KNOWING YOUR SOILS

SOUTH AUSTRALIA

LANDSCAPE SOUTH AUSTRALIA

KNOWING YOUR SOILS

SOUTH AUSTRALIA

Published in 2025 by Soil Science Australia
www.soilscienceaustralia.org.au

Authors: Emily Leyden, Edward Scott, Mary Rowland, Philip Rowland.

ISBN: 978-0-646-71237-6

This project is supported by the Kangaroo Island Landscape Board through funding from the Australian Government and the Hills and Fleurieu, Murraylands and Riverland, SA Arid Lands, Northern and Yorke Landscape Boards.

Soil Science Australia also acknowledges the contributions of Grant Flanagan to the *Knowing your soils South Australia handbook*.

The *Knowing your soils South Australia handbook* is based on the Corangamite Region ‘Brown Book’ project, which was supported by the Corangamite Catchment Management Authority, through funding from the Australian Government Caring for our Country Program.

SOIL SCIENCE AUSTRALIA

LANDSCAPE SOUTH AUSTRALIA

Australian Government

Soil Science Australia acknowledges and respects the traditional custodians of South Australia, and we pay our respects to their Elders past, present and emerging. We acknowledge and respect the deep spiritual attachment and the relationship that Aboriginal and Torres Strait Islander people have to Country.

Introduction

Soils and soil health are critical for the viability and sustainability of our farming systems. Landholders and land stewards need to understand their soils and how they function in their landscape. This includes the physical and chemical characteristics of their soil types and the importance of soil biota, microbial systems and soil organic matter.

The *Knowing your soils South Australia (SA) handbook* and its companion *Knowing your soils South Australia ute guide*, aim to provide comprehensive information for landholders to manage the health of their soils and improve their productivity, resilience and sustainability. This handbook explains the key elements of soil management while the ute guide is a tool to help landholders understand and manage their soils and soil constraints by using simple DIY soil tests in the paddock.

Contents

Section four: Principals of soil health and soil biology

Section five: Knowing your soil constraints

Section one

Assessing your landscape and knowing your soil

Reading your landscape

To assess the soil on your property, it is important to look at where it is in the landscape. Soils often vary due to underlying geology, topography, wind and water erosion and local vegetation. For example, if you are in a higher location in the landscape, the soil may have eroded resulting in shallow soils. A point lower in the landscape would accumulate layers of soil material resulting in deeper soil profiles.

Key questions to ask when assessing soils in your landscape

- Where is water flowing?
- Is the water ponding or collecting anywhere?
- Does the soil get boggy after a small rain event or only during large winter rain events?
- What is degree of slope on your property?
- Are there any visual signs of parent material?
- What vegetation is growing where?

The size of your property also determines the 'scale' of the changes you might expect in the landscape. Smaller properties or more intensive production systems such as horticulture and viticulture will require smaller scale soil assessments, whilst larger broadacre cropping and grazing properties need to be assessed on a larger scale.

When thinking about scale, the intended use of the landscape and the long-term management unit size is important. For example, viticulture rows will be set approximately 3 m apart that require narrower machinery, operate on a small scale. A larger broad acre farm using a 36 m wide boomspray or spreader operates on a larger scale management unit. The scale should also take into consideration the amount of 'known' variability. If the property has significant changes in topography (i.e. high and low elevation areas) or you can visually identify a 'patchwork quilt' pattern of soils in the landscape, then the scale of the management units will need to match the variability in the landscape.

Understanding the different soil types on your property and where they are in the landscape will help you to determine the suitability or limitations of the soil for different uses. Figure 1 is a map of the general soil types across southern South Australia. Knowing the soil type on your property is a key step in managing your soils.

The five main soil-forming factors

1. Parent material
In South Australia, the main parent materials are ancient basement rocks or a range of younger, often unconsolidated sediments laid down by wind and water, and older soils. The parent material breaks down or 'weathers' to form soil.

2. Climate
The type of climate changes the soil formation. A dry environment might lead to more wind-blown material depositing, wetting cycles influence movement and deposition of material through a catchment and higher sea levels lead to marine incursion which can leave behind old dune systems.

3. Topography
The position of a soil in the landscape influences different rates of erosion and deposition, drainage, and leaching. Soil depth is often determined by its position in the landscape.

4. Biological influences
Soil organisms, plants, growing season and the type of organic matter influence mineral weathering, nutrient availability, and organic matter formation and decomposition in soils.

5. Time
The longer soil materials are acted upon by soil-forming processes, the more weathered, leached and infertile the soils become.

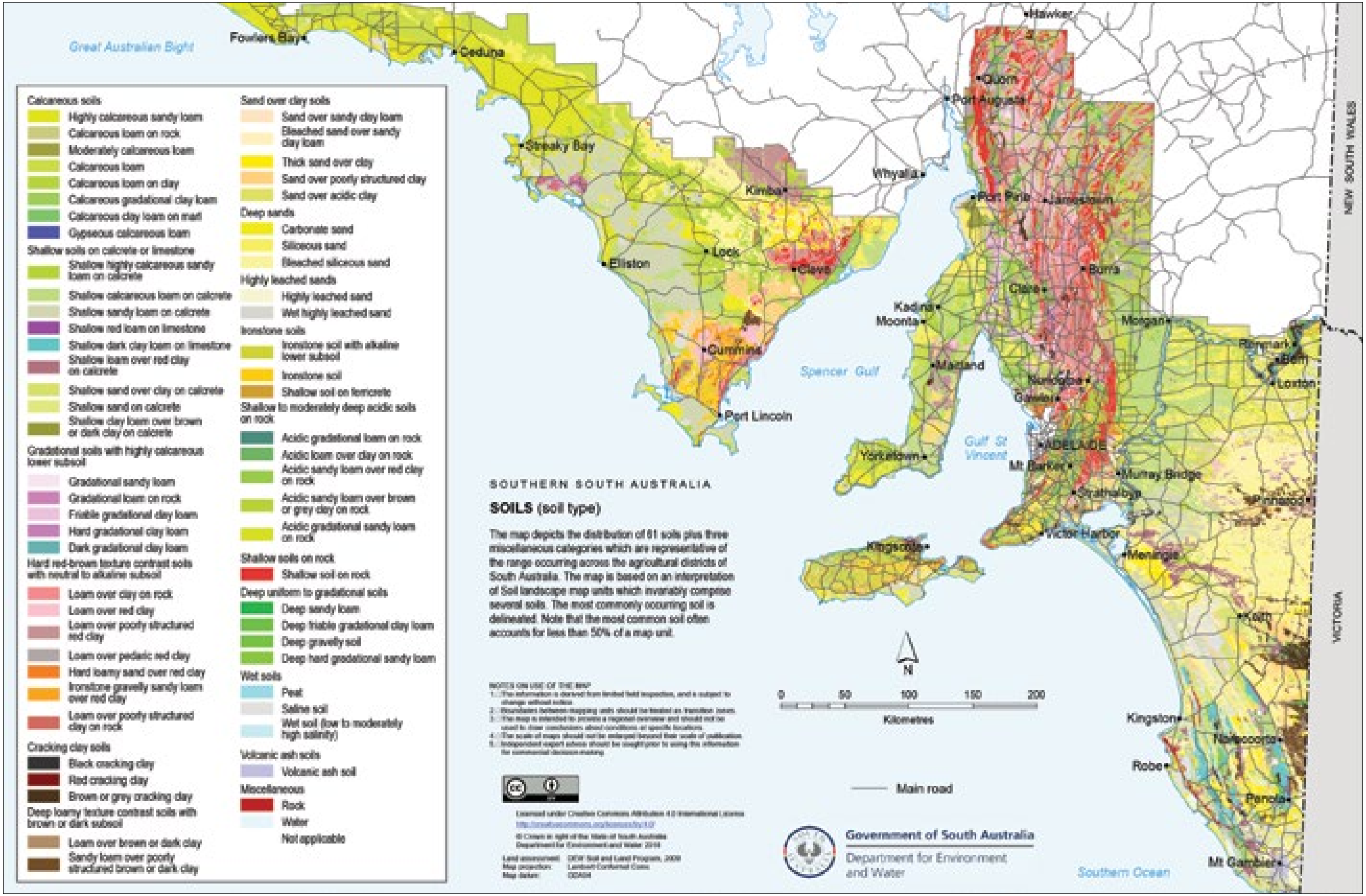


Figure 1: Map of the major soil groups in Southern South Australia. Source: South Australia Department for Environment and Water 2018*

South Australian soil mapping resources

Many areas of South Australia have mapping resources that inform landholders and land stewards about their soil types and soil conditions. They can be sourced in different ways. For instance:

- Simple search engine approach – Google can be a great starting place to find maps that may support your approach to better understanding your soils. Searching key words such as 'South Australia Soil Maps', or '*your region* Soil Maps', 'soil constraints map *your region*'. This approach can provide general maps to put the region into perspective.
- *NatureMaps* – This is a free digital mapping resource developed by the South Australian Government. NatureMaps allows you to access different layers to access data about land systems, vegetation, soil types and soil constraints.

  Land systems are broad landscape areas within which there are recurring patterns of geology, topography, soils and vegetation. Land systems have local geographic names which are abbreviated to a three-letter code. *Land system Reports* provide a summary of local geology, topography, soils and other features affecting land use and management.

Soil horizons explained

In many soil profiles, three soil horizons can be identified: the A horizon (topsoil), B horizon (subsoil) and C horizon (parent material). However, C horizons can be quite deep and thus do not necessarily need to be identified in agricultural settings. Sometimes one or more of the A, B and C horizons can be further subdivided.

Each horizon provides unique insights into the soil's fertility and suitability for different land uses and production types. The A horizon usually has the highest amount of organic material, making it darker, and supports most plant roots and biological activity. It also often has less clay because, over time, clay is washed down to the B horizon.

The B horizon has often accumulated higher concentrations of clay, iron, aluminium, manganese, carbonate or gypsum. The B horizon often has the most structure and brighter colours than the A horizons above. The C horizon consists of weathered parent material but contains no or very few roots and supports minimal biological activity.[1]

The Australian Soil Classification system is based on identification of key soil horizons that can be identified in the field based on their distinct properties. These distinguishing properties are usually combinations of colour, texture, structure and composition.

The land systems are comprised of soil landscape map units (or 'soil landscapes'). The soil landscape map units are smaller areas of land formed on a particular geological material or group of materials and are defined by recognisable topographic features. The map units have a defined range of soils and *soil and land attribute* conditions. Similar soil landscapes therefore have similar features, land use and management limitations, and land use potential. You can also find *Soil Characterisation* sites which show particular profiles, attributes and soil chemistry information.

Ask your Landscape Board for information about how to access *NatureMaps*.

Soil horizons

Most soils consist of two or more soil horizons, which are distinct layers that develop over time due to various soil-forming processes. These horizons can differ in physical, chemical or biological characteristics. Splitting the soil profile into horizons can help us to understand soil constraints and management.

When looking for different soil horizons, be guided by the features present such as:

- the texture of the soil (page 7 Soil texture)
- the structure of the soil (page 10 Soil structure)
- the colour of the soil
- change in pH (page 14 Soil pH)
- increase in salinity (page 72 Salinity)
- presence of sodicity (page 67 Sodicity)
- presence of coarse fragments such as ironstone gravel (page 25 Coarse fragments and ironstone gravels)
- colour changes such as mottling that could indicate waterlogging (page 26 Waterlogging in soils).

Soil testing has historically focussed on analysis of the topsoil (0-10 cm). However, a topsoil analysis doesn't identify what may be a constraint down below. Understanding the distribution and characteristics of soil horizons helps to predict how soils will respond to various agricultural inputs, such as fertilisers and irrigation. It also helps in assessing the soil's drainage capacity, root penetration depth, and potential for nutrient leaching. Recognising soil horizons can help you make informed decisions about crop selection, soil amendment needs, and sustainable land use practices.

Example soil profile

Table 1 shows a soil profile from Kangaroo Island in which the A horizon and B horizon can be distinguished and subdivided. The A horizon includes the darker organic matter layer and the underlying lighter coloured horizon of the same texture (sandy loam). There is ironstone gravel in the A horizon which will be an important consideration for nutrient availability (page 25 Coarse fragments and ironstone gravels).

The B horizon starts at 30 cm, identified as the depth at which there is a sudden increase of clay and structure. The C horizon is deep for this soil profile and so is not shown.

Table 1: Soil profile near Parndana, Kangaroo Island

0-12 cm – **A horizon** - Dark brown friable massive sandy loam with more than 50% ironstone nodules (2-20 mm)
12-30 cm – **A horizon** - Pink friable massive sandy loam with more than 50% ironstone nodules (2-20 mm)
30-50 cm – **B horizon** - Brownish yellow and red hard light clay with strong fine polyhedral (block-like) structure (Accumulation of clay, development of structure and colour designates this as the B horizon).
50-75 cm – **B horizon** - Yellowish brown, light yellowish brown and red firm light clay with weak coarse prismatic (column-like) structure
75-115 cm – **B horizon** - Pale yellow, yellowish brown and red firm medium clay with structure as above, and minor ironstone nodules
115-140 cm – **B horizon** - Light grey, yellowish brown and red hard medium clay with medium subangular (rounded edges) blocky structure and 10-20% ironstone fragments (20-60 mm)

*Image: South Australia Department for Environment and Water**

Soil texture

Soil is a porous composite material, consisting of a collection of solid particles of varying sizes. The space between the particles is also an important part of soil. It is filled with a mixture of liquid (soil solution) and gases. Almost all soil properties and functions are influenced by the size of the solid particles and associated pores, so it is important to understand particle sizes in a soil.

Soil texture and pore size

The soil texture also dictates the size of soil pores. Large particles have large pores between them, while small particles have small pores between them. Pores of different sizes play different roles in soil. Pores can act like a 'sponge'. They hold water strongly enough to prevent it from quickly draining away but weakly enough that plant roots can access them. Other larger pores allow the soil to 'breathe' providing a network of passages that store air. This allows oxygen to enter the soil and carbon dioxide to be removed. Large pores also allow rapid water movement during rainfall and irrigation events, and root growth from plants.

Soil texture summarises the particle size distribution in a soil – i.e. amount of sand, silt and clay proportions in a soil. Almost all soil properties and functions are influenced by these sizes and the space between them (the pores). Anything bigger than 2 mm is not considered 'soil'. However, it is necessary to consider gravel because it can influence how the soil functions.

Sand is the largest particle, followed by silt and clay. Clay and silt particles cannot be seen without a microscope. Due to their tiny size, clay particles typically accumulate lower in the profile as they can easily move downward as the soil weathers. Some soils have a strong change in texture down the profile, some soils change more gradually and others not at all.

The function of a soil changes depending on the relative amounts of the smallest (i.e. clay) and largest (i.e. sand) particles. Soils which have more than 90% sand are generally poor at holding water and nutrients. They drain very easily and the individual particles don't hold together at all strongly. Soils which are more than 50% clay are very good at holding water and nutrients. They can drain very poorly and the individual particles do hold together strongly. Soils with intermediate properties between sands and clays are loam.

All possible distributions of particle sizes are summarised on the *Soil texture triangle* in Figure 2.

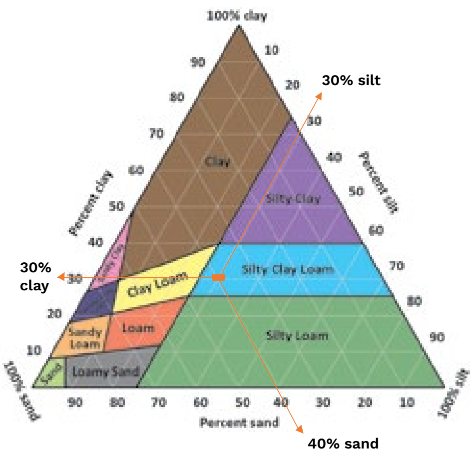


Figure 2: Soil texture triangle. An example is shown for a silty clay loam. This soil is 30% clay, 30% sand and 40% silt.

Testing soil texture

Although texture formally describes the distribution of particles of different specific sizes in soil, it is possible to simply assess soil texture in the field based on the degree to which soil particles hold together and can be moulded and squeezed into a ribbon. This is called *hand texturing*, or the ribbon test.

To hand texture, place crushed soil in your palm and dampen with water (Figure 3). You are trying to form a ball of soil which can be moulded. It is easiest to add water with a spray bottle. If it gets too wet, add more dry soil. Look at how your soil is holding together and how it feels. Some soils won't stick together (sands), some are like plasticine (clays) and some feel spongy (loams). You can use the following questions to describe your texture in the field. Laboratory tests can give you a more precise amount of the sand, silt and clay present in your soil.

Assemble equipment. You may need a mortar and pestle to crush the soil. Remove any roots or gravel. Pour out some soil into your hand.

Wet up the soil with a spray bottle gradually.

Bring the soil into a ball (bolus) with your hand. You may need to add more dry soil, then more water gradually until the soil comes together. Assess the ball for coherance and begin the flow chart to the right.

Try to roll a sausage with the soil ball. Bend the sausage, assess for cracks, feel if the soil is spongy, gritty, smooth and/or silky. Determine your texture via the flow chart.

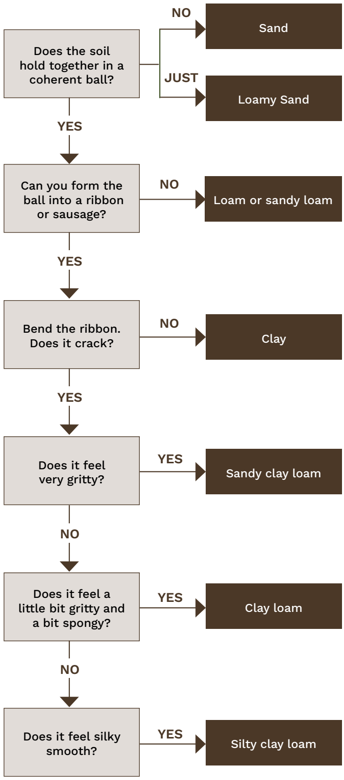


Figure 3: Hand texturing a soil

Soil structure

Clays and loams do not have large pore spaces for the movement of water, roots, air and nutrients. The soil particles (i.e. sand, silt and clay) tend stick together to form larger clumps called aggregates. The aggregates form because of the electrical attraction between clay particles, and with organic matter particles. The pore spaces between the aggregates allow the soil to 'breathe', allow water movement, and easier root growth.

Soil structure describes the way soil clumps together in topsoil and subsoil. Good soil structure has both micropores (which are important for water storage) and macropores (which allow movement of air, water, nutrients and roots through the soil). Soil structure is crucial for productive farming as it allows water retention, good drainage, aeration, root penetration and nutrient availability. It also promotes seed germination and emergence, crop yields and grain quality.

Clays tend to form stronger aggregates than loams. The organic matter provides an important 'glue' that helps hold the aggregates together.

Sandy soils tend to have weak, or even no structure. But because they contain large pores, the lack of structure is not as critical as it is for loams and clay. The weak structure of sandy soils can make them particularly susceptible to wind erosion, and also water erosion(page 76 Soil erosion).

Soil structure can be lost in farming systems due to compaction (e.g. by vehicles or animals), high levels of sodium and the rapid wetting of dry soils. Long term tillage practices lead to increased organic matter decomposition which reduces structural stability.

An important goal of soil management is to encourage aggregation. You can improve the soil structure by:

- maintaining and building the organic matter content (page 16 Soil carbon and soil organic matter)
- reducing soil sodicity via gypsum applications (page 70 Applying gypsum)
- using ground covers or stubble retention to add organic matter to the soil over time (page 54 Maintaining ground cover)
- using minimum or strategic tillage to reduce the loss of organic matter.

Figure 4 illustrates soil structure in two different soils. Soils can have minimal structure (left) and more defined structure (right). You can assess soil structural stability using the slaking and dispersion tests (page 66 Assessing soil structural stability).

