ECO VINEYARDS
GROWING RESILIENCE NATURALLY

BEST PRACTICE MANAGEMENT GUIDE

ON SOIL HEALTH IN AUSTRALIAN VINEYARDS PART A: CHEMICAL AND PHYSICAL

by Dr Amanda Schapel and Dr Mary Retallack

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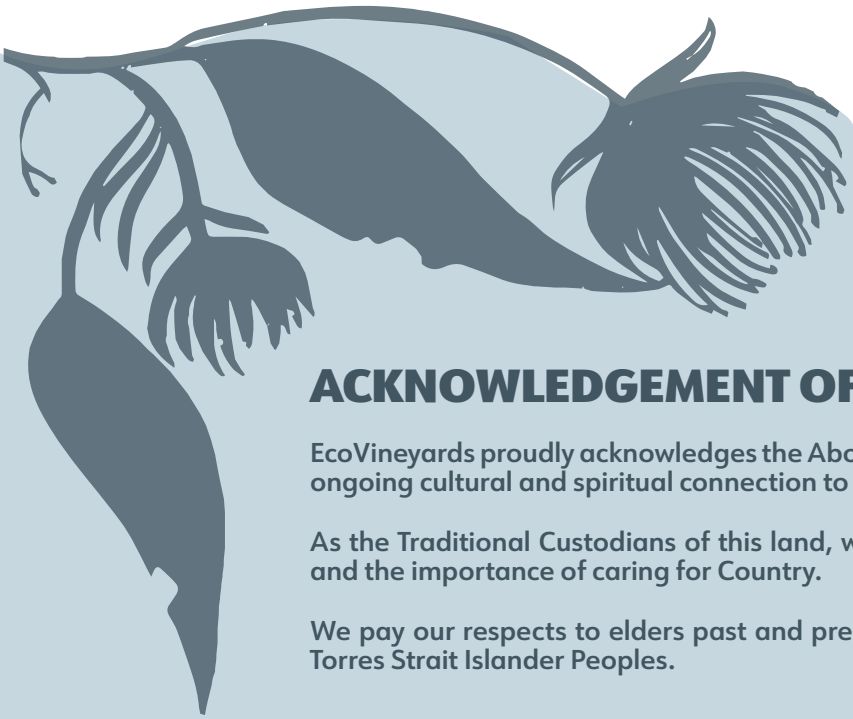
For more information about the National EcoVineyards Program please visit www.ecovineyards.com.au @EcoVineyards



ACKNOWLEDGEMENT OF COUNTRY

EcoVineyards proudly acknowledges the Aboriginal and Torres Strait Islander Peoples, and their ongoing cultural and spiritual connection to this ancient land on which we work and live.

As the Traditional Custodians of this land, we recognise their wealth of ecological knowledge and the importance of caring for Country.

We pay our respects to elders past and present and extend this respect to all Aboriginal and Torres Strait Islander Peoples.

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ACRONYMS

AMF	arbuscular mycorrhizal fungi
BPMG	best practice management guide
CEC	cation exchange capacity
CO_2	carbon dioxide
C:N	carbon to nitrogen ratio
EC	electrical conductivity
ESP	exchangeable sodium percentage
GHG	greenhouse gases
IPM	integrated pest management
MAOC	mineral associated organic carbon
MAOM	mineral associated organic matter
MBC	microbial biomass carbon
NMR	nuclear magnetic resonance
OC	organic carbon
OM	organic matter
PCR	polymerase chain reaction
POC	particulate OC
POM	particulate OM
SOC	soil organic carbon
WHC	water-holding capacity

SOIL HEALTH DEFINITIONS

Term	Definition
Apedal	Soils with no or poor structure are apedal (single grains like beach sand or have a massive structure with no defined peds).
Carbon efficiency	Carbon efficiency (CO_2 release back to the atmosphere) differs depending on the energy required to decompose OM material and this affects the OC balance in the soil. Decomposing POM is carbon inefficient whereas the adsorption of root exudates and microbial by-products including necromass (dead plant and animal material including macrofauna and microbes) by the mineral surface is highly carbon efficient and helps build stable OC in soil.
Healthy soil	A healthy soil feeds the plants and soil biology and will have a balanced soil chemistry, such as pH and macro- and micro-nutrients, low concentrations of toxic elements, such as salt, good structure to enable air and water movement, sufficient food and nutrients (organic matter and root exudates) to ensure that the soil functions well including provision of plant-available nutrients, infiltration and storage of water, balanced populations for pest and disease suppression, and greater longevity of soil organic carbon.
Mineral-associated organic matter (MAOM)	MAOM is important for long term stabilisation of OC, and mostly comprises root exudates and microbial by-products that are small enough to attach to minerals or within aggregates in the soil.
Particulate organic matter (POM)	POM is mainly derived from plant shoots and roots and is readily decomposable, freeing nutrients and releasing the carbon component as CO_2 gas back to the atmosphere.
Peds	Soil particles are held together by clay, OM, fungal hyphae and secretions from worms and other soil biology into aggregates. They often look like crumbs and are technically known as peds.
Redox potential	Redox potential (Eh) measures the reduction-oxidation reactions (transfer of electrons) in soil using a specialised electrode and is expressed in volts. Conditions favourable for plant growth are between 350 to 500 mV and optimum between 400 and 450 mV.
Root exudates	Root exudates refer to a suite of substances (simple sugars, amino and organic acids) in the rhizosphere that are secreted by the roots of living plants and microbially modified products of these substances. When plants are photosynthesising under optimal conditions, they produce exudates that feed soil microbes and they in turn help to cycle organic matter and convert nutrients into plant available forms.
Macropore	The space or pores between aggregates are called macropores and are important for water drainage, air movement (aeration) and enable root growth.
Necromass	The mass of dead plant material lying as litter on the ground surface and animal material (including macrofauna and microbes).

EXECUTIVE SUMMARY

The 'eco' in EcoVineyards stands for 'ecological' vineyard production and regardless of the management system currently employed, we work closely with wine growers across Australia to provide complementary practices with an ecological focus, so we can collectively grow in harmony with nature.

Moving towards more ecologically focused and regenerative production systems is at the heart of the National EcoVineyards Program, and the development of best practice management guides is a key part of this initiative.

This best practice management guide (BPMG) is part of a series on the following topics:

- soil health in Australian vineyards,
  - Part A (chemical and physical) – **this guide**
  - Part B (biology)
- ground covers (including cover crops) in Australian vineyards, and
- functional biodiversity in Australian vineyards

A summary of each BPMG is included in the table below. These insights are relevant for all wine growing regions in Australia and a broad range of production systems.

Table 1. Summary of the EcoVineyards BPMG series

Soil health	Ground covers	Functional biodiversity
Soil health underpins plant health and vice versa. Soil biology is a key component of pathogen suppressive soils, nutrient cycling, soil structure, carbon storage, and much more. Unfortunately, the living components of soil have often been overlooked when considering soil health. The BPMG on soil health details the tools and resources available to improve soil health in vineyards, with a particular focus on the chemical and physical components in Part A and soil biology in Part B. The BPMG takes growers through the benefits of improving soil health, how to get started, how to assess soil health indicators, setting a benchmark, and monitoring progress over time.	Ground cover plants provide many ecosystem services that ultimately benefit vineyard management and wine grape production. Ground covers include sown ground covers (such as multi-species cover crops), and/or the use of endemic or native species across the entire vineyard floor, including the mid-row and under-vine (natural recruitment, sown and/or planted). The BPMG on ground covers details the tools and resources available to improve ground cover management in vineyards. The BPMG takes growers through the benefits of improving ground cover management, how to get started and how to monitor the outcomes of the changes being made.	Functional biodiversity includes all the fauna (animals) found in association with soils and plants (flora) and the interactions between them, for example, predatory arthropods, microbats, insectivorous, and raptor bird species along with all other life found in association. These species provide a range of ecosystem services, including biocontrol of grapevine insect pests. Biodiversity is the variety of plant and animal life. Each species has a niche in the ecosystem and contributes towards its functionality. The resilience of a system describes its capacity to reorganise after local disturbance (including extreme weather events). The BPMG on functional biodiversity details the tools and resources available to improve functional biodiversity in vineyards and how to monitor progress.

An electronic version of this document is available via https://ecovineyards.com.au/bpmg/

WHAT IS A BPMG?

The EcoVineyards best practice management guides (BPMG) are written by a team of experienced research and extension viticulture, agroecology, and ground cover subject specialists.

Each guide is designed as a 'living document' that can be updated as new information becomes available. It provides a summary of both peer-reviewed scientific information and practical insights for wine growers on each topic covered by the National EcoVineyards Program as well as support materials.

The National EcoVineyards Program aims to accelerate adoption and practice change outcomes specified in Wine Australia's Strategic plan 2020 to 2025 specifically:

- To increase the land area dedicated to enhancing functional biodiversity by 10 per cent, and
- To increase the use of vineyard cover crops and soil remediation practices by 10 per cent

Grower knowledge gaps

During events held as part of the National EcoVineyards Program, wine growers were asked to identify knowledge gaps they felt were limiting their ability to implement soil health practices.

The topics ranged from how to support soil biology and plant health, to how to compost at scale, which soil inputs will support populations of soil microbes and earthworms, how does nutrient cycling work, how to manage compacted soils, what is the optimal fungal to bacteria ratio, how to store organic matter and increase water-holding capacity, how to manage weedy species and ways to assess the benefits of organic inputs.

This BPMG addresses these questions and provides growers with a 'how-to' guide to progress their soil health journey in their vineyards.

Ecological restoration and functional biodiversity measures that can be employed to help 'future proof' the production of vineyards in Australia against the effects of climate change and extreme weather events are also explored in the EcoVineyards BPMG series.

Focus areas

The BPMG for soil health in Australian vineyards (Part A and B) focuses on:

- understanding the importance of soil microbiology and the interactions between living organisims in the soil
- soil health and structure, including key soil health indicators and how to assess them
- the importance of soil and plant nutrition and the impact this has on plant health (including photosynthetic capacity), and soil function
- how plant health influences soil health and integrity, including the benefits of pest and disease suppression for both plants and soils
- how to improve soil organic matter and structure
- compost and compost tea production
- using biostimulants in vineyards.

An extensive 'ask the expert' section at the end of Part B provides answers to grower questions and many of these questions have guided the content of each BPMG.

Please read this guide followed by the **EcoVineyards BPMG on soil health in Australian vineyards: Part B (biology)**.

Join us in exploring this topic with practical insights from subject specialists.

SECTION 1:
INTRODUCTION

WHAT IS SOIL HEALTH?

Soil health describes the condition of the system and is measured by the ability of the soil to function as a living ecosystem in relation to its natural capacity. A healthy soil sustains biological productivity, maintains environmental quality, promotes plant, animal, and human health, and is resilient and profitable.

Like our bodies, soil health and integrity can range from excellent to sluggish and unhealthy condition. How we feed and look after ourselves and our soils determines where we sit on the health scale.

Soil health is relative to the system of production and is defined by what we consider 'fit for purpose' for the plants growing in it and the animals supported by it. Some characteristics are influenced by the inherent properties of the soil, but many are changed by the management practices we adopt.

Soil health has a strong focus on the ecosystem services of water infiltration and storage, nutrient cycling, aeration, disease and pest suppression and organic matter. Improving soil health can help wine growers build climate resilience, increase nutrient availability, suppress diseases, reduce erosion, reduce nutrient losses, and potentially capture and store carbon.

Soil is a living ecosystem and how we treat it has big effects on its condition or soil health.

Why is soil health important?

Healthy soil is the foundation of productive viticulture and can be degraded by management practices that lead to reduced soil function i.e., any practice that negatively affects soil structure, organic matter inputs and soil biological balance. Many soil health functions are driven by functional plant cover and their interactions with living organisms.

