of these soils and make them less prone to waterlogging by replacing the sodium in the soil with calcium.

Apply 5–10 t of gypsum per hectare, preferably before the start of the wet season and well before planting. This will help leach the sodium beyond the root zone before planting. Gypsum will temporarily increase the salinity of the soil solution, which could adversely affect seed germination and plant growth. It may take several years and several applications of gypsum before there is a noticeable improvement in soil structure and drainage.

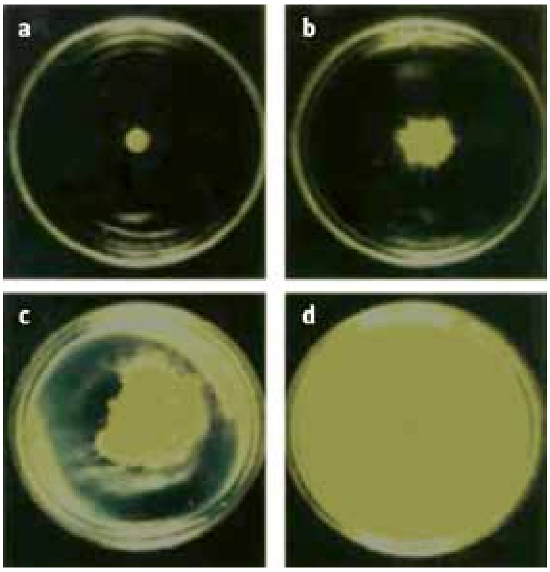


Figure 6. Dispersion due to high sodium content in the soil (a to d over time)

Alkalinity

Excessive soil alkalinity means that there are too many hydroxyl ions (OH^-) in the soil solution. An excess of OH^- increases the soil pH. Excessively high soil pH causes deficiencies for iron, manganese, copper and zinc and, depending on parent material, may also cause boron toxicity.

Indicators

Things to look for that may indicate the constraint:

- poor crop performance
- visible symptoms of trace element deficiencies.

Measurement methods

Measurements that may indicate the constraint:

- high field pH or standard soil analysis test pH reading (pH greater than 8.5).

Management

The availability of several trace elements is reduced in highly alkaline soils. The most effective method for managing this constraint is foliar applications of the nutrients.

High phosphorus fixation

Soils that are high in iron, aluminium or calcium react strongly with soluble phosphorus (P) fertilisers. Calcium forms insoluble compounds that make the phosphorus unavailable to plants, whereas soil iron and aluminium oxides adsorb the added phosphorus and 'fix' it. This fixation reaction is most evident in ferrosol soils because they have a high content of iron oxides.

The phosphorus buffer index (PBI) measures the amount of phosphorus 'bound' to the soil and unavailable to plants. A high PBI (>280) means the soil is able to fix phosphorus, making it unavailable to plants. A low PBI means phosphorus is not strongly bound to the soil and is more available to plants. At extremely low PBI (<15) such as occurs in sandy soils, phosphorus leaching is probable because the soil is unable to retain phosphorus.

Indicators

Things to look for that may indicate the constraint:

- phosphorus deficiency in crops
- red soils.

Measurement methods

Measurements that may indicate the constraint:

- PBI greater than 840. For more information see 'Extractable phosphorus and phosphorus buffer index (PBI)' on p. 27.

Management

Phosphorus fertiliser management for high phosphorus-fixing soils depends on reducing contact between the soil and water-soluble phosphorus sources, such as fertilisers. This can be achieved by placing the fertiliser in concentrated bands below and to the side of crop seeds (band placement), so that emerging roots contact the fertiliser early in crop development. Placing the fertiliser in concentrated bands rather than dispersing the applied phosphorus through the soil reduces the chance of phosphorus fixation by minerals in the soil.

Freshly incorporated organic matter in the soil releases plant-available phosphorus as it decays. Also, phosphorus that is bound to soil particles can be accessed by some soil fungi such as mycorrhizae, passing the phosphorus onto the plant. These fungi form special relationships with the plant root; however, their populations decline if too much phosphorus is added to the soil. Phosphorus uptake by plants can also be reduced by soil compaction, plough pans and waterlogging due to the restricted growth of the root system.

A soil with an extremely low PBI means the soil cannot retain much phosphorus in an adsorbed form, meaning phosphorus may be lost by leaching or water run-off . On these soils, phosphorus application needs to be carefully managed to limit losses. Phosphorus losses potentially cause environmental problems off-site.

Low organic matter content

Soil organic carbon (SOC) is critical for maintaining the chemical, physical and biological health of soil. In general, as SOC increases, so does the amount of organic nitrogen that can be converted into plant-available mineral forms (ammonium and nitrate) by soil microbes.

In sandy soils and soils high in iron oxides, SOC makes an important contribution to CEC (the ability of the soil to hold the nutrient cations of calcium, magnesium and potassium).

Soil microbes require a carbon source for energy. Thus, increasing SOC is generally associated with increasing microbial activity in the soil. This in turn increases the rate that nutrients are released from the soil organic matter. SOC also helps to bind soil particles into aggregates, which helps maintain soil porosity, water infiltration and soil aeration. Stable aggregates also resist compaction caused by tillage and machinery. Soils with optimum SOC may be less prone to soil-borne plant diseases.

Indicators

Things to look for that may indicate the constraint:

- light-coloured soil with a sandy texture.

Measurement tools

Measurements that may indicate the constraint:

- low SOC (measured by standard soil nutrient analysis)
- low level of labile (or active) carbon.

Management

Because SOC has a role in many important soil properties, attempt to maintain or increase SOC whenever possible. This can be achieved by:

- mulching and incorporating green manure crops (e.g. legumes or forage grasses) into the topsoil
- retaining all crop residues in the field where the crop has grown
- not burning crop residues—burning causes the loss of carbon as carbon dioxide gas and exposes the soil surface to erosion
- controlling erosion—erosion is particularly detrimental to SOC because of the off-site movement of topsoil, which is richer in SOC than subsoil
- using minimum or zero-tillage farming systems to reduce the loss of SOC from cultivation
- applying organic materials (e.g. animal manure, composted municipal waste, and locally available industrial organic wastes) obtained from off-site. Always check your customer’s food safety requirements before using these materials.

For detailed descriptions of organic matter, soil carbon and labile carbon see Part 4.

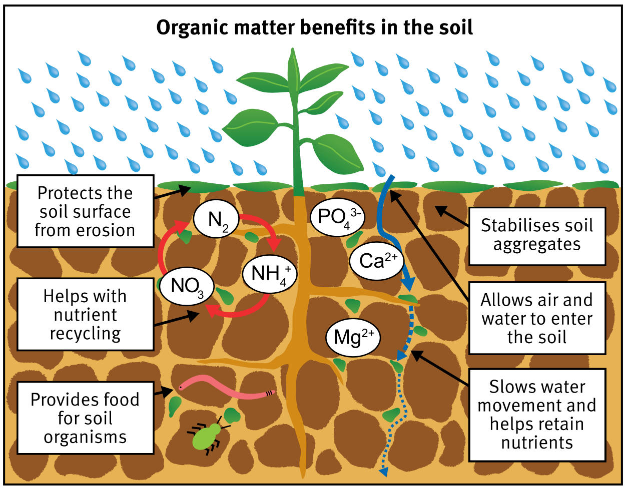


Figure 7. Adding organic matter to the soil benefits the soil in many ways. It protects the soil surface, increases nutrient recycling, provides food for soil organisms, stabilises soil aggregates, increases air and water movement into the soil and helps retain water and nutrients in the root zone

Case study 3: Dealing with soils low in organic carbon

Maintaining adequate soil carbon levels is a problem for vegetable growers in dry tropical climates. The higher soil temperatures mean that soil microbes tend to be very active, especially in irrigated crops where water is rarely limiting. When soil microbes find carbon in the soil, they consume it and release it as carbon dioxide (CO_2) into the atmosphere. Tillage speeds up this process.

Over the past eight years, Paul LeFeuvre has developed a minimum tillage and mulch system for growing zucchinis on his farm south of Townsville. Forage sorghum is grown on permanent beds over the summer fallow period, slashed regularly and then killed with a herbicide in autumn. This produces a thick mat of mulch that suppresses weeds and protects the soil against rain drop impact and erosion. Zucchinis are planted through the mulch. The permanent beds help minimise interruptions to farm operations through wet weather.

Beds are renovated every 4–5 years when soil is tilled, new subsurface trickle tape is laid and beds are reformed. This lowers bulk density, improves soil porosity and counteracts compaction caused by many feet during the almost daily manual harvesting of zucchinis. This strategic tillage seems to have had little negative impact on organic carbon or aggregate stability as there was little difference between the five-year-old and newly renovated beds.

By converting to a minimum till–mulch system, Paul has achieved SOC levels well above 1%, which is considered very high for this region and soil type. He has established a production system that saves on inputs, provides better management flexibility and improves soil health. This has helped Paul overcome the constraints associated with low organic carbon in the soil.

Indicators	Five-year-old beds	Newly renovated beds
Texture	Clay loam	Clay loam
Bulk density (g/cm^3)	1.23	1.18
Aggregate stability (%)	55	46
Organic carbon (%) (Walkley–Black method)	1.4	1.4
Labile carbon (mg/kg)	691	692
CEC (meq/100 g)	17	24
Colwell-P (mg/kg)	257	247

Biological constraints

Soil-borne diseases

Soil-borne diseases are caused by pathogenic soil microbes such as bacteria, fungi and plant-parasitic nematodes, and can be a severe constraint in some vegetable production systems.

Most soil microbes are saprophytic (i.e. grow only on dead organic matter) and help decompose organic material and recycle nutrients. The free-living nematodes in the soil feed on fungi, bacteria and other nematodes, helping to release nutrients and making them available to plants.

Physical and chemical soil constraints such as waterlogging, poor soil structure, compaction and acidity can all interfere with root growth, stunting the plant and reducing the uptake of water and nutrients. These soil constraints cause plant stress and favour conditions that lead to soil-borne diseases.

Some soil-borne diseases such as the plant-parasitic root-knot nematode (*Meloidogyne* spp.) are associated with certain soil types. For example, the root-knot nematode causes greater yield losses in sandy soils than in heavier textured soils.