Figure 4: Comparing soils with minimal (L) and more defined structures (R). Photos: Edward Scott

A strong texture or structural change (i.e. from sandy in the topsoil and clay in the subsoil) can reduce water, root and nutrient penetration at depth. Understanding the change in soil texture and structure (or lack of change) in your soil profile can help you understand how water, plant roots and nutrients will move (or be retained) in the soil. The characteristics of different soil types and their impacts on soil water, nutrient availability, soil structure and soil organic carbon are shown in Table 2 (see following page).

Cation exchange capacity

Cation exchange capacity (CEC) is a measure of a soil's ability to hold and exchange positively charged ions, known as cations. These cations include essential nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and ammonium (NH_4^{+}), and most trace elements. Cation exchange capacity (CEC) is measured with a soil test (page 30 Planning your soil sampling) and is an important indicator of soil fertility because it reflects the soil's capacity to hold onto and supply nutrients to plants.

Soils with a high CEC provide a more consistent supply of nutrients to plants, which is beneficial for crop growth and productivity. High CEC is typically found in soils with high levels of clay and organic matter (Figure 5). On the other hand, sandy soils usually have a lower CEC.

To learn more about CEC, watch the light-hearted *Cation exchange* animation from the United States Department of Agricultural (https://www.youtube.com/watch?v=HmEyymGXOfI).

Table 2: The influence that soil groups have on drainage, nutrient availability, soil structure and soil organic carbon

Soil type	Impact on soil water	Impact on nutrient availability	Impact on soil structure	Impact on soil organic carbon (SOC)
Sandy soils	Larger particles = rapid drainage. Water and nutrient leaching likely during periods of precipitation or irrigation. Runoff is a risk in sandy soils where 'non-wetting' sand is present.	Lower nutrient retention often requires more frequent nutrient applications to meet the demands of crops.	The loose and non-cohesive structure can hinder nutrient exchange leading to potential fertility challenges.	Sandy soils have a limited capacity to significantly increase soil organic carbon. Their coarse texture exposes the soil organic matter to breakdown by soil organisms. SOC can be maintained or built with reduced tillage, ground cover preservation and organic amendments (i.e. compost or biochar). The degradation of organic matter in sands can result in the build up of a wax coating on sand grains leading to non-wetting soils. (page 88 Non-wetting soils)
Clayey soils	Finer particles = water held in the soil. May suffer from waterlogging, hindering root health because of reduced aeration.	Compaction can hinder nutrient accessibility to plant roots.	Compaction and loss of structure can limit root penetration and aeration.	Clay particles protect the soil organic matter from being exposed and broken down by soil microbiological organisms. SOC accumulation assists with soil structure.
Loamy soils	Mix of particle sizes = optimal drainage and retention. Water is efficiently used by plants.	Loamy soils provide optimal nutrient retention and accessibility.	The mix of particle sizes allows aeration, water movement and an ideal microbial environment. This assists in root development and nutrient cycles.	The range of soil particles protects the soil organic matter from being exposed and broken down by soil microbiological organisms. SOC can be maintained or built with reduced tillage, ground cover preservation and organic amendments (i.e. compost).

The science of cation exchange

One of the beneficial properties of clay particles is they are negatively charged. This means they can 'hold' onto nutrients which are positively charged like calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), ammonium (NH_4^{+}) and most trace elements. These positively charged nutrients are called cations.

Cations themselves can only be 'released' from the soil surface by swapping with another cation from the soil solution. Plants can swap their cations (hydrogen ions) with the soil cations that they need for growth.

CEC is an important indicator of soil fertility because it reflects the soil's capacity to supply these nutrients (cations) to plants.

Clay soils and soils with high levels of organic matter particles are naturally negatively charged and have a large surface which means they can retain more cations. Sandy soils have larger particle size and lower surface area which means that they retain fewer cations (Figure 5).

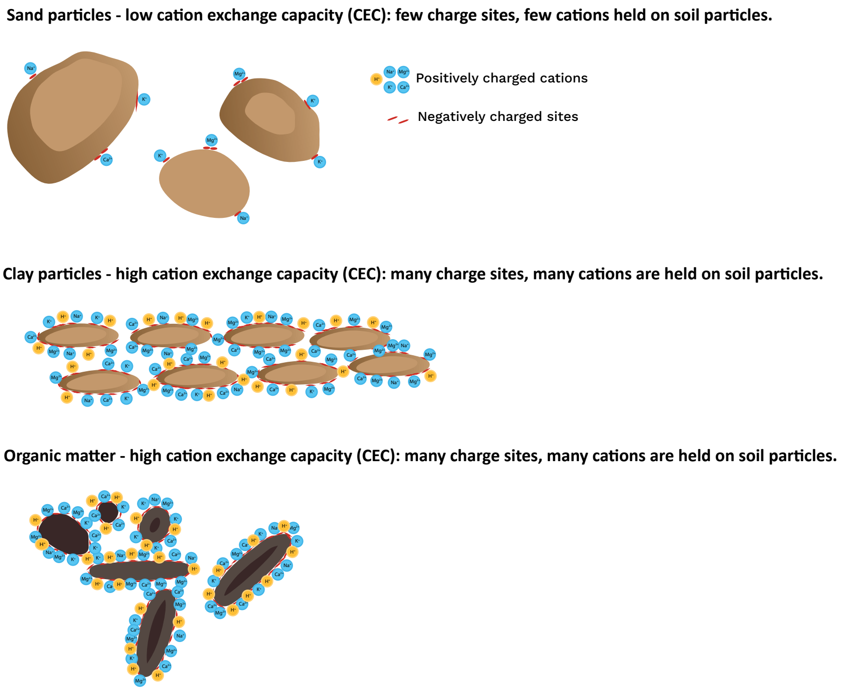


Figure 5: Comparing cation exchange capacity between sand and clay particles and organic matter. Adapted from Soil Quality: 3 Soil Organic Matter (Hoyle and Murphy, 2018).

Soil pH

Soil pH measures the soil acidity or alkalinity. Neutral soils have a pH of 7.0, although soils with pH in the range 5.5 to 8.0 are generally considered to be near neutral. Acid soils have a low pH (pH 2 to 5.5), while alkaline soils have a high pH (pH 8 to 10). Some soils, particularly those in high rainfall climates, are naturally acidic. However, soil acidity can also be affected by agricultural practices such as removing produce, adding fertilisers (especially nitrogen or sulfur), or the accumulation of organic acids from organic matter. Alkalinity is usually an inherent characteristic of soils, although it can be increased by irrigating with alkaline or saline water.

Soil pH is a logarithmic scale, therefore the difference between pH 5 and pH 6 is 10 times and the difference between pH 5 and pH 7 is 100 times. This is why small changes can have dramatic effect on plant performance. Determining the soil pH is important for:

- assessing the likelihood of soil acidification
- identifying calcareous soil
- estimating nutrient deficiencies
- assessing crop suitability.

Most agricultural plants prefer near neutral (5.5 to 8.0) pH levels. Excessively acidic or alkaline soils are often less productive. Figure 6 shows the effect that pH has on the availability of soil elements to plants. The wider the band for each element, the more available that element is for uptake by plants. For example, nitrogen and phosphorus have a wider band between pH 6 and 7. This means that these elements are more available for plant growth at this pH. Other elements can be toxic at certain pH levels. An example is the wide band of aluminium between pH 4 to 4.5. The availability of aluminium at this pH is toxic to plant growth (page 82 Aluminium toxicity).

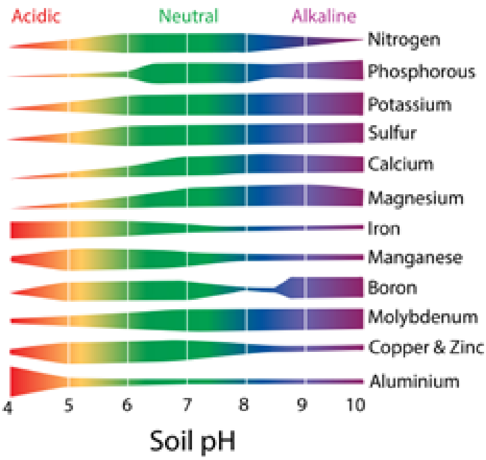


*Figure 6: Effect of soil pH on the availability of plant nutrients.[1**]*

Measuring soil pH

Soil pH can easily be measured in the field to give an indication of whether the soil is acid or alkaline (Figure 7). The soil pH test kits are available from hardware stores or garden centres. The test involves collecting some soil from each soil horizon, mixing it with some indicator dye and barium sulphate, and matching the dye colour using the colour wheel provided in the kit.

Conducting a pH test in the field can assist in identifying where pH changes may be occurring down the soil profile. It can help to decide where the soil should be 'split' into soil horizons, especially when no obvious soil colour change is apparent. Use the field test kit as a guide and confirm pH results with a laboratory analysis.

For more information on soil acidity and alkaline soils (calcareous soils), refer (page 82 Soil acidity, page 23 Calcareous soils).

Figure 7: Using a pH test kit in the field

You can submit samples for a laboratory pH test. It is recommended that you test soil pH in the 0 to 5 cm, 5 to 10 cm, 10 to 15 cm, 15 to 20 cm, and 20 to 30 cm depth ranges. In the laboratory, soil pH is measured in a 1:5 soil solution extract using either water or a dilute calcium chloride ($CaCl_2$) solution. The reason a soil extract is needed is that the measurement is made using a glass electrode that needs to be fully immersed in solution.

pH 1:5 water vs pH 1:5 calcium chloride

For acidic to neutral soils, measuring pH in 1:5 water extracts give a higher pH value (by around 1 pH unit) than measuring pH in 1:5 calcium chloride extracts. This is because calcium ions in the calcium chloride solution 'push' acidic hydrogen ions into solution that remain on 'cation exchange sites' (page 11 Cation exchange capacity). Often this provides a better replicate of a soil solution than the water extract and is preferred when monitoring pH changes over time.

For alkaline soils, 1:5 calcium chloride extracts also usually give lower pH values than 1:5 water extracts, but for a different reason. In this case, the calcium ions reduce the capacity of calcium carbonates to dissolve in the soil water.

For sodic alkaline soils, measurement of pH in a water extract is more informative because the combination of carbonate and 'exchangeable' sodium ions allows much more carbonate to dissolve into solution resulting in more extreme pH values of 9, 10 or even 11.

Soil carbon and soil organic matter

Soil organic matter (SOM) consists of anything in the soil of biological origin – such as roots, fungi, bacteria, crop stubble and animal manures – in various states of decay. High levels of soil organic matter help to maintain agricultural production by maintaining soil health, raising fertility, improving water holding capacity, reducing erosion and encouraging soil biota. Soils with higher SOM levels are generally more fertile, more productive and easier to manage than soils with low SOM levels.

Soil organic carbon (SOC) is a specific component of SOM. It represents the carbon in these organic materials. SOC is the most abundant and most easily measurable element contained in soil organic matter, so SOC is typically measured and reported in a standard soil test.

The part of organic matter that is broken down relatively quickly is the main energy source for biological activity in soil. This consists mainly of discrete pieces of plant cell wall material and is called the particulate organic carbon.

Once organic material has decayed to a point where it can no longer be recognised as discrete pieces of plant material, it is called humus. Humus plays a role in all key soil functions, particularly in the provision of nutrients.

While the addition of organic matter is almost always positive for soil health, it is important to note that during the breakdown of organic matter, hydrophobic organic materials can bind to certain soil particles or aggregates. This can cause or worsen non-wetting properties in some soils (page 88 Non-wetting soils).

Organic carbon is usually in the top of the A horizon in the soil profile (Figure 8). The amount of organic carbon that can potentially be stored in the soil is determined by soil type, climate and management. Different land uses and management practices can negatively impact on carbon levels in the soil. It is a good idea to increase soil organic carbon for the soil health and production benefits, not just for carbon accounting purposes.

Figure 8: Soil organic matter in the A horizon.
Photo: Emily Leyden

Organic matter residues can cause short-term nitrogen deficiencies as microorganisms break down the organic matter. Over longer time frames, organic matter is converted to soil organic matter which breaks down, releasing nutrients.

Managing your soils to increase carbon

Carbon levels in the soil are a balance between the rate at which organic matter is added (inputs) and the rate at which it decomposes and returns to the atmosphere as carbon dioxide. Without continual inputs of organic matter, the amount stored in the soil will decrease over time because the organic carbon is continually decomposed by soil microbes and released as carbon dioxide.

Under perennial pasture production, soil organic carbon and soil organic matter will remain relatively stable. However certain management practices, like intensive tillage, overgrazing and removal of crop residues, can quickly degrade organic matter levels in soils. Table 3 provides recommended management practices that improve soil organic matter in both pastures and cropping.

Table 3: Cropping and pasture management practices that improve soil carbon and soil organic matter levels

Management practice	Comments
Reduce soil disturbance	Consider stubble retention, direct drilling and minimum tillage practices (page 60 Managing stubble, page 76 Soil erosion). Tilling a paddock prior to pasture renovation or crop seeding reduces the amount of organic carbon in the soil because it decomposes faster and more completely.
Use pasture rotations or use perennial pastures	Pasture rotations and growing pastures in the inter-rows for vines can help build organic matter. Plant perennial species where possible.
Manage grazing	Adopt appropriate grazing management strategies that minimise the impact of grazing on soil structure. Loss of soil structure allows soil carbon to be depleted.
Maintain ground cover	Maintain and conserve ground cover. To maximise erosion control, stubble should cover a minimum of 70% of the soil surface, preferably be left standing so it is anchored by roots (page 76 Soil erosion).
Promote plant growth	Grow high yield, high biomass crops and pastures. Utilising good rotation management in continuous cropping systems maintains soil cover. It also minimises root disease that can limit below ground organic matter production.
Maintain soil fertility	Maintain soil fertility with inorganic and organic fertilisers to maximise production. Soil testing can help you track soil fertility and the amount of inorganic and organic fertilisers needed in your soil (page 30 Planning your soil sampling, page 37 Plant nutrients and fertilisers, page 51 Organic fertilisers).
Use green or brown cover crops	Cover crops can increase organic matter inputs between winter crop seasons. Evidence suggests that a mix of species from a variety of plant groups is more effective.
Use organic amendments	If available locally, use manure, compost or other organic amendments to help build soil carbon.
Monitor changes in soil carbon levels	Test your soil to assess whether the management change is depleting or restoring the carbon resource (page 30 Planning your soil sampling).

Soil water holding capacity and plant available water

Soil is the main source of water storage and supply to plants between episodes of rainfall or irrigation. Understanding the soil's capacity to store water will improve your decisions about the potential return on crop inputs and other management practices.

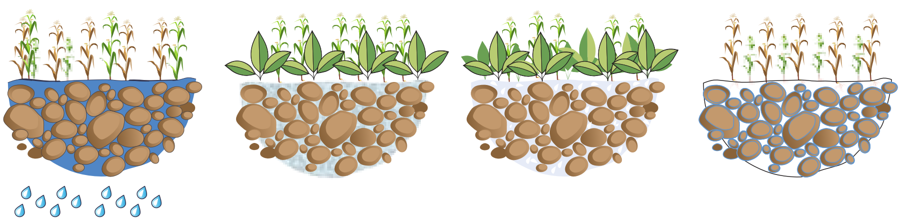
Controlled traffic, minimum tillage, stubble retention and subsoil amelioration practices can improve a soil's ability to capture and store water. Subsoil constraints (e.g. sodicity, hardpans) significantly reduce the amount of water that crops can access from the subsoil.

Water is held in the soil in the spaces between the soil particles (called pore spaces). The number, size and connectivity of the pores in soils determine how much water a soil can store.

Water is held in the soil in different ways and not all water held is available to plants. Water that is held by electrostatic forces between the water and clay particles and other minerals is not available to plants. Similarly, gravitational water is held in very large pores and drains rapidly under gravity after rain or irrigation.

Capillary water is the water that is available to plants. It is held around the soil particles and in the soil pores so plants roots can access it easily. Water is drawn out of the large pores first and then out of the finer pore spaces. After soil saturation and the gravitational water drains from the soil, *field capacity or drained upper limit (DUL)* is established, and water is drawn rapidly by roots. As water is used by the roots, water is extracted more slowly until no more water is available. This is called *wilting point* or *crop lower limit (CLU)*. The plant available water is the water which can be extracted between *field capacity* and *wilting point* (Figure 9). At this point plants can suffer stress, lose vigour and yield is reduced.

The soil water holding capacity is determined by the root depth. The depth of roots can be limited by subsoil constraints, such as waterlogging, carbonates,



Saturation:
Profile is full of water. Water fills all pore space. No oxygen available for plant growth. Water is transported out of the soil.

Field capacity:
Water remaining in the soil after it has been thoroughly saturated and allowed to drain freely.

Available Water
Between field capacity and permanent wilting point. Water available for plant growth. Both water and oxygen present in pore space between soil particles.

Wilting point:
No water available for plant growth. Water is held around soil particles but is inaccessible to plants.

Figure 9: Water holding capacity of the soil illustrating saturation, field capacity and wilting point.

soil acidity, salinity, soil texture, soil structure and the presence of coarse fragments such as ironstones (page 26 Waterlogging in soils, page 23 Calcareous soils, page 82 Soil acidity, page 72 Salinity, page 7 Soil texture, page 10 Soil structure, page 25 Coarse fragments and ironstone gravels).

The higher the water holding capacity, the better the plants can survive during periods of low rainfall. The table below indicates a basic soil profile and how to calculate available water holding capacity. All layers in which root growth occurs should be included and the texture of each horizon is required. Note that excess gravel content (i.e. ironstone gravels) can lower total soil water holding capacity as it occupies the space that can otherwise be storing water.

Assessing water holding capacity

The water holding capacity of a site can be estimated by using the texture of each horizon in the soil profile and the root depth. Include the horizons where roots are visible. First, determine the soil texture for each horizon. Next, use Table 4 to find the total available water holding capacities of each horizon depending on texture.

Organic matter and structure affect how much water a soil horizon can hold. Where the structure is dense and there is little organic matter, the low end of the range should be used. Where there is good, open soil structure with higher organic matter content, the upper end of the range can be used.

Table 4: Total available water holding capacity estimates for different soil texture types

Texture	Total available water holding capacity (mm water/m soil)
Medium to coarse sand	40-80
Fine sand	60-100
Loamy sand	80-120
Sandy loam	100-140
Light sandy clay loam	110-170
Loam	140-200
Sandy clay loam	130-180
Clay loam	150-220
Clay	120-220
Clay (weak structure)	30-90

Once you have your texture and the total available water holding capacity (AWC) for each horizon, multiply by the depth in meters to determine the total water holding capacity for each horizon. Add the total for each horizon together for a total available water holding capacity for the soil profile. See Table 5 for an example.

Note that it is important to adjust for gravel (including ironstone gravel) in your calculations. If there is 10% gravel in the horizon you need to reduce the available water holding capacity by 10% (as the gravel is occupying more volume).

For example,
Sandy loam soil = 100 mm/m. With 10% gravel, reduce the AWC by 10% by multiplying by 0.9.

Adjusted AWC for a sandy loam layer with 10% gravel = 100 mm/m x 0.9 = 90 mm/m.

Table 5 (following page) indicates soil water holding capacity for this soil profile and indicates the total amount of moisture potentially available for non-irrigated crops. The total available water holding capacity for this example (73.4 mm) can be classified as Medium using the classification criteria in Table 6. Readily available water values are different and are typically needed by irrigators to determine irrigation schedules. Seek help from your Landscape Board staff to get more exact estimates of readily available water holding capacity for your soil. Water holding capacity is not considered to be limited if the storage in the root zone is above 100 mm.