A healthy soil will support vine growth to produce grapes of a suitable quality and quantity for wine production and makes the system more resilient, efficient, and profitable. It will have the right balance of nutrients, an optimal structure that allows for the easy movement of water, air and roots, and a thriving community of beneficial organisms.

Soil is made up of sand, clay, silt, gravel (solid particles), organic matter, air, water, nutrients, and biological organisms (the essential living component). The harmonious interaction between the physical, organic, biology and plants is key to a healthy and functioning system.

WHAT DOES A HEALTHY SOIL LOOK LIKE?

A healthy soil is fed by plants and soil biology.

It has integrity and balanced soil chemistry such as pH and macro- and micro-nutrients, low concentrations of toxic elements, such as salt, good structure to enable air and water movement, sufficient food and nutrients (organic matter and root exudates) to ensure that the soil functions well including provision of plant-available nutrients, infiltration and storage of water, balanced populations for pest and disease suppression, and greater longevity of soil organic carbon.

What makes a healthy, functioning soil?

Chemical

- Source of and sufficient nutrients for plants and biology
- Good cation exchange capacity
- Healthy pH
- Low toxicities (heavy metals/pesticides) in the rootzone

Physical

- Structure able to provide water and air (infiltration and storage)
- Structural stability
- Few restrictions to root or microbial growth

Biological

- Good food supply, driven by plant exudates
- Diverse and key functional populations present
- Disease and pest suppression

Soil Functions

water availability | nutrient cycling | soil biology | GHG mitigation | productivity

Figure 1. What makes a healthy, functioning soil?

Physical, chemical, and biological components of a soil are very closely linked. Physical structure and chemical nutrients (including water) influence soil life. Soil biology influences the structure (physical) and organic and chemical components of soil.

What we do to soil affects not just the physical and chemical components but also biological communities which, in turn, affect soil structure, water and nutrient availability and therefore plant growth.

SOIL FUNCTIONS

Nutrient cycling and storage

Nutrient supply to plants relies on soil organisms that decompose organic, mineral, or synthetic food sources to provide nutrients in a form suitable for plants and microbes to use. Diverse plant or crop rotations, growing multi-species mixes or the addition of composted organic amendments can increase the diversity of soil organisms and supply a wider range of nutrients.

Nutrients, such as nitrogen, phosphorus, and sulphur, are required to feed soil organisms that decompose plant residues and form more stable organic matter (OM).

Using practices such as minimum or no tillage, increasing plant diversity, growing ground cover in the mid-row and in some cases under vine area, selecting plants that have longer growing periods (e.g. perennials) and applying organic amendments (e.g. plant or animal residues, composted products) will increase the supply and cycling of nutrients in the soil.

Nutrient cycling is affected by soil texture (clay concentration), mineralogy, cation exchange capacity, soil moisture and temperature, soil organisms, microbial activity, and the supply of nutrients.

Water cycling and storage

Soil texture and the arrangement of sand, clay and silt particles create pore spaces that allow water and gases to move into and through the profile. Management practices can affect this particle arrangement, creating compacted layers or high soil strength which in turn affect air and water movement that influence root and biological growth.

OM is important in improving soil structure. Soil biology produce carbon-rich secretions from the decomposition of plant or animal litter, or root exudates act as glue, binding soil particles together and creating aggregates.

Water cycling and storage can be improved by reducing compaction or high soil strength where possible, introducing OM to feed microbes that produce glues to improve aggregation, addressing water repellence, maximising ground cover, and minimising soil disturbance to protect aggregates.

Water cycling is affected by soil texture (particle composition and size), arrangement of particles, soil disturbance, soil moisture, water repellence and OM.

Soil biological organisms

Increased activity and diversity of soil biology leads to more resilient and efficient systems. The more microbial species present, the more likely systems will suppress disease and be more carbon efficient (less CO_2 gas released to the atmosphere with decomposition of OM).

Improving soil biological function can be achieved by increasing the amount (abundance) and diversity (richness) of soil organisms and supplied OM. This can be achieved through ground cover, cover crop or mid-row diversification, addition of organic amendments including fertilisers, avoidance of synthetic fungicide use and, where possible, improving poor soil structure.

Soil microbial activity can be affected by soil texture (clay concentration), soil properties (pH, salinity, structure, temperature), soil disturbance, moisture, availability, and type of OM (food).

Rhizophagy

The zone of soil directly surrounding the roots is called the rhizosphere. Roots supply 20 to 30% of what they photosynthesise as root exudates (labile OC) to this area to generate a community of microbes that benefit the plant. The exudates grow bacterial and fungal populations while plants wait for nematode and protozoal activity to release the nutrients contained in the bacteria and fungi. The plants then take up this harvest of nutrients from the soil.

The rhizosphere has high microbial activity with a wide diversity of populations around 100 times higher than the surrounding bulk soil (Stirling et al., 2016).

Due to the microbial secretions in this area, soil particles stick to the roots and form rhizosheaths.

Moreover, plants also consume bacteria and some yeast-type fungi for nutrients; this process is called rhizophagy (which means 'root eating').

For example:

- Bacteria are corralled just inside root meristem cell walls. There, the bacterial walls are shorn off and absorbed by the plant as nutrients.
- In response, bacteria produce nitric oxide to protect themselves, supplying the plant with nitrogen.
- Then the plant causes the bacteria to multiply.
- Finally, the plant grows a root hair and puts the flock of bacteria back out to pasture to get ready for the next season's shearing (Lowenfels and Lewis, 2022).

Figure 2. Plant root, exuding exudates (left) [Photo: James White] and compost coated seed showing rhizosheath development from root colonisation (right) [Photo: Mark Tupman].

Organic carbon function and greenhouse gas mitigation

The forms or fractions of OM influence the stability and longevity of soil organic carbon (OC).

For example:

- Particulate OM (POM) is important as an energy and nutrient source for soil organisms and plant improving soil function. It is mainly derived from plant shoots and roots and is readily decomposable, freeing nutrients and releasing the carbon component as CO_2 gas (70 to 90% of POC) back to the atmosphere.
- Mineral-associated OM (MAOM) is important for long term stabilisation of OC, and mostly comprises root exudates and microbial by-products that are small enough to attach to minerals (clay particles, iron, aluminium, or calcium complexes) or within aggregates in the soil. A small portion will come from POM that has been highly decomposed and attach to mineral surfaces.

Carbon efficiency (CO_2 release back to the atmosphere) differs depending on the energy required to decompose OM material and this affects the OC balance in the soil. Decomposing POM is carbon inefficient whereas the adsorption of root exudates and microbial by-products including necromass (dead plant and animal material including macrofauna and microbes) by the mineral surface is highly carbon efficient and helps build stable OC in soil.

Think of carbon efficiency in terms of our bodies that thrive on food with high nutritional content and is easy to digest. Rather than junk food that may be tasty but has little long-term value.

Increasing organic storage can be achieved by growing and retaining more soil OC, increasing species diversity (plant and soil organisms) and sources of OM to maximise carbon efficiency, minimising soil disturbance to protect OC in aggregates, and identifying, rehabilitating, or repurposing areas of low productivity.

Organic carbon storage is affected by soil texture (clay concentration), mineralogy, iron and aluminium oxides, soil structure and aggregates, soil disturbance, rainfall, temperature, soil moisture, carbon efficiency, OM inputs and OC losses.

OC is constantly cycling through the living, actively decomposing and stable fractions, providing many functional benefits. It is important to realise that OC might not increase in systems that are functioning at high rates.

In these soils, OC is constantly cycling through the fractions providing many functional benefits but not always resulting in a carbon sequestration benefit.

Be mindful about what happens to every gram of plant matter that we grow. It can either be oxidised back to CO_2 (by clearing, creating bare soils, cultivating, and using weedicides), or it can be converted into stable soil carbon, humates and glomalin via microbes and fungi.

Productivity: growing vines, grapes and wine

The focus of growing grapevines is the wine grapes rather than the vegetative biomass that is common in other systems. As water is often a limiting factor, large OM inputs via decomposing plant matter are often not seen.

Some practices such as tillage in the mid-row and bare under-vine areas actively increase OM decomposition, loss of soil structure and unbalanced biological communities. This can lead to a decrease in soil functionality and OM.

Increased production can be achieved whilst maintaining or improving the soil resource. Improving production efficiency and yield (plant-available nutrients, water), selecting species to grow more root mass, and ensuring ground is covered by plant residues as long as possible can aid improvement of the soil resource.

Soil productivity is affected by climatic conditions, soil type and properties, nutrition, plant species selections and soil moisture.

SOURCES OF OM

OM comes from:

- Plants grown in the soil
  - Plant shoots and residues that accumulate on the surface
  - Roots, their exudates (simple sugars, amino and organic acids) and glomalin produced by mycorrhizal fungi found in association
- Dead macrofauna and microbes (microbial necromass)
- External inputs:
  - Manure, compost, mulch including grape marc
  - Other organic additions such as biochar and clay

OM FRACTIONS

Managing soil organic matter and organic carbon requires understanding their forms or fractions. There are several models used to understand how OM/OC changes in our soil.

For many years we have described particulate and humus fractions. This has been updated to particulate (P) and mineral-associated (MA) fractions in more recent years.

The two forms are different in their formation, persistence, and function but the key difference is that MA is protected from decomposition through association with soil mineral surfaces or within micropores or small aggregates that make them less accessible to microbes and their enzymes.

Particulate (also known as labile or active) organic matter

- Lightweight fragments that are relatively undecomposed
- Larger, insoluble molecules, but quality for decomposers is less consistent than MAOM. Quality relies on chemistry and nutrient content and follows the quality of plant inputs
- Easily decomposed, faster-turnover (weeks to years)
- Can be easily lost and decomposed in the soil and released back into the atmosphere as carbon dioxide
- Soil microbes use POM as a primary energy source
- POM is only limited by OM inputs and microbial activity

Mineral associated (also known as stable) organic matter

- Single molecules or microscopic fragments or OM that have leached from plant material or been chemically transformed by soil microbes
- Tend to be more nutrient rich and requires less energy to decompose so MAOM that dislodges from mineral particles will be quickly decomposed by microbes releasing N important for microbes and plants
- Slowly decomposed, slower turnover (decades to centuries)
- Consists of organic compounds that are bound to the surfaces of soil minerals and largely made of microbial by-products that are higher-N containing, and can persist in the soil through strong chemical bonding to mineral surfaces
- MAOM is limited by the mineral surface it can attach to