Bacterial infections can cause quick decline of plants because of their ability to reproduce rapidly. Bacterial pathogens cause the plant to wilt and lead to the formation of ooze, often with a bad odour.

Soil fungi that cause disease produce symptoms such as stunting, yellowing of leaves, wilting and plant death. The incidence of fungal diseases may be increased by leaving crop residue on the soil, not using crop rotations, and poor soil conditions.

Plant-parasitic nematodes reduce plant growth by feeding on plant roots. This reduces the plant's ability to take up water and nutrients and may produce nutrient deficiency symptoms, stunting and yellowing of the leaves. Plant roots affected by nematodes may appear stunted, or have dead areas or galls (depending on which nematode is causing the problem).

Management

Crop rotation and good farm hygiene practices are fundamental for limiting plant disease problems. Improving soil conditions and overcoming other soil constraints will reduce plant stress and increase a plant's resilience and ability to withstand soil-borne diseases.

Incorporating organic matter into the soil and reducing nitrogen inputs can help to suppress plant-pathogenic nematodes by increasing soil organisms that parasitise and prey on these nematodes. Other management strategies are to use resistant varieties and healthy seedling transplants or seed of high vigour.

Figure 8. Severe infestation of root-knot nematode on carrots

Figure 9. Female root-knot nematode (stained pink) feeding within a tomato root

Soil insect pests

Insects affecting vegetable crops may use the soil as a temporary residence to complete their life cycle or they may live permanently in the soil. Since insects and other arthropods are mobile, they can cause damage to above ground and below ground parts of plants, sometimes very quickly (e.g. cutworm damage to newly planted seedlings).

Either the developing larvae of the insect or the adult can cause damage, and sometimes both life stages are damaging (e.g. false wireworm and crickets). Root feeding by insects can also create entry sites for soil-borne diseases, thus making plants more susceptible to root and stem rots.

Management

Reducing soil constraints can help maintain a healthy root system, allowing the plant to tolerate damage caused by soil insects. It may also help to increase the number of beneficial organisms, such as fungi and nematodes, which can parasitise insects. Conversely, high levels of freshly incorporated organic matter can provide the right soil conditions for some insect pests.

An integrated approach based on regular monitoring of pests can reduce reliance on pesticides for insect control, thus reducing the detrimental effect of pesticides on soil biological diversity. Some practices can help reduce insect problems; for example, cultivating at particular times to expose soil insect larvae and pupae to bird predators, and allowing sufficient time for organic matter (from weedy or grassy paddocks) to decompose.

Part 4: Measuring soil health

You can't manage what you can't measure. While soil changes due to management practices can take months or even years to become apparent, they can be monitored and measured to track changes in soil health.

Crop performance will flag that there may be a soil health problem and will always be the ultimate measure of soil health. However, the following measurements will help to identify specific soil issues that may need to be addressed.

A standard commercial laboratory soil analysis includes information that can highlight changes in soil health and indicate problems with soil constraints or their management.

The following key measurements are explained in detail:

- soil organic carbon (SOC)
- nitrate-nitrogen
- extractable phosphorus
- phosphorus buffer index (PBI)
- cation exchange capacity (CEC)
- sodium saturation.

Other measurements can provide a lot of information about physical aspects of soil health. They require some additional equipment and skill, but descriptions are given on how to undertake these tests. They include:

- bulk density (see p. 30)
- aggregate stability (see p. 32)
- drop penetrometer to measure soil resistance (see p. 33)
- Emerson dispersion test (see p. 6).

Table 10 lists indicators useful for measuring changes in soil health. It includes brief comments on what each indicator measures and for which soil types it is suitable. Indicators are grouped according to their commercial availability; some indicators are readily available as part of standard soil laboratory analyses, while others will be in addition to the standard analysis. These additional indicators can be measured on-farm.

Table 10. Indicators for measuring soil health

Indicator	Why include?	Clay	Loam	Sand
Indicators available as part of a standard soil analysis test				
Organic carbon	Central to all soil properties including nutrient supply/retention, water-holding capacity/ infiltration, structure, biological activity. A measure of soil organic matter	✓	✓	✓
Nitrate-nitrogen	Immediate nitrogen supply; readily leached	✓	✓	✓
Extractable phosphorus—Colwell method	Related to available phosphorus when interpreted with PBI	✓	✓	✓
PBI	Measures ability of a soil to fix added phosphorus	✓	✓	✓
CEC	Nutrient cation (Ca^{2+}, Mg^{2+}, K^{+}) storage	✓	✓	✓
Sodium saturation	Sodicity, soil structure	✓	✓	✗
Indicators requiring additional measurements				
Bulk density	Related to texture, compaction, water infiltration and soil aeration/porosity	✓	✓	✓
Aggregate stability	Related to structure, erodibility	✓	✓	✗
Penetrometer	Measure of hard pans, soil structure	✓	✓	✗
Emerson dispersion test	Related to sodicity, dispersion, slaking, soil aeration, responsiveness to gypsum	✓	✓	✗
Soil drop test	Visual assessment of soil structure	✓	✓	✓

Table 11 lists some indicators that are currently under development in research laboratories and are not yet available through commercial laboratories. They are being used in research trials and experiments to determine their usefulness. This includes a biological test that requires further validation to set sound thresholds. Descriptions of each test are located towards the end of this chapter.

Several other measurements may also be useful from a soil health perspective. High soil chloride levels are indicative of water quality or soil salinity problems. Low levels of extractable micronutrients such as iron, zinc, copper and boron are associated with deficiencies, whereas high levels of extractable manganese or aluminium indicate toxicity problems.

Table 11. Future indicators still under development

Indicator	Of interest because?	Clay	Loam	Sand
Labile (active) carbon	SOC that is a readily available source of energy for microbes	✓	✓	✓
Nematode diversity	An indicator of soil biological health and disease suppression	✓	✓	✓

Soil organic carbon (SOC) and labile carbon

Organic matter is central to most, if not all, physical, chemical and biological processes in the soil. It drives soil biological processes. However, organic matter is not measured directly; it is estimated from SOC measurements.

In this section, we describe different methods for measuring organic carbon in the soil and also take a closer look at what makes organic matter so crucial to soil health.

What is organic carbon?

Carbon (C) is a constituent of all organic matter. Generally, more organic carbon is present in the layers of the soil close to the soil surface. Carbon is present in decaying plant and animal materials and organic compounds such as carbohydrates, proteins and humates.

The carbon present in the soil is continually recycled. SOC is distributed across several pools that vary in their stages of decomposition. Labile carbon (or active carbon) is the most active pool of organic carbon with rapid turnover and is highly sensitive to disturbance and farm practices. The humus pool is more stable in the soil, is more difficult to decompose by microbes and has nutrient retention and water-holding properties. It also helps to build soil structure. The resistant soil carbon pool is made up of compounds like charcoal, which remain in the soil for thousands of years. These compounds are resistant to further decomposition and do not stimulate microbial activity.

What is organic matter?

The original source of soil organic matter is living plants and animals. When plants and animals die in an undisturbed system, their parts are broken down and decomposed by a wide range of insects and microbes in the soil to form complex compounds essential for good soil health. The dead bodies of past generations of soil insects, bacteria and fungi decompose and further add to the organic matter in the soil.

The end result of all this decomposition is called 'humus'. Humus is the stable part of soil organic matter. It is made up of large, complex, organic molecules of varying sizes and types. These molecules contain mainly carbon, hydrogen and oxygen, but also some nitrogen, sulphur and smaller amounts of other elements. The humus compounds withstand rapid breakdown in undisturbed soils, particularly soils high in clay content. However, they will rapidly decompose under aggressive and regular cultivation because of increased exposure to soil micro-organisms.

Organic matter is the main source of organic carbon in the soil.

Why is organic carbon important?

The amount of organic carbon in a soil influences a range of physical, chemical and biological properties. SOC is generally less than 5% of the total soil volume but is the fraction of soil that has the greatest influence on soil properties.

SOC impacts on nutrient recycling, nutrient-holding capacity, water storage and drainage, the soil's ability to resist erosion, and the activity and diversity of soil-dwelling organisms.

Increasing organic carbon content (i.e. soil organic matter) has a number of beneficial effects on soil properties.

Physical properties:

- Reduces the soil bulk density while increasing soil porosity and aeration.
- Increases the amount of plant-available water stored in the soil and helps reduce evaporative water losses.

- Improves the stability of soil aggregates, making soil less prone to compaction, surface crusting and erosion.

Biological properties:

- Increases quantity, activity and diversity of soil micro-organisms that need carbon as an energy source. Much of the recycling of carbon and nutrients is done by these micro-organisms.

Chemical properties:

- Improves nutrient storage and release.
- Increases CEC.
- Increases soil pH buffering (i.e. it slows soil pH increase or decrease).
- Increases sorption/deactivation of contaminants such as heavy metals.

An increase in organic carbon can lead to immobilisation of some nutrients, particularly nitrogen, as soil micro-organisms compete with crops for these nutrients as they decompose organic matter. This can lead to temporary nutrient deficiencies. However, as the micro-organisms die, nutrients are released back into the plant-available nutrient pool.

How is organic carbon measured?

Organic carbon is measured by several different methods. Soil fertility test results from accredited Australian commercial laboratories often report SOC measurements using the Walkley–Black method, a measurement of organic carbon using concentrated sulphuric acid.

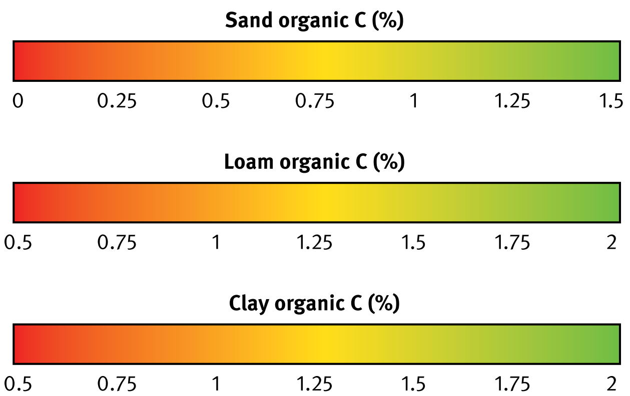


Figure 10. Guide to the interpretation of Walkley–Black organic carbon values for sand, loam and clay soils

Total organic carbon (TOC) determined by combustion methods is the more common method used internationally, and is an absolute measure of TOC. Because of a close association with soil clay minerals, not all of the TOC is measured by the sulphuric acid digestion used in the Walkley–Black method, and an average recovery of 74% of TOC is often assumed for this method. However, the recovery varies with soil type and can be 100% in soils of low clay content.