Table 6: Classification criteria for available water holding capacity (AWC)*

AWC capacity	Root zone AWC
High	>100 mm
Moderate	70-100 mm
Moderately low	40-70 mm
Low	20-40 mm
Very low	<20 mm

** This information is for non-irrigated crops.*
Source: Adapted from Assessing agricultural lands, South Australian Government[2]

Table 5: Calculating total water holding capacity (AWC) of a soil profile

Soil Profile - CK026 Near Parndana, KI	Soil Profile - CK026 Near Parndana, KI	Total available water holding capacity for horizon mm water/m	Adjusted for gravel	Multiplier	Total for each horizon
	0-0.1 m = Sandy loam Depth of horizon = 0.1 m	140 (higher end of the scale for sandy loam due to high organic matter)	Nil	= 0.1 m x 140	14
	0.1 - 0.2 m = Sandy loam with 10% ironstone gravel Depth of horizon = 0.1 m	100 (lower end of the scale for sandy loam due to low organic matter)	Reduced to 90	=0.1 m x 90	9
	0.2 - 0.27 m = Sandy loam with 10% ironstone gravel Depth of horizon = 0.07 m	100 (lower end of the scale for sandy loam due to low organic matter)	Reduced to 90	=0.07 x 90	6.3
	0.27 – 0.45 cm = Clay loam Depth of horizon = 0.18 m	150 (lower end of the scale for sandy loam due to poor structure)	Nil	=0.18 x 150	27
	0.45 – 0.92 m = Silty light clay Depth of horizon = 0.47 m (below 0.92 m is hostile for plant grown)	30 (lower end of the scale for clay (weak structure) due to limited root growth	Nil	= 0.47 x 30	14.1
			Total available water holding capacity for the soil		**73.4 mm** **Medium AWC**

*Image: South Australia Department for Environment and Water**

Improving soil water holding capacity

To improve water holding capacity, landholders can:

- plant deep rooted crops that can access water deeper in the profile
- limit subsoil constraints to root growth
- add soil ameliorants such compost and organic matter to assist with better soil structure (page 10 Soil structure)
- use calcium amendments such as gypsum and lime (page 70 Applying gypsum, page 86 Applying lime)
- increase soil cover with stubble retention practices to reduce evaporation losses from the soil surface (page 76 Soil erosion)
- select plants tolerant of local soil and climatic conditions
- use strategic tillage with gypsum application.

For more in-depth information about plant available water and how to calculate it, see the Grains Research & Development Corporation booklet, *Estimating plant available water capacity*.[3]

Calcareous soils

Calcareous soils contain high levels of carbonates that result in these soils being alkaline, i.e. they have a high pH (page 14 Soil pH). Mostly the carbonate is present as calcium carbonate but small amounts of sodium carbonates or bicarbonates, or magnesium carbonates can also be present. Calcareous soils are common in many agricultural regions in South Australia, especially where annual rainfall is low (between 350 and 600 mm) (Figure 10). The presence and distribution of carbonates is the result of complex, long-term processes including wind deposition, leaching, precipitation and cementation.

Fine carbonates, which include calcareous sand, silt and clay-sized particles, are often dispersed throughout the soil. They can be uniformly distributed, appear in concentrated nodules, or as calcrete sheets in the soil. Nodular or rubbly carbonates form due to wetting and drying cycles near the soil surface. These nodules can range from a few millimetres to over 300 mm in size and are typically found near the top of calcareous layers. Multiple periods of formation can create alternating layers of rubbly and fine carbonates.

Calcrete is a more continuous sheet or pan of cemented carbonate. It forms from prolonged wetting and drying cycles of calcareous materials near the surface. This layer can vary significantly in thickness and can transition to softer calcareous material below. The presence of calcrete can affect plant growth by limiting root zone depth and impeding drainage, especially when it forms a continuous, unfractured layer.

The chemical and physical effects of soil carbonates are significant for land use and management. The high alkalinity of calcareous soils can affect nutrient availability and plant growth. High carbonate levels can suppress the plant availability of essential nutrients, especially phosphorus, zinc, manganese, copper, and iron.

Physically, fine carbonates can restrict drainage in certain soil types, while nodular and rubbly carbonates can reduce water holding capacity. Understanding the type and distribution of soil carbonates is essential for managing soil health and optimising plant growth.

Testing for soil carbonates

Soil carbonates can be easily detected using one molar (1M) hydrochloric acid. When applied on a small soil sample, it effervesces or bubbles (Figure 11). You can also use vinegar if hydrochloric acid is not available. The strength of this reaction indicates the carbonate content. It is important to measure for carbonates in each horizon down the soil profile (page 5 Soil horizons).

The chemical effects of soil carbonates depend on the surface carbonate amount and the depth of the calcareous layers. Surface carbonates can affect potential soil nutrient availability, while subsoil carbonates can affect the growth of carbonate-sensitive crops, such as lupins.

Unlike acidic soils, calcareous soils cannot be easily neutralised. If calcareous soils are identified, nutrient availability to plants needs to be closely monitored to ensure adequate trace elements and soil phosphate reserves. In very highly calcareous soils, trace elements might need to be applied via foliar application for effective nutrient uptake by the plant. If you identify that you have calcareous soils, the most effective strategy will be to plant alkaline soil-tolerant crops and appropriately managing nutrition with knowledge of the constraints.

Figure 10: Calcareous soil in South Australia. Photo: Edward Scott

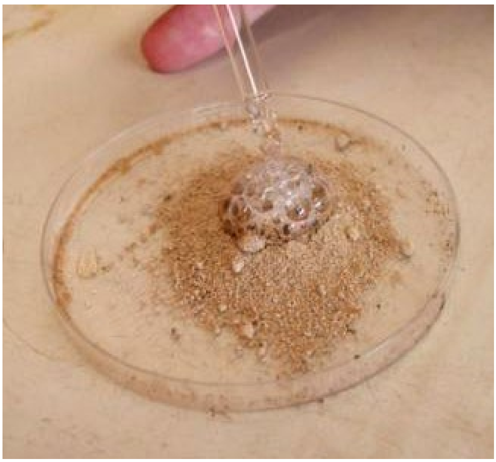


Figure 11: Soil carbonates bubble when hydrochloric acid is added. © Soil Science Australa

Course fragments and ironstone gravels

Coarse fragments are particles in the soil profile bigger than 2 mm. They are typically rock fragments and gravel, charcoal or shells. Coarse fragments can be located deep in the soil profile or on the surface. Soils with a high proportion of coarse fragments can have limited total soil water holding capacity, plant available water and nutrient availability.

Ironstone gravel is commonly found on South Australian agricultural land. (Figure 12). Ironstone gravel forms through the process of *laterisation*. In this process, iron-rich minerals undergo weathering and leaching, causing the iron oxides in the soil to accumulate and cement together. This typically occurs in warm, humid climates with alternating wet and dry seasons. The silica in the soils and rocks is dissolved and leached out and the iron is concentrated in the gravels.

Ironstone gravels often form a hard, cemented layer called *duricrust*. They can be found at or near the surface, or within the subsoil, depending on the local environmental conditions and geological history.

Ironstone gravels present challenges for farmers and land managers and soils containing ironstone gravel may not be suitable for cropping. The hard, cemented layers can severely restrict root growth and water infiltration, limiting the depth at which plants can access nutrients and moisture. This can result in poor crop performance and reduced agricultural productivity, particularly in dry seasons. Additionally, ironstone gravel can make soil management practices such as tilling and harvesting more difficult and costly due to increased wear and tear on farming equipment.

Also, when ironstone gravels are present, the uptake of phosphorus by plant roots can be reduced. This is because phosphorus preferentially binds to ironstone gravels. In some areas of Western Australia where ironstone gravels are present, up to 60% of the phosphorus (Cowell P) has bound to the gravel surface rather than the soil, and hence, is unavailable to plant roots.[4]

In addition, the rapid water drainage of ironstone gravel soils means that the application of soluble nutrients can wash out of the soil before they can be taken up by plant roots. Where these soils are suitable for cultivation, it is important to know the nutrient holding and exchange capacity of the soil profile as well as the amount of gravel so that you can estimate fertiliser application rates and frequency. Testing soil and plant tissue, and applying less fertiliser more frequently during the growing season, can be useful tools to match nutrient availability with plant demand.

Managing ironstone gravels

Research is currently investigating methods to increase production on soils with ironstone gravels. It is important to be aware of limitations to plant growth and seek specialist advice for dealing with your individual circumstance, especially regarding how to manage the type and frequency of fertiliser inputs and which crops and pastures to plant.

Figure 12: Ironstone gravels in a soil profile from Kangaroo Island.
Photo: Edward Scott

Waterlogging in soils

Waterlogging occurs when soil becomes saturated with water. When water fills all the pore spaces, there is no space for air. This condition typically arises after heavy rainfall or flooding, or because of ineffective irrigation practices. More permanent waterlogging occurs in areas where there is poor drainage or compacted soils.

At the landscape scale, clearing native vegetation in agricultural settings can worsen waterlogging in soils in lower parts of the landscape. This is because less water is taken up by deep-rooted native vegetation and transpired to the atmosphere. Removal of this ‘sink’ of water increases the flow to groundwater, raising the water table to the point where some soils are saturated continuously.

Waterlogging in soils impacts both crop growth and soil function. Saturated soils restrict root respiration because the soil pore spaces are filled with water and are oxygen deficient. Root rot, reduced nutrient uptake and stunted plant growth are common. Crops such as wheat, barley and canola are particularly susceptible to waterlogging. In severe cases, prolonged waterlogging can lead to soil erosion, loss of topsoil and degradation of soil structure.

Identifying waterlogged soils

Waterlogged soils can be identified through various physical and visual indicators. A key sign of seasonal or intermittent waterlogging is mottling in the colour of the soil. The mottling appears as irregular patches of different colours in the soil profile – typically red, yellow or grey. Mottling is usually seen deeper in the soil profile in the B horizon. Mottling occurs because a lack of oxygen in some parts of the subsoil results in chemical and biological processes that turn insoluble orange-red iron oxides into soluble iron species that are temporarily mobile until they encounter soil with adequate oxygen or the soil dries sufficiently to allow oxygen to re-enter the soil and the iron oxides re-form.

Soils that are more permanently waterlogged can be identified by the presence of a *gleyed* (bluish gray) horizon in the soil profile. This happens when the soil is subject to prolonged saturation and the iron oxides cannot re-form.

In South Australia, areas susceptible to water logging have been mapped by the South Australian Government (Figure 13).

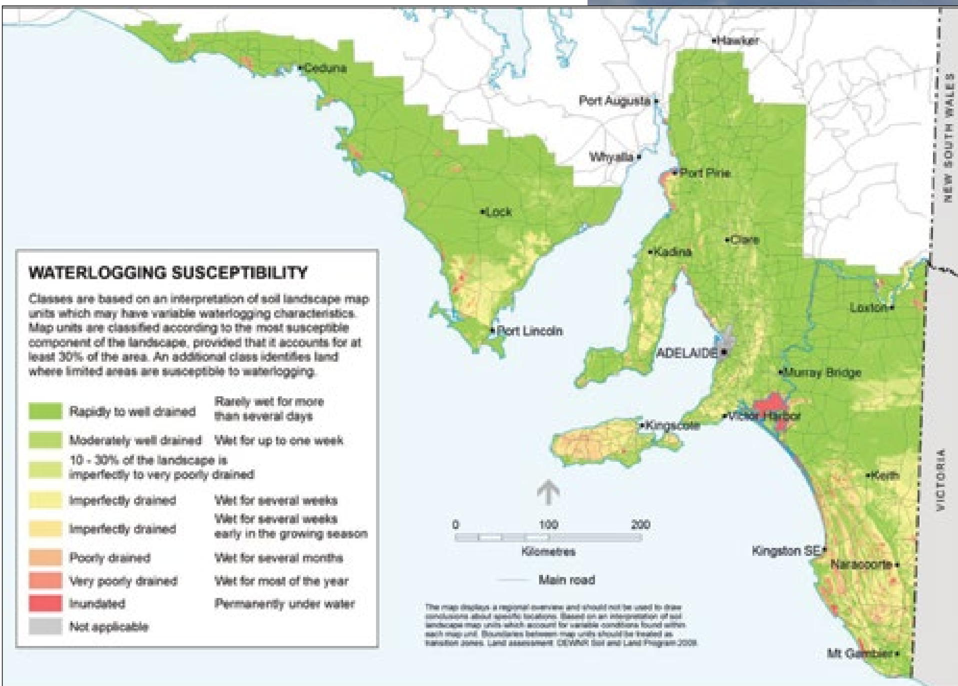


Figure 13: *Waterlogging susceptibility map for southern South Australia. Source: South Australia Department for Environment and Water**

Managing waterlogged soils

Addressing waterlogging requires a combination of short-term and long-term strategies to improve soil drainage and structure. Immediate measures include implementing surface drainage systems, such as ditches, drains or diversion banks to quickly remove excess water from fields. Subsurface drainage, using pipes, can also be effective in areas with persistent waterlogging issues. Check with your local Landscape Board prior to any drainage installation, as it may require a permit.

A longer-term strategy is to improve soil structure by incorporating organic matter. This can enhance soil permeability and reduce compaction. Additionally, selecting waterlogging-tolerant crop varieties and practicing crop rotation can help reduce the impacts. In areas where waterlogging is persistent, consider revegetation strategies throughout the catchment area using plants native to the region.

Section two

Soil sampling and planning

Planning your soil sampling

Soil sampling and analysis is an important data collection step. It ensures that actions and inputs are targeted to optimise soil improvement for a particular purpose. A soil sampling plan ensures the variability in soil constraints and nutritional requirements are considered.

The *Knowing your soils SA ute guide* provides a simple approach to look at your soils year on year. This can be the simplest way to see where your most limiting soil constraints are across the paddocks on your property and to keep track of soil health and potential emerging issues that may affect production.

For a more in-depth approach to soil sampling and understanding potential limitations to your production, it is important to consider the following information when designing a soil sampling plan. Working with a soil advisor or your Landscape Board can further help to ensure that soil sampling is customised to your particular soil type, constraints and aims. It is important to define the *purpose* of your soil sampling plan. Why do you need a soil sample? For instance, you may want to:

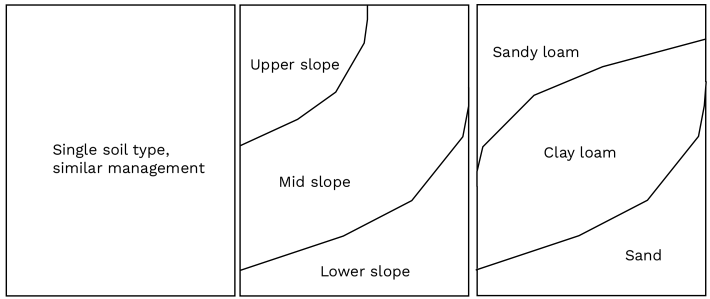
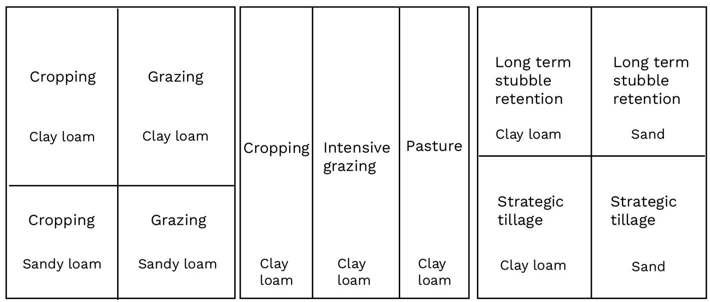
- diagnose nutrient deficiencies and optimise fertiliser applications
- diagnose soil constraints (topsoil and/or subsoil)
- monitor soil health
- target a specific goal, i.e. increasing soil carbon
- troubleshoot why certain areas are under-performing.

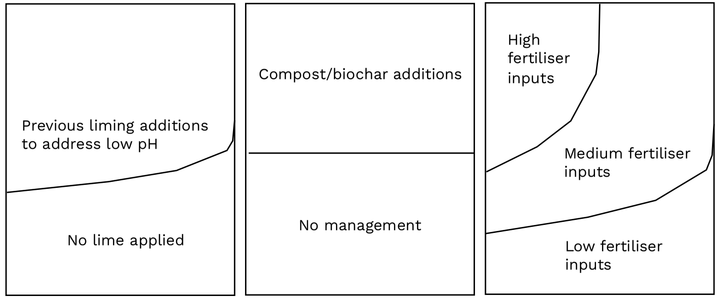
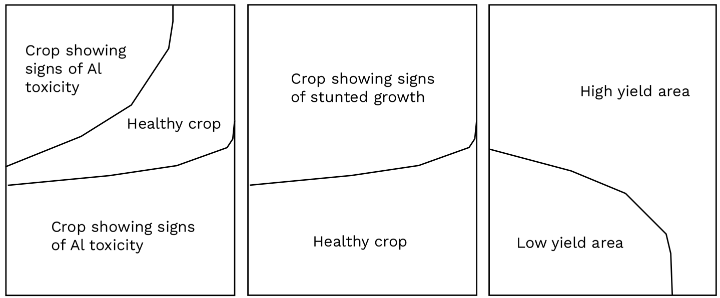
Planning steps

1. Decide which paddocks to sample. The type of soil sampling should be chosen based on the paddock characteristics, the goals of the sampling program, and the resources available. Table 7 describes the difference between zonal soil sampling and targeted soil sampling.

Non-targeted or non-zonal sampling is completed when very little is known about the area. A defined sampling pattern (usually uniform grid or random pattern as per Figure 14) can investigate an area in detail to determine variability.

Table 7: Types of soil sampling

Type of soil sampling	How	Why	Examples
Zonal soil sampling	Soil samples are collected from specific zones within the paddock, often based on topography, management zones, land use history or apparent soil differences.	Zonal soil sampling considers several factors when deciding what to sample like soil type, topography, land use history and production types. Comprehensive soil tests are usually taken in particular zones in a paddock and compared. Only one sample per zone may be comprehensively analysed, or several samples may be collected in a pattern (Figure 14) and composited together. Zonal soil sampling can reduce the number of samples and sampling costs while maintaining acceptable information on variability.	**Soil sampling to understand paddock variability**  **Soil sampling to understand impact of paddock management** 

Type of soil sampling	How	Why	Examples
Targeted sampling	Specific areas of interest identified through visual inspection, crop performance, or previous soil data.	Targeted soil sampling is used to investigate known problem areas or specific research questions. It provides detailed information on specific issues or areas of concern but may not provide a comprehensive overview of the entire paddock. Often several samples are collected in a pattern (Figure 14) and composited together.	**Soil sampling to understand influence of previous season inputs**  **Soil sampling to understand impact of surface or subsurface constraints** 

Adapted from Fertcare sampling guide https://fertilizer.org.au/Portals/0/Documents/Fertcare/Fertcare%20Soil%20Sampling%20Guide.pdf?ver=2019-06-17-095413-863

2. Decide how to sample within the paddock or zone. There are different ways of collecting samples to get a representative sample (Figure 14). The different patterns each have advantages and disadvantages (Table 8). The design of the sampling sites should fit the purpose of your soil sampling plan (step 1). Atypical zones, such as changes in soil type, breaks in slope, fence lines, waterlogged patches and obvious stock camps zones, should be excluded.

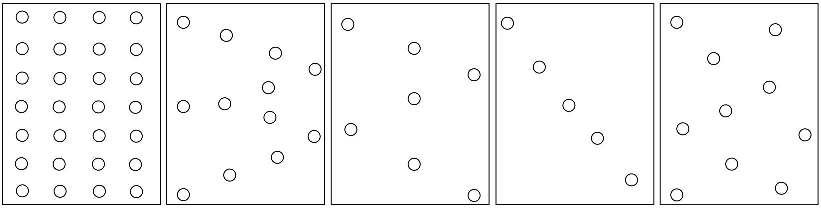


Figure 14: Patterns for zonal soil sampling sites

Table 8: Patterns for soil sampling

Patterns for soil sampling (Figure 14)	How	Pros and cons
Uniform grid soil sampling	Soil samples are collected in a grid pattern.	Enables a good representative sample of the area of interest or provides precise location data as needed for research and precision agriculture. Helps to identify patterns and variations that inform better management practices. Is labour intensive. However, results in data which can be effectively used for statistic or mapping distribution of soil characteristic across the field.
W-pattern and zigzag sampling	Soil samples are collected following a W-shaped or zigzag pattern across the paddock.	Commonly used in small paddocks to get a representative sample. Simple and effective for ensuring samples cover different parts of the paddock but may not capture fine-scale variability in larger paddocks or those which have high variability in constraints or nutrient requirements.
Transect soil sampling	Soil samples are taken along a straight line or a series of lines (transects) across the field.	It is useful to assess soil variability, identify distinct management zones, or where precise data is needed for research and precision agriculture. Helps to identify patterns and variations that inform better management practices.
Random	Soil samples are taken in a random pattern across the area of interest.	Commonly used in small paddocks to get a representative sample. Simple and effective for ensuring samples cover different parts of the paddock.