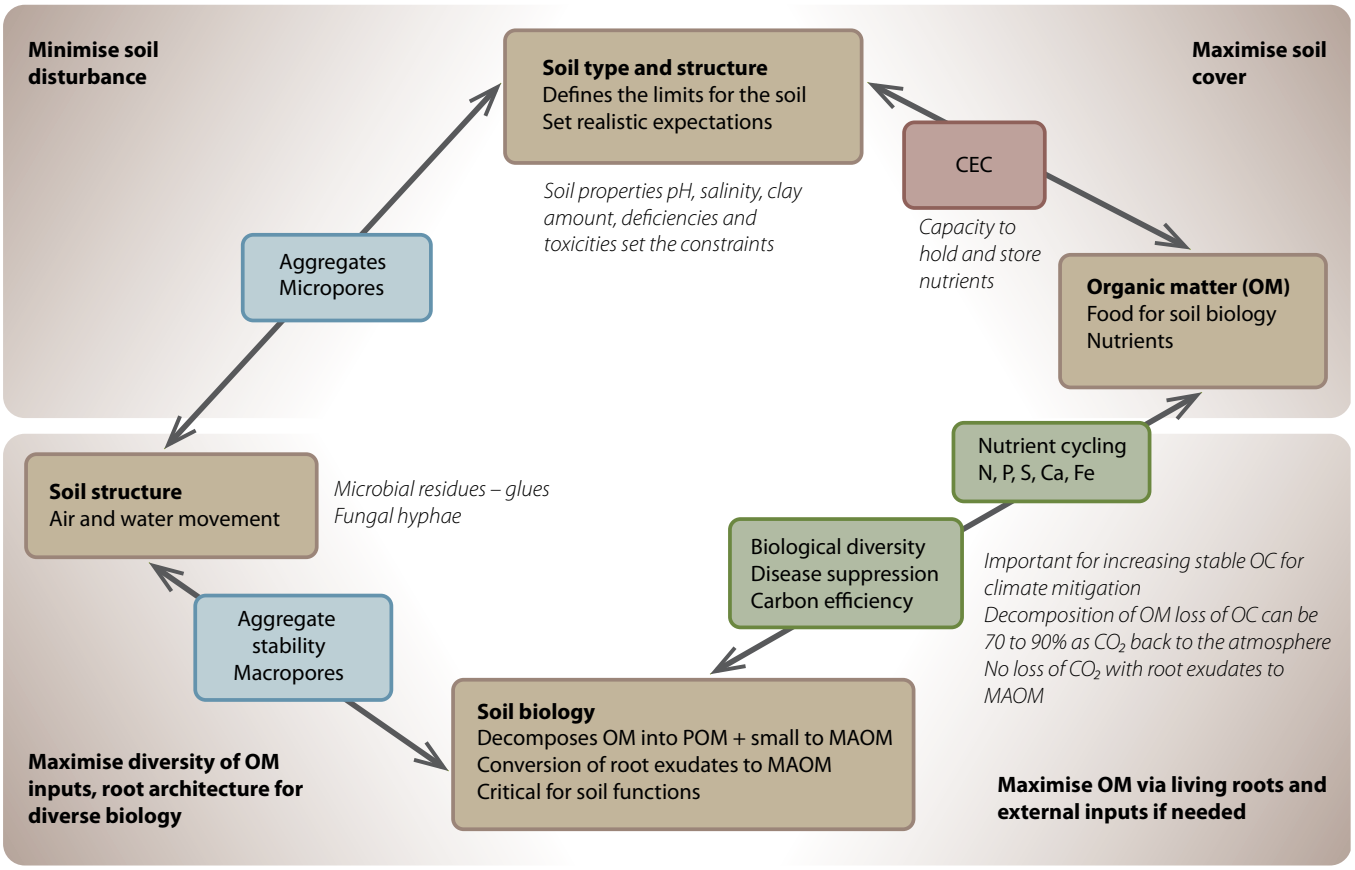


Figure 3. Complexity of soil health processes.

OM is the food source for soil biology that determines which species and the abundance of biology needed to decompose it. It is only through decomposition do we see soil functional benefits of nutrient and water (soil structure) cycles, increased biological diversity, plant productivity and greenhouse gas mitigation.

SOIL HEALTH INDICATORS

What are they?

Soil health indicators are a set of measurable physical, chemical, and biological properties of soil that relate to soil function and are used to evaluate the health of soil. There is a lot of discussion about the most appropriate indicators to use and how to consistently measure them. To be useful as a soil health indicator, a parameter needs to satisfy several criteria (Lehmann et al., 2020).

It needs to be:

- relevant to soil health, its ecosystem functions, and services
- sensitive, able to detect change quickly and able to distinguish between seasonal fluctuations
- cheap, practical, and short turn-around
- informative for management.

The final choice of soil health indicators will depend on the soil type, management practices used, questions asked, budget and objectives of the vineyard in terms of productivity, grape quality, and natural capital.

Soils vary over short distances in depth of topsoil or depth to clay within a few metres and these can have large effects on soil physical, chemical, and biological properties. Be aware and curious about what changes affect root and vine growth in your vineyard.

Soil type can be assessed by digging a small hole and observing the colour, texture, and depth of layers. Changes in soil type often follow topographical changes (top, middle, and bottom of a slope).

Where possible, assess soil health from each of the main soil types in the vineyard and choose a few variations (e.g. shallow clay, deep clay). Make sure you record what is happening in the vine and mid-row as they are managed differently. If a vine appears unthrifty, a below-ground assessment of roots and soil is a good place to start (along with above-ground symptoms and observations).

Which soil health indicators do we use?

The tables below show a detailed list of indicators and methods that can be used to evaluate soil health with on-site and laboratory assessment options. The indicators in bold are more simple assessments that can take place on-site along with some requiring laboratory analysis.

To build your knowledge of soil health in the vineyard make sure you come back to the same location and in the same season each time, so you know the changes are real and not due to soil or weather variation.

Table 2. List of soil health assessments for physical properties

Category	Test or assessment	On site	Laboratory
Localised site and soil description	Slope and aspect	Visual	
	Soil temperature	Visual (use Bureau of Meteorology climate data or measure soil temperature with a thermometer)	
Morphological characteristics	● Soil colour	Visual (Munsell)	
	Mineralogy	Visual	X-ray diffraction
	● Horizon depth	Visual (measure)	
	● Topsoil, depth to restriction and rootzone depth	Visual (measure)	
Soil capacity	● Texture	Hand ribbon	Particle size analysis
Soil structure and stability	● Soil structure	Visual: friable, hard, restrictions	
	● Aggregate stability	Slaking / dispersion test Slakes app	Wet sieving
Soil porosity	Bulk density	Intact core (weight/volume)	
	Pore size distribution	Visual: examine and look for channels. Can use fuse wire to assess size.	Mercury porosimetry
Soil Strength	● Penetration resistance	Penetrometer, heavy gauge wire Consistence	
Water movement and storage	● Water infiltration rate	PVC ring, or infiltrometer and timer	
	Available water-holding capacity, and capacity of water to percolate through the soil profile	Estimated from texture and horizon depth, soil moisture probes	
	Saturated hydraulic conductivity		Pressure plates
	Water repellence	Visual: assessment on sandy soil for patchy plant growth, moist soil at the surface but dry below Water droplet test	Water droplet and ethanol test

● = simple assessments that can take place on-site along with some requiring laboratory analysis.

Table 3. List of soil health assessments for chemical properties

Category	Test or assessment	On site	Laboratory
Organic carbon (matter)	● OC	Cotton undies, t-shirts or calico strips	Walkley Black
	● Total OC/total C (for carbon accounting)		Leco and acid pre-treatment if carbonate present
	OC fractions (labile and stable)	NIR spec (hand-held with backpack apparatus)	Potassium permanganate, MIR UV (dissolved OC), NMR
Soil reaction	● pH	Field pH kits Rhizobia nodulation	pH_{water} or pH_{CaCl_2}
Soil capacity	● Cation exchange capacity		Sum of base cations
Soil stability	● Sodicity	Slaking /dispersion	Exchangeable sodium percentage
Salinity	● Electrical conductivity (EC)	Field EC 1:5 Sentek SoluSAMPLER	EC 1:5, EC saturation extract, chloride
Macronutrients	Total N, P		Leco
	● Available N, P, K		Colwell, Olsen, Bray
Micronutrients	Trace elements		Various
Base cations	Ca, Mg, Na, K, Al		Various

● = simple assessments that can take place on-site along with some requiring laboratory analysis.

Table 4. List of soil health assessments for biological properties

Category	Test or assessment	On site	Laboratory
Nutrient release	Enzyme activity		e.g. dehydrogenase, cellulase, chitinase, amylase, phosphatase and phytases
	Potentially mineralisable N/C		Potentially mineralisable C or N
Microbial activity	● Soil respiration	Solvita	Microbial respiration
	● Cotton strip test	Cotton undies, t-shirts, or calico strips	
Microbial biomass and community	Microbial biomass	● microBIOMETER	Microbial biomass carbon (MBC) Potentially mineralisable N, Hot water extractable OC
	Microbial diversity		Direct Microscopy, DNA, Next-gen DNA sequencing, qPCR
	Microbial composition Functional biodiversity		Active fungi, active bacteria, Bacteria to Fungi ratio, protozoa, nematodes, mycorrhizal fungi
Rhizobia symbiosis	Nodule counts and distribution	If legumes present, look for and record nodules	PCR – 16S rRNA sequencing
Macrofauna community and abundance	Earthworms and macro-arthropods (insects, spiders, springtails) etc	Record what and how many are present e.g. earthworms, mites, spiders, ants	Next gen DNA sequencing (research only)

● = more simple assessments that can take place on-site along with some requiring laboratory analysis.

How to compare results

Consider how to report soil function and changes to soil health. Ideally, soils should be compared to an example of a 'good' or healthy agricultural soil of similar location and soil type to account for climatic, textural, and mineralogical variability.

Comparison of agricultural and native systems should only be in the context of establishing the natural capacity of a soil for defined functions, such as OC storage capacity. Natural systems are closed loops with virtually no losses from the system. They do not require inputs of nutrients and their microbial communities are mostly at equilibrium and stable.

In contrast, agricultural systems remove OM and nutrients from the system and require inputs to balance the removals. The way a vineyard is managed will affect microbial community dynamics and large fluctuations in 'who is there' could occur. So, comparison of soil health between native or natural systems and vineyards is only useful for some of the parameters.

Soil function scorecards can be used to monitor the same site over time and the scores can be used for comparison at the vineyard scale when compared on similar soil types. However, they are not recommended to benchmark soils to compare a neighbouring vineyard, or at a regional or state level due to the complexity of living systems, effect of management, rainfall, irrigation, and soil texture being assessed. There are several existing scorecards and soil health assessments, and these can be used for guidance.

Table 5. Soil health management manuals and scorecards

Body	Name	Description	Link	Year
Australian				
Agriculture Bureau of SA	Better soils		Better soils modules Index (soilwater.com.au)	1997
NSW DPI	SoilPak	Dryland farmers on red soil of central western NSW	SOILpak – dryland farmers on the red soil of central western NSW	1998
Tuckombil Landcare	Good soil and good worm projects	Northern Rivers soil health card	https://www.dpi.nsw.gov.au/agriculture/soils/soil-testing-and-analysis/health-card	2002
Soil Quality Australia	Soil quality Australia	Benchmarks	https://www.soilquality.org.au/.	2014
Terrain NRM	Soil health	Tropical soils: A guide to soil health	Soil health: Supporting rural Industries in the wet tropics (terrain.org.au)	2022
International				
Cornell University	Comprehensive assessment of soil health		Manual | Cornell soil health	2016
Food and Agriculture Organisation of the United Nations (FAO)	Soil testing methods		Soil testing methods, a farmer to farmer training program	2020
NZ Bragato Research Institute, Merfield, C.	DIY soil health tests		Behind membership login	2022
NZ Graham Shepherd	Visual soil assessment	Pastures – Part 1	Pasture_vol1_2011.pdf (fao.org)	2011
		Pastures – Part 2	03-Folder.indd (fao.org)	2011
United States Department of Agriculture USDA	Soil health assessment	Soil quality indicator sheets	https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health/soil-health-assessment	2015

Agriculture Victoria evaluated several soil health and decision support tools which can be found on the **tools and systems for assessing soil health website** including the USDA and the NSW Northern Rivers soil health card and is a good source of information.

There are a few commercial soil health apps available to record and store your information (e.g. **The regen platform**).

We have created a recording sheet to capture most of the soil health properties. For more information please refer to the Excel sheet **EcoVineyards soil data recording and water infiltration**.