Labile carbon

This measuring tool is still under development. It measures the easily oxidisable carbon fraction of the soil using a potassium permanganate method, and is described in more detail in the SCAMP manual by Moody and Cong (2008).

This measurement may be useful for monitoring biological activity in the soil as it is correlated with microbial biomass. This carbon fraction has also been shown to be more closely related to aggregate stability and CEC in acidic soils than TOC, and more sensitive to changes in management practices than TOC. With some simple equipment, labile carbon can be measured in the field and may therefore be a very useful measurement for monitoring the effects of management changes on soil health.

Labile carbon is made up of simple carbohydrates (sugars and starches) but also some proteins, celluloses, lipids, waxes, tannins and even small amounts of lignins, which are important building blocks of humus. New organic matter contributes most of the labile carbon. Thresholds for labile carbon are still being developed as the test becomes more widely used.

There are several different measures of SOC. Always compare the same type of measure when interpreting SOC results.

Figure 11 shows the relationship between some of the different methods of measuring SOC.

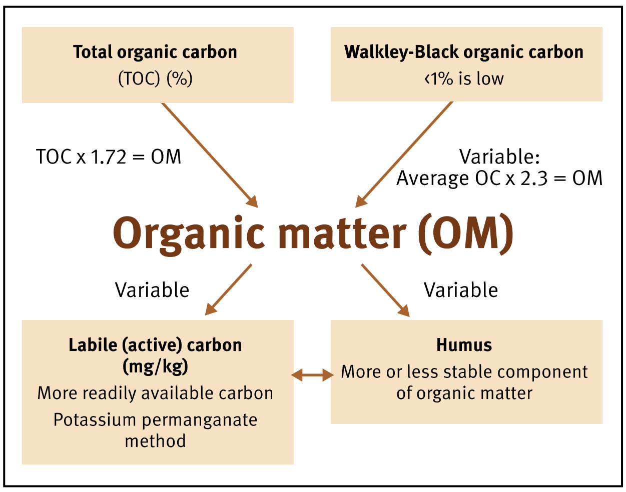


Figure 11. Relationship between different soil carbon pools measured in the soil and soil organic matter

What practices change organic carbon?

Since organic carbon impacts on most soil properties, it is important to maintain or increase SOC levels wherever possible. Ways to maintain organic carbon include:

- incorporating mulches or green manures in to the soil
- retaining crop residues
- not burning crop residues
- controlling erosion
- reducing tillage
- applying composted organic materials (animal manure, municipal waste) obtained off-site
- reducing excessive levels of mineral nitrogen in the soil, which speeds up decomposition.

The amount of organic carbon in the soil is strongly affected by microbial activity. Microbial activity is required to decompose organic matter and recycle nutrients, and the rate of this activity is determined by the quality of the added organic material, availability of water and oxygen, and temperature.

Leguminous residues have a low carbon/nitrogen ratio and a high content of readily decomposed compounds such as proteins and carbohydrates. They are decomposed very quickly, releasing large amounts of mineral nitrogen. On the other hand, grass and grain crop residues have a higher carbon/nitrogen ratio and tend to be composed of more resistant compounds such as lignins. They are not decomposed as quickly as leguminous residues and may cause a temporary nitrogen immobilisation in the soil because the microbes decomposing the residue require nitrogen and compete with the crop for the limited nitrogen available.

Nitrate-nitrogen

What is nitrate?

Soil nitrate (NO_3^-) is a form of inorganic nitrogen that is available to plants. Ammonium (NH_4^+) is another form of inorganic nitrogen readily available to plants but it is generally present in the soil in lower amounts than nitrate because, under aerobic conditions, specialised bacteria rapidly convert ammonium-nitrogen to nitrate-nitrogen (the nitrification process). Nitrogen also exists as organic forms in soil organic matter and soil microbes, and is unavailable to plants until it is converted to the inorganic forms through decomposition (the mineralisation process) and nitrification.

Plants need significant quantities of nitrogen for rapid growth. Most soil tests report NO_3^- levels in the soil since this is the most common form of nitrogen available to the plant. However, NO_3^- levels in soil are dynamic and can change rapidly during crop growth as plant roots and soil organisms absorb it as a nutrient source, or it is leached by rainfall or irrigation, or it is lost to the atmosphere as a nitrogenous gas through the process of denitrification.

Why is nitrate important?

Nitrogen is required by plants to make chlorophyll, amino acids and proteins. Chlorophyll is the green substance in plants that is able to capture the energy from sunlight and convert carbon dioxide (CO_2) from the atmosphere into carbon within the plant through photosynthesis. Amino acids within the plant are the building blocks of proteins and are developed by combining nitrogen with sugar or starch compounds. Without sufficient nitrogen, plants show signs of nitrogen deficiency by becoming light green or yellow due to a lack of chlorophyll.

Nitrogen is often low in natural systems. If excessive nitrogen is applied to the soil it will stimulate the activity of microbes that reproduce rapidly (e.g. bacteria). The fast-growing micro-organisms dominate the soil food web causing an imbalance of soil organisms. This may reduce the number and diversity of beneficial soil organisms, such as those that suppress soil pests and diseases.

If nitrogen leaves the farm through leaching or run-off and gets into waterways, organisms that are able to quickly use the nitrogen (e.g. algae) will proliferate. This can cause eutrophication (lack of oxygen in the water) with disastrous consequences for water quality and aquatic organisms.

Nitrogen management becomes a balance of supplying enough nitrogen to maximise plant yield, but not so much that excess moves off-site. Remember that nitrate-nitrogen is soluble and moves wherever soil water moves. Under waterlogged or excessively wet soil conditions, nitrate can also be lost as nitrous oxide (a greenhouse gas) through the process of denitrification.

Why measure nitrogen for soil health?

Nitrate-nitrogen measures the amount of available nitrogen in the soil that can be absorbed immediately by plants. It is measured as milligrams of nitrogen per kilogram of soil (mg/kg), which is the same as parts per million (ppm).

The amount of nitrate required in the soil for specific crops varies from crop to crop but in general the levels should not fall below 10 mg/kg and should not exceed 50 mg/kg. However, nitrate moves with soil water and so levels can fluctuate widely depending on soil water movement.

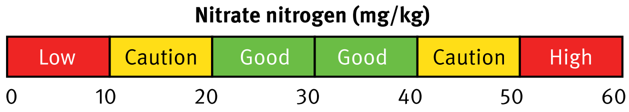


Figure 12. Guide to the interpretation of nitrate-nitrogen values for soils

There are other methods of measuring nitrogen, which include total soil nitrogen (organic plus inorganic forms), ammonium (NH_4^+) levels in the soil, and potentially mineralisable nitrogen. Potentially mineralisable nitrogen is a laboratory method that measures the amount of nitrogen that is mineralised from organic forms to mineral nitrogen in a standard period of time (generally seven days).

Always know which of these measures of nitrogen you are getting with your soil test and how this relates to crop production.

What practices change nitrate?

The form of nitrogen added to the soil will influence its availability to plants. Organic nitrogen is available over time as it is mineralised, but it may not be released quickly enough to meet crop demand. On the other hand, inorganic nitrogen is immediately available to plants, but there is a risk of losses from leaching, run-off or denitrification. Growing legumes, returning crop residues to the soil and adding fertilisers are practices that influence the level of nitrates in the soil.

Extractable phosphorus and phosphorus buffer index (PBI)

What is phosphorus?

Phosphorus (P) is relatively immobile in the soil and can be tightly bound to soil particles, thus limiting its availability to plants. The amount of phosphorus in the soil solution is usually quite low. Soil phosphorus is present in three forms:

- plant-available
- slow-release or fixed
- unavailable.

Why is phosphorus important?

Plants require a steady supply of phosphorus, particularly during early plant growth to ensure proper cell division. A small amount of starter fertiliser at planting may help the root system establish rapidly and better use available soil phosphorus.

How is extractable phosphorus measured?

Phosphorus is strongly attached to soil particles and requires the use of special solutions to extract it from the soil. There are many different methods and each method has different extraction efficiency. Therefore, it is important to know which method is used as the results are not readily converted from one test to another.

Some of the commonly used methods for extracting phosphorus from soil are:

- Colwell
- Bray
- Olsen
- lactate
- Bureau of Sugar Experiment Stations (acid)
- total phosphorus (Kjeldahl).

It is important to know which method is being used to test your soil for extractable phosphorus, particularly if you change laboratories, as this may change the results that appear in the soil analysis report.

The Colwell method is the method most commonly used in Australia, and critical levels for near-maximum yield have been determined for many crops. However, the availability of phosphorus measured by the Colwell test (i.e. the Colwell-P value) is dependent on the phosphorus buffering capacity (or phosphorus fixing ability) of the soil.

What does the PBI measure?

PBI measures the phosphorus buffering capacity (or phosphorus fixing ability) of a soil. This is the ability of the soil to limit changes in phosphorus concentration of the soil solution when phosphorus is added to or removed from the soil. Australian agricultural soils have a wide range of phosphorus buffering capacities and this soil property has important implications for phosphorus fertiliser management from both productivity and environmental viewpoints.

Soils with different textures and/or iron and aluminium oxide contents have different abilities to fix phosphorus. In general, sandy soils have an extremely low PBI and clay soils have a high PBI. (For more information on high phosphorus fixing soils see ‘High phosphorus fixation’ on p. 19). If PBI is less than 15, soluble phosphorus will leach through the soil. If PBI is greater than 840, soluble phosphorus is fixed into unavailable forms and requires special management practices such as banding to minimise contact between the soil and phosphorus fertiliser.

Interpreting Colwell-P and PBI results

The measurement of PBI is important for interpreting some soil phosphorus tests in order to adjust critical soil phosphorus concentrations.

