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.

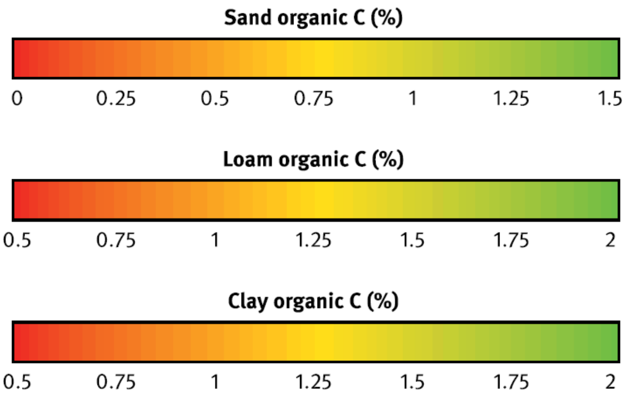

Figure 10. Guide to the interpretation of Walkley–Black organic carbon values for sand, loam and clay soils

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.

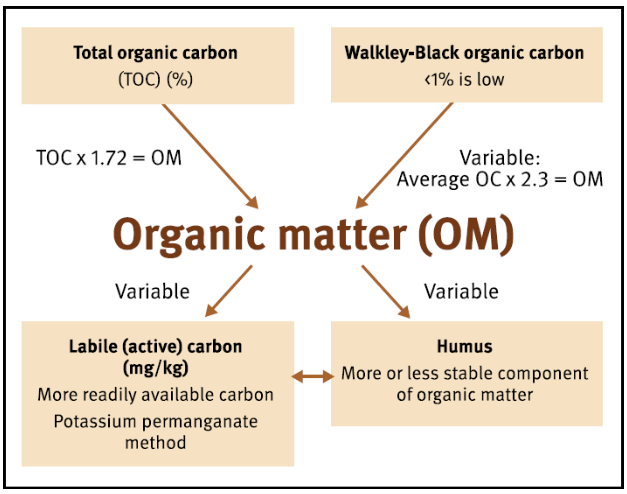

Figure 11. Relationship between different soil carbon pools measured in the soil and soil organic matter

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.

Nitrate nitrogen (mg/kg)

Low	Caution	Good	Good	Caution	High
0–10	10–20	20–30	30–40	40–50	50–60

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).

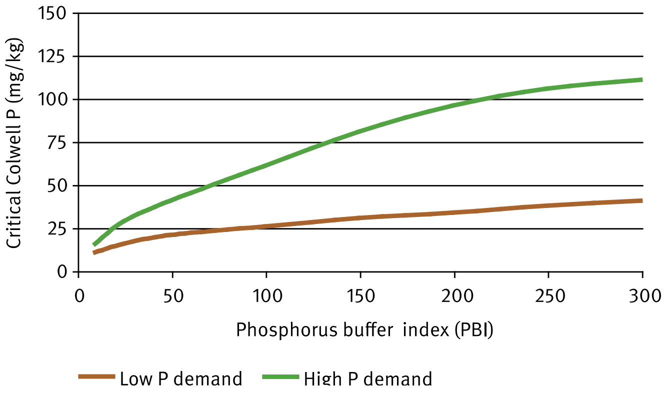

Figure 13. Critical soil phosphorus levels (measured by the Colwell method) for high P demand and low P demand crops for soils of different PBI values (Source: Moody 2007)

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.