ONLINE INFORMATION FOR SOIL HEALTH INDICATORS

AWRI Fact Sheet: Assessing soil health in a vineyard

EcoVineyards: Soil health indicators for Australian vineyards

Wine Australia: Soil health

GWRDC: Assessing soil quality and interpreting soil test results

GWRDC: The status of soil health in the viticulture and wine industry – a review

Government of SA, DEW: Soils of South Australia

Government of SA, DEW: Describing and interpreting soil profiles

NQ Dry Tropics: Rapid assessment of soil health (RASH) **videos and manual**

Soil Science Australia: Soil resources to help manage your soil

VITICARE ON FARM TRIALS

AWRI: Viticulture on farm trial manuals

Manual 2.1: Improving Soils 1 – Improving soil acidity and managing hard-setting and crusting of under-vine soil surface

Manual 2.2: Improving Soils 2 – Managing soil moisture under mulches and managing soil using cover crops

Manual 3.2: Soil profiling – Soil moisture monitoring, infiltration, soil organic matter, soil sampling, earthworms, porosity, root examination, soil strength, soil salinity, soil structure

STATE SOIL AND LAND INFORMATION

Victoria https://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil-home

NSW https://www.environment.nsw.gov.au/topics/land-and-soil/managing-land-and-soil

Western Australia https://www.agric.wa.gov.au/climate-land-water/soils/managing-soils

South Australia https://www.environment.sa.gov.au/topics/soil-and-land-management

Tasmania https://nre.tas.gov.au/agriculture/land-management-and-soils

Queensland https://www.qld.gov.au/environment/land/management/soil

Northern Territory https://www.territorynrm.org.au/nt-healthy-soils-hub

NATIONAL SOIL STRATEGY

Australian Government: National soil strategy

Menzies Research Centre: From the ground up: Unleashing the potential of soil

SECTION 2:

KEY SOIL HEALTH INDICATORS

PHYSICAL

Mineralogy

Rocks are made of different minerals and their properties depend on how they were created. Weathering of these rocks (parent material) releases minerals and when this is mixed with OM, soil is formed. The composition, size and inherent properties of soil particles are affected by the base parent material (e.g. kaolinite, quartz) and what processes were involved in the weathering of the parent material (glacial, erosion, chemical).

Mineralogy largely influences the clay particles and determines the inherent fertility of the soil and surface area available for the storage of anions, cations (cation exchange capacity) and carbon. This, in turn, affects plant productivity and the quality of produce.

Inherent soil properties are determined from the parent material and influenced by the environment. They are not easily changed through management unless extreme modifications are made (earth moving, severe erosion). Inherent properties include, soil texture, mineralogy, cation exchange capacity, nutrient or elemental deficiencies, and toxicities in subsoil layers.

Dynamic properties can be readily changed by management and are commonly monitored for soil health. These include soil structure, aggregate stability, pH, OC, salinity, and microbial activity.

Morphological characteristics

Morphological characteristics are used to describe soil and allow for groupings of similar characteristics to compare between sites and over time. There are many soil properties that could be recorded, and the 'yellow book' (McDonald et al., 1998) provides standards for description. Many states have their own handbooks (see links on the opposite page). A brief description of key characteristics is listed below.

Depth of soil layers (horizons) is important to record, especially the depth of topsoil, depth to a subsoil clay layer or a restrictive layer (often indicated by roots not growing through the layer or growing sideways) and depth of the rootzone (where most roots are growing).

Colour can tell us a lot about the inherent properties of soil and don't readily change over time:

- dark coloured surface soils often have higher OM and fertility than very pale or white colours
- bright colours, such as red, indicate good aeration and moderately well drained
- mottles of grey or green indicate poor drainage and waterlogged conditions.

Carbonates (calcium and magnesium) affect soil pH, nutrient availability, and water movement through the profile. Calcium and magnesium carbonates are common in southern Australia where annual rainfall is less than 500 mm. Carbonate values above 20% in clays can severely restrict root growth.

Further information

- Government of SA, DEW: Assessing agricultural lands
- Government of SA, DEW: Soils of southern South Australia
- Government of WA DPIRD: A simple guide for describing soils
- Soil Science Australia: Soil standards

Soil texture

Texture is a defining characteristic of soil, and the amount of sand, silt, and clay sets the limits and realistic expectations of the soil capacity and what it can support and produce. Soil texture generally does not change with land management as it is an inherent property of soil.

Table 6. Soil texture assessment

Important for:	Measured by:	Can it be changed?
• Water and air movement • Nutrient-holding capacity • Ease of root growth • Workability • Resistance to erosion	• On site: hand texture • Laboratory: particle size analysis	No *The addition of sand or clay amendments will affect the texture grade, but this is not common practice.*

Soil texture, particularly the amount of clay in the soil, determines the ability of the soil to hold and make water available for plants and biology, the rate of movement of water and air through the soil, the soils capacity to hold on to nutrients (cation exchange capacity), the ease of root growth, its workability and resistance to erosion.

The solid particles in the soil can be divided into:

- gravel (> 2 mm)
- sand (2.0 to 0.02 mm)
- silt (0.02 to 0.002 mm)
- clay (< 0.002 mm)

The amount of sand, silt, and clay in the soil determines the texture grade and these range from sand to loam to heavy clay.

While gravel is not included in soil texture it is important to estimate how much is present (1 to 100%) as it affects the water, carbon, and nutrient-holding capacity of the soil.

Solid particles make up about 50% of the soil and the rest is space. The space or 'pores' can be filled with liquid (mostly water) or air. The size of the pores determines what function they play in the soil – water drainage, storage, availability, aeration, and root growth.

The size of the solid particles affects the smaller spaces, and they determine how much water is readily available (mesopores) as well as unavailable (micropores) to plants.

The more clay that is in a soil, the more micropores hold water that is unavailable to plants. On the flip side, soils with more sand have less micropores because of their larger size, so water is more readily available to plants.

Table 7. Properties of different soil texture grades (Maschmedt, 2004)

Property	Texture grade				
	Sand	**Sandy loam**	**Loam**	**Clay loam**	**Clay**
Total available water	Very low to low	Low to medium	High to medium	Medium to high	Medium to low
Infiltration	Very fast	Fast to medium	Medium	Medium to slow	Slow
Nutrient supply capacity	Low	Low to medium	Medium	Medium to high	High
Leachability	High	High to moderate	Moderate	Moderate to low	Low
Tendency to set hard	Low	High	High to moderate	Medium	Medium to low
Susceptibility to compaction	Low	Moderate	Moderate to high	Low	High

Water-holding capacity

Soil holds water that grapevines can extract during the growing season. As the soil dries out, the water is held with increasing strength that requires more effort by the plant to extract it. Soil texture influences the suction required for a plant to remove water. Available water-holding capacity can be calculated using soil texture, depth of the soil layer, and plant rootzone.

kPa PRESSURE THRESHOLDS

- Saturated soil is when all the soil pores are full of water and there are no air spaces (0 kPa)
- Field capacity is the maximum water a soil can hold after gravity has drained the water and, depending on soil structure, this can take a few hours or a few days (8 to 10 kPa)
- Available water-holding capacity is the water in the soil held between field capacity and the point that plant roots are not able to extract (wilting point suction of 1500 kPa).
- Readily available water-holding capacity is the water in the soil held between field capacity and the water that is easily extracted by the plant (60 kPa)
- Deficit available water is harder for the plant to extract and results in water stress to the plant (between 60 and 200 kPa).

Water-holding capacity is primarily controlled by soil texture (particle size) and OM. Sands have lower total water-holding capacity than clays because of their lower proportion of capillary and micropores.

Further information

- DPI NSW: **Determining readily available water to assist with irrigation management**
- GWRDC: **Water management for wine grapes in a drying environment**

Soil structure

Soil structure is a critical component of soil health and determines the ability of air to move, water to infiltrate, be held and drain, seedlings to emerge, roots to explore and the capacity of the soil to bounce back from raindrop impact and mechanical or animal disturbance.

Table 8. Soil structure assessment

Important for:	Measured by:	Can it be changed?
• Water and air movement • Ease of root growth • Ease of seedling emergence • Resistance to erosion	On site: visual assessment by size, shape, and strength of soil aggregates Home lab: aggregate stability through slaking and dispersion test Laboratory: aggregate stability through wet sieving	Yes *Management practices that affect OM inputs and disturbance that changes the space and strength of the bonds between aggregates.*

A new phone app by the Soil Health Institute can help objectively assess slaking **SLAKES: A free smartphone app to measure aggregate stability**

Soil particles are held together by clay, OM, fungal hyphae, and secretions from worms and other soil biology into aggregates. They often look like crumbs and are technically known as peds. The way the aggregates are arranged together is called soil structure. The space or pores between the aggregates are called macropores and are important for water drainage, air movement (aeration) and enabling root growth.

Soils with no or poor structure are apedal (single grains like beach sand or have a massive structure with no defined peds). Soils that have the peds grouped together into well-defined aggregates and can separate easily from one another are pedal. Pedality describes the shapes and can be used to indicate the physical condition of soil.

The most favourable pedal structure are crumbs, polyhedral and blocky (< 5 mm). Prismatic, columnar, and platy structures are unfavourable as they affect root growth and water and air movement.

Good soil structure has enough macropores to allow air and water to move freely, providing an environment that encourages plants and soil biology to thrive. Soil will have a lot of small peds (< 5 mm) that separate easily and, when dry, can be crushed by hand.

Poor soil structure has few aggregates and macropores which hinders air and water movement, root, and microbial growth. The soil will have no structure (massive) or large peds > 25 mm across that are too hard to break between the fingers when dry.

Further information

- Agriculture Victoria: **Soil structure**

Soil porosity

Soil porosity is a measure of the pore spaces filled by air or water in soil. The size, distribution, and connection of pores is important for a soil to function.

- Macropores or transmission pores are visible to the naked eye (size between 30 to 60 µm) and need to occupy more than 10% of the soil volume so plant roots can get adequate oxygen.
- Mesopores or storage pores (size between 0.2 and 60 µm) hold onto water against gravity and is available for plant roots and soil biology. Solid particles (texture) influence the size of pores and the volume of soil occupied can range from less than 10% in a loamy sand to more than 20% in a structured loam.
- Micropores or residual pores (size less than 0.2 µm) hold water so tightly that plants and most biology can't extract it (water held below wilting point). The proportion of clay particles in the soil directly influences the volume of pores in this category and can be as high as 25% in a heavy clay.

For reference, 1 µm = 0.001 mm

Arbuscular mycorrhizal fungi can access water for plants from normally inaccessible micropores.

Most plants stop growing when air porosity is below 10% at field capacity. Note that some plants, such as rice or reeds, can grow at lower levels of aeration (Hazelton and Murphy, 2007).

Macropores are the most easily compressed by machinery because they are usually full of air.

Porosity can be estimated by visual examination of the macropores in the soil or by calculation with the bulk density of the soil.

Bulk density measures the density of a porous material and accounts for the solid particles and the pore spaces. If we know the density of the solid particles (specific gravity) we can work out the volume of air spaces. As a rule of thumb, the specific gravity of solid particles is taken to be 2.65 t/m^3 (Hazelton and Murphy, 2007).

Soil porosity can be calculated as:

(1 – (soil bulk density at the location / specific gravity of solid particles)) x 100

If a soil had a bulk density of 1.32 t/m^3 then:

(1 – (1.32 /2.65)) x 100) = (1-0.498) x 100

= 50% of the soil volume is pore space.

Further information

- Agriculture Victoria: Porosity
- CRCV: Vineyard activities 6, Measuring soil porosity

Aggregate stability

The strength of the bonds between aggregates determines if soil structure holds together and bounces back when a change occurs, such as wetting or disturbance by machinery or animal.

Slaking

Poorly structured soils have weak bonds that disintegrate (slake) into separate microaggregates as water moves rapidly into dry soil and forces the air out. A typical feature of these soils is low organic matter/carbon levels which restricts the soil biological population and the resultant processes that create the aggregate bonds.