3. Decide on the timing and frequency for soil testing. Not every field has to be tested every year but is useful to rotate which paddocks are getting soil testing each year. Some nutrients, such as nitrogen, and some salts, are more mobile and dynamic are often tested annually whereas phosphorus and cations may be tested periodically. It is also useful to decide when in the season you plan to soil sample. For instance, will you test before pasture rejuvenation or before a cropping phase?

4. Consider other data sources of information in your sampling plan, if available. These can include historical knowledge of field variability, previous yield maps, satellite imagery, NDVI biomass index data, and state government soil and landscape mapping.

5. Determine the sample depth required. Depth samples of 0 to 10 cm are commonly collected to assess the nutrient content of the soil. However, soil can vary significantly down through the profile. Subsoil sampling (10 to 30 cm and 30 to 60 cm) is always recommended, particularly if subsoil constraints are likely. Recent research has shown that 5 cm increments for the top 20 cm is beneficial if soil acidity is the targeted concern. This is because soil acidity can vary significantly between soil layers (page 82 Soil acidity).

6. Decide how you will collect the samples. Soil samples can be collected with a shovel, intact corers or augers. Samples should be clearly labelled and kept cool before sending to laboratory for analysis.

Requesting laboratory tests

Typically soil testing in a laboratory is focussed on the soil chemical attributes of the soil. This provides insights into the physical behaviour and nutrient conditions of the soil profile. This improves decision-making about nutrient applications and soil constraint management.

Not all soil samples sent to the laboratory will need to undergo the same testing suites. The topsoil (0 to 5 cm, 5 to 10 cm) may require a full comprehensive test, but the subsoil layers may only require subsoil analysis testing.

Laboratory analysis of soil can include a simple assessment of pH and salt content or a more comprehensive analysis of all nutrients and attributes.

It may be necessary to contact your Landscape Board for further information on what tests to request from the laboratory.

Table 9 provides some guidance on recommended soil chemistry testing suites. Please note that laboratory testing suites may vary.

Table 9: Soil chemistry testing suites

Purpose	What analysis is required?
Use when you have limited background information or if an extended length of time has elapsed since the previous soil sampling.	***Comprehensive soil analysis*** This analysis is conducted generally for pH, EC (salts), organic carbon, macronutrients (N, P, K, S), cations (Ca, Mg, Na, K, Al), cation exchange capacity (CEC), exchangeable sodium percentage (ESP), micronutrients (Zn, Mn, Cu, B, Fe). Often there is an option for a technical report which will present the desirable ranges for nutrients rather than a basic table of results.
Use when troubleshooting a potential subsoil constraint.	Use the *Comprehensive soil analysis* as above. Augment with a subsoil constraint test option. Generally, this includes pH, EC, nitrogen, cations, cation exchange capacity (CEC), exchangeable sodium percentage (ESP), boron, chloride.
Use when assessing field variability with multiple individual samples, such as grid or zone sampling.	This requires more targeted testing. Commonly this analysis includes pH, phosphorus, EC, exchangeable sodium percentage (ESP). This data is used for variable rate lime, phosphorus and gypsum applications and calculations.

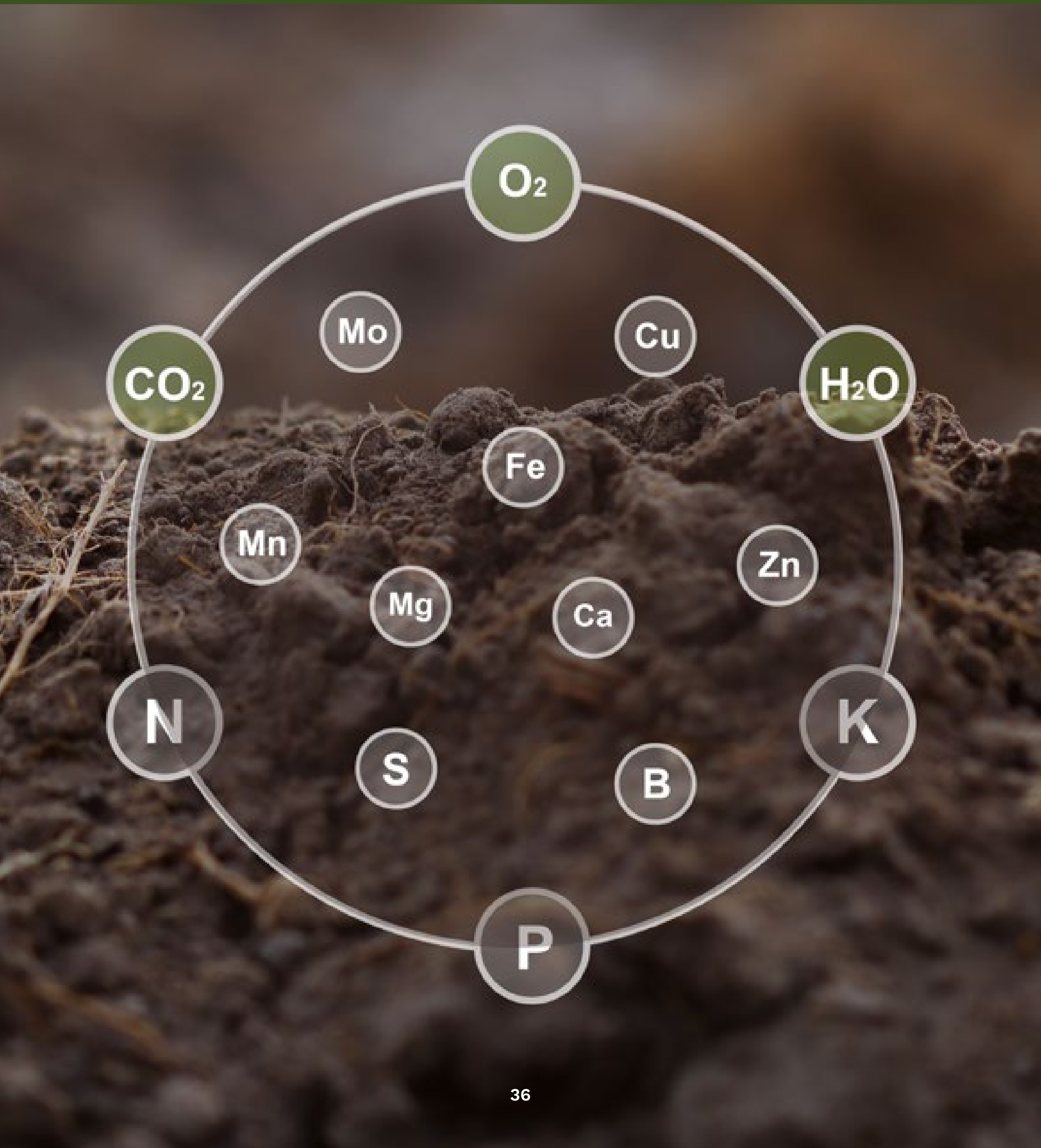
Testing your own soil

Laboratory soil testing is very useful but there are some simple tests that can be conducted on your own property to give a broad understanding of possible constraints and variability. You can use the *Knowing your soils SA ute guide* as a starting point. These include:

- assessing soil horizons (page 5 Soil horizons)
- simple home pH test kits (page 14 Soil pH)
- the water and ethanol test for non-wetting soils (page 88 Non-wetting soils)
- soil dispersion test (page 66 Assessing soil structural stability)
- soil carbonate fizz test (page 23 Calcareous soils)
- the ‘soil your undies’ method for assessing soil biology (page 48 Soil biology).

Section three

Nutrients for productivity



Plant nutrients and fertilisers

Plant nutrients

All plants require essential nutrient elements. Plant nutrient elements can be broken down into macronutrients, secondary nutrients, and micronutrients.

Macronutrients

nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg)

Secondary nutrients

sodium (Na), silicon (Si)

Micronutrients

zinc (Zn), manganese (Mn), copper (Cu), iron (Fe), boron (B), molybdenum (Mo), cobalt (Co), nickel (Ni), chloride (Cl), silicon (Si)

Nutrient management in soil requires knowledge about:

- the nutrient requirements of the plant type and how much has been taken up by the plants (Figure 15)
- the amount of nutrition removal from the farm gate per year (Table 10)
- how the soil types, conditions and constraints affect availability of the nutrients.

Using this information, a nutrient balance can be calculated and nutrients can be replaced in the system, ensuring deficiencies are detected early.

It is also important to consider the soils' nutrient requirements needed to optimise its function and performance. For example, calcium is an essential plant nutrient but is also a critical nutrient for improving soil structure and drainage.

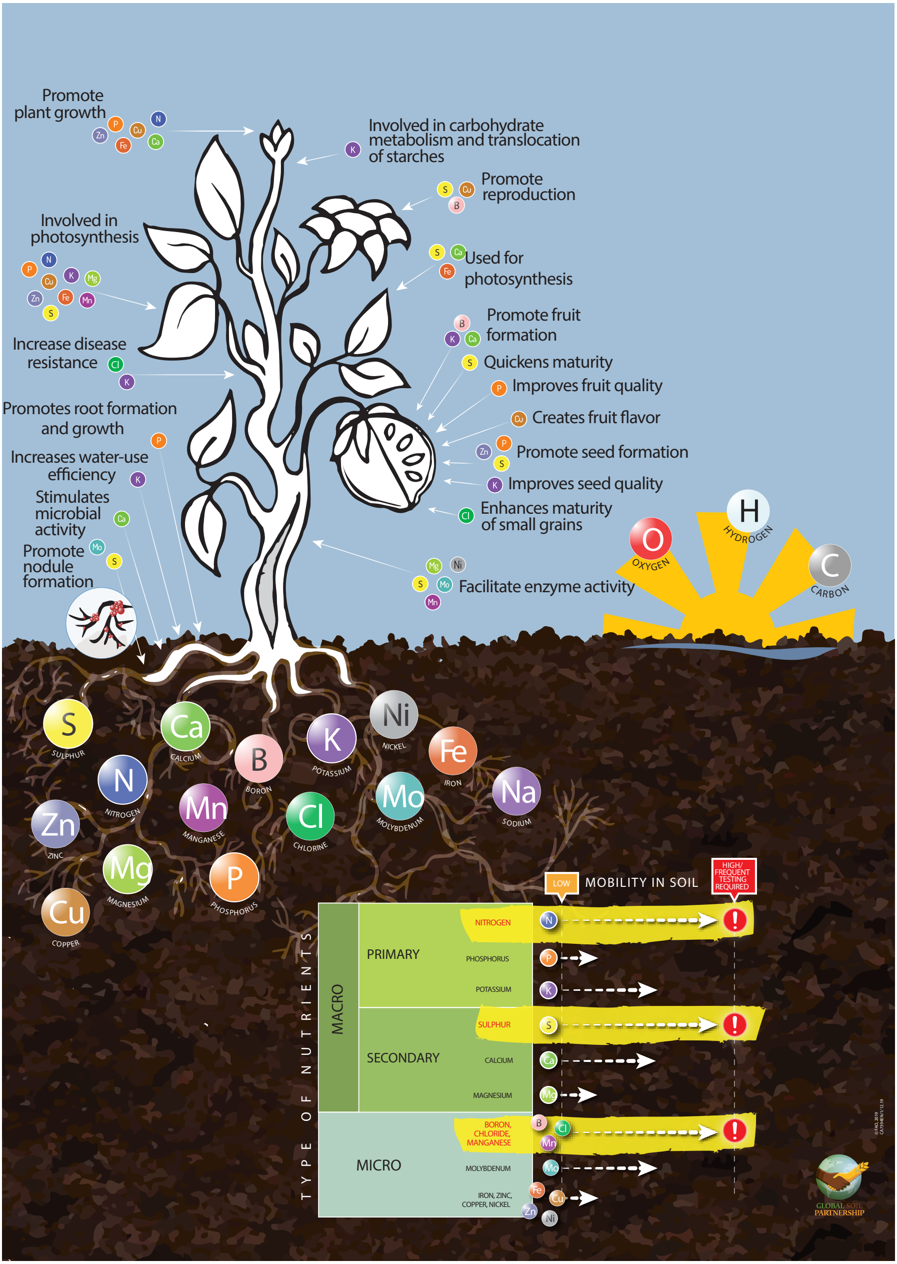


Figure 15: Role of nutrients necessary for plant growth.[5**]

Table 10: Nutrients removed from the farm gate by each crop type, per ha, per season

Crop type	N (kg)	P (kg)	K (kg)	Ca (kg)	S (kg)	Mg (kg)	Cu (g)	Zn (g)	Mn (g)
Cereals									
Wheat	23	3	4	0.4	1.5	1.2	5	20	40
Barley	23	2.7	5	1.3	1.5	1.1	3	14	11
Oats	17	3	5	1.5	1.6	1.1	3	17	40
Grain legumes									
Chickpeas (Desi)	33	3.2	9	1.6	2	1.4	7	34	34
Chickpeas (Kabuli)	36	3.4	9	1	2	1.2	8	33	22
Faba beans	41	4	10	1.3	1.5	1.2	10	28	30
Lentils	40	3.9	9	0.7	1.8	0.9	7	28	14
Lupins (sweet)	53	3	8	2.2	2.3	1.6	5	35	18
Lupins (white)	60	3.6	10	2	2.4	1.4	5	30	60
Peas (field)	38	3.4	9	0.9	1.8	1.3	5	35	14
Mung beans	45	5.1	11	1.6	1.1	n/a	6	n/a	n/a
Soybeans	70	4.8	17	n/a	n/a	n/a	n/a	n/a	n/a
Oil Seeds									
Canola	41	7	9	4	10	3.8	4	40	40
Linola	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Safflower	25	4.3	9	2	4	n/a	n/a	14	13
Pastures									
Lucerne hay	33	3.3	28	11	2.4	2.1	6	21	56
Lucerne seed	60	2.9	n/a	10	1.4	n/a	n/a	n/a	n/a
Medic hay	30	3	2	n/a	2	n/a	n/a	n/a	15
Medic seed	64	8.4	12	2	5	8.4	7	23	13

Adapted from: Hazelton, P., & Murphy, B. (2016). Interpreting Soil Test Results: What Do All the Numbers Mean? Chemin de Baillarguet: CSIRO Publishing. https://doi.org/10.1071/9781486303977

Plant nutrient efficiency in soils

When adding nutrients to the soil in the form of fertilisers, it is important to make sure that applications to the paddock are appropriate for the nutrient requirements of the crop and farm. Excessive fertiliser use can lead to high input costs and off-site impacts to the environment.

It is important to identify soil constraints by undertaking a soil health assessment. This is because physical constraints such as compaction and waterlogging, and chemical constraints such as low or high pH can reduce nutrient use efficiencies by plants. A soil test and nutrient planning tools can be used to develop a nutrient budget (page 30 Planning your soil sampling).

It is possible to calculate the amount of nutrient required, based on the current fertility status of the soil (by doing soil tests), the target nutrient level (depends on the type of farming) and the amount of seasonal nutrient removal (uptake by plants). The use of precision agriculture and variable rate technology will ensure nutrient application is needs-based and more cost effective and efficient (page 45 Precision agriculture).

Fertilisers should NOT be applied to:

- bare soil (except when sowing)
- on paddocks with low surface cover if heavy rain is forecast within 4 days
- waterlogged soils
- drainage lines, riparian buffer areas and waterways
- stock camps.

Foliar fertilisers

Some soils in South Australia have low nutrient-holding capacities and can be prone to nutrient deficiencies. These typically include sandy soils or those with very low or very high pH. Periods of low rainfall and high temperatures can exacerbate uptake of nutrients from the soil.

Foliar fertilisers, which are applied directly to the leaves of plants, offer a rapid and efficient means of supplying essential nutrients during the growth stage. This method bypasses soil-related issues, ensuring that nutrients are available for absorption through the leaf surface.

Foliar fertilisers need to be assessed as part of the whole nutrient management system. They are often unable to meet the complete nutritional needs of most crops, especially macronutrients like nitrogen, phosphorus, and potassium. Foliar burn, high labour costs and variable uptake by plants are also important considerations. Foliar fertilisers are best used in conjunction with considered soil nutrient management practices.

Identifying nutrient deficiencies

Plants can show the effects of certain nutrient deficiencies in their leaves and growth habits. Figure 16 gives some examples in cereal crops for manganese, nitrogen, sulfur and copper deficiencies. Table 11 gives more detail about each nutrient and the leaf and growth symptoms to look out for in crops.

Interveinal chlorosis indicating deficiency of manganese in cereal crop

Deficiency in cereal crop leading to chlorosis (yellowing) of leaves. Nitrogen typically expresses as chlorosis of lower leaves, sulfur expresses as chlorosis of newer leaves.