The amount of Colwell-P needed for optimum crop growth will vary depending on the crop, and will increase as soil PBI increases (see Figure 13). For example, the critical Colwell-P for 95% maximum tuber yield of potatoes is 14 mg/kg in the extremely low PBI sands of Western Australia but 118 mg/kg in the high PBI Ferrosols of north Queensland. As a generalisation for soils supporting vegetable production, Colwell-P should not exceed 50 mg/kg in soils with PBI less than 35 (because of the risk of phosphorus leaching) and not exceed 150 mg/kg in soils of higher PBI (because of the risk of off-site phosphorus movement by erosion).

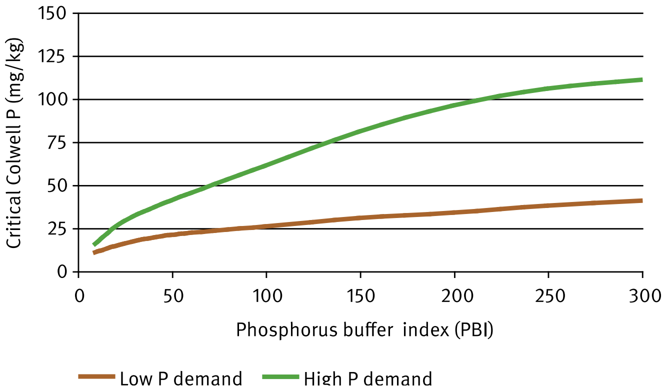


Figure 13. Critical soil phosphorus levels (measured by the Colwell method) for high P demand and low P demand crops for soils of different PBI values (Source: Moody 2007)

What practices change extractable soil phosphorus?

Phosphorus can be managed by matching fertiliser inputs with the phosphorus being exported in crop products, and by reducing soil erosion. Phosphorus behaves differently in the soil compared with nitrogen. Therefore, it should not be assumed that because soil nitrogen is low, soil phosphorus is also low. The two nutrients must be evaluated separately.

If phosphorus fertilisers are spread on the soil surface, or fertigated by surface application (e.g. mini-sprinklers or surface trickle tape), then phosphorus is prone to loss by erosion. When phosphorus fertilisers are applied they should be incorporated into the soil or subsurface banded or fertigated to minimise the risk of loss.

Controlling soil erosion is the best method for keeping soil phosphorus on farm. Erosion can be reduced by:

- maintaining ground cover, especially in periods when heavy rain is expected
- reducing tillage
- improving soil structure through addition of organic matter
- establishing vegetation buffer zones
- maintaining grassed areas around paddocks
- establishing and maintaining sediment traps.

Cation exchange capacity (CEC)

What is CEC?

CEC refers to the number of negative charges in the soil that are capable of holding onto cations (which are positively charged). CEC is often used as an indicator of the soil's ability to hold nutrients, and is therefore used as a measure of soil fertility.

The major soil cations are calcium (Ca^{++}), potassium (K^{+}), magnesium (Mg^{++}) and sodium (Na^{+}). They are held on the surfaces of negatively charged clay minerals and organic matter (exchangeable) or, in the case of potassium, within the crystalline framework of some clay minerals (non-exchangeable).

The exchangeable forms (and, under some circumstances, non-exchangeable potassium) constitute the soil reservoir of the nutrients calcium, magnesium and potassium. As these nutrients are removed from the soil solution, either by leaching or uptake by plant roots, they are replaced from the exchangeable pool. The relative proportions of exchangeable nutrients change when fertilisers or soil amendments are added.

Some soil surfaces have a greater capacity to hold onto ions than others. For example, on a weight basis, soil organic matter has a much higher exchange capacity than the clay minerals in the soil.

For acidic soils, the appropriate method for determining CEC is referred to as the effective cation exchange capacity (ECEC). ECEC is the sum of the exchangeable cations (Ca^{++}, Mg^{++}, K^{+}, Na^{+}) and the exchangeable acidity (Al^{+++}, H^{+}).

In neutral and alkaline soils, CEC is measured directly.

Calcium is usually the dominant cation in surface soils, followed by magnesium. However, this is not always the case and excessive amounts of magnesium or sodium can interfere with the uptake of calcium and potassium by crops.

Why is CEC important?

The CEC of a soil determines the ability of the soil to store and supply essential nutrient cations such as calcium, magnesium and potassium to plants.

CEC is particularly important in areas of high rainfall or irrigated agriculture. It enables the soil to hold onto nutrients that would otherwise be leached below the root zone.

How is CEC measured?

CEC is included in soil tests from most reputable laboratories. Basically, the number of sites in a soil sample that can hold cations is measured.

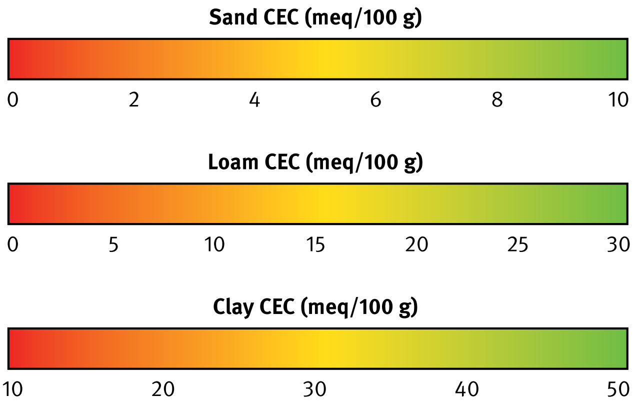


Figure 14. Guide to the interpretation of CEC values for sand, loam and clay soils

What practices change CEC?

CEC is closely linked to the level of organic carbon in the soil, so changes in CEC over time should reflect changes in organic carbon. However, some soils that have very high clay content—such as vertosols (black cracking clays)—will have a naturally high CEC due to the clay minerals.

> For most soils the best method for increasing CEC is to increase the amount of organic carbon in the soil by adding organic matter.

Increasing soil pH also increases the CEC of some acid soils.

Individual cations can be applied to correct any imbalances. For example, calcium can be applied as lime to raise soil pH, or as gypsum to counteract sodicity when there is a lot of exchangeable sodium present. If magnesium is required it is usually applied as a top dressing of dolomite or magnesium oxide. Potassium can be applied in blended fertilisers in conjunction with nitrogen and phosphorus, but can also be added as potassium nitrate, potassium chloride or potassium sulphate. Other cations such as sodium, aluminium, and hydrogen are not essential for plant growth and, if present in excess, cause toxicities.

Splitting the application of fertilisers to soils with low CEC will reduce leaching of added nutrients below the root zone.

Sodium saturation

What is sodium saturation?

Sodium saturation measures the amount of sodium as a percentage of CEC. The units may be written as sodium percentage (Na%) or exchangeable sodium percentage (ESP), but they are the same measure.

Soils with a high proportion of exchangeable sodium (greater than 5% of the CEC) are referred to as sodic soils. (For more information see 'Sodicity' on p. 18).

Sodicity is different from salinity, although these conditions can occur together. Salinity refers to the amount of salts present in the soil and is often measured by electrical conductivity (EC). The greater the salt concentration, the higher the EC.

Why is sodium saturation important?

Sodium saturation is important in determining the physical properties of a soil. Soils with high sodium saturation tend to lose aggregation and disperse. As they lose structure they become less permeable to water and surface crusts may develop. This results in poor conditions for root growth. Soils tend to disperse when Na% is greater than 5% of the CEC.

How is sodium saturation measured?

Sodium saturation is included in soil tests from most reputable laboratories. It is calculated as the amount of sodium as a proportion of the CEC.

The Emerson dispersion test (see p. 6) is linked with sodium saturation in that it identifies a dispersing soil.

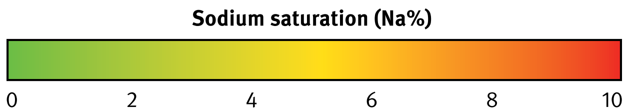


Figure 15. Guide to the interpretation of sodium saturation values for soils

What practices change sodium saturation?

Sodic soils with a high Na% can be corrected by applying calcium, normally as gypsum. Calcium ions displace the sodium ions attached to soil particles. In acid-sodic soils, lime can be applied, which will increase the soil pH as well as increase the calcium content of the soil. However, in soils with a neutral or high soil pH, gypsum is preferred because it will increase the calcium content of the soil without further increasing soil pH.

Once the Na% is corrected it is important to maintain a low sodium content by reducing sodium inputs from saline irrigation water. It is also important to maintain calcium levels in the soil so that they are not displaced by additional sodium. Poor quality irrigation water, high in sodium, can cause sodium to displace calcium from the clay particles, resulting in sodicity.

Increasing SOC can help reduce some of the dispersive effects caused by high Na%. Practices such as reduced tillage and mulching of green manure crops can increase SOC without increasing sodium. In sodic soils with a high Na%, be careful that added organic amendments or biological products are not high in sodium. If the sodium content of the amendment is not known, then it is a good idea to get the amendment or product tested before applying to soils with high sodium content.

Practices such as using mouldboard ploughs on soils with sodic subsoils should be avoided because of the risk of bringing sodic subsoil material to the soil surface.

Bulk density

Bulk density is a measure of soil porosity and is the best indicator of compaction layers (e.g. plough pans) in the soil and soil structure.

What is bulk density?

Bulk density is the ratio of the weight of oven-dried soil (its mass) to its volume. Bulk density is influenced by the structure of the soil, how tightly packed the soil particles are and the size and number of air spaces within the soil. Soil texture will affect bulk density readings. Clay soils tend to have lower bulk densities than sandy soils because they have a greater number of pore spaces due to their smaller aggregate size.

Why is bulk density important?

Bulk density relates to the number of pores of various sizes in the soil. This is important for water and air movement through the soil and good root growth. If there are not enough soil pores then roots need to work harder to take up water and nutrients as well as to push through the soil. During compaction or aggregate breakdown larger pores are lost. Root development is severely retarded in these soils, leading to restricted root systems and an overall decrease in plant health and crop yield.

What does bulk density measure?

$$\text{Bulk density (BD)} = \frac{\text{Mass of oven-dried soil (g)}}{\text{Volume of soil (cm}^3\text{)}}$$

Bulk density is measured in g/cm^3. A higher value means the soil has fewer spaces between the soil particles. High bulk density measurements indicate compaction, poor soil structure and restriction to root growth.