Dispersion

Dispersive soils are structurally unstable because of a chemical reaction between water and sodium in the clay particles where microaggregates separate into individual particles (sand, silt, and clay). These soils respond to gypsum (calcium sulfate) application to replace the sodium with calcium on the clay particle.

For soils that slake or disperse, the solid particles move into pores and can form a crust at the soil surface or a hard layer in the subsurface. The blocked pores affect air and water movement and create a barrier to seedling emergence in the surface and root growth in the rootzone. Dispersive clays increase the erodibility of the soil.

In well-structured soils, the aggregates remain intact due to their strong bonds, allowing water to enter and drain quickly and enabling the balance of air and water for plant and biological growth. There will be no obvious surface crusts and the soil is resilient to erosion and some disturbance.

The slaking and dispersion test is commonly used on site to assess the strength of the bonds holding the aggregates together (slaking) and the stability of the clay particles within the aggregates (dispersion). Chemical analysis measuring the amount of exchangeable sodium as a percentage of the total cation exchange capacity also identifies dispersive soil.

Figure 4. An example of slaking and dispersion.

Further information

- CRCV: Vineyard activities 5: Assessing soil structure
- EcoVineyards: Soil health indicators for Australian vineyards
- Soil Health Institute: SLAKES: A free smartphone app to measure aggregate stability

Soil strength

Soil strength is the ability of the material to resist imposed forces and indicates the amount of energy required to break apart soil aggregates. We often use it to determine if a soil will restrict root exploration or will withstand compaction. High soil strength resists deformation forces, such as compaction, but will also resist root penetration.

Soil strength varies with soil moisture so what can be hard and restrictive to root growth when dry can be fine when moist. Alternatively, a soil that is resistant to machinery compaction when dry can be very susceptible to severe compaction when wet—the reason animal and machinery traffic is avoided in wet conditions on most soils.

Soil strength influences aggregate stability and structure and is a useful soil health indicator. As soil strength changes with soil moisture, it is important to monitor and compare at a standard time and moisture content. However, this is not always possible, so it is good to record the moisture content when assessing the soil (dry, moderately moist, moist, wet).

Soil strength can be approximated by assessing the consistency of a 20 mm ped of soil using the force of fingers or foot. Alternatively, the force required to push a piece of wire into the soil will also identify where layers may restrict root growth. A cone penetrometer (a more technical form of the wire) can measure the resistive forces. Values above 2.5 MPa (2,500 kPa) indicate the likelihood of severe restrictions to root growth. Penetrometers work best when soil moisture is at field capacity to the depth of inspection otherwise you are picking up the wetting front or textural change boundary. Bulk density of the soil can provide an indication of soil strength and values above 1.6 t/m^3 are considered difficult for root growth.

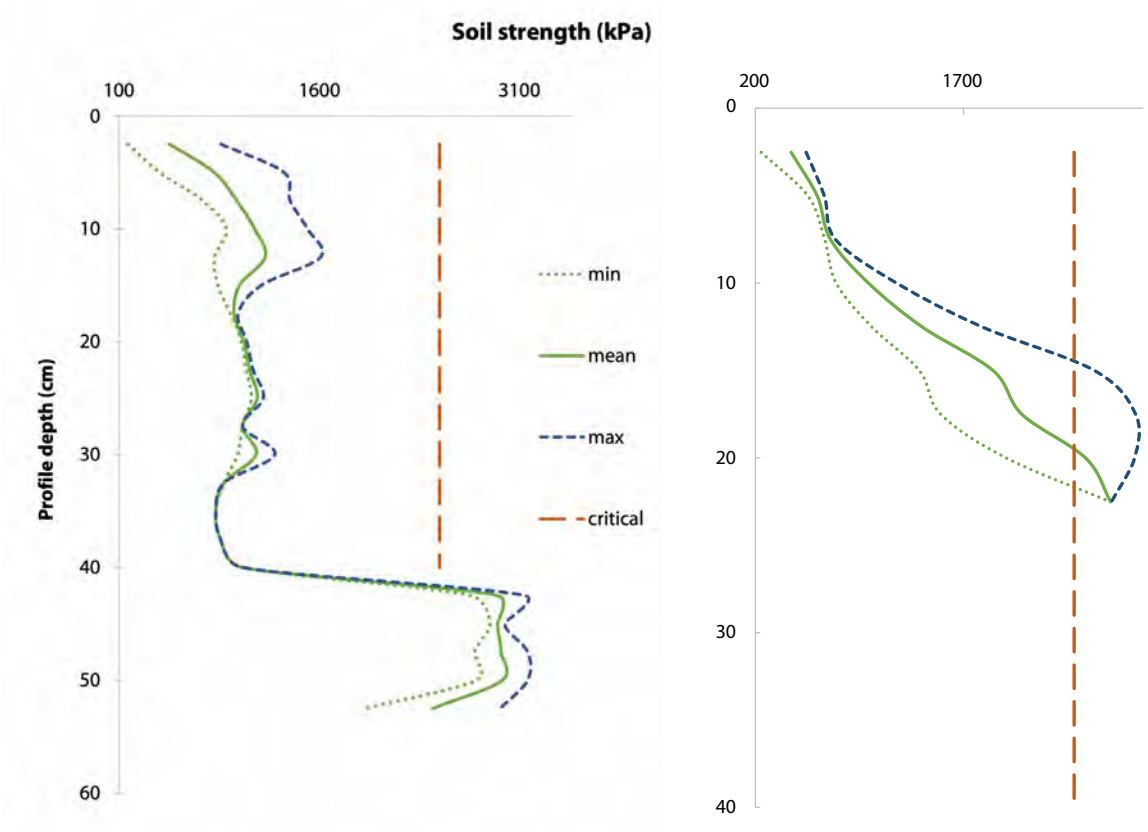


Figure 5. Testing soil strength with a penetrometer and the critical point of 2.5 MPa (2,500 kPa) [Data: Amanda Schapel].

Further information

- CRCV: Vineyard activities 7, Measuring soil strength and Research to Practice: Measuring soil strength
- EcoVineyards: Soil health indicators for Australian vineyards

Water infiltration

Water infiltration evaluates many physical properties in one test including structure, aggregate stability, porosity, and soil strength. It measures the rate of water movement into the topsoil, through the subsurface and is highly dependent on soil texture. As soil structure is associated with management practices, water infiltration can be used as an indicator of change.

High infiltration rates reduce run-off and have a lower risk of waterlogging; however, very high rates can indicate nutrient leaching and poor water storage in the rootzone.

Table 9. Water infiltration for different soil types (SARDI, 2024)

Soil type guide	mm/hr
Sand	20 to 250
Sandy loam	10 to 80
Loam	1 to 20
Clay loam	2 to 15
Light clay	0.3 to 5
Medium heavy clay	0.1 to 8

Slow infiltration indicates low permeability somewhere in the profile and should be followed up with visual observations. Faster infiltration indicates soil structure with few restrictions to water movement and can be due to the soil texture (e.g. sandy soils), or soil with many macropores, old root channels or cracking soil where water flows preferentially down the cracks instead of through the pores in the soil. Moisture content affects infiltration rate, and it is recommended to test at, or wet the soil to, field capacity prior to recording the result.

Figure 6. The rate of water infiltration is important, so rainfall isn't lost as evaporation or runoff

Water infiltration is not as sensitive an indicator to structural change as the more intensive, laboratory saturated hydraulic conductivity tests. However, refinements can be made to the simple on-site test to help monitor change to structure over time. Recording the water infiltration at set time periods can assess changes to where water movement is restricted (often due to change in soil textural boundary or a hard layer that has a change in pore structure).

Water repellence

Water repellence can greatly affect water infiltration into soils. Waxy organic compounds from the decomposition of water-repelling waxy materials from plant residues or fungal hyphae coat soil particles.

Sandy soils (< 5% clay) are the most susceptible and repellent soils have uneven water distribution where water can remain ponded on the surface to be evaporated, lost as runoff, or slow infiltration through less repellent areas.

This leads to patchy and uneven plant emergence and the lack of plant cover and runoff can lead to significant erosion on sloping sites with heavy autumn or summer rains. It is best to sample for water repellence when soils are dry as wet soils do not exhibit obvious water repellence.

Further information

- CRCV: Vineyard activities 8, Measuring the infiltration rate of water into soil
- EcoVineyards: Soil health indicators for Australian vineyards

CHEMICAL

For plants and biology to grow soil needs to provide an environment that supplies nutrients within a range and form that is suitable for the plant. The supply of nutrients can be affected by deficiencies or toxicities inherent to the soil or an inability to access the nutrients.

pH: measure of acidity/alkalinity

Soil pH has a large influence on the supply of nutrients (cations and anions) to plants, the chemical behaviour of toxic elements and the activity of soil biology. All flora and fauna that live in soil prefer specific pH ranges for growth – generally neutral to slightly acidic or alkaline. As pH becomes more acidic or alkaline the flora and microfauna become less productive.

pH = the potential or power of hydrogen

- **Soil pH measures the amount of hydrogen and hydroxyl ions in the soil and uses a logarithmic scale from 1 to 14.**
- **A pH of 7 is neutral, less than 7 is acidic (high v ions) and above 7 is alkaline (low H^+ ions).**
- **As pH is a logarithmic scale, a change in number changes the result by tenfold.**
- **A pH of 5 is ten times more acidic than a pH of 6 and a pH of 4 is one hundred times more acidic than a pH of 6.**

Table 10. Soil pH assessment.

Important for:	Measured by:	Can it be changed?
• Availability of nutrients for plants and soil biology • Deficiency or toxicity of macro and micronutrients • Buffering capacity • Soil structure	On site: field pH test kit Laboratory: pH_{water} or pH_{CaCl_2} 1:5 soil:water test	Yes, for acid soils – application of lime, use of non-acidifying fertilisers. No – for strongly alkaline soils.

Soil pH can be measured by two methods: a 1:5 soil-to-solution ratio measured in water (pH_{water}) or in calcium chloride (pH_{CaCl_2}). The methods give different results, so it is important to indicate which method has been used for interpretation.

Optimum plant growth occurs when pH_{water} is between 6.0 to 8.0 or pH_{CaCl_2} is between 5.5 to 7.5.

Outside of these ranges the concentration of major nutrients (phosphorus, potassium) and micronutrients (manganese, iron, zinc, copper, calcium, molybdenum, copper, sodium, boron) are affected.

pH_{water} can be used for alkaline soils. Soil pH_{CaCl_2} gives a more accurate result in neutral to acid soils and has less variability during seasons and is usually 0.5 to 1.2 units below pH_{water}.

Acidity

Acidity is a severe soil issue. It affects nutrient availability and plant uptake, decreases microbial activity especially for nitrogen-fixing bacteria and at pH_{CaCl_2} below 4, permanent damage to clay structure can occur. Acidity can be inherent (naturally occurring) and often occurs in high rainfall areas in soils with low buffering capacity. Acidity can also be induced and can increase under horticultural production and the use of nitrogen fertilisers. Applications of lime (target pH_{CaCl_2} of 5.5) and the use of non-acidifying forms of fertilisers can help manage acidity.

Alkalinity

Soil alkalinity is an inherent condition and is generally not an issue until pH_{water} is above 9 when toxic amounts of bicarbonate, carbonate, aluminium, and iron and nutrient deficiencies (especially copper and zinc) occur. At this range, sodium bicarbonate is common and clays with this pH often have very high boron and salinity. Microbial activity can be affected at high pH.