Chlorosis and necrosis of the leaf tip and leaf 'pig tailing' indicating copper deficiency

Figure 16: Plants can show the effects of certain nutrient deficiencies when their leaves are discoloured. Photos: Edward Scott

Table 11: Deficiency symptoms in plants and the effects of soil conditions on nutrient availability

Nutrient	Deficiency symptoms	Soil conditions reducing nutrient availability
Nitrogen	Light green- or yellow-coloured leaves (first evident in older leaves) Stunted growth Lower protein levels in pasture and grain Delayed maturity Decreased resistance to disease or insect attack Smaller grain and light test weight	Light textured or sandy soils where nitrate nitrogen is leached Waterlogged soils Mineral soils low in organic matter Soils where nitrogen has been depleted by a previous crop
Phosphorus	Stunted or reduced growth Dark green leaves or leaf purpling (severe) Reduced tillering in cereals	Soils with a pH less than 5.5 or more than 7.5 Soils with a high clay content Mineral soils low in organic matter Soils with high levels of available aluminium, iron or calcium
Potassium	Light green to yellow older leaves which later develop marginal leaf scorch or chlorosis (a yellow mottling of the leaves) Green 'spear tips' appear on the leaf tips	Continuously cropped soils with low organic matter Light sandy soils where potassium has been leached Dry conditions due to drought Prolonged periods of heavy rain High biomass export such as hay production
Sulfur	Very similar to nitrogen deficiency – a uniform pale green to yellow leaf Starts in the new leaves whereas nitrogen deficiency starts in the old leaves Poor, low yielding plants and low protein in field crops Canola leaves can have a cupped appearance	Soils low in organic matter that have been continuously cropped Low pH soils Acid sandy soils where sulfate has been leached (common in areas with high winter rainfall) Where high rates of nitrogen have been used

Nutrient	Deficiency symptoms	Soil conditions reducing nutrient availability
Magnesium	Interveinal chlorosis beginning in the tips of older leaves Veins remain green, the chlorotic areas change from yellow to brown (other colours in some plants) Leaves become brittle and necrotic and may drop prematurely Grass tetany in sheep and cattle	Sandy acid soils – particularly in high rainfall areas Cold wet conditions Where high rates of potassium or nitrogen have been used
Zinc	Leaf striping – light striping on both sides of the midrib Shows up initially as spotting along the middle of the leaf Chlorosis (yellow mottling of leaves) leading to necrosis and premature leaf fall Stunted growth In legumes, there is bronze spotting on older leaves, giving a mottled appearance Leaves reduced in size and misshapen	High pH soils or soils which have been heavily limed Where high rates of nitrogen and phosphorus have been used Cold wet conditions Soils high or very low in organic matter Soils with a history of significant topsoil drift and erosion which exposes the sub-soils Clay soils with high magnesium levels
Manganese	Chlorosis of recently matured leaves with no reduction in leaf size Loss of turgidity in cereals (leaves go floppy and weak) Cereal leaves can show multiple longitudinal striping Less pronounced mottling in some broad leaf plants	High pH soils Light sandy soils Soils with low organic matter Cold wet periods Limed soils Soil high in copper, iron or zinc
Copper	Marginal chlorosis of young leaves and necrotic tips Grains missing in the head of cereals Necrotic and brown spots over leaf surface Reduced growth and yields In cereal crops, there can be ‘pig tailing’ in new, flag leaves	High pH soils Soil with low organic carbon High rates of nitrogen and phosphorus have been used Alkaline and calcareous soils or soils which have been limed Cold wet periods Leached acidic soils Soils with high concentrations of iron and manganese

Nutrient	Deficiency symptoms	Soil conditions reducing nutrient availability
Iron	In young leaves, it appears as interveinal chlorosis Late in the season, leaf can yellow (veins remain green) Scorched margins and tips can appear Stunted growth Reduced yield and quality In legumes, nodules are pale to white in colour	High pH soils Poorly drained or aerated soils Compacted soils during cold, wet years Soils with high levels of metallic ions like zinc, copper and manganese Soils which have been heavily limed
Boron	Thick, curled and brittle tissues – cracking and splitting Surfaces of leaf, petioles, stems and midribs develop cracks Growth points can die when forming multiple side shoots	Soils with high levels of nitrogen or calcium Sandy soils that are easily leached Soils with low organic carbon Cold wet weather (especially following a protracted dry period)
Molybdenum	Like nitrogen deficiency – yellowing or pale leaves, stunting, necrotic leaf margins and tips starting in older leaves first Flowers can wither or be suppressed In legumes, nodules are pale to white in colour	Soils with low phosphate levels Low pH soils – particularly if they contain aluminium or iron oxides Soils with high copper levels or undergoing copper foliar applications
Nickel	Yellowing leaves and may lead to some dead spots on leaf margins Stunted growth and reduced vigour	pH adjustments can affect availability, increasing pH can reduce availability
Chloride	Deficiency appears as chlorosis of the younger leaves Plant wilts Distinct chlorotic and necrotic lesions (spotting) with abrupt boundaries between live and dead tissue Wilting of leaves at margins Highly branched root systems in cereal crops	Sandy soils in some inland high rainfall areas (chloride is present in coastal rainfall)
Silica	Weak plants that may be prone to lodging High susceptibility to pests or diseases	Silica is generally abundant in soils, but plant availability is dependent on soil pH, weathering, organic matter content

Nutrient	Deficiency symptoms	Soil conditions reducing nutrient availability
Cobalt	Poor nitrogen fixation, especially if molybdenum is adequate and legumes inoculated	Applications should be treated cautiously as overapplication can result in toxicity
Selenium	Poor plant recovery after stress	Applications should be treated cautiously as overapplication can result in toxicity

Precision agriculture

Precision agriculture (PA) enables land and crop variability to be identified and managed. Precision agriculture technologies are a suite of tools which include Global Positioning Systems (GPS), yield maps, auto-steer tractors, controlled traffic systems, variable rate (VR) and site-specific technologies. PA tools are discrete products that can be adopted individually or as a package.

Variable rate technologies (VRT) allow growers to specifically treat areas within a cropping field. It can include more accurate management of soil nutrition (e.g. the rate of application of fertilisers) and soil improvement (e.g. monitoring of pH changes). Benefits of VR application will vary between regions and between farmers within a region.

Do the sums before investing in PA to ensure any investment in new technology will increase returns, improve efficiency, or help meet other goals including maintaining or enhancing soil health.

Implementing precision technologies

When first shifting to variable rate inputs, start with those tasks that are not time-critical such as applying lime (page 86 Applying lime).

Variable rate technologies match nutrient or lime application to the specific area it is required. This approach can overcome inefficiencies in fertiliser and lime use and off-farm loss of nutrient in runoff.

At seeding, PA tools such as GPS guidance, auto-steer and variable rate application allow seed and fertiliser inputs to be changed on-the-go and placed where they are most needed. In many situations this results in improved productivity.

The first step is to start collecting spatial and quantitative data about the farm such as yield, biomass, elevation etc. This step will identify in-paddock variation that will allow you to decide whether the paddock or whole farm would benefit from variable management.

In-paddock crop or pasture variation can be measured and mapped at harvest and during the growing season. Soil variation is best measured between seasons. This data can be combined to map management zones.

If in-paddock variation is present, then consider investing in low-cost PA tools first. You can add tools as your experience and confidence grows. For example, many growers start with a yield monitor with GPS guidance that provides ±10 cm accuracy. They then combine this with some soil sampling to identify blocked management zones. Rates of treatment can then be changed manually.

More experienced growers may install or share a base station with real time kinematic (RTK) guidance that gives ±2 cm accuracy. They may add auto-steer equipment that can vary rates on-the-go to manage more complex zones.

Initially, the rate of lime or top-dressed phosphorus can be varied within or between paddocks based on a comprehensive nutrient analysis involving soil and plant tests. Starting variable rate technology with these activities allows operators to gain experience with the equipment set-up and coverage maps at periods when breakdowns or delays will not impact on harvest returns. As experience and confidence grows, inputs can be varied at seeding and at other key periods.

Section four

Principals of soil health and soil biology

Soil biology

Soil biota relates to the organisms (other than plants) within soil. The sizes range from relatively large soil animals such as ants, worms and dung beetles to microscopic organisms such as mycorrhizal fungi and bacteria. These organisms carry out a wide range of processes that are important for soil health and fertility.

All these organisms depend – directly or indirectly – on the organic matter in the soil. That means that some organisms feed on the organic matter in the soil while others eat the organisms that feed on the organic matter. These feeding relationships between the different types of organisms in the soil are very complex. However, the simple consequence of this complicated food web of feeding relationships is that the higher the levels of organic matter in the soil, the higher the diversity and populations of soil organisms.

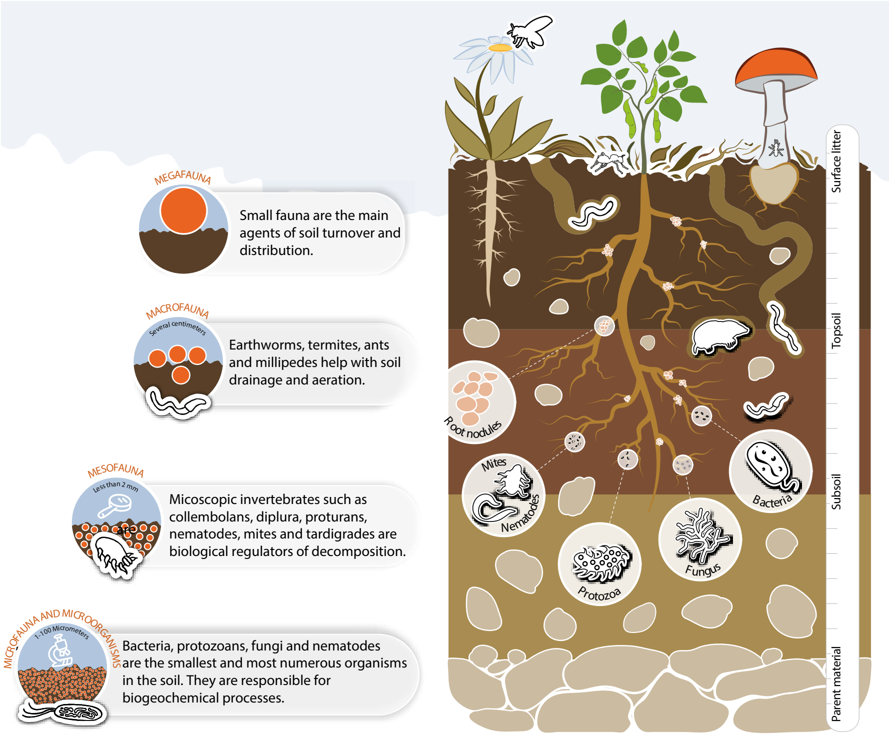
This means that soil with a wide variety of soil biological organisms and higher levels of organic matter can produce crops with higher yields and increase the sustainability of farming. This is because a healthy soil biota can:

- increase nutrient cycling and nutrient transformations
- regulate plant nutrient supply and loss (page 37 Plant nutrients and fertilisers)
- decompose plant residues
- improve soil structure.

Soil biological processes can assist in building soil organic matter which maintains soil health, increases fertility, improves water holding capacity, reduces erosion and encourages additional soil biology. These processes develop slowly. Growth and survival of soil organisms is dependent on varying soil conditions and land management practices. Table 12 explains the management practices that can improve the productivity and sustainability of soil.

Table 12: Management practices that improve soil biology, productivity and sustainability

Management practice	Why
Retaining organic matter (ⓘ page 60 Managing stubble)	When organic matter is retained in the system, it provides energy for biological activity in the soil.
Minimising soil disturbance through no or minimum till farming (ⓘ page 54 Maintaining ground cover)	Maintaining good soil structure through minimum till practices retains organic matter (energy for biological activity), promotes beneficial fungal communities, water infiltration and water holding capacity.
Managing soil constraints – maintaining good soil structure, treating soil acidity and sodicity, preventing waterlogging (ⓘ page 10 Soil structure, page 82 Soil acidity, page 67 Sodicity, page 26 Waterlogging in soils)	Managing soil constraints provides a favourable habitat for soil biota to be able to decompose organic matter, cycle nutrients and improve soil structure.
Using a diverse range of crops and pasture species	A diverse range of plant species helps avoid a build-up of pathogens which can be harmful for soil biology and crops.
Including cover crop rotations (ⓘ page 58 Living roots and cover crops)	Crop rotations provide living roots in the soil year-round which allows soil organisms, in particular fungi, to survive year-round. Cover crop residues can also provide energy for soil biology.
Using organic fertilisers and amendments in combination with inorganic fertilisers (ⓘ page 51 Organic fertilisers)	Composts and manures can help provide energy for soil biology. Organic amendments can also help to build a favourable habitat (good soil structure) where soil biology can thrive.
Maintaining ground cover using effective stocking rates and fertiliser management (ⓘ page 54 Maintaining ground cover)	Ground cover can help prevent erosion, regulate temperature, and retain moisture which can help provide a favourable habitat for soil biology. It also assists in supressing weeds which reduces the need for herbicides which can affect soil biology.
Ensuring proper inorganic fertiliser inputs.	Overuse of fertilisers can inhibit soil biological function.



*Adapted from Food and Agriculture Organization of the United Nations 'Soils Biodiversity: the world beneath our feet' (2019)***

Assessing soil biology

Soil biology can be assessed with laboratory tests. However, research is still assessing the best methods to relate the amount and type of biology with soil health. A simple and inexpensive way for landholders to assess soil biology is by using the 'Soil your undies' method.

To do this, bury a pair of 100% cotton underwear in the ground for around two months, after which it is excavated to assess the extent of decomposition. The decomposition of the cotton serves as a proxy for microbial activity in the soil. Remember to mark the location of the undies when you bury them.

Healthy, biologically active soils, rich in microorganisms such as bacteria and fungi, will decompose the cotton fabric more rapidly and completely. Conversely, poor soil health with low microbial activity will result in minimal decomposition. This test provides a simple way for farmers visualise presence of soil microorganisms in organic matter breakdown and nutrient cycling.

For more information about the 'Soil your undies' test, watch the video 'Dirty film unearths NT soil health' [6:57] at https://youtu.be/7D0B-JB6HB0. It was produced by Territory Natural Resource Management and shares the experiences of three Northern Territory farmers.

Organic fertilisers

Organic fertilisers refer to fertilisers supplied or manufactured from animal or plant by-products. A fertiliser is any material added to the soil or applied to a plant that improves the supply of nutrients and directly promotes plant growth.

A soil conditioner is a product which is added to soil to improve the soil's physical qualities, especially its ability to indirectly provide nutrition for plants. Biological inoculants, biochar and humic acids are considered soil conditioners.

It is important to compare nutritional value between products to ensure efficient application as well as to determine if the product will meet the needs of the crop or soil. A nutritional analysis should be sourced from the provider, or it would be a good idea to send samples to a soils laboratory for analysis.

Organic fertilisers typically have lower N, P, K values per kg compared to inorganic fertilisers, with nutrients being variable in quantity and composition. They are also slower releasing, meaning that it takes time for the nutrients to become available in the soil for plants. Organic fertilisers have the added benefit of improving the physical structure and biological composition of the soil. This helps to increase organic matter, cycle nutrients, and assist in improving productivity.

Recycled organic wastes, manures and biological amendments are a more environmentally friendly source of nutrients to improve soil health and productivity. Organic fertilisers have become popular with farmers and are used in combination with inorganic fertilisers, to gain the benefits offered by both fertiliser types.

Currently, some areas in South Australia do not have sufficient sources of organic fertilisers to meet the needs of the broadacre cropping and grazing industries. Transportation of organic fertilisers is an expensive option when compared to inorganic fertilisers. Thus, organic fertilisers are often not an economically feasible fertilising option for broadacre cropping and grazing industries. Local sourcing of wastes will improve the economics of their use on-farm due to lower freight costs.

Currently farming systems largely rely on energy-intensive inorganic fertilisers to supply nutrients because it is often simpler to apply and to time applications in response to plant demand. However, some farming enterprises are experimenting with the use of compost and compost tea liquid fertiliser to augment their existing nutrition program. As above, if practicable, composts should be tested before use for nutritional composition and presence of heavy metals. Composts should be spread when they are cool.

Adding other biological products

The interest in soil biology has encouraged market responses in the form of organic amendments, biological inoculants and microbial stimulants. The use of biological products is becoming more widely accepted by the farming community. However, the effectiveness of some biological amendments remains poorly understood.

Manures and composts have been in use for many years and have shown positive results for soil health and biology. However, cost-effective integration remains a challenge for some farming systems. Some biological inoculants have been subject to rigorous trials and have been proven to be useful across different soil and production types. An example is the use of rhizobia, the bacteria responsible for nitrogen fixation in legumes. This inoculant has a long history of research and development, and quality assurance.

Many organic amendments, inoculants and stimulants are now entering the market with varying levels of research and validation. Some excellent and novel research has been conducted in this space. However, ensuring research is replicated and trialled in your area can improve the chances of successful outcomes for your property. As with all new products it is advised to review the data, ensure the product is a fit for your production system and trial it on a smaller area of your property to validate it for yourself.

When deciding whether the addition of biological products is cost effective to your production system, it is important to be aware first of the physical and chemical constraints of a soil. The physical and chemical constraints influence the effectiveness of biological products. For example, when a soil is low in pH and high in acidity, adding soil biological products is ineffective until the soil pH is increased by liming (page 86 Applying lime). In this case, it is better to implement a long-term liming strategy first, and then add biological amendments once soil pH has been rectified.

A soil assessment of compaction, waterlogging, soil acidity and low soil organic matter content is beneficial before adding biological products (page 64 Soil compaction, page 26 Waterlogging in soils, page 82 Soil acidity, page 16 Soil carbon and soil organic matter).

What about biochar

Biochar is a form of charcoal produced from organic materials through pyrolysis (heating to a high temperature in the absence of oxygen) (Figure 17). Biochar has significant interest in Australia as a soil amendment due to its potential to enhance soil health, improve crop yields, and sequester carbon.

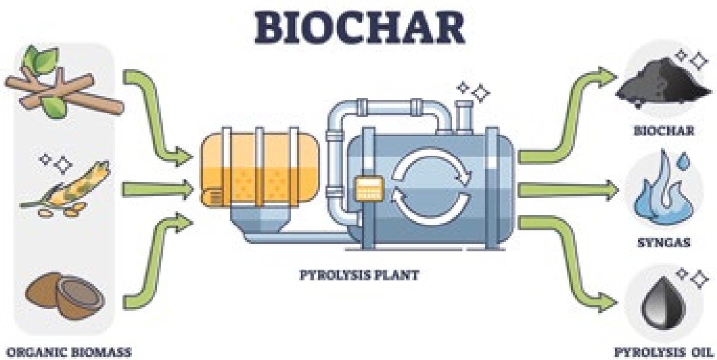


Figure 17: Biochar is a form of charcoal produced from organic materials through pyrolysis

Biochar has a high surface area and porosity, and can retain nutrients and water in some soils. Research trials have shown that there is, in some cases, an increase in soil organic carbon levels, improved soil structure and enhanced water retention, particularly in arid and semi-arid regions. Some trials have shown that adding biochar at the same time as compost can be beneficial in some soils.

Research has also highlighted that the benefits of biochar can vary widely depending on the type of feedstock used, the pyrolysis conditions (the pyrolysis temperature affects availability of some nutrients), the soil type, and the specific crop. Some studies have reported neutral or even negative effects on crop yields. The chemistry of pyrolysis is complex and so long-term data has yet to determine the impact of biochar of soil ecosystems and nutrient cycling.

Inadequate quality control remains a challenge for biochar production. This leads to significant variability in biochar quality and flow-on benefits for soil condition. Further research and monitoring are essential to fully understand the potential of biochar for soil health.

Some areas of South Australia, like Kangaroo Island, have local sources of biochar due to the 2019-2020 fires and so are ideally placed to test its effectiveness in different soil types and conditions. Biochar may benefit your soil for varying reasons, for example biochar can increase the capacity for sandy soils to retain nutrients and can also be utilised in soils with high sodium to aid in ‘binding up’ some of the sodium.

Trialling biological products

If farmers wish to conduct a trial on their farm, there are a few steps to follow to determine if the product delivers on its promise and the investment is worthwhile.

1. Have a clear understanding of what the product is claimed to do and how its effectiveness should be measured.
2. Choose a trial site paddock which is underperforming (but not the worst performing site).
3. Make sure boundaries are clearly marked with a GPS or physical markers.
4. Isolate the paddock from grazing animals.
5. Split the trial areas into an area to test the product and a similar sized adjacent area on the same soil type as a control (not treated).
6. Complete a suite of soil and pasture tests before adding the product.
7. Apply only the product to the trial site.
8. Have detailed records of the trial including dates, application rates, weather, pasture responses and other observations. Take photos during the season.
9. The trial should be undertaken for a minimum of 3 years to recognise any improvement in production and soil health.

Maintaining ground cover

Soils become more susceptible to wind and water erosion when there is no protective vegetative soil cover, particularly during dry periods. Valuable topsoil can be lost, leading to long-term decreases in productivity, soil structure and soil biology. Invasion of weeds is also common when ground cover is not maintained, and grazing pressure can further exacerbate soil structural stability and erosion.

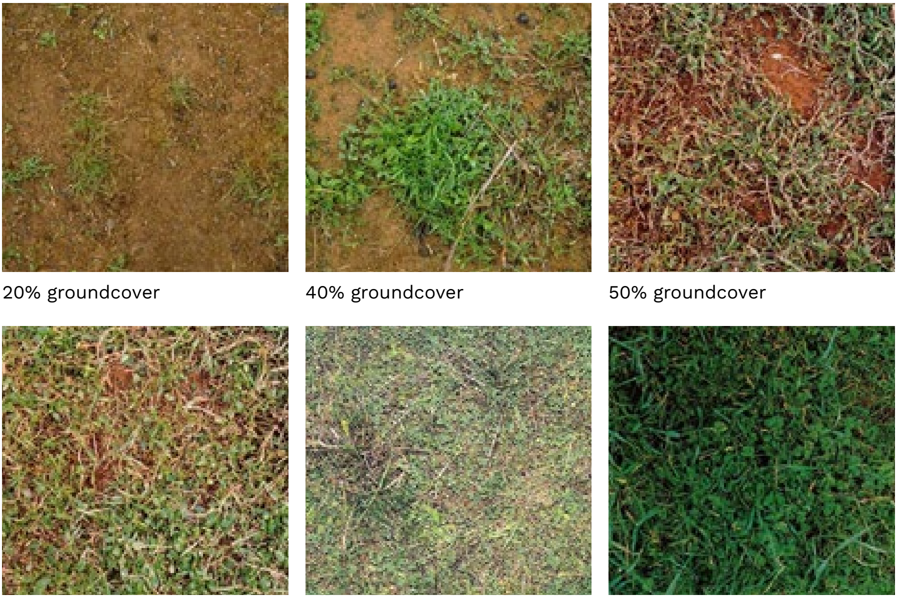
Photo: Cassandra Douglas Hill

Photo: Edward Scott

Management that maintains a protective vegetative cover on the soil surface can help minimise potential damage and allow rapid the recovery after rain. The vegetative cover can be living plant material, failed crops, crop stubbles or pasture residues.