Soil porosity (%) can be calculated from bulk density as 100 x (1– BD/2.65) where 2.65 g/cm^3 is assumed to be the absolute density of soil solids.

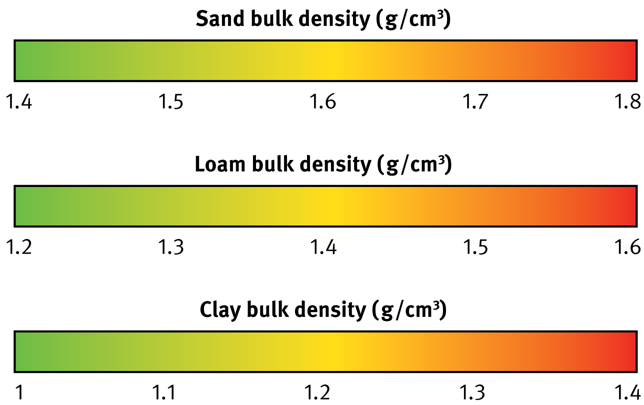


Figure 16. Guide to the interpretation of bulk density values for sand, loam and clay soils

How to measure bulk density

Bulk density is not measured by commercial laboratories. However, with the right equipment and procedure anyone can measure bulk density.

What you need

- 7.5 cm diameter aluminium cylinder (length can vary, but about 10–12 cm works well)
- rubber mallet
- block of wood
- long-bladed shovel or spade
- paint scraper
- sealable plastic bag
- permanent marker.

Steps to follow

- A 7.5 cm (or 3") aluminium cylinder is used to determine the soil bulk density (for example use old aluminium irrigation pipe). Sharpen the edge on one end of the cylinder. This is the end that is driven into the ground.
- Determine the volume of the cylinder—volume = length x 3.14 x (radius)^2.
- Determine the weight of the cylinder. This can be written in permanent marker on the cylinder as this weight is needed later for calculating the amount of dry soil in the cylinder.
- Carefully remove the surface vegetation from the sampling point.
- Use the block of wood and a rubber mallet to drive the cylinder into the soil until its top edge is level with the soil surface.
- Carefully dig up the cylinder. Trim the soil core level to the top and bottom of the cylinder with the scraper and scrape any soil from the outsides.
- If there are big clods of soil that fall out of the cylinder it will give an underestimation of the soil bulk density. It is important to retain all the soil from within the cylinder.
- Very carefully, put the cylinder and the entire soil core into a labelled plastic bag.
- When you return from the field carefully take the cylinder of soil out of the plastic bag. The soil will still contain the same moisture it had in the field. This is referred to as the 'wet soil' – (including any loose soil). Determine the wet weight of the soil and the cylinder together. Record this weight on a recording sheet.
- Place the cylinder with the soil core onto a metal tray with at least 2cm high edges (along with any soil that had dislodged from the cylinder), and then place in an oven to dry. Ideally, the soil should be allowed to dry for three days at 105 °C.
- Once the soil is dry, determine the weight of the cylinder and the soil again. Subtract the weight of the cylinder from this measurement. This gives the dry weight of the soil, with all the water removed from the pore spaces.

$$\text{Bulk density (BD)} = \frac{\text{Mass of oven-dried soil (g)}}{\text{Volume of soil (cm}^3\text{)}}$$

What practices change bulk density?

Tillage can have both a negative and positive effect on bulk density. Tillage itself is a tool to decrease bulk density, reduce compaction and increase soil aeration at least in the short term.

However, working soils that are wetter than their plastic limit will lead to compaction. Working soils when they are too dry or using aggressive tillage will break up natural aggregates and damage soil structure. Any practices that cause a decrease in soil organic matter levels is also likely to impact on soil structure and hence soil porosity and aeration.

Reduced tillage can help preserve organic matter while crop rotations, green manure crops, and compost and other organic soil amendments will help increase organic matter. In permanent bed systems, bed renovation every few years can be a useful tool for decreasing bulk density and improving soil aeration (see 'Tillage'on p. 38).

Aggregate stability

What is aggregate stability?

Aggregate stability is an indicator of soil structure. It refers to how well soil particles hold together when wet or exposed to dispersive or deforming forces such as rainfall or tillage. The soil particles are naturally held together by organic glues to form irregular-shaped aggregates, and it is these aggregates that give soil its structure.

Aggregate stability is largely influenced by organic matter and biological activity in the soil.

Aggregates are formed by several processes:

- Fungal hyphae can entangle fine soil particles.
- Exudates from plant roots and the decomposition of organic matter can act as glues.
- The activity of soil fauna (e.g. earthworms and termites) contributes to stable aggregates.

Why is aggregate stability important?

A soil with good aggregate stability has good soil porosity, which favours water infiltration, good water-holding capacity, good tilth and adequate aeration for plant growth, nutrient recycling and root development. When soils with poor structural stability become wet, the aggregates disintegrate causing surface crusting. Surface crusting leads to increased run-off and an increased risk of erosion.

Figure 17. 20 g of sieved soil is wetted to determine its stability against the dispersal forces of water

What does aggregate stability measure?

Aggregate stability measures the ability of aggregates to withstand the disruptive forces of water and machinery and is expressed as a percentage of aggregated soil remaining after soaking in water.

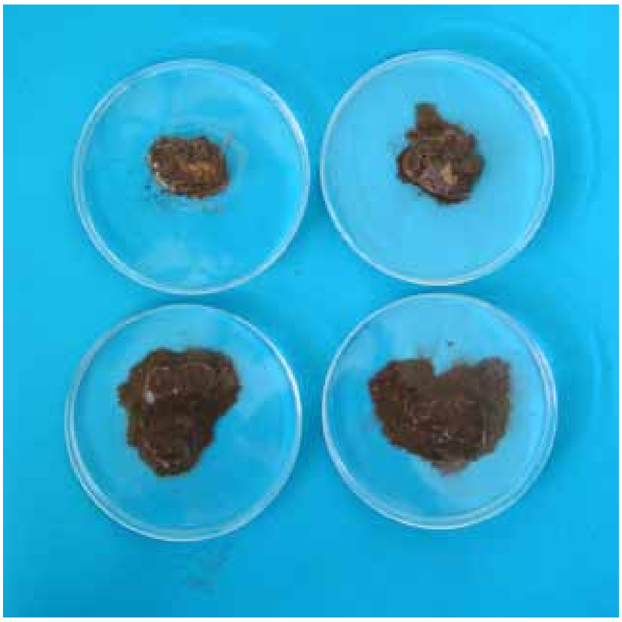


Figure 18. Low organic matter soil aggregates fall apart when wetted (bottom dishes) while those with high organic matter maintain their stability (top dishes)

How to measure aggregate stability

There are several methods for measuring the stability of soil aggregates. A simple method is:

- Pass some dry soil through a 4 mm and then a 2 mm sieve.
- Weigh a small bag made from 0.5 mm mosquito netting (see Figure 17). Record the weight. Take a 20 g sample of soil that is retained on the 2 mm sieve and place this into the bag.
- Gently lower and raise the soil bag in distilled or deionised water at around 30 dips per minute for two minutes.
- Place the bag and the remaining soil on a metal tray, dry in an oven at 40°C overnight and then weigh the bag and soil, including any loose soil on the tray. The weight of soil is total weight minus weight of the bag.
- Aggregate stability is then calculated as the percentage of soil remaining after washing as a proportion of the soil that was originally placed in the bag. The more stable the aggregates, the greater the amount of soil remaining.

Aggregate stability (%) =

$$\frac{\text{Dry weight of soil after washing} - \text{Weight of bag (g)}}{\text{Dry weight of soil before washing} - \text{Weight of bag (g)}}$$

This test is not appropriate for sandy soils. Sandy soils will generally not form aggregates because of the large size of the soil particles. However, aggregate stability is very important in loam and clay soils.

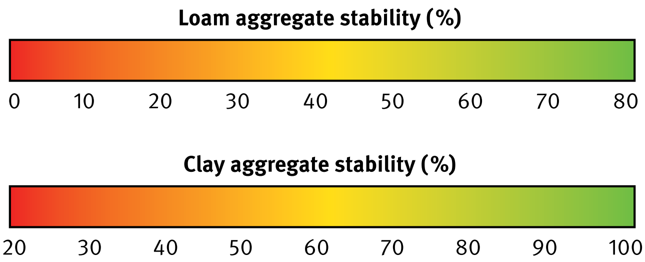


Figure 19. Guide to interpretation of aggregate stability values for loam and clay soils

What practices change aggregate stability?

Management practices such as minimum tillage, increasing soil organic matter and increasing biological activity can improve the soil's ability to resist forces that destroy aggregation.

Drop penetrometer to measure soil resistance

What is a drop penetrometer?

A penetrometer is any device designed to measure soil resistance. That is, the ease with which an object can be pushed or driven into the soil. Soil resistance will vary depending on soil conditions such as texture but particularly soil moisture. It takes less force to push a penetrometer into wet soils than dry soils. Therefore, penetrometer resistance readings are a relative measure of the soil conditions at that point in time.

It is possible to standardise penetrometer readings by either taking the measurements at a certain soil moisture content (e.g. two days after irrigation or rainfall) or by comparing two different practices on the same soil type that has received the same rainfall and irrigation.

Why is soil resistance important?

Resistance of the soil to penetration may be an indication of surface crusting or subsoil compaction. In soils that have a relatively high resistance to penetration, root growth may be severely restricted and drainage may be poor. Also, more power is required to cultivate soils resistant to penetration. This results in greater costs of production.

What does a drop penetrometer measure?

A drop penetrometer measures the soil resistance by dropping a known weight over a specific distance to force the penetrometer into the soil. It provides a consistent measure of resistance, and reduces the variability caused by operator error. Soil resistance is measured in kg/cm^2 and indicates the level of soil compaction.

Resistance measurements can be compared at two different areas in the same paddock, such as in wheel tracks and the row area. Also, the shape of the curve that joins the resistances readings at different soil depths may indicate subsoil compaction (Figure 22). Some increase in soil resistance with depth is expected but a sharp increase or a doubling of the resistance is usually an indicator of subsurface compaction.