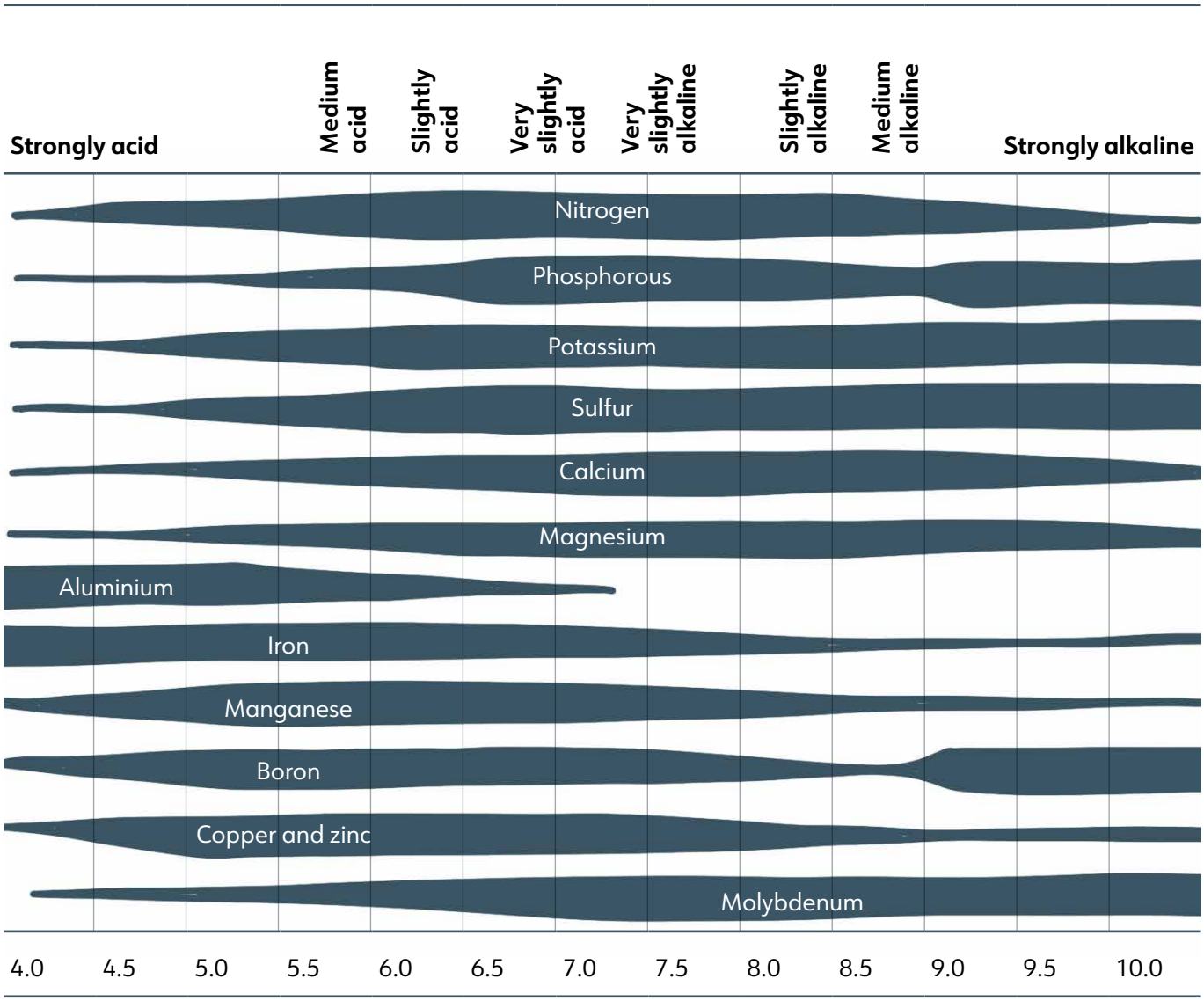


Figure 7. Influence of pH_{water} on nutrient availability (Price, 2006, in Maschmedt, 2004).

Further information

- GRDC: **lime and soil acidity calculators**

Redox potential (Eh)

Soil redox potential (Eh) is used as an indirect measure of soil oxygen status and indicates how reduced (anaerobic) or oxidised a soil is. It is by measured by the difference between reduction (gain of electrons) and oxidation (loss of electrons) (Husson, 2013). There is interest to use redox as an integrative measure of soil and plant condition and an Eh-pH model has been proposed to develop a one health approach (Husson et al., 2021).

Eh is expressed in volts and conditions favourable for plant growth are between 350 to 500 mV with optimum conditions between 400 and 450 mV. It is measured in the field using a specialised electrode.

There are many aspects of this work that are fascinating and have potential applications in production systems. For example, the relationships between Eh, nutrient availability, plant stress and the susceptibility of plants to pathogen and pest species (Husson et al., 2016).

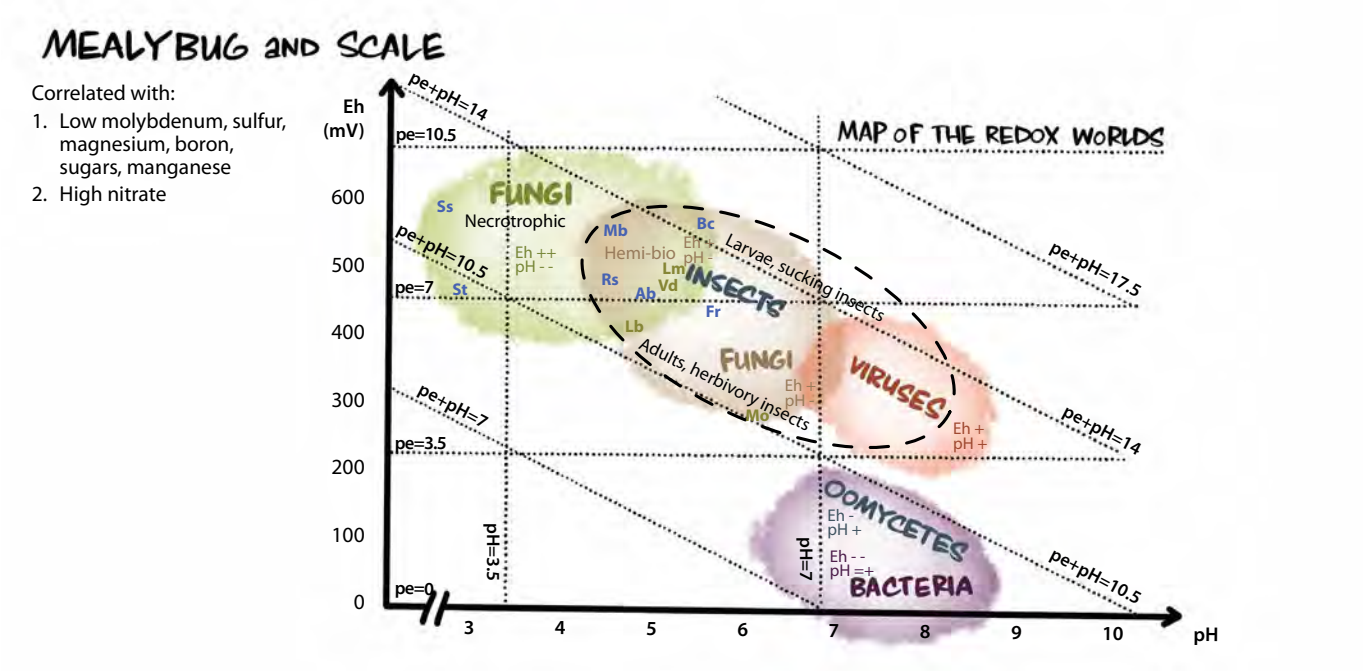


Figure 8. The role of redox potential, nutrient availability and the impact on plant susceptibility to fungi, insects, viruses and bacteria (Husson, 2019; Kempf, 2023).

pH is a measure of the acid-base reaction (transfer of protons) whilst redox measures the oxidation-reduction reactions (transfer of electrons).

Stay tuned for more news on the application of redox potential as a measure of soil health and how it relates to the susceptibility of grapevines to pests and diseases.

Further information

- Investing in regenerative agriculture and food: **Olivier Husson, photosynthesis is the biggest lever we have in health, climate, droughts, floods, but most plants are too sick to do it properly**
- 2019 Soil and Nutrition Conference: **The role of redox potential and reduction-oxidation reactions**

Organic matter: organic carbon

Soil organic matter (OM) has an essential role in soil function as it regulates many of the ecosystem services. It is important for stabilising soil structure; aggregating soil particles; increasing water infiltration and overall water-holding capacity; the storage and release of nutrients; and improving cation exchange and buffering capacity. It is also essential for providing a food source for a range of soil biology, stimulating diversity and activity so they can cycle nutrients, bind aggregates, compete, and provide a balance of pest, pathogens, and beneficials and convert active soil OC to a more stable form.

Soil organic matter (carbon) strongly influences key properties in the physical (structure), chemical (nutrients) and biological (food) categories. It can fit equally well as a chemical or biological soil health indicator.

Table 11. Soil OM assessment

Important for:	Measured by:	Can it be changed?
• Food and energy source for soil biology • Water and air movement and storage (soil structure) • Nutrient storage (CEC) and cycling • Greenhouse gas mitigation • Soil resilience	On site: soil colour Home lab: aggregate stability through Slakes App or aggregate stability in water test (ASWAT) Laboratory: soil OC, carbon fractions	Yes *Rainfall (irrigation), temperature, topography, soil texture (clay amount and mineralogy).* *Management practices that affect OC inputs (plant, external) and losses (soil disturbance, erosion).*

Soil OC is a measurable component of OM and makes up about 58% of OM with the remaining mass consisting of other nutrients, such as nitrogen, phosphorus, and sulfur. It includes all living and dead organic material in the soil, such as plants, soil organisms, and animal materials. It does not include fresh, undecomposed plant material on the surface.

Multiply OC concentration by 1.72 to get an estimate of the OM concentration.

OM in vineyards can come from plant inputs – shoots, roots, root exudates, microbial secretions, dead microbes – and external inputs – composts, manures, mulches. There are two ways to build soil OC: the decomposition and soluble carbon pathways.

Decomposition pathway

OM enters the soil from leaves, residues, and roots and is decomposed by soil biology. This pathway is essential for soil function including cycling nutrients for plants to take up and produce secretions important for binding aggregates that influence air and water movement. As these inputs have low carbon efficiency, a large proportion (70 to 90%) can be released back to the atmosphere as CO_2.

As the microbes continue to decompose the OC, it becomes more nutrient rich and eventually resistant to further decomposition as it becomes stabilised by attaching to the surface of clays, within soil aggregates, within iron, aluminium, and calcium complexes.

This form of OC is known as mineral associated organic carbon (MAOC) and can reside in soil for decades and is important for offsetting greenhouse gases. The more active form of OC is called particulate organic carbon (POC) and is essential as a food source for soil biology, the nutrients and water storage services we need in our soils.

Soluble carbon pathway

The soluble carbon (also known as the 'liquid carbon' named by Dr Christine Jones) pathway focuses on the production of root exudates (simple sugars, amino, and organic acids) via photosynthesis and their microbial interactions (such as mycorrhizal fungi).

The root exudates and their microbial by-products (mostly from fungi and bacteria) can bind directly to minerals (MAOC) and are important for long-term OC storage.

OC from root exudates and microbial by-products can be directly bound to the mineral surfaces without any loss of carbon to the atmosphere.

Below-ground OM inputs (roots, their exudates, and microbes) have a greater role on stable OC than above-ground OM that has a greater role in soil function.

Mycorrhizal fungi that live inside plant roots and extend hairlike filaments or hyphae into the surrounding soil to obtain more nutrients and water for the plant are also associated with producing glomalin, a 'super glue' that helps soil aggregates stick together.