The measurement and monitoring of ground cover is important in both grazing and cropping systems. A minimum of 70% ground cover is the accepted benchmark where rainfall is high. In sloping country, closer to 100% ground cover is needed.

Use the following photos as a guide to the amount of ground cover in your paddocks (Figure 18).



20% groundcover | 40% groundcover | 50% groundcover

80% groundcover | 90% groundcover | 100% groundcover

Figure 18: Visual representation of ground cover %. Images: Greg Lodge, NSW DPI; Primary Industries South Australia, 1996; Easy estimation of pasture dry matter levels, Appila / Bundaleer Pasture Group, Appila, SA.

Maintaining vegetative cover on pastures

The following practices will assist in maintaining vegetative cover on pastures:

- Reduce grazing pressure on pastures where groundcover is patchy or below acceptable levels.
- Remove stock from paddocks once the pasture falls below the following triggers:
  - 70% ground cover on flat country
  - 90% ground cover on hilly country
  - 800kg dry matter per ha.
- Reduce stock numbers prior to summer (e.g. sell lambs, poor breeders or mothers).
- Establish a stock containment area, where selected areas of the property are set up to hold, feed and water livestock during adverse weather periods. Once established, containment areas should be maintained and be available for use during emergencies.
- Plant kikuyu (not near watercourses), summer fodder, cover crop or a diverse range of summer active species suitable to climate and soil conditions to provide feed and groundcover in summer (page 58 Living roots and cover crops).

- Try to maintain and manage perennial pastures during dry periods as these will be the first to provide feed following breaking rains. If not managed properly however, the cost of repairing or re-sowing perennial pastures will be high.
- After a dry period, annual pastures may need to be re-sown with a subsequent lag in providing feed following breaking rain.

Maintaining vegetative cover in cropping land

The following practices are recommended to provide vegetative cover in cropping paddocks:

- Maintain groundcover through stubble retention.
- Consider green manure cover crops for summer soil cover (page 58 Living roots and cover crops).
- Standing anchored crops or stubble provide more protection than flat crops.
- After harvest, assess the quantity of stubble remaining to determine the extent of grazing it can support without risking topsoil loss. This will depend upon soil type, location and whether the stubble is standing or flat.
- Avoid the burning of stubbles and cultivate sparingly.
- Establish stock containment areas. These are selected areas of the property which are set up to hold, feed and water livestock during adverse weather periods. They should be considered as part of the property management plan and once established should be maintained and be available for use during emergencies.

Dung beetles and soil improvement

Like earthworms, introduced dung beetles can significantly improve the overall health of your soil. Dung beetles break down dung and build tunnel systems under dung pads, and so create large pores (macropores) in the soil.

Dung beetles benefit you and your soils by:

- improving water infiltration
- aerating the soils
- breaking down organic matter
- providing habitat for soil organisms
- enhancing plant root growth
- reducing soil compaction
- cycling nutrients and minerals between the subsoil and the surface
- incorporating organic matter and applied lime in the soil profile
- removing dung to reduce flies, odours and dung-borne diseases
- sequestering carbon in the soil.

Dung beetle tunnels vary in depth from less than 10 cm to up to 1 m, depending on the beetle species and the soil type. The tunnels are often lined with dung. The beetles lay their eggs in 'brood balls' made from dung.

Soil casts around dung pads indicate beetle activity.

Managing dung beetles

Check your dung pads to assess the number and species of dung beetles you already have. The poster, *Introduced dung beetles of the Limestone Coast*, provides information about the 9 dung beetle species found in southern South Australia.[6] The poster includes useful management advice about the seasons when different dung beetle species are active.

Maintain healthy populations of dung beetles by selecting parasite control chemicals, insecticides and other farm chemicals that do not harm dung beetles.

For information about how you can increase and manage your dung beetle population, go to the webpage, *Dung beetle benefits*.[7]

This webpage contains a series of three videos that explain:

- the importance of dung beetles
- establishing your dung beetle population
- managing threats to your dung beetle population.

To help manage your dung beetle population, consult with your neighbours to implement a neighbourhood program to establish sustainable dung beetle populations in your area.

Photo: Andrea Tschirner

Living roots and cover crops

Deep rooted cover crops can provide living roots over the winter and or the summer season. Summer cover crops and perennial pastures take advantage of episodic summer rains and prevent premature annual pasture germination and erosion. They also provide energy for soil biology (page 48 Soil biology). Some cover crops (corn, sorghum and sunflowers) have the added advantage of providing either summer fodder or cash income to offset establishment costs.

Stocking rates need to be carefully managed over summer. Release paddocks or confinement feeding provide a safety net in dry summers.

South Australia has low summer rain. Harvesting is often still underway when soil moistures are high enough to ensure successful planting. For these reasons, it can be advantageous to harvest and plant in close succession. Cover crops can also be used to rejuvenate pastures in grazing systems or in rotation over the winter growing season in annual cropping production.

Often cover crops are considered when soil condition is already degraded. This can make establishing cover crops difficult. Select a variety of plant species and consider drought tolerant species, particularly deep-rooted ones. The improved soil and additional soil organic matter helps water retention. Table 13 explains the productive and sustainable benefits of using cover crops. Seek advice from your Landscape Board staff about which species are more successful in cover crop mixes in your area.

Table 13: Benefits of cover crops

Benefit of cover crops	Why
Soil structure improvement	Living roots create pores and channels, which enhance soil aeration and water infiltration. This leads to better root growth and nutrient uptake for subsequent crops.
Increase in soil organic matter and carbon	When cover crops decompose, they contribute organic matter to the soil with essential nutrients, supporting an active soil microbial community, nutrient cycling and soil fertility.
Erosion prevention	Cover crops protect the soil from wind and water erosion by providing a continuous ground cover.
Water retention	Cover crops increase organic matter and build soil structure which are important for nutrient retention
Nitrogen fixation	Leguminous cover crops, such as clover and vetch, fix atmospheric nitrogen and convert it into a form that plants can use.

Benefit of cover crops	Why
Weed suppression	Cover crops suppress weed growth by outcompeting weeds for sunlight, water and nutrients.
Habitat for beneficial insects	Cover crops provide habitat and food sources for beneficial insects, such as pollinators and natural pest predators.
Crop diversity	Crop diversity can disrupt pest and disease cycles and reduce the prevalence of crop-specific pests and diseases.

Photo: Cassandra Douglas Hill

Managing stubble

Stubble management involves retaining stubble either in or on the seedbed between crops. The key benefits of retaining stubble are:

- maintaining or increasing soil organic carbon (SOC) levels (page 16 Soil carbon and soil organic matter)
- promoting nutrient recycling
- increasing both the amount and activity of microorganisms in soil (page 48 Soil biology)
- providing cover that reduces erosion risk (page 76 Soil erosion).

Retaining crop stubble can also improve soil moisture retention by reducing evaporation and increasing rainfall infiltration rates. This can maximise grain yield potential and water use efficiency in the following season.

Managing high stubble loads requires careful planning to ensure effective sowing during the following season. There is a suite of measures that can be applied to manage stubble including no-till and minimum till cultivation systems, incorporation, mulching, grazing, fire, and the use of emerging technologies such as stubble digesters.[8]

Photo: Edward Scott

Photo: Edward Scott

Stubble management requires a planned approach with the flexibility to make changes as the harvest cycle progresses.

Minimum or no-till farming practices should be used as they have benefits for soil health as well as retaining stubble cover. They can be integrated with wide row spacing and inter-row planting (particularly for grain crops) and with other practices like tramlining and slot planting.

For weed control during the fallow period, disc implements can be used to handle high stubble loads and minimise soil disturbance. However, the implements need to be able to handle high stubble and trash loads.

Keeping stubble on ground for as long as possible on erosion-prone paddocks during the fallow period will minimise the erosion risk. Stubble will break down naturally to some extent depending on the season, particularly with rainfall.

When faced with a combination of stubble issues such as weed, pest and disease pressures during higher rainfall periods, it may be necessary to intervene with tillage disturbance or to burn the stubble. Use best management practices to achieve a burn that minimises the detrimental effects on soil health, erosion risk and environmental impacts.

There are three key cropping stages in which decisions need to be made about managing stubble loads.

1. At harvest, you need to decide the height of the header cutting and the spread pattern of the stubble. A stubble cutting height of at least 10 cm is required to effectively reduce erosion risk and the stubble chaff should be evenly spread.

2. Post-harvest, you need to consider:

   - the amount of stubble left on the paddock now and is likely to be present when sowing
   - the post-harvest stubble characteristics
   - the amount of stubble your sowing implement can handle.

Recommended post-harvest practices include:

- using minimum or no-till practices
- grazing with livestock – monitor stubble levels to ensure paddocks are not overgrazed or compacted. Also, the nutritional value of stubble is variable depending on the crop grown.
- mulching to incorporate and break down stubble using harrows, prickle chains, disc chains, stubble crunchers or trash cutters
- incorporating stubble using either shallow or deep incorporation. This practice provides similar benefits to mulching but is more aggressive.

Excessive tillage, apart from removing stubble, can reduce soil health and degrade soil structure. Burning and baling are effective in removing stubble but results in a loss of soil carbon and nutrients. If used regularly it will result in a decrease in soil health. Burning is used as a last resort to manage heavy stubble loads and invasive weeds or pests.

3. At sowing, there are several options for managing stubble and achieving successful sowing. The seeding equipment used may require that stubble needs to be reduced for efficiency. If stubble needs to be reduced, it is preferable that this is done as close to sowing as possible.

Disc implements can often handle heavier stubble loads and disturb the soil less than tined implements. But the use of disc implements can result in ‘hair pinning’ (that is, stubble is bent rather than cut and pushed into the sowing groove with the seed). This reduces the seed to soil contact. Other equipment combinations including press wheels, coulter discs and trailing harrows can be used to reduce stubble loads.

High stubble load planters or alternative cultivation methods (no-till and minimum till cultivation) can be used without the need to reduce stubble loads. If using tramlines and inter-row sowing, standing stubble will make sowing easier.

Section five

Knowing your soil constraints

Soil compaction and soil structural stability

Soil compaction

A compacted soil is a denser section or layer of soil within the soil profile (Figure 19). The soil particles are packed closer together with reduced pore spaces between them. Compacted layers can be formed by natural processes or by human activity such as heavy traffic. In South Australia, soils are mainly compacted by the movement of machinery or livestock, particularly when the soil is moist. Although compaction may also occur in dry, light textured soils.

Figure 19: Identifying compacted soil. Photos: Edward Scott

The decrease in pore spaces is a problem in cropping paddocks and pasture because large pores are needed to store air and water, for roots to grow in and support soil biology for plant growth. The diagram on the left of Figure 20 shows a normal soil which allows good movement of water and air through the pore spaces. While the diagram on the right shows a compacted soil where the movement of water and air is constricted. Hence, compaction leads to rough seedbeds, poor crop establishment, slow root growth, reduced water infiltration, reduced biological activity and reduced crop yields.

Compacted layers hinder water infiltration by preventing root growth and the storage of organic matter in the soil. Reducing the use of farming practices that cause compaction such as uncontrolled machinery traffic or pressure from livestock. Minimum tillage can prevent the loss of organic matter in your system. Soils with more organic matter have better structure. Retained stubble and cover crops decompose in the soil adding organic matter to the profile. This acts like a glue to aggragate soil particles together.

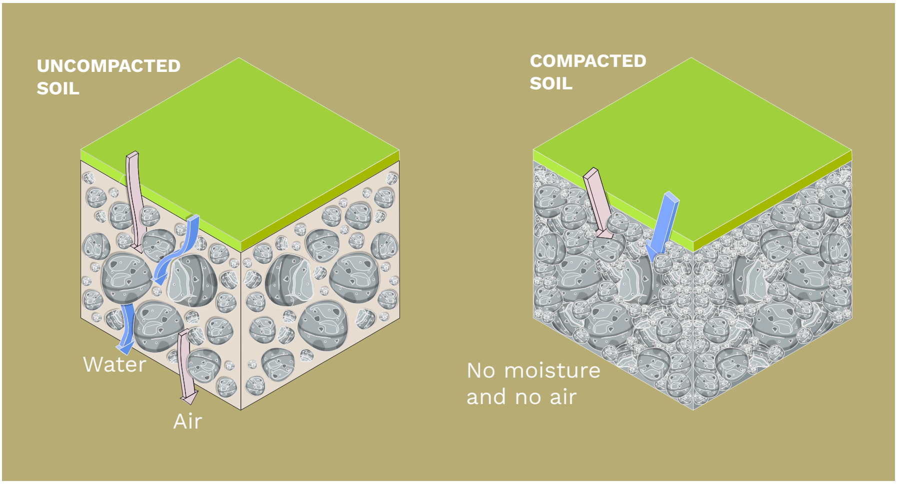


Figure 20: The effect of compaction on soil structure

Assessing soil compaction

You can evaluate the density and resistance of soil to penetration using tools like a penetrometer. Commercial penetrometers with pressure gauges are available. But you just need a steel rod with a pointed end.

Using moderate pressure, push the rod into the soil and feel for any difference in the strength required to push the rod into the soil. Note the depth at which you feel more resistance.

Using a penetrometer can give you a good indication of any surface or subsurface compaction layers. Be careful to watch for tree roots or rocks. To assess if the soil is truly compacted the penetrometer test should be conducted when the soil is moist. An option is to conduct the test around rainfall events to ensure the soil is moist. Repeat at several locations. The penetrometer test can be conducted on drier soils, especially in sands, to identify hard-setting soils. If the soil is dry, then the assessment is commonly 'comparative' between sites to assess the depth to which the resistance increased.

You can also look at root depth and growth habit. If plant roots begin to grow sideways or are stunted, there may be a subsurface compaction or hard-set layer blocking their growth.

Prevent soil compaction by:

- using controlled trafficking of machinery and permanent raised beds (cropping and horticulture)
- retaining stubble (cropping) and maintaining good groundcover (grazing)
- using effective rotational grazing practices to provide good ground cover to help cushion the effect of livestock hooves on soil (grazing).

Controlled traffic farming (CTF) limits compaction zones to permanent wheel tracks. It involves the use of precision agricultural technologies (page 45).

Repair compacted soils by:

- growing deep-rooted perennial pastures (grazing) and 'primer' crops (cropping). For instance, growing tap-rooted plants such as lucerne on alkaline soils. Primer crops such as tillage radish and chicory are sometimes able to 'drill' through gaps in compacted layers.
- strategic deep ripping or delving paddocks. This needs to be done with specialist advice to make sure the soil structure created is not quickly lost.
- introducing deep burrowing earth worms and dung beetles (page 57 Managing dung beetles).

Soil structural stability

Soil structural stability refers to the soil's ability to maintain its structure and porosity under external stresses like water, wind and mechanical forces. Stable soils resist erosion and compaction, and have better water infiltration, root penetration and air exchange.

Factors influencing soil structural stability include:

- soil texture (page 7 Soil texture).
- organic matter content (page 16 Soil carbon and soil organic matter)
- microbial activity (page 48 Soil biology).

These factors help bind soil particles together. Sodicity (the amount of sodium in the soil) can also affect the soil stability (page 67 Sodicity). Improving soil structural stability involves practices like adding gypsum, organic amendments, reducing tillage and maintaining vegetation cover.

Assessing soil structural stability

When you test for soil stability, you are looking for either slaking or dispersion.

Slaking is the process whereby soil aggregates fall apart when they become wet, especially when dry soils rapidly become wet. During this wetting up process, the dry soil inside the aggregate strongly attracts water and the air escaping the previously dry soil pores can produce enough outward pressure to break apart the aggregate, a situation exacerbated by the cohesive forces weakening as the aggregate becomes wetter.

Topsoils are more susceptible to slaking than subsoils because they (a) become drier and (b) wet up more quickly during rainfall or irrigation events. Organic matter provides a great deal of protection against slaking because it both acts as a 'glue' that holds aggregates together and its presence tends to slow the rate of wetting of aggregates enough to reduce the pressure of escaping air bubbles.

Dispersion is a process whereby individual clay particles are released into soil solution. Dispersion usually requires some degree of physical disturbance of wet soil, but the degree to which dispersion occurs depends on the amount of sodium present.

Dispersive soils can cause many land management challenges including:

- gully and tunnel erosion
- surface crusting
- reduced seedling emergence
- increased runoff.

When erosion is a risk, they may require specialist management. Applying gypsum (page 70) can assist in managing dispersive soils.

Note that some sodic soils do not disperse (i.e. if they are saline as well) and some dispersive soils are non-sodic. A laboratory soil test for exchangeable sodium percentage (ESP) can help identify sodic soils (page 68 Exchangeable sodium percentage test).

Sodicity

Sodicity refers to the presence of high levels of sodium ions in the soil relative to calcium and magnesium ions. This condition can cause problems for farmers because it leads to poor soil structure, reduced water infiltration and lower soil aeration. All these factors negatively impact plant growth.

Sodic soils can have high pH. They have a slippery, soapy texture when wet. For more detailed information on dispersive soils see the *GRDC Dispersive Soil Manual* https://grdc.com.au/__data/assets/pdf_file/0031/585463/GRDC_DispersiveSoilMan_Final.pdf

These soils tend to form hard crusts when dry, which can prevent seedling emergence. Sodicity becomes a significant problem for farmers as it can restrict the crops which can be grown, decreasing agricultural productivity (Figure 21).

Managing sodic soils often involves the application of gypsum (calcium sulfate) to displace the sodium and improve soil structure (page 70 Applying gypsum). Specific water management practices are also needed to ensure that the excess sodium is leached from the soil profile, particularly if the water table is less than one metre from the surface (page 26 Waterlogging in soils).

You can do an easy test for soil dispersion in the field (page 69 Testing for soil dispersion and slaking). Laboratory tests will also give a good indication of the degree of sodicity using the exchangeable sodium percentage ESP test (page 34 Requesting laboratory tests).

Exchangeable sodium percentage test (ESP)
Exchangeable sodium percentage is calculated as the proportion of the cation exchange capacity (CEC) occupied by the sodium ions and is expressed as a percentage. An ESP test can be conducted by most soil laboratories. For more information on laboratory soil testing refer to (page 34 Requesting laboratory tests).

In Australia, sodic soils have an ESP of 6 to 14% and strongly sodic soils have an ESP of 15% or greater. Soils with an ESP of greater than 6 are usually responsive to gypsum. However, predictions based on ESP alone may be inaccurate. Therefore, a soil dispersion test should also be done.

Typical application rates for gypsum are around 5 t/ha and are applied every 3 to 5 years. Longer-term management strategies need to be in place to maintain and increase organic matter in soils to improve hardsetting soils and to enhance the effect of gypsum.

Figure 21: Surface soil crusting in sodic soils. Photos: Edward Scott

Testing for soil dispersion and slaking

1. Collect some surface soil aggregates (10 to 20 mm in diameter).

2. Gently place the aggregates into a flat bottom dish with enough distilled water or rainwater to cover the aggregates. It is important to use rainwater or distilled water for this test. Tap water contains minerals that will affect the test.

3. Watch the aggregates carefully for the first few minutes to observe if slaking occurs i.e. the soil aggregates fall apart. It will typically occur within the first 20 minutes. Use Figure 22 to score the degree of slaking. The lower the number, the higher the degree of slaking.