Figure 20: Using a drop penetrometer in the field to measure soil resistance

How to measure soil resistance

Penetration resistance is measured by converting the number of drops it takes to push the penetrometer tip (of a given surface area) through 10 cm of soil with a known weight, falling over a known distance. This information is then converted to a resistance reading using the information below:

$$\text{Resistance (kg/cm}^2\text{)} = \frac{M^2 h\, n}{2(M + m)\, S\, Z}$$

Where:

M = weight of hammer (kg)

m = weight of penetrometer (kg)

h = height of hammer drop (m)

n = number of hammer drops

S = area of penetrometer tip (cm^2)

Z = depth of penetration (cm)

Figure 21. Blueprint for constructing a drop penetrometer

Materials & specifications:

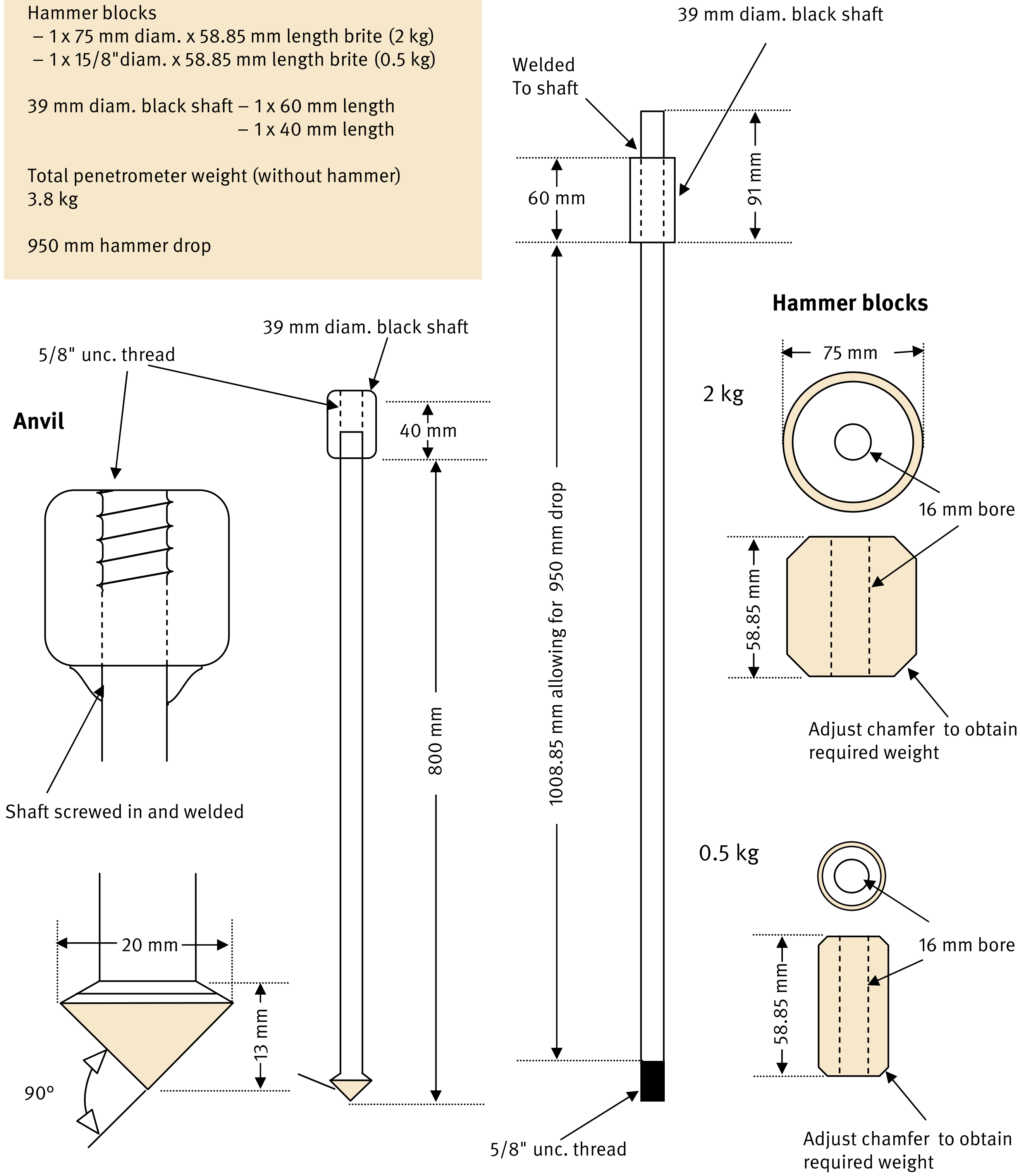
15.88 mm diam. 4140 steel shaft
– 1 x 825 mm
– 1 x 1145 mm

Hammer blocks
– 1 x 75 mm diam. x 58.85 mm length brite (2 kg)
– 1 x 15/8"diam. x 58.85 mm length brite (0.5 kg)

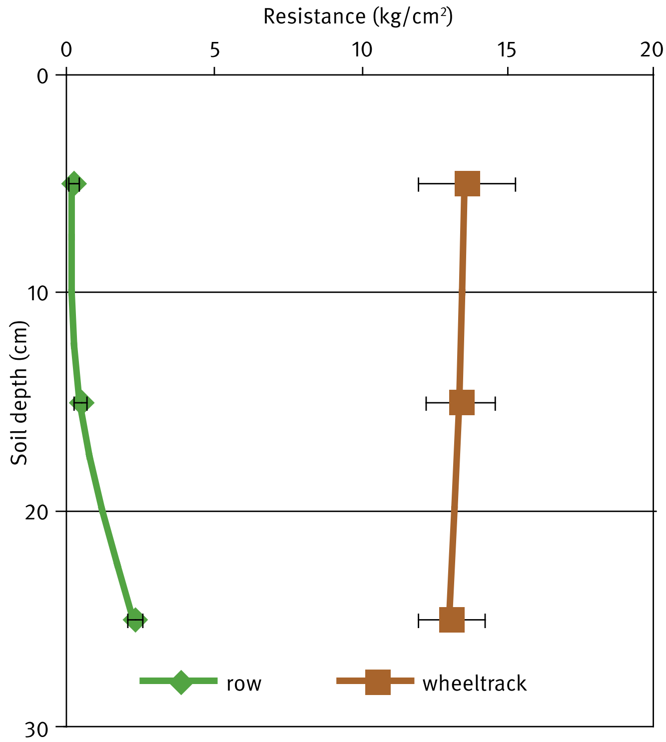
39 mm diam. black shaft – 1 x 60 mm length
– 1 x 40 mm length

Total penetrometer weight (without hammer)
3.8 kg

950 mm hammer drop



A drop penetrator can be easily constructed by an engineering firm using the 'blueprint' in Figure 21. Alternatively they can be purchased from some Australian distributors as a 'dynamic cone penetrometer'.



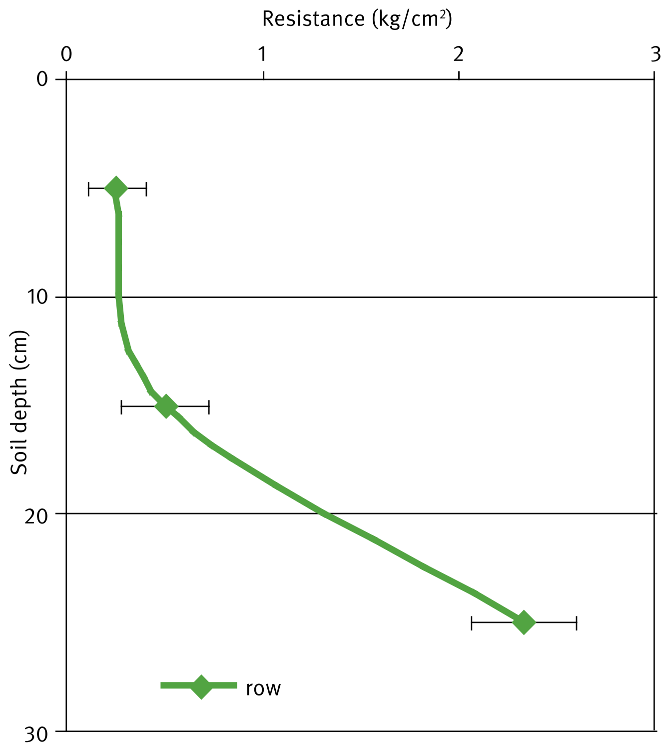


Figure 22. Soil resistance is greater in wheel tracks than row area down a soil profile to 30 cm (top graph). The shape of the resistance curve is important, a sharp increase in the resistance reading can show a subsurface compaction layer (bottom graph)

What practices change soil resistance?

Reduced machinery trafficking, deep tillage, minimum tillage, permanent beds and increased mulching are some practices that can minimise the risk of compaction. Alternating between crops with fibrous and tap roots can help break compacted soils by allowing the roots to push past soil particles and develop deep channels where old root systems once were.

Soil drop test

What is the drop test?

A soil drop test is a simple visual assessment of the soil structure. The test assesses how the soil breaks apart when dropped from a standard height. The soil can be rated as having poor, moderate or good soil structure.

Why is the drop test important?

Good soil structure regulates soil air and water. Soils with poor structure may have large, dense clods that make root penetration difficult. Soils that have no structure and produce a powder—often from over-tillage—may produce surface crusts.

What does a drop test measure?

The assessment of soil structure is based on the size and abundance of soil aggregates and clods when the soil is dropped. A soil with good soil structure will have an even distribution of friable fine aggregates. Soil with poor soil structure will have an abundance of large clods or they may shatter into a fine powder with no aggregate formation. A description of a rating system is given by Shepard (2000).

How to do the drop test

What you need	Steps to follow
• spade • plastic bucket • plastic sheet • camera. 	• The test is best done within a week after either rainfall or irrigation. • Remove a cube of topsoil with a spade. Aim for a cube with width and depth equal to the width of the spade blade. • Drop the soil cube once from the spade from about 1 m high (hip height) onto a firm base within a large plastic container. • Then pick up and drop individual larger clods a maximum of two more times. If clods break into smaller units, they do not need to be dropped again. • Place all the soil onto a plastic sheet to sort the soil in ascending order of aggregate size to obtain a size distribution (see photo). Using different size sieves can help to categorise the soil aggregates. • This distribution of aggregate size can be assessed, compared and photographed for future reference. Well-structured soil should break apart into fine aggregates, with few coarse clods and minimal fine powder.