The hyphae are especially important for soil structure in sandy soils where they stick and hold individual sand particles together. Glomalin deposition is thought to improve soil OC storage through stable MAOC.

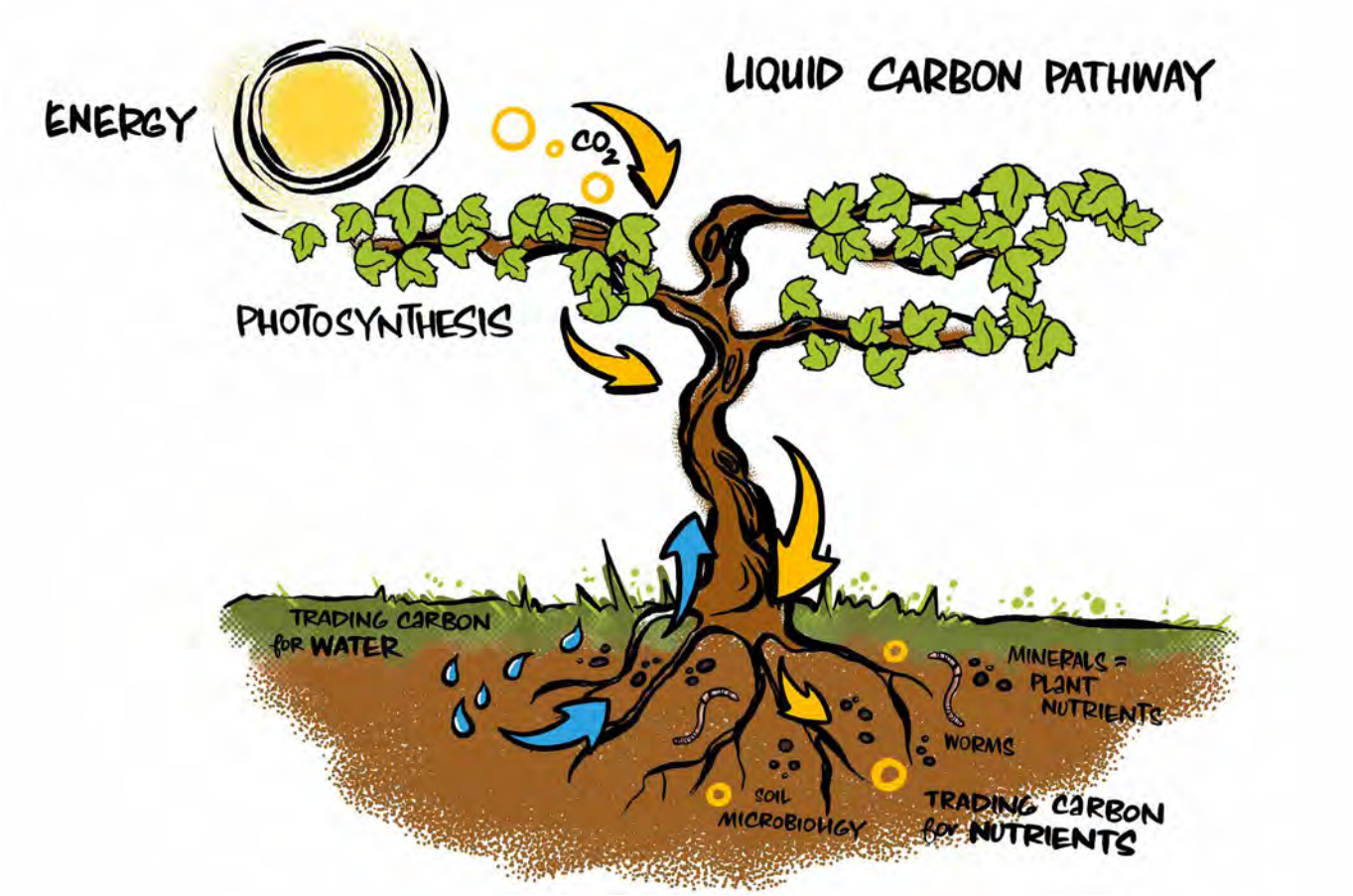


Figure 9. Soluble or liquid carbon pathway.

The potential for improving OC depends on a soil's measured (baseline) level of OC and its storage capacity. Climate and management practices affect the amount of OM that can be grown and put into soil. Soil type (texture, density, and mineralogy) determines the amount of soil OC that can be protected and stored long term. Any OC that is surplus to the protective capacity of the soil type is susceptible to decomposition from microbes.

All soils have a finite capacity to store OC (upper limit). Sandy soils have a lower potential to store OC than loamy soils due to their lesser clay content.

Management influences the type and amount of organic material produced; crop selection, provision of nutrients and soil amendments, residue management, tillage practices and pest management strongly influence soil OC content. Losses of OC can occur from topsoil erosion, breaking of soil aggregates with machinery or animal disturbance and the removal of plant and animal products.

Many tests assess soil OC and the Walkley and Black method is most commonly used. Total carbon is the method required for carbon accounting (total OC if there is carbonate present in the soil) and active carbon fractions can be estimated using the potassium permanganate test.

Soil sample collection for soil chemistry is suitable for assessing soil carbon.

Table 12. Soil organic tests

Test	Method	Measures	Benefits / limitations
Organic C	Wet oxidation (Walkley Black method)	OC	Incomplete reaction: measures 75 to 90% of Total OC. Doesn't measure CO_3 which can be a benefit.
Total C	High temperature combustion (Dumas method)	OC and IC	Measures Total OC in acid or neutral soils. In soils with CO_3 and charcoal can be difficult to measure change in OC
Total Organic C	Acid pre-treatment then high temperature combustion	OC	Preferred method for soils with CO_3 present. Need to ensure that have complete removal of CO_3 before combustion or results will be incorrect.
Mid Infrared	Spectroscopy	OC and fractions	Quick and relatively cheap, not as accurate as other methods until calibrated. Sensitive to CO_3 and requires acid pretreatment. Not commercially available in high pH soil and more calibrations required.
Labile C	Potassium permanganate	(P)OC	Measures energy source used by microbes. Sensitive to changes in soil health and fertility due to management. No Australian standards
Haney C	Water extractable	(P)OC	Measures energy source used by microbes. Not sufficient data in Australia for standards.

Generally, 2% is used as a target value for OC and adjusted to 1% for sandy soils. Values less than 1% OC are considered below the soil's capacity to perform key functions (Kay and Angers, 1999). It can be difficult to improve OC in these soils as soil biology is often constrained and there may be a delay in measuring changes to OC if management to improve OM inputs are used whilst waiting for the microbiological community to function and soil properties to improve.

Higher OC values are often seen in the mid-row and can be used as a benchmark for what the vine-row can achieve.

Soil OC values above 2% are considered to have very good structure, high buffering capacity and sufficient OM to decrease bulk density and improve water-holding capacity (Hazelton and Murphy, 2007).

Many soils can measure higher than 2% OC but for long-term storage and contribution towards mitigation greenhouse gas emissions, the OC needs to be stabilised to the mineral surface of clay, iron, aluminium, or calcium complexes (mineral associated OC). Any OC that is not stabilised to the mineral surface or encased in soil aggregates is exposed to decomposition by microbes and values can fluctuate dramatically when conditions change the microbial community.

There are areas where it will be much easier to increase soil OC above 1% for sands and 2% for other soils and areas that will struggle to maintain the improvements, particularly during summer.

High rainfall systems that can sustain a high proportion of perennial plants will be able to aim for higher OC targets, such as 4 or 6%.

In lower rainfall, high summer temperature systems, it can be a struggle to maintain the improvements made over the season. In these systems, mulch becomes an important management tool where living (i.e. native plants) plants that have died or imported materials have a large role in regulating the soil environment.

The ratio of total carbon and total nitrogen (C:N) provides an indication of the rate of breakdown of organic residues. Values below 25:1 C:N indicate fast decomposition and above 25:1 C:N will be slow unless nitrogen is added (Hazelton and Murphy, 2007).

Available nitrogen is tied up in soil microbes rather than available for plant growth as they decompose the OM unless the plant material has sufficient nitrogen present (e.g. legumes).

Soil OC is often used as an indicator of health, but results need to be interpreted in the context of the associated biological, chemical, and physical properties. For example, in highly acidic soils (with pH_{CaCl_2} below 4.5) there is reduced diversity and activity of soil biology that reduces the turnover of OC.

Therefore, the soil may have high OC levels but is not favourable for healthy plant growth. It is critical to understand the soil being tested and identify any soil properties that could be limiting soil function.

Further information

- Agriculture Victoria: Introduction to soil carbon e-learn module
- CRCV: Vineyard activities 4, Measuring soil organic carbon in soil
- The Australian and New Zealand Grapegrower and Winemaker Journal: The importance of soil organic matter
- The University of Adelaide: Soil carbon undervine video
- The University of Adelaide: Clarifying Carbon: plants, soils, and carbon?

Salinity

Soil salinity affects plant growth and quality and soil biological activity.

Table 13. Soil salinity assessment

Important for:	Measured by:	Can it be changed?
• Low levels are needed for efficient water and nutrient uptake	On-site: handheld salinity meter Laboratory: EC 1:5 soil:water, EC saturation paste extract, chloride	Yes *Irrigation water can have high levels of salt (sodium chloride) and excessive irrigation can lead to water table induced salinity.*

Soil salinity measures the presence of soluble salts in the soil. The main salt is sodium chloride but other ions, such as calcium, potassium carbonate, bicarbonate, sulfate, borate, and nitrate, can also contribute. While some salts, such as fertilisers, are needed for plant growth, excess salt is detrimental to plants, biology, and soil.

If the concentration of soluble salts is high enough, vines may not be able to take up water and nutrients from the soil. Sodium and chloride ions can accumulate in the vine, fruit, and wine and, in severe cases, can kill the vine and biology.

Analysis is commonly conducted by a 1:5 soil:water solution measuring electrical conductivity (EC 1:5) but requires a conversion factor to approximate the more accurate (but more expensive) saturation paste extract test.

Chloride analysis will also indicate salinity and plant damage can occur when levels are above (Maschmedt, 2004):

- 120 mg/kg for sands to sandy loams
- 180 mg/kg for loam to clay loams
- 300 mg/kg for clay soils.

EC measurement conversions:

1 dS/m	**= 1 mmho/cm**
1 dS/m x 640	**= 1 ppm salt (approximate)**
	= 1 mg/l salt (approximate)
1 dS/m x 1,000	**= 1 µS/cm**
	= 1 EC unit

Further information

- CRCV: Vineyard activities 3, Measuring soil salinity
- GWRDC: Salinity management interpretation guide
- GWRDC: Sustainable salinity management in your vineyard
- Wine Australia: Sustainable salinity management in Australian vineyards

Cation exchange capacity

Cation exchange capacity (CEC) is important for the nutrient-holding capacity of soil.

Table 14. Soil CEC assessment

Important for:	Measured by:	Can it be changed?
• Store and exchange nutrients • Buffering capacity	Laboratory: exchangeable cations, cation exchange capacity	Yes *Acid soils can reduce whereas OM can increase the number of cation exchange sites.*

CEC is a measure of the total negative charge of the soil and assesses its ability to attract, hold, and exchange positively charged cations (calcium, magnesium, potassium, sodium, aluminium, hydrogen) by electrical attraction. It is associated with the amount and type of clay (mineralogy) and OC, commonly called colloids. As plant roots take up cations, other cations in the soil water solution replace them on the colloid surface.

The higher the CEC, the higher the potential fertility of the soil and lower leaching of nutrients. Soils with a low value (< 5), which include sands, generally have low fertility status and low resistance to changes in soil chemistry (low buffering capacity) caused by land management practices. In these soils, addition of OM can help improve CEC.