4. After 20 minutes, check for dispersion. it is indicated by cloudiness or milkiness around the base of the aggregate. Use Figure 22 to score the degree of dispersion that has occurred. Again, the lower the number, the higher the degree of dispersion. If the soil is dispersive, use the 'testing for gypsum-responsive soils' information below to assess whether the soil can be treated with gypsum (page 67 Sodicity).

Slaking test		
Complete slaking. Aggregates break apart in less than one minute.	1	
Partial slaking. Aggregates remain partially intact.	2	
No slaking. Aggregates remain intact.	3	

Dispersion test		
Dispersion present. Obvious milkness after 20 minutes.	1	
Slight dispersion present. Faint milkness observed after 20 minutes.	2	
Not dispersive. No milkness observed after 20 minutes.	3	

Figure 22: How to score the slaking and dispersion tests. © Soil Science Australa

Applying gypsum

Gypsum is a soft, soluble sulfate mineral composed of calcium and sulfate ions. When added to sodic soils, the gypsum replaces the sodium with calcium on the exchange sites of charged clay particles. This makes the soil less prone to dispersion and hardsetting when dry. Calcium also improves the soil structure, so the soil is less prone to swelling and surface crusting.

Some soils do not respond to gypsum treatment e.g. non-sodic soil, saline soil and some sandy soils.

Assessing gypsum-responsive soils

To identify gypsum-responsive soils:

1. Do a soil dispersion and slaking tests (page 69 Testing for soil dispersion and slaking).
2. If the soil is sodic, do the ‘testing for gypsum-responsive soil’ to show if the soil responds to added gypsum (Figure 23).
3. Check the exchangeable sodium percentage (ESP) values using a laboratory soil test explained below.

Testing for gypsum-responsive soils

1. Place a small handful of soil in each of two glass jars (or transparent containers with lids) half-filled with distilled water or rainwater. Write 'gypsum' on one jar with a marker.

2. Add a small handful of gypsum to the 'gypsum' jar.

3. Shake the two jars and leave them for 24 hours.

4. If the soil is dispersive and responsive to gypsum, the soil will settle out in the 'gypsum' jar. But the jar without gypsum will remain cloudy. As shown in Figure 23, the jar on the left is dispersive soil without gypsum, jar on the right is the dispersive soil with gypsum. The gypsum helps to aggregate the clay particles together rather than staying as individual particles in solution. In aggregates, the clay can fall to the bottom of the jar.

Figure 23: Example of the gypsum jar test. Jar on the left is dispersive soil without gypsum, jar on the right is the dispersive soil with gypsum. The application of gypsum aggregates the clay particles out of suspension. Photo: Edward Scott

Salinity

Salinity has a negative impact on the productivity of agricultural land. Salinity in South Australia is a problem in all principal agricultural areas. It can affect dry and irrigated land.

The clearing of deep-rooted native vegetation following European settlement triggered a rise in groundwater tables resulting in the spread of saline seepage. Salinity not only affects the growth of crops and pastures but also impacts on the quality of surface water, groundwater and biodiversity.

Salinity and sodicity are often confused. Salinity refers to the accumulation of salts. These salts can be composed of sodium, calcium and magnesium combined with chloride, sulfate or carbonate to form salt molecules. Sodicity refers to the presence of a high proportion of sodium in the soil.

You can recognise soil salinity by looking at the types of plants in the landscape. In pastures, plant indicator species such as samphire and sea barley grass can indicate elevated levels of salinity (Figure 24). In cultivated land, salinity can be identified by poor crop yields or boggy areas.

Figure 24: Finding samphire in the paddock can help identify high salinity.
Photos: Cassandra Douglas Hill, Nick Modra

Units used for measuring electrical conductivity

- deciSiemens per metre (dS/m)
- milliSiemens per centimetre (mS/cm)
- microSiemens per centimetre (µS/cm)

To convert between these units:

1000 µS/cm = 1 mS/cm = 1 dS/m

Testing soil salinity

Salinity, or total soluble salt content, can be measured in a soil solution. Usually this is done by mixing a 1:5 ratio of soil and distilled water (i.e. 10 g of soil with 50 mL of distilled water), shaking the sample and measuring with an electrical conductivity (EC) probe. The probe will give the salinity of the sample in deciSiemens per metre (dS/m). The reading usually is labelled EC ($1:5_{water}$) in laboratory test results.

The threshold levels of soil salinity [EC ($1:5_{water}$)] which affects plant growth varies depending on the soil texture. The salinity threshold values are commonly 0.15 dS/m in sands, 0.2 dS/m in loams or 0.3 dS/m in clays. They differ because soils with higher clay content contains more water which is unavailable for plants to use.

An alternative measure of soil salinity provides salinity thresholds that don't vary with soil texture. This test is known as EC for a saturation extract and is usually labelled ECe in laboratory test results. ECe values are higher than EC ($1:5_{water}$) values because their measurement involves adding only enough water to create a 'paste', so the dissolved salts are much less diluted than when 1 part of soil is mixed with 5 parts of water. To estimate ECe from an EC ($1:5_{water}$) reading, multiply the EC ($1:5_{water}$) reading by the conversion factor for the soil texture (Table 14).

Table 14: Conversion factors for estimating ECe from EC ($1:5_{water}$) readings

Texture	Conversion factor
Sand to clayey sand	14
Sandy loam to clay loam	9.5
Clay	6.5

Source: South Australian Government[9]

For agricultural production, several salinity categories can be defined based on ECe ranges (Table 15). These can be used to make decisions about how salt-affected areas might be managed.

ECe vs EC ($1:5_{water}$)

The measurement of ECe is much harder than measurement of EC ($1:5_{water}$) because most electrical conductivity probes are designed to measure EC of water (rather than 'mud'). In fact, laboratory test results showing ECe are usually not measured but are calculated from EC ($1:5_{water}$) using conversion factors like those shown in Table 13. The main benefit of ECe over EC ($1:5_{water}$) is that the additional water needed to create a paste from a clay soil almost exactly counteracts the 'dilution benefit' of strongly held water that clays provide. This makes interpreting ECe simpler because the same threshold values apply to all soil textures.

Table 15: Vegetation indicators for each salinity category

Salinity category	Water table	Vegetation indicators	Indicative ECe (dS/m)
Low	None	No evidence of salt effects	< 2 surface < 4 subsoil
Moderately low	Deeper than 2 m	Subsoil salinity, deep rooted horticultural species and pasture legumes are affected.	< 4 surface 4-8 subsoil
Moderate	Shallower than 2 m	Many field crops and lucerne are affected. Halophytic species like sea barley grass are evident.	4-8 surface 8-16 subsoil
Moderately high	Varies seasonally within 1 m of surface	Most field crops and lucerne will not grow. Halophytes such as curly rye grass and saltwater couch are common. Strawberry clover productivity is diminished.	8-16 surface 16-32 subsoil
High	Varies seasonally within surface	The land is dominated by halophytes and bare areas. Samphire and ice plant are evident. Puccinellia and tall wheat grass may grow.	16-32 surface > 32 subsoil
Very high	Near surface most of the year	The land is too salty for productive plants. It supports samphire, swamp tea tree or other halophytes.	> 32 surface
Extreme	Near or at surface most of the year	The surface is bare and salt encrusted.	> 32 surface

Source: Adapted from Assessing agricultural land[9]

Managing salinity

Saline land is land that contains enough salt to negatively affect the growth of most plants. It can be managed as pasture to improve ground cover and maintain productivity. Remediating saline land takes time and money. Some highly saline land may not be able to sustain vegetation growth at all.

Where land is strongly saline, fence the affected area to prevent livestock overgrazing the groundcover. Then revegetate with native salt-tolerant trees and shrubs, if possible. This will also protect the soil surface from erosion.

In some cases, you may need to construct surface drains or subsurface drains. Manage waterlogging by installing shallow drains or constructing diversion banks to reduce run-off onto the site. Check with your Landscape Board prior to any drainage installation as it may require a permit.[10]

Mildly saline-affected grazing areas can be managed by:

- sowing tolerant pasture species
- allowing 12 to 18 months for plants to establish before grazing
- ensuring that established tall wheatgrass is well grazed to maintain the pasture in a vegetated state
- fencing small areas and managing them separately to avoid under- or over-grazing
- planting deep rooted vegetation like trees in groundwater intake areas. This will stabilise or reduce the level of the groundwater table.
- minimising irrigation in areas of shallow groundwater levels.

Salt tolerant pasture species

A range of salt-tolerant native grasses and introduced grass and legume species can be established as pasture on saline land. These include:

- *Puccinellia* and tall wheatgrass – *Puccinellia* seed should be dropped on the surface while tall wheat grass needs to be sown beneath the soil surface. Seed *Puccinellia* at 6 to 10 kg/ha and tall wheat grass at 10 to 20 kg/ha (or at 8 to 12 kg/ha if sown with tall wheat grass).
- *Balansa*, strawberry clover or messina
- Saltbush is an option if waterlogging is not an issue. Cultivate and seed in early autumn. Leave the soil as ridged and rough as possible to allow some salt leaching out of the soil profile.

Control weeds such as sea barley grass, through chemical topping the previous spring. Also control existing volunteer plants on saline land, including natives. Volunteer plants are plants which grow on their own without being planted.

Soil erosion

Soil erosion, the mass movement of soil particles by wind and water, is a significant threat to vulnerable soils in South Australia (Figure 25). Soil erosion depletes the productive capacity of the land by removing nutrients, organic matter and clay from soil. The removal of 1 mm of topsoil represents 10 to 12 tonnes per hectare, with the loss of approximately 10 kg/ha of nitrogen and 2 kg/ha of phosphorus.

Large tracts of agricultural land can be lost due to gully erosion, while silt in watercourses and dams can damage aquatic and marine habitats and interfere with the respiration of fish and other species.

The risk of erosion is increased by the physical disturbance of soil and the removal of ground cover. Ground cover can be living plant material, cover crop, failed crops, crop stubbles or pasture residues. Very dry seasonal conditions increase the risk of erosion because of the poor growth of crops and pasture.

Fortunately, there has been an overall improvement in erosion protection in South Australia over the last 20 years despite several years of very dry seasons. The risk and incidence of soil erosion has significantly reduced by:

- the adoption of minimum tillage (now used for sowing around 80% of crops) and stubble retention farming practices
- improved grazing management including confinement feeding.

However, erosion still occurs predominately because of episodic and extreme wind or rainfall events, particularly after severe or prolonged drought or fire. Reclaiming areas subject to soil erosion is difficult, costly and typically takes decades.

Figure 25: Wind and water erosion in South Australia

The loss of ground cover due to fire also significantly increases the risk of erosion. Also, high soil temperatures from fire affects the mineral, organic and structural properties of the soil. This makes it more prone to erosion.

Climate change is likely to increase soil erosion risk because it is expected to deliver a warmer, drier climate with an increase of severe weather events.

Assessing soil erosion risk

Measure and monitor your ground cover regularly. This applies to both pasture and cropping (growing crops and stubble). Use Figure 18: *Visual representation of ground cover %* (page 55) as a guide to estimate the percentage of ground cover in your paddocks.

Wind erosion risk

Wind erosion is more likely to occur on sandy soils. Sandy soils lack structure and individual sand particles, because they don't strongly cohere (hold together), are susceptible to being moved by strong winds. The tendency of clay particles to cohere means that the surface of loam and clay soils is usually aggregated and individual aggregates are usually too big to be moved by strong winds. The low water holding capacity of sandy soils also means they are more likely to be bare, especially during dry periods.[11] Sandy soils susceptible to wind erosion are primarily found in the southern coastal areas of Kangaroo Island, Eyre peninsula South-east of the state and the Mallee region.

Water erosion risk

If ground cover is less than 70%, most soils are at risk of soil erosion. Land slope is also a key factor (moderate to high risk above 3%). Sodic soils are more vulnerable to water erosion, particularly if the topsoil is lost or degraded.

Managing erosion risk

At a paddock scale, the critical management practices that affect the risk of soil erosion are:

- the occurrence, intensity and timing of tillage operations
- the quantity and nature of surface cover (growing crops, stubble and pasture)
- application of gypsum.

Land management should aim to maintain a protective ground cover of the soil surface. See Table 16 for the desirable and minimum percentage cover to minimise wind and water erosion. The vegetative cover can be living plant material (native vegetation or pasture), crops and stubble.

Table 16: Protective ground cover percentages to minimise wind and water erosion

	Minimum cover %	Desirable cover %
Wind erosion		
Loam	15	35
Sandy Loam	20	50
Sand	50	70
Water erosion		
Level land	60	75
Sloping Land	75	85

Source: Government of South Australia https://cdn.environment.sa.gov.au/landscape/docs/ki/amlr_managing_soils_for_production.pdf

Also, maintain and improve soil health. A decline in soil health will reduce plant growth and yield, reduce grain and pasture quality, and increase the risk of soil erosion.

Minimise land disturbance by:

- maintaining native vegetation particularly on areas identified as high erosion risk because of soil type, topography (slopes above 3%) or in degraded areas
- not overgrazing
- minimising soil disturbance by cultivation
- retaining vegetation (preferably native) in gullies and watercourses
- fencing off areas already prone to erosion will assist in stabilising the soil. It makes it easier to manage grazing pressure and revegetation.

The highest soil erosion risks associated with grazing occur in late summer and autumn when feed availability and pasture cover is declining.

Minimising soil erosion in pastures

- Include grazing rotations where possible.
- Adopt appropriate grazing management strategies that minimise the impact of grazing on soil structure and maximise soil organic matter.
- Maintain and conserve ground cover. To maximise erosion control in susceptible areas, ground cover should be a minimum of 70% of the soil surface.

- Move stock on before the soil becomes so disturbed and the ground cover so poor that the risk of soil erosion is high. During drought or prolonged dry spells confinement feeding will reduce disturbance to a small distinct area. Other strategies such as selling down stock especially unproductive individuals or those with poor genetics will reduce grazing pressure and improve production efficiency.

- Use pastures in the inter-rows for vines and other perennial row crops. Plant perennial species where possible.

The *Erosion control measures for pastoral land factsheet* provides more information on ways of minimising or rehabilitating soils in pasture areas.[12]

Minimising soil erosion in cropping

- Maintain ground cover with growing crops and stubble retention. Sufficient stubble should be left to ensure a minimum ground cover of 70% remains up to the next planting, preferably be standing (anchored by roots) and be a minimum height of 10 cm. Take advantage of summer rains to plant green manure crops, summer crops or a grass.

- Use no tillage farming practices.

- After the harvest of winter crops, assess the quantity of stubble remaining. Determine the extent of grazing it can support without raising the risk of soil erosion. This will depend upon soil type, location (particularly slope) and whether the stubble is standing or flat.

- When sowing avoid burning stubble and cultivate sparingly. Use sowing machinery capable of dealing with the amount of stubble present.

Maintaining and improving soil structure

Sandy loams, sandy clay loams, and sodic duplex soils are most vulnerable to soil structure decline. A decline in soil structure is not erosion although the outcome is much the same – lower productivity which is likely to increase the risk of erosion.

A decrease in soil structure can lead to:

- reduced crop and pasture establishment
- poor rainfall infiltration
- reduced microbial activity
- lower crop yields and pasture growth
- less cover
- increased runoff and soil erosion.

Managing drought conditions

In dry periods, soils become more susceptible to wind and water erosion because of the removal of the protective vegetation soil cover. Areas subject to erosion can seriously affect farm productivity in the long term.

Grazing stock may also cause irreparable damage to perennial pastures if the grazing pressure is too high. In addition, the invasion of weeds during the recovery period is common.

Apply drought management options early to maintain a protective ground cover on the soil surface to give pasture the best chance to recover after rain.

Aim to maintain a minimum of 70% ground cover. This rule applies to both grazing and cropping. For sloping country, the ground cover needs to be closer to 100% because the erosion risk is greater on hills and rises.

Use Figure 18: *Visual representation of ground cover %* (page 55) as a guide to estimate the of amount of vegetation cover in your paddocks.

Managing pastures during drought
Drought management for pastures includes:

- reducing grazing pressures on pastures before ground cover is below acceptable levels. This means removing stock from paddocks before the vegetation cover falls to the following trigger points:
  - below 70% ground cover on flat country
  - below 90% ground cover on hilly country
  - below 800kg dry matter/ha (DM/ha).
- reducing stock numbers prior to summer (e.g. selling lambs, poor breeders or mothers)
- establishing stock containment areas[13]. These are selected areas of the property which are set up to hold, feed and water livestock during adverse weather periods. They should be considered as part of the property management plan and once established should be maintained and be available for use during emergencies.

Pasture responses after drought
Perennial pastures, if managed properly through drought, will be the first to provide feed following breaking rains. However, if not managed properly the cost of repairing or re-sowing perennial pastures will be high.

Annual pastures that are severely degraded may need to be re-sown with a subsequent lag in providing feed following breaking rain.

The following factsheets provide specific advice about how to deal with other challenging events such as:

- stock containment areas for emergencies[14]
- extreme wind conditions[15]
- fire.[16]

Soil acidity

Soil acidification is a significant problem in cropping lands in South Australia. The extent and severity of the problem is mainly due to:

- high use of nitrogen fertiliser
- increased cropping
- the removal of crop and hay yields
- build-up of organic matter which can cause an accumulation of organic acids.

Soil acidification affects plant growth by decreasing the availability of plant nutrients such as phosphorus, calcium and molybdenum. High soil acidity also increases the availability of some elements to toxic levels, particularly aluminium and manganese.

Aluminium toxicity

Aluminium (Al) is a major constituent of most soils but is not required for plant growth. It is present in a variety of forms but in neutral and alkaline soils, the overwhelming majority of aluminium is strongly bound to soil particles or organic matter. Aluminium only affects plants when soil acidity increases and the aluminium dissolves in the soil solution (soluble aluminium). In this form, the aluminium can enter plant roots and affect their growth. Seedling growth is particularly affected. Plant species differ widely in their tolerance of soluble aluminium in the soil.

Soluble aluminium levels rise with increasing acidity (i.e. pH_{CaCl} below 4.8). Increasing acidity on agricultural land normally occurs because of management practices such as the inefficient use of nitrogen fertilisers and the export of alkalinity in produce.

High soil acidity is also detrimental to soil biological activity, reducing the nodulation of legumes and harming earthworms.

If untreated, soil acidification reduces plant growth, limits crop and pasture choices, increases pressure from weeds and affects the soil structure (e.g. soil compaction).

The distribution of soil acidity and aluminium toxicity in South Australia can be seen in Figure 26.

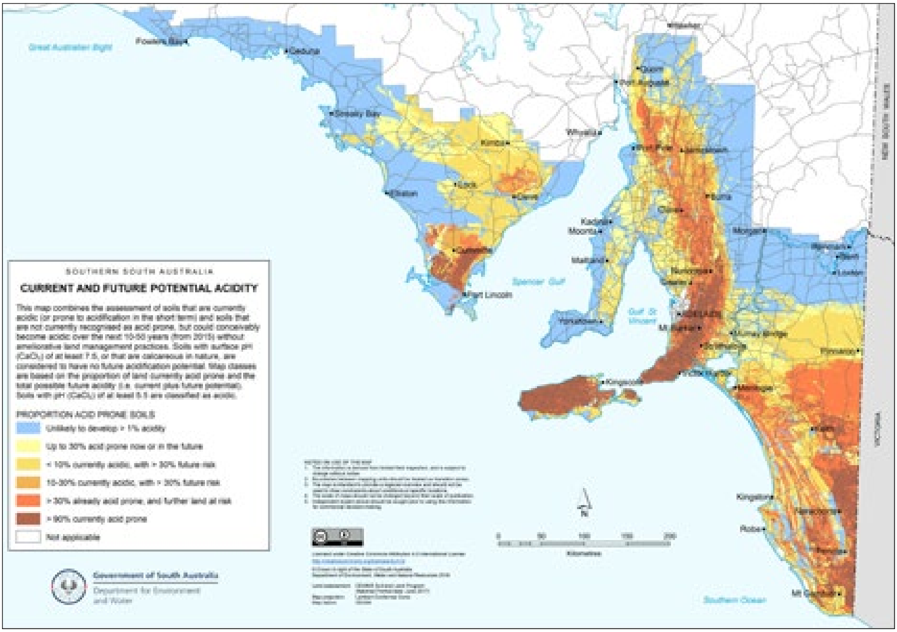


*Figure 26: Map of South Australia's current and future soil acidification risk. Source: South Australia Department for Environment and Water**

The pH scale

As mentioned in Section 1, soil pH is an indicator of the acidity or alkalinity of the soil. pH is based on a numerical scale of 0 to 14 where:

- a pH of 7 is neutral
- a pH below 7 is acid
- a pH above 7 is alkaline.