What practices change a soil drop test?

To maintain soil structure it is important to minimise disturbance (e.g. tillage, trafficking), retain crop residues on the soil surface and maintain ground cover.

Measures of soil biology

Nematode diversity

This measurement is still under development in research laboratories and is not yet available through commercial laboratories. The measure has good potential to be an indicator of the activity of living organisms in the soil. The measure requires further validation to set sound thresholds.

What is a nematode?

Nematodes are unsegmented, worm-like organisms found in a wide range of environments and organisms, including seawater, freshwater, animals, plants and soils. Nematodes are the most abundant multi-cellular organism on the earth, and plant-feeding (parasitic) nematodes can cause a lot of damage to some agricultural crops.

In soils, nematodes inhabit water-filled pore spaces and can be classified into the following feeding groups:

- fungal feeders
- bacterial feeders
- plant-feeders
- predators and omnivores.

The mouth structures are used to differentiate species into their feeding groups. Other morphological details may be used to distinguish nematodes that feed on the same type of food substrates.

Figure 23. Soil nematodes can be useful indicators of soil health because of the many different types that can be found in the soil

What is nematode diversity?

Diversity refers to the proportion of different types of nematodes present in the soil. Nematode diversity is an indicator of the overall biological diversity in the soil.

Why is nematode diversity important?

Different types of soil-dwelling nematodes have a wide range of feeding levels. Some nematodes are parasitic (they feed on plant roots), others are beneficial (they feed on micro-organisms in the soil) and others are predatory (they feed on other nematodes).

The life strategies of different types of nematodes differ. Some are quick to reproduce and dominate the soil when conditions are favourable (e.g. following the addition of nutrients or organic matter). Others are slow to reproduce and take a long time to reach peak numbers after soil disturbance such as tillage or the application of soil pesticides. Therefore, by knowing the life strategy and what the nematodes feed on we are able to infer the impact of management practices on soil biology.

Not all nematode species feed on plant roots. Some feed on bacteria, some on fungi and some on other nematode species. Soils with high nematode diversity tend to have greater resilience to disturbance and have been linked to the natural suppression of plant diseases.

Nematodes occupy a central part of the soil food web. Their numbers do not fluctuate as quickly as fungi or bacteria, but they are still relatively quick to respond to changes in the soil environment. They are numerous in the soil, with around 50 nematodes present in each gram of topsoil.

Nematodes are relatively easy to extract from the soil but require a microscope and specialist training to be able to identify the different types.

What does nematode diversity measure?

By measuring the diversity of nematode types in soil we have information on how complex the soil food web is. Soils with a low nematode diversity have a simple food web, which has little biological buffering. Therefore, if plant parasitic organisms become established they are able to dominate the soil food web, because there will be very few predators or parasites to check their growth.

A greater nematode diversity in the soil also indicates greater nutrient recycling of complex substrates such as organic matter. Because organic matter is made up of a range of different compounds, it is broken down by a range of different organisms—including different nematode types.

How is nematode diversity measured?

Nematodes are removed from a soil sample using water. The number and evenness of different nematode species removed from the sample is then determined by microscopic examination. Nematode diversity is calculated using the Shannon–Weiner index of diversity.

If a lot of different nematode species are present, in roughly equal proportions, the diversity index will be high. However, if the soil nematode community has a high proportion of an individual species, the soil will have a low diversity index.

What practices change nematode diversity?

Nematode diversity will change with changes in soil conditions. Practices that increase nematode diversity include:

- increasing the diversity of plants growing on the soil surface
- rotation cropping
- avoiding bare fallows
- adding organic matter
- reducing tillage and soil disturbance
- reducing use of soil applied pesticides
- reducing fertiliser application.

Some soils (such as sandy soils) tend to have a lower nematode diversity. More intense soil use usually results in a lower diversity.

Part 5: How to improve soil health

Tillage

Tillage (cultivation) is used to produce a fine seed bed, to control weeds, to incorporate crop residues and to break up compacted soil. However, too much tillage can damage the structure of clay and loam soils. When this happens, large pore spaces are lost—leading to surface sealing; compaction; and poor water, air and nutrient movement into the soil. Tillage may also remove vegetative cover, which allows raindrops to further break down aggregates, and can lead to soil erosion.

Advances in implement design and selective herbicides have meant that less aggressive forms of soil preparation can be used to grow vegetable crops.

A soil with less disturbance will have a greater chance of being healthy and having a functioning ecosystem. Also, thoughtful use of tillage and using the correct implement may help to overcome some of the inherent constraints of the soil.

Some tillage and soil disturbance will always be necessary to produce vegetables. However, by understanding the limitations and benefits of different tillage implements, we can minimise soil disturbance. Some of the implements commonly used on vegetable farms are listed in Table 12, with a description of their benefits and limitations.

Minimum tillage systems have been developed for a number of vegetable crops. The benefits from minimum tillage systems include:

- improved soil structure
- increased nutrient retention
- increased plant-available water capacity
- less soil erosion
- savings in land preparation costs and
- not having to wait for ideal weather conditions to plant crops.

Table 12. General characteristics associated with different tillage implements

Implement	Benefits	Limitations
Rotary implements (hoes, tillers) 	• Thoroughly mixes soil • Surface residue buried • Incorporates weeds and kills old crop • Leaves a fine seedbed	• High soil disturbance, extensive pulverising and shattering of soil aggregates • Destroys natural soil aggregation • High fuel usage
Mouldboard plough 	• Incorporates soil surface residue • Incorporates weeds and kills old crop • Leaves a fine seedbed • Complete inversion of furrow • Very little soil pulverisation	• High soil disturbance completely shatters the soil • Destroys natural soil aggregation • High fuel usage • Compaction at depth if soil is wetter than its plastic limit
Disc implements (ploughs and harrows) 	• Buries a large proportion of surface residue • Effective kill of old crop • Partial inversion of the furrow	• Leaves soil surface rough, requiring secondary tillage • High fuel usage • May not effectively kill all weeds • Can pulverise and shatter soil • Compaction at depth if the soil is wetter than its plastic limit

Table 12. (continued)

Implement	Benefits	Limitations
Tyned implements (chisel ploughs, scarifiers and harrows) 	• Narrow furrows. No subsoil brought to soil surface • No pulverising of the soil and only partially shatters the soil • Very little compaction at depth • Retains soil moisture • Good weed control	• Only moderate surface fineness • Surface trash remains on soil surface • Partial kill of the old crop

Green manures and cover crops

Green manures are crops that are grown to improve the soil. They are not normally harvested or sold, although grain legumes such as soybeans may be harvested for seed but with residues remaining on site. They are usually ploughed back into the soil to add organic matter and to recycle nutrients for the next crop. They are also used as ground covers to protect the soil from erosion during fallow periods.

The return of organic matter from green manure crops benefits soil health by boosting organic carbon levels and stimulating microbial activity.

Legumes are often grown as green manure crops because they have a high nitrogen content that is released for the next crop as the residues decompose.

Growth of forage sorghum as a summer cover crop can produce a lot of biomass and form a thick mulch on the soil surface. (Photo: Rob Pengilley)

Cover crops are often left on the soil surface and not incorporated into the soil. The mulch that forms on the soil surface after growing cover crops not only protects the soil surface from erosion but can also be used to suppress weeds and reduce evaporation of soil moisture. If stubble from green manure crops is left standing, rather than being ploughed back into the soil, it acts as both surface mulch and a slow-release nitrogen source. In the subtropics and tropics, some growers kill the crop with herbicide and leave it to form a surface mulch.

Choosing the right green manure or cover crop is important if the maximum benefits are to be obtained. Ideally, the crop you choose should:

- produce a large amount of biomass
- not carry over pests and diseases
- be easy to kill so it will not compete with the following crop.

It may also be possible to mix a number different species together to increase the benefits from green manures and cover crops. The green manure or cover crop is usually grown when vegetables are not being produced. In areas that produce vegetables all year round, a system where some land is taken out of production to grow the green manure or cover crops in rotation with the vegetable crops may be required. Applied Horticultural Research conducted studies to identify which cover crops are suited to vegetable production in tropical and temperate climates, including both summer or winter growth (Tables 13 and 14).

Green manures and cover crops will benefit soils that are constrained by:

- excessive, prolonged wetness and waterlogging
- low water-holding capacity
- hard-setting and surface sealing
- compaction
- sodicity
- low nutrient retention
- high phosphorus fixation
- low organic matter content.

Table 13. Summer cover crops and their suitability as green manures or cover crops in vegetable production

Cover crop	Establishment	Cover	Killing method	Mulch quality	Comments
Grasses					
Indian blue grass—Hatch	Good	Good	Spray	Good	Can be mowed; very high biomass
Indian blue grass—Keppel	Good	Good	Spray	Good	Expensive seed
Sorghum	Good	Good	Spray	Coarse	Cheap alternative, but coarse mulch
Shirohoe millet	Good	Early seed	Spray and roll	Good	Good winter cover crop
Rye grass	Good	Moderate	Spray and roll		Good winter cover crop
Japanese millet	Good	Early seed	Spray		Seeds too early for thick cover
Legumes					
Clovers	Poor	Poor	Spray	Poor	Poor competition with weeds
Centrosema	Slow	Good	Spray	Good	Excellent cover; hard to kill
Lucerne	Poor	Poor	Spray	No kill	Hard to kill
Verano stylo	Poor	Poor			Poor establishment
Sunn hemp	Good	Moderate	Spray and roll	Poor	Thin stalks, poor seed viability
Villosa mixes	Poor	Poor		Poor	Poor establishment
Biofumigants					
BQ mulch	Good	Good	Spray	Poor	Tissue too watery for good mulch
Rangi rape	Good	Good	Spray	Poor	Tissue too watery for good mulch
Brassica napus	Good	Good	Spray	Poor	Tissue too watery for good mulch
Fumus	Good	Early seed	Spray	Poor	Tissue too watery for good mulch
Mustards	Good	Early seed	Spray	Poor	Tissue too watery for good mulch

Source: Rogers (2001)

Table 14. Winter cover crops and their suitability as green manures or cover crops in vegetable production

Cover crop	Establishment	Cover	Killing method	Mulch quality	Comments
Grasses					
Shirohoe millet	Good	Good	Spray and roll	Good	Good winter cover crop
Rye grass	Good	Good	Spray and roll	Good	Good winter cover crop
Cereals					
Wheat/triticale	Good	Good	Spray and roll	Good	Excellent winter cover crop
Barley	Good	Good	Spray and roll	Good	Good winter cover crop
Oats	Good	Good	Spray and roll	Good	Excellent winter cover crop
Legumes					
Clovers	Good	Moderate	Spray	Poor	Poor competition with weeds
Lucerne	Good	Good	Spray	No kill	Hard to kill
White lupin	Good	Poor			
Biofumigants					
BQ mulch	Good	Good	Spray	Poor	Tissue too watery for good mulch
Rangi rape	Good	Good	Spray	Poor	Tissue too watery for good mulch
Brassica napus	Good	Good	Spray	Poor	Tissue too watery for good mulch
Fumus	Good	Early seed	Spray	Poor	Tissue too watery for good mulch
Mustards	Good	Early seed	Spray	Poor	Tissue too watery for good mulch

Source: Rogers (2001)

Crop rotation

Crop rotation is an important component of soil and pest management. Continual monoculture of the same crop over a long period of time tends to select organisms that survive on that crop. This usually increases organisms that cause plant diseases.