As soil becomes more acidic, the number of negative charges on the colloid decreases, effectively decreasing CEC. Liming can help increase pH and CEC. The ratio of cations can be an important indicator for soil structure where values below 2 for calcium : magnesium indicates potential issues.

If levels of salts, gypsum, or carbonate (lime) are high, then it is worth asking for the exchangeable cations to be analysed with a 'pre-wash' to remove excess cations from the soil solution.

Sodicity

Is an indicator of structural stability (please refer to the section on aggregate stability) sodicity measures the amount of sodium ions adsorbed onto a clay particle as a proportion of the cation exchange capacity.

Table 15. Soil sodicity assessment

Important for:	Measured by:	Can it be changed?
• Aggregate stability	On site: Dispersion test	Yes
	Laboratory: exchangeable sodium percentage, sodium absorption ratio	*Application of gypsum can replace sodium ions with calcium*

Sodic or dispersive soils are structurally unstable because of a chemical reaction between the water and sodium in the clay particles where microaggregates separate into individual particles (sand, silt, and clay). When water or soil exchangeable sodium to total CEC (exchangeable sodium percentage) is more than 6, structural issues can occur and above 15% sodium toxicity can occur.

Sodicity issues can be inherent or induced by irrigation with saline or brackish water. Sodic soils respond to gypsum (calcium sulfate) application to replace the sodium with calcium on the clay particle.

Macro and micro-nutrients

Important for grapevine and microbial growth, grape and wine quality.

Table 16. Soil nutrient assessment

Important for:	Measured by:	Can it be changed?
• Nutrient supply • Plant and soil biology growth Grape and wine quality	• Laboratory: macro (N, P, K, S) and micro (Cu, Zn, Mn, Fe, Al, B)	Yes *Application of fertilisers, organic amendments high in nutrients*

Plant tissue rather than soil analysis is considered more reliable for assessing grapevine nutritional status. However, soil testing provides valuable information and assessment on fertility including deficiencies and toxicities in the soil and how it changes over time.

Soil testing is particularly important to assess pH, salinity, sodicity, OC, cation exchange capacity phosphorus, potassium, boron, and aluminium.

Further information

- GWRDC: Assessing soil quality and interpreting soil test results

Biological indicators

Soils collected from bulk soil do not reflect the microbial activity around the rootzone. When sampling for soil biology, target the soil directly around the roots (rhizosphere) for a clearer picture of soil biology associated with vines or mid-rows.

Please refer to the EcoVineyards best practice management guide on soil health in Australian vineyards: Part B (biology) for an in-depth analysis of soil biological indicators.

SECTION 3:

HOW TO ASSESS SOIL HEALTH INDICATORS

SOIL SAMPLING TECHNIQUES

The following are a collection of how-to sampling techniques for the key physical, chemical, and biological soil health indicators. There are many assessments that can provide an indication of soil health, and a basic suite is outlined in the table over.

Table 17. A basic suite of soil health indicators

Physical	Chemical	Biological	Plant
• Soil structure: pedality • Aggregate stability: slaking and dispersion • Soil strength: penetrometer and/or consistence • Water infiltration	• pH • OC • Salinity	• Microbial activity: cotton strip • Macrofauna: earthworm abundance • Macrofauna: diversity • Legume nodulation	Root depth Plant health

Soil function indicators are often not differentiated by soil texture. This can result in poor scores or ratings for sandier soils that inherently do not have the capability to support function that more clayey soils do. We have tried to score soil health indicators by soil texture, but the ratings are often based on educated thinking rather than backed by numerous studies.

How to take a soil sample

It can take many years to realise a change in soil parameters and it is suggested to re-sample the sites in 3 to 5 years' time. However, some soil properties are more dynamic and can change faster, especially biological and OM. More regular sampling can be conducted for these indicators.

Measuring change can often be difficult in soil due to inherent spatial variability. However, selecting a combination of physical, chemical, biological, and visual measurements should enhance the ability to detect change.

A soil sample is only a small representation of a vineyard block, so there will always be a degree of uncertainty due to natural variability. To minimise the uncertainty and improve the confidence of the results it is good to:

- collect samples from a single soil type and topography where possible
- use a representative area in a block, targeted area in a row or across several rows (e.g. 10 x 10 m or 25 x 25 m), or single point to monitor change over time with similar management
- sample at the same time and same depth(s), soil moisture, ground cover and the presence of roots will have the biggest influence on properties
- sample from the vine-row and/or mid-row depending on the reason for sampling
- consider the spacing from drippers and plants as salinity and nutrients will change with distance from a dripper and biological activity will be affected by soil moisture and the presence of active growing roots
- use the same in-field or laboratory method for testing and preferably use the same laboratory.

Photos are the best way to record change. Take lots of them as you are very unlikely to remember what the soil looked like before.

Please refer to the soil health recording sheet **EcoVineyards soil data recording and water infiltration.**

Table 18. What type of sampling do I need (number of samples and depths)?

Sampling	Icon	Number	Technique
Soil chemical analysis		20 to 30 samples 0 to 15 cm 15 to 30 cm 30 to 45 cm	Use this technique if you are interested in a general picture of a range of chemical analysis. Often a couple of rows are monitored in the same soil type/topography. Collect 20 to 30 samples, typically taken from the 0 to 15 cm depth, place into a clean bucket, mix together, and sub-sample before sending to a laboratory for analysis. Sampling below the topsoil is encouraged (15 to 30 cm and/or 30 to 45 cm) to assess for issues in the rootzone.
Targeted sampling		10 to 20 samples Soil layer or 0 to 15 cm 15 to 30 cm 30 to 45 cm	A smaller area than general chemical sampling as sampling is targeted to an area of interest, e.g. 25 x 25 m or 10 x 10 m, to provide more specific information. Depth of sampling will be determined by what is being measured and will often include the topsoil layer and a subsurface or subsoil layer. As the area is smaller, 10 to 20 samples are usually sufficient to capture the variability in soil properties.
Point sample		1 to 3 samples Soil layer	Are usually placed in a specific area of interest. It is possible to collect soil from just one point (e.g. a soil pit) but if using a shovel to dig a small hole, a minimum of three holes along a monitoring transect will ensure you are capturing the variability and not sampling an atypical point. Samples are often collected from the soil layers (horizons) rather than set depths.

Table 19. How do I measure the indicator (visual, on-site or laboratory)?

Sampling	Icon	Technique
Visual		Using your observation skills and basic tools, like a shovel and tape measure, collect information, record, and take a photo.
On-site		Using some specialised tools and a little time, samples can be assessed on-site.
Laboratory		Sample collected and sent to a laboratory for analysis.

Further information

- AWRI: Collecting a soil sample

SOIL CHARACTERISATION

Sampling **Measure by**

It is recommended to characterise your soil to allow for similar soils to be grouped for comparison across your vineyard and help define the boundaries of what is expected from the soil. Recording observations and taking a photo of soils in your vineyard will help you monitor similar soils and changes over time.

Dig a hole with a shovel and look for different soil layers. These can be indicated by a change in colour, texture, structure, or root behaviour. When you have identified the different layers, record the depth and colour.

Figure 10. Examples of different soil horizons (layers) [Photos: Amanda Schapel].

Soil temperature

Measuring soil temperature using a simple kitchen (or meat) thermometer can highlight the differences between different areas on the vineyard floor.

Comparing bare earth to soil that has over 50% ground cover can show differences up to 20°C. This has a large effect on water availability through evaporation and microbial activity.

Figure 11. Measuring soil temperature in a vegetated versus ambient location [Photo: Mary Retallack].

Soil texture

Sampling **Measure by**

What

Texture is a measure of the amount of sand, silt, and clay in the soil, and it determines the soil texture grade. As texture does not readily change with management, you only need to determine it once.

Why

Soil texture is not a health indicator, but it defines the limits and sets the expectations of what your soil can realistically achieve. It determines the ability of the soil to:

- hold and make water available for plants and biology
- hold onto nutrients (cation exchange capacity).

How

The percentage of sand, silt, and clay in the soil can be:

- estimated by field texture – making a ribbon of the moist soil and measuring the length
- measured in the laboratory by particle size analysis.

Assessment tools

Shovel or trowel, water bottle, tape measure.

Field texture

Take a handful of the soil and crumble it, then moisten with water a little at a time and knead until the ball just fails to stick to the fingers, is smooth and the moisture is even (about 1 to 2 minutes). Squeeze it out into a flat ribbon 2 to 3 mm thick and see how long you can make the ribbon.

Figure 12. Hand texturing soil samples in the field Photos: Maschmedt, 2004].

Table 20. Field texture chart (Maschmedt, 2004)

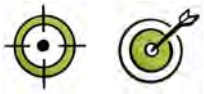
Broad groups	Texture grade	Clay (%)	Behaviour of the soil ball	Ribbon (mm)
Sands	Sand (S)	0 to 5	Ball will not form	0
	Loamy sand (LS)	About 5	Ball just holds together	5
	Clayey sand (CS)	5 to 10	Ball just holds together, leaves clay stain on fingers	5 to 15
Sandy loams	Sandy loam (SL)	10 to 20	Ball forms, feels sandy, but spongy	20 to 25
	Silty loam (ZL)	About 25	Ball forms, feels smooth and silky	25
Loams	Loam (L)	About 25	Ball forms, feels smooth and spongy	25
	Sandy clay loam (SCL)	20 to 30	Ball is firm, feels sandy and plastic	25 to 40
Clay Loams	Silty clay loam (ZCL)	30 to 35	Ball is firm, smooth, silky and plastic	40 to 50
	Clay loam (CL)	30 to 35	Ball is firm, feels smooth and plastic	40 to 50
Clays	Light clay (LC)	35 to 40	Ball holds together strongly, feels plastic	50 to 70
	Medium clay (MC)	40 to 50	Ball holds together very strongly, feels like plasticine	Over 75
	Heavy clay (HC)	Over 50	Ball holds together very strongly, difficult to manipulate, like hard plasticine	Over 75

Further information

- Government of SA, DEW: Soils of southern South Australia
- NQ Dry Tropics: Rapid assessment of soil health (RASH) videos and manual
- Soil Science Australia: Video how to texture soil

SOIL HEALTH INDICATORS

Root depth

Sampling  **Measure by** 

What

The depth that roots grow can tell us a lot about the condition of soil.

Why

To identify restriction to growth due to constraints, such as hard layers, water availability, pH, and toxicities.

How

Observe where roots are growing. Record the abundance of roots for each layer and the depth that most (60 to 80%) roots are growing (effective rootzone) and depth that the deepest roots grow.

Record the depth where you can see restrictions to root growth – could be a hard layer, a dense clay layer or rock. You may see roots growing sideways in severe cases of restriction or the numbers of roots may decline.

Assessment Tools

Shovel, tape measure.

Table 21. Scoring rootzone depth (cm)

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Effective rootzone	0 to 10	10 to 30	30 to 50	> 50

Carbonates: fizz test

Sampling **Measure by**

What

The presence of calcium or magnesium carbonates affect soil pH, nutrient availability, and water movement through the profile. Calcium and magnesium carbonates are common in southern Australia where annual rainfall is less than 500 mm. As an inherent character, it only needs to be assessed once.

Why

Carbonate values above 20% in clays can severely restrict root growth in some plants.

How

From each area of interest, the presence of fine earth carbonates can be identified, and percentage estimated by adding one or two drops of hydrochloric acid to the soil. If the soil contains carbonate, the carbonate will react. The strength of the effervescence will indicate the percentage of the fine earth carbonate.

Assessment Tools

Trowel or shovel, weak (1N) hydrochloric acid solution, dropper, container for samples.