The pH scale is logarithmic. This means that a soil of pH 6 is 10 times more acidic than a soil of pH 7.

In the laboratory, soil pH can be measured either in water or in a calcium chloride solution ($CaCl_2$) (page 16 pH 1:5 water vs pH 1:5 calcium chloride). pH in calcium chloride (pH_{CaCl}) is the preferred measurement when monitoring pH changes over time. Generally, pH_{CaCl} is 0.6 to 0.8 of a pH unit lower than pH measured in water. In the field, pH_{water} can be measured using relatively cheap and easy-to-use field test kits (Figure 27, page 15 Measuring soil pH).

Figure 27: Testing pH in the field. Photos: Cassandra Douglas Hill

Recognising high acidity in the paddock

Soil acidity is best diagnosed by soil testing, but you can see symptoms of soil acidity in the paddock. These include:

- uneven pasture growth
- poor nodulation of legumes
- stunted root growth and high incidence of root diseases
- invasion of acid-tolerant weeds (for example, fog grass, sorrel and geranium).

Managing soil acidity

Testing the soil

If the field tests have shown low pH in your soil profile, it is recommended to test the 0 to 5 cm, 5 to 10 cm, 10 to 15 cm, 15 to 20 cm and 20 to 30 cm depth ranges using a laboratory pH_{CaCl} test. This will ensure any banded layers of acidity are identified. Compositing the 0-10 layer together is no longer advised when examining soil acidity, as a high acidity layer can be overlooked. Soil pH levels and soil aluminium analyses are more reliable than plant analysis in detecting aluminium toxicity.

Interpreting your results

Table 17 explains the impact that different soil pH levels have on soil and plant growth.

Table 17: The production effects of soil pH_{CaCl} levels

pH^{CaCl}	Production effect
Greater than 5.4	The balance of major nutrients and trace elements are available and there is net movement of lime beyond 10 cm depth.
Less than 5.3	There is potential for molybdenum deficiency in legumes.
Less than 5.1	Biological activity is reduced including the effectiveness of rhizobia.
Less than 4.8	Soil aluminium begins to reach toxic levels, affecting root growth of sensitive plants. Phosphorus combines with aluminium and may be less available to plants. Calcium and magnesium are leached out of soil and replaced by aluminium, leading to calcium and magnesium deficiency in plants. Plants don't establish and pastures fail. Increased nitrogen inputs are required because nitrogen fixation is reduced. Plants have reduced tolerance to environmental stress, drought, waterlogging and disease. There is an increase in acid-tolerant weeds.
Less than 4.5	Manganese becomes soluble and toxic to plants in some soils. Molybdenum is less available, and aluminium becomes soluble in toxic quantities.
Less than 3.8	Soil structural damage begins to occur.

Setting your targets

You should aim for a pH_{CaCl} of greater than 5.5 in the 0 to 10 cm depth to minimise the impact on agricultural production and soil health.

However, if there is acidity at depth (10 to 30 cm), a pH_{CaCl} of greater than 5.5 is needed in the 0 to 10 cm depth. This enables the applied lime to neutralise acidity in the top 10 cm and to move down the soil profile to neutralise acidity at depth.

Below 10 cm, soil pH_{CaCl} should be maintained above 4.8 to minimise the impact of aluminium toxicity on root growth and function.

Applying lime

If symptoms and testing indicate that acidity levels are too high, applying lime (calcium carbonate, $CaCO_3$) is the most practical way of reversing soil acidification (Figure 28). Research shows that even the short-term response to lime can be profitable. Over the longer term, profitability is greater if soil productivity is maintained at an optimal pH.

Figure 28: Lime is commonly applied to agricultural land to correct soil pH for productivity

Lime quality is an important consideration. As carbonate is the key agent for neutralising acid, the amount of carbonate in the liming source affects the neutralising value (NV). An NV of above 80% and small particle size (no greater than 0.3 mm) will give the quickest response.

The amount of lime required to counteract soil acidity depends on several factors such as the existing soil pH, desired or target soil pH, soil texture and lime quality. For practical purposes the aim should be to keep the topsoil above pH_{CaCl} 5.5. A pH_{CaCl} greater than 5.5 also assists in allowing any lime applied to move down the soil profile. Use the equation in the *Calculating lime requirements* box to estimate the amount of lime you require.

Subsoil acidity is more difficult to treat as lime must be incorporated at depth. To avoid the need to incorporate lime at depth, you need to maintain the surface pH at greater than 5.5. Strategic tillage may be needed to help neutralise subsurface acidity.

If the soil pH values are near pH_{CaCl} 5.5 then maintenance levels of lime will be needed to counteract ongoing acidification. This may be needed every 5 to 10 years.

Where topsoil and subsurface soil pH values are below pH_{CaCl} 5.5, you will need lime application over several seasons and continue to monitor soil pH.

Lime can be applied at any time of the year but is usually applied during summer or autumn. Lime can be incorporated into the soil or simply top-dressed and left to leach into the soil with subsequent rainfall.

As pH often varies considerably across a paddock, it can be more cost effective to spread lime only where it is needed. Soil testing and precision agriculture help in applying lime at the correct rate for different areas (page 30 Planning your soil sampling, page 45 Precision agriculture).

Calculating lime requirements

Lime requirement (t/ha) = (target pH - current pH) x soil texture factor

Texture factor: loam to clay loam – 4, sandy loam – 3, sand – 2

For example, to raise a sandy loam soil of pH_{CaCl} 4.8 to pH_{CaCl} 5.5, (5.5 - 4.8) x 3 = 2.1 tonnes of lime per hectare is required].

Online tools to help with decision-making

The Acid Soils SA website has useful resources to help including online tools to estimate loss of crop and pasture production, a maintenance lime rate calculator and a tool to estimate lime application rates with effective sources of lime for your property.[17]

LimeAssist is an online tool that assists growers to analyse the economic benefits of lime applications.[18] Additional information about lime application is provided in the *Lime application and soil acidity – the economics of current rules of thumb paper* (2022) published by Grains Research & Development.[19]

The 2017 case study, *The dollars and sense of liming: the Stantons' story*, explains how the Stanton family (Stokes Bay and central plateau, Kangaroo Island) tested the decision-making tools mentioned above to plan their liming strategy for one of their cropping paddocks. Liming resulted in significant crop yield improvements.[20]

Non-wetting soils

Non-wetting soils, also known as hydrophobic soils, are a significant challenge for agriculture. These soils repel water instead of absorbing it, leading to poor infiltration and uneven moisture distribution (Figure 29). Non-wetting soils are prevalent in sandy soils where organic coatings or fungal hyphae on soil particles create hydrophobic conditions. This phenomenon typically occurs after long dry periods when soil organic matter undergoes decomposition, releasing hydrophobic waxy compounds that coat the soil particles. Non wetting soils are common in sandy textured soils with less than 10 % clay and can be severe in sandy textured soils with less than 5 % clay.

Non-wetting soils pose several challenges for Australian farmers, primarily affecting crop establishment and growth. Poor water infiltration leads to uneven soil moisture distribution, resulting in patchy germination and inadequate root development. The patchy germination also promotes the growth of weeds. Significant yield losses, particularly in cereal crops like wheat and barley, are common.

Non-wetting soils can also exacerbate erosion risks because water runs off the surface, carrying away valuable topsoil and nutrients. The uneven moisture also makes it difficult to manage soil fertility and irrigation effectively, making overall farm management even more complicated.

Identifying non-wetting soils

Non-wetting soils can be identified during rainfall or irrigation, when water will pool on the surface or run off rather than infiltrating into the soil. Upon closer examination, non-wetting soils often appear dry beneath a thin moist surface layer. Poor germination and stunted plants can also indicate non-wetting conditions.

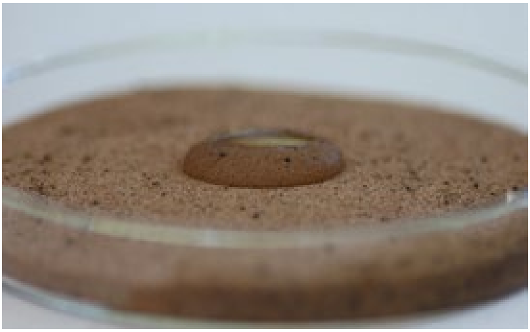



Figure 29: Non-wetting soils, also known as hydrophobic soils, repel water instead of absorbing it, leading to poor infiltration and uneven moisture distribution. Photos: Edward Scott

A common field test to identify non-wetting soils involves placing water drops on the soil surface. Non-wetting soils will cause the water to bead up and remain on the surface for an extended period. An additional test of the severity of non-wetting soil is to apply ethanol solutions in increasing concentrations to a soil until the solution penetrates the soil in under 10 seconds. The higher concentration of ethanol needed, the more severe the water repellence.[21]

Managing non-wetting soils

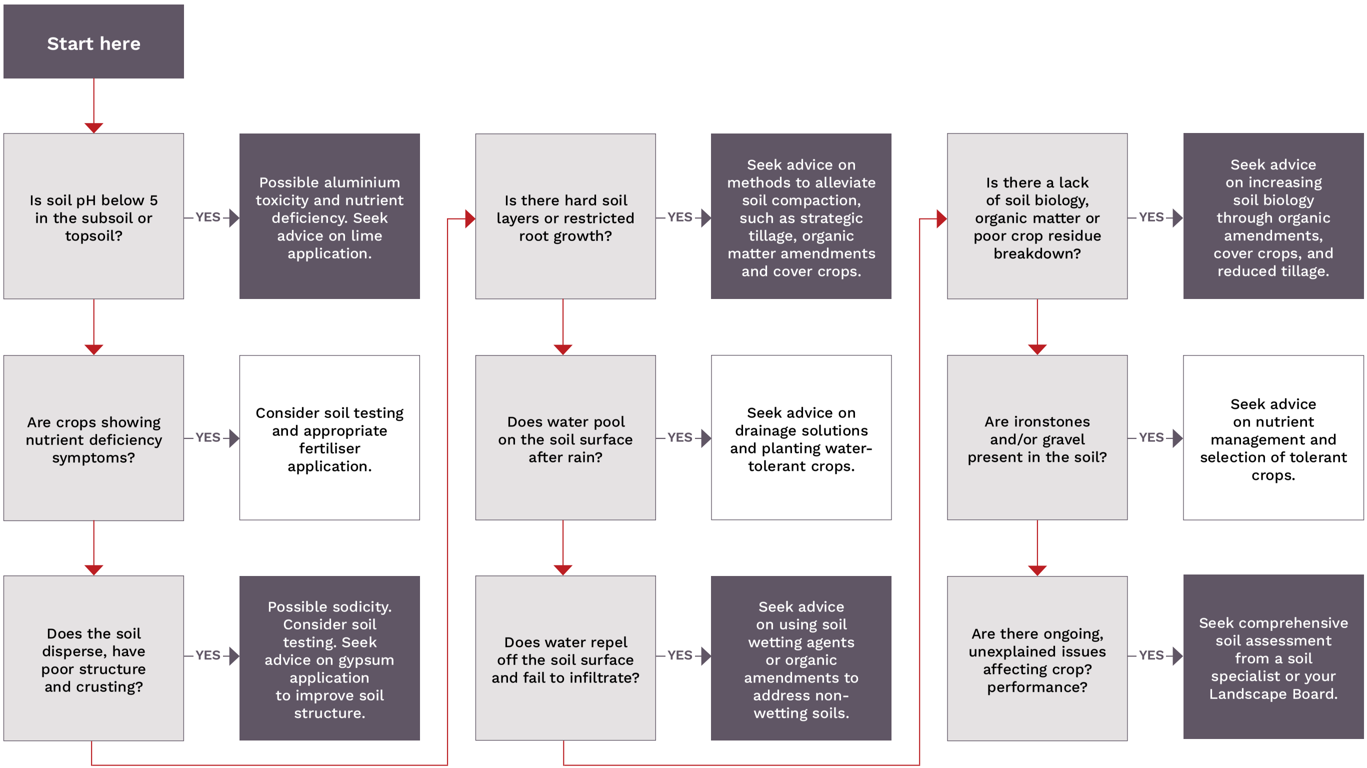
Non-wetting soils can be managed using mechanical, chemical and biological strategies (or a combination of these), to improve water infiltration and soil structure.

Amelioration techniques, such as deep cultivation, rotary spading, clay spreading or soil inversion (deep ripping or tillage) can help to break up the hydrophobic layer, allowing water infiltration. Some trials have found positive production increases from these techniques. However, these techniques need to be balanced with the high economic cost and potential for negative effects such as soil structural decline and soil organic carbon loss.

Smaller scale amelioration strategies such as soil wetting agents or surfactants, on-row or furrow seeding, deep or delayed seeding, and stubble retention can also help, but can have inconsistent results.[22]

Incorporating organic amendments can enhance soil structure and water holding capacity and allow microbial degradation of waxy compounds on the soil surface. Increasing acidic soil pH using liming can also increase the populations of beneficial bacteria which degrade waxy coatings (page 86 Applying lime).

When to seek help



References

1. Food and Agriculture Organization of the United Nations (FAO), *What is soil pH*, 2019, accessed 1 July. 2024. https://www.fao.org/3/ca7162en/ca7162en.pdf.

2. D Maschmedt, *Assessing agricultural land*, Government of South Australia, 2002, page 21, accessed 15 April 2024. https://data.environment.sa.gov.au/Content/Publications/Assessing-Agricultural-Lands.pdf.

3. Grains Research & Development Corporation (GRDC), *Estimating plant available water capacity*, 2013, accessed 15 April 2024. https://grdc.com.au/resources-and-publications/all-publications/publications/2013/05/grdc-booklet-plantavailablewater.

4. F Brailsford, C Scanlan, D Weaver, K Holmes and M Leopold, *Soil Quality: 9 Gravel Soil*, SoilsWest, 2023, accessed 15 March 2024. https://library.dpird.wa.gov.au/sq_ebooks/7.

5. FAO, *What are the soil nutrients*, 2019, accessed 1 July. 2024. https://openknowledge.fao.org/server/api/core/bitstreams/c1ff1417-159c-4d88-b268-2df44291362c/content.

6. Limestone Coast Landscape Board, *Introduced dung beetles of the Limestone Coast*, 2023, accessed 5 May 2024. https://cdn.environment.sa.gov.au/landscape/docs/lc/Dung-Beetles-web.pdf.

7. Landscape Boards South Australia, *Dung beetle benefits*, n.d., accessed 5 May 2024. https://www.landscape.sa.gov.au/hf/landscapes-hills-and-fleurieu-stewardship-program/care-for-soils/information-on-soil-health/managing-soil-and-pastures/dung-beetle-benefits.

8. GRDC, *Stubble retention in cropping systems*, 2013, accessed 5 June 2024. https://grdc.com.au/__data/assets/pdf_file/0017/202229/developments-in-stubble-retention-in-cropping-systems-in-southern-australia-11dec2013-pdf.pdf.pdf

9. Government of South Australia, *Assessing agricultural lands*, 2002, accessed 12 April 2024. https://data.environment.sa.gov.au/Content/Publications/Assessing-Agricultural-Lands.pdf.

10. Kangaroo Island Landscape Board, *Applying for permits for water affecting activities*, 2024, accessed 12 April 2024. https://www.landscape.sa.gov.au/ki/land-and-farming/water-affecting-activity-permits.

11. Government of South Australia, *Wind erosion potential*, 2016, accessed 12 April 2024. https://data.environment.sa.gov.au/Content/Publications/SoilAttrib_FactSheet18_WindErosion.pdf.

12. Government of South Australia, *Erosion control measures for pastoral land*, n.d., accessed 11 April 2024. https://cdn.environment.sa.gov.au/landscape/docs/saal/191105-erosion-control-fact-sheet.pdf.

13. Government of South Australia, *Stock containment areas*, 2017, accessed 10 April 2024. https://cdn.environment.sa.gov.au/landscape/docs/mr/cattle-stock-containment-areas-amlr-gen.pdf.

14. Agriculture Victoria, *Stock containment areas (SCA) for emergencies*, Agriculture Victoria, 2023, accessed 11 April 2024. https://agriculture.vic.gov.au/farm-management/land-and-pasture-management/stock-containment-areas-for-emergencies#:~:text=A%20stock%20containment%20area%20is,periods%20or%20after%20a%20fire.

15. Government of South Australia, *Emergency measures to curb wind erosion*, 2017, accessed 11 April 2024. https://cdn.environment.sa.gov.au/environment/docs/Emergency-Measures-to-curb-wind-erosion-RSSA-FS-20180911.pdf.

16. Government of South Australia, *A review of the effects of fire on South Australia's agricultural soils*, 2021, accessed 10 April 2024. https://cdn.environment.sa.gov.au/environment/docs/Review-of-Effect-of-Fires-on-Agricultural-Soils-SA-Report-Aug-2021.pdf.

17. GRDC, *Resources*, n.d., accessed 11 Apr 2024. https://acidsoilssa.com.au/index.php/home/resources/.

18. Southern Farming Systems, *LimeAssist*, n.d., accessed 11 Apr 2024. https://limeassist.sfs.org.au/.

19. GRDC, *Lime application and soil acidity: the economics of current rules of thumb*, 2022, accessed 11 Apr 2024. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/02/lime-application-and-soil-acidity-the-economics-of-current-rules-of-thumb#:~:text=In%20the%20HRZ%2C%20the%20rule,1990s%2C%20about%2020%20years%20ago.

20. Natural Resources Kangaroo Island, *The dollars and sense of liming: the Stantons' story*, 2017, accessed 11 April 2024. https://cdn.environment.sa.gov.au/landscape/docs/ki/liming-stanton-fact2-2017.pdf.

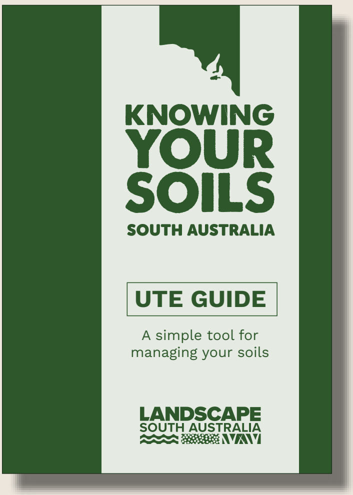
21. J Sheppard, F Hoyle and D Murphy, *Detecting water repellence*, Soil Quality, 2024, accessed 15 May 2024. https://www.soilquality.org.au/factsheets/water-repellency.

22. GRDC, *Combatting non-wetting soils: a tour of on-farm research in Western Australia*, 2014, accessed May 15 2024. https://grdc.com.au/__data/assets/pdf_file/0031/82777/combatting-non-wetting-soils-pdf.pdf.

Photo: Molly O'Dea

Knowing your soils South Australia is an essential resource for landholders and land stewards looking to enhance the health and productivity of their soils. This handbook provides comprehensive guidance on understanding soil function within the landscape, covering key physical and chemical characteristics, as well as the vital role of soil biota, microbial systems, and organic matter.

Accompanied by the *Knowing your soils South Australia ute guide*, this resource empowers farmers with practical, DIY soil tests to assess and manage soil constraints directly in the paddock. Together, these guides offer valuable insights to support sustainable farming practices, improve soil resilience, and optimise land management for long-term productivity.



Companion publication
Knowing your soils South Australia ute guide