Crop rotation can be simple, such as switching between two crops in alternate years. Some crop rotations can be complex and involve numerous crops over several years. When crops are rotated properly, pest and diseases do not become a problem. However, this may take many years of trial and error to perfect.

Rotating crops can also help manage nutrients and maintain soil structure. Leguminous crops return extra nitrogen to the soil, which benefits crops with a high nitrogen demand (e.g. sweet corn). Rotating crops with different types of root systems, such as tap roots and fibrous roots, can enhance soil structure. Plants with tap roots are able to penetrate deep into the soil, making channels to help with air and water movement. Plants with fine and fibrous roots are able to get in between tightly packed soil particles, helping break them apart or, conversely, holding loosely packed soil particles together.

Growers often obtain yield increases when rotating crops from different genera, compared with a continual monoculture. This is referred to as the rotation effect. The rotation effect is a combination of suppressing pests and diseases, increasing nutrient recycling and improving soil structure.

Some general principles for crop rotation developed at Cornell University (Gugino et al. 2007) include:

- Follow a legume forage crop with a high-nitrogen demanding crop such as sweet corn.
- Grow the same annual crop for only one year and don't rotate with closely related crop species to decrease likelihood of insects, nematodes and diseases becoming a problem.
- Plan the crop sequences that promote healthier crops. Some crops seem to do well following a particular crop; others may have an unfavourable effect.
- Use crop sequences that aid in controlling weeds. Rotating broad leaf and grass crops and using selective herbicides can help keep weed populations low.
- On sloping land or where erosion is a high risk, use perennial crops to protect the soil surface and provide continual cover.
- Use deep-rooted crops (e.g. lucerne) that are able to scavenge the subsoil for water and nutrients. The resulting root channels help with the movement of air and water into the soil profile.
- Include crops that leave a large amount of crop residue to help boost organic matter levels in the soil.
- When growing a wide mix of crops, try grouping them into blocks according to family, type of crop, planting time or crops requiring similar cultural practices.

By developing a good crop rotation system you can address the following soil constraints:

- hard-setting and surface sealing
- compaction
- low nutrient retention
- low organic matter content
- soil-borne diseases
- soil insect pests.

Amendments

Amendments are applied to the soil to overcome a deficiency or to correct an imbalance. They usually need to be applied in large quantities to have an effect on the soil. The cost of application needs to be weighed against the long-term benefits to make sure that amendments are economically viable.

Amendments can either be inorganic or organic. Inorganic amendments are typically applied to correct a nutrient deficiency or imbalance. Examples of inorganic amendments are lime (to correct low soil pH) or gypsum (to correct a calcium imbalance).

Organic amendments can be any material that has been derived from plant or animal origin and include:

- composts
- crop residues
- manures
- municipal and industrial wastes.

Adding organic amendments needs to be viewed as a long term practice. A single application may create only a temporary change in soil properties. Often, repeated applications are required to stabilise soil properties and have a lasting effect.

Amendments may also be used with other soil management practices to speed soil improvement. The application of non-composted organic amendments risks the introduction of pests, disease and weeds, damage to groundwater and risks for human health, so they need to be considered carefully.

Composts

Compost is stable, aerobically decomposed organic matter that is the result of a managed decomposition process. It is a biologically active material mostly of organic origin, which has a succession of aerobic micro-organisms break down and transform organic material, thereby generating heat. The microbial activity decomposes simple organic compounds like sugars and proteins into a range of increasingly complex organic substances. The remaining material is transformed into more complex organic substances referred to as humus. Humus is typically dark brown with an earthy appearance that can vary in smell and texture.

Compost can be made from a number of different sources. However, the level of compost maturity will have the greatest effects on its properties. The availability of nutrients (particularly nitrogen) may decrease temporarily following initial applications of composts. However, with repeated use soil nitrogen levels build up and mineralisation can significantly reduce future nitrogen requirements.

The humus material in composts can increase soil organic carbon (SOC), improve water and nutrient retention, increase soil aggregation and change soil microbial composition (supressing pests and diseases). This is mainly through increased biological activity in the soil, promotion of beneficial organisms that compete with pests and diseases in the soil, production of antibiotics, and increased plant resistance to attack. The effectiveness of composts to suppress pests and pathogens depends on the level of maturity of the compost, what microbes colonise the compost, and the crop being grown.

Composts may also be able to supply some of the nutrients required by plants during vegetable production but be cautious if you intend to use it as a fertiliser as nutrients from compost may take longer to be released than for conventional fertilisers.

In general, rates of 20–30 m^3/ha of compost are initially required to improve soil health of degraded soils. However, follow-up applications are often required. The amount of compost required to maintain soil properties may need to be determined using trials or with a specialist.

The properties of compost will vary between different manufacturers. Not all composts are suited for use in vegetable production. The manufacturer of the compost should be able to provide information about their product, but in general it is recommended (Paulin 2005) that the compost have:

- carbon to nitrogen ratio less than 20
- total nitrogen greater than 1%
- available nitrogen greater than 100 mg/kg
- nitrate to ammonium ratio greater than 0.14.

Crop residues

Crop residues are an important source of organic matter. Some vegetable crops are able to return more residues to the soil than others. As the organic matter from the crop residue decomposes it can help to increase soil carbon and improve the structure of the soil. Crop residues left on the soil surface help protect the soil against erosion, prevent evaporation of soil moisture and protect the soil from surface crusting.

However, crop residues may also carry inoculum that can cause diseases in following crops. Therefore, if crop residues are being retained it is important to rotate crops to different plant families that are non-hosts to any possible pests and diseases that may be carried over. Also, the crop residue should be fully decomposed before replanting the same crop to minimise the potential of losses due to pests and diseases. Incorporating the crop residue into the soil can help speed its decomposition.

Manures

Because of nitrogen leaching, fly breeding, health risks from potential food contamination and odours, raw forms of manure should not be applied to vegetable crops. Furthermore, their low carbon to nitrogen ratio means that any contribution to improving SOC is small compared to their application rate.

Manures can be applied as a solid or liquid. They should be composted before application. The composted forms of manure are more stable than uncomposted manure and do not present the same risks. There is a risk that overuse of manures or manures applied at the wrong time can damage crops and pose an environmental threat to waterways. It is important to know the nutrient content of the manure because this is extremely variable and depends on the age of the manure and the conditions under which it has been stored.

Some customers do not allow use of un-composted manures in some high-risk vegetable crops because of food safety concerns.

Municipal and industrial wastes

Municipal wastes tend to come from households. Using un-composted green waste in vegetable production is highly questionable, as it may have variable composition and quality and can be a source of pests, diseases and weeds. However, it is an excellent source for compost manufacture. Composted municipal green waste has shown to benefit soils in vegetable production.

Similarly, *industrial wastes* are also not often suitable for use in vegetable production without composting or processing first. Even then take care with amendments that have been manufactured from industrial wastes to ensure that they do not contain heavy metals that can contaminate soil, or micro-organisms that may result in food safety violations in harvested product. Check with customers about their food safety requirements before you consider using industrial wastes.

Biosolids such as stabilised sewage should not be used in vegetable production because of food safety risks.

Adding organic soil amendments can address the following soil constraints:

- excessive, prolonged wetness and waterlogging
- low water-holding capacity
- hard-setting and surface sealing
- compaction
- low nutrient retention
- sodicity
- alkalinity
- high phosphorus fixation
- low organic matter content.

Controlled traffic

The movement of machinery and equipment across the soil surface during normal vegetable growing operations (such as land preparation, crop management and harvesting) can cause compaction.

When equipment is allowed to move unrestricted over a paddock it compresses large areas of the soil. The risk of developing serious compaction problems can increase as a result of working and travelling on fields when they are too wet.

Soil does not necessarily compact more with each pass of machinery. This is because the heaviest load (or heaviest machine) causes most of the compaction and the soil does not necessarily compact further when other lighter machines pass.

Controlled traffic aims to restrict the movement of equipment within a field to defined pathways or roadways. Therefore, the wheel track areas receive all of the compaction, and the crops are planted outside the compacted areas. This means the crop does not grow in compacted soil, and there is no hard compacted soil needing cultivation that would add to the wear and tear on machinery and require more fuel.

Adopting controlled traffic lanes typically requires field equipment to have consistent axle widths. It also requires considerable discipline from machinery operators. While guided GPS systems have been developed to assist with controlled traffic operation, it is also possible to use field-based markers to guide machinery operators. The field markers may not be as accurate as GPS, but they can help restrict traffic to the same track in the paddock each time and greatly reduce compaction over the field.

Controlled traffic management is able to reduce the following soil constraints:

- excessive, prolonged wetness and waterlogging
- hard-setting and surface sealing
- compaction
- low organic matter content.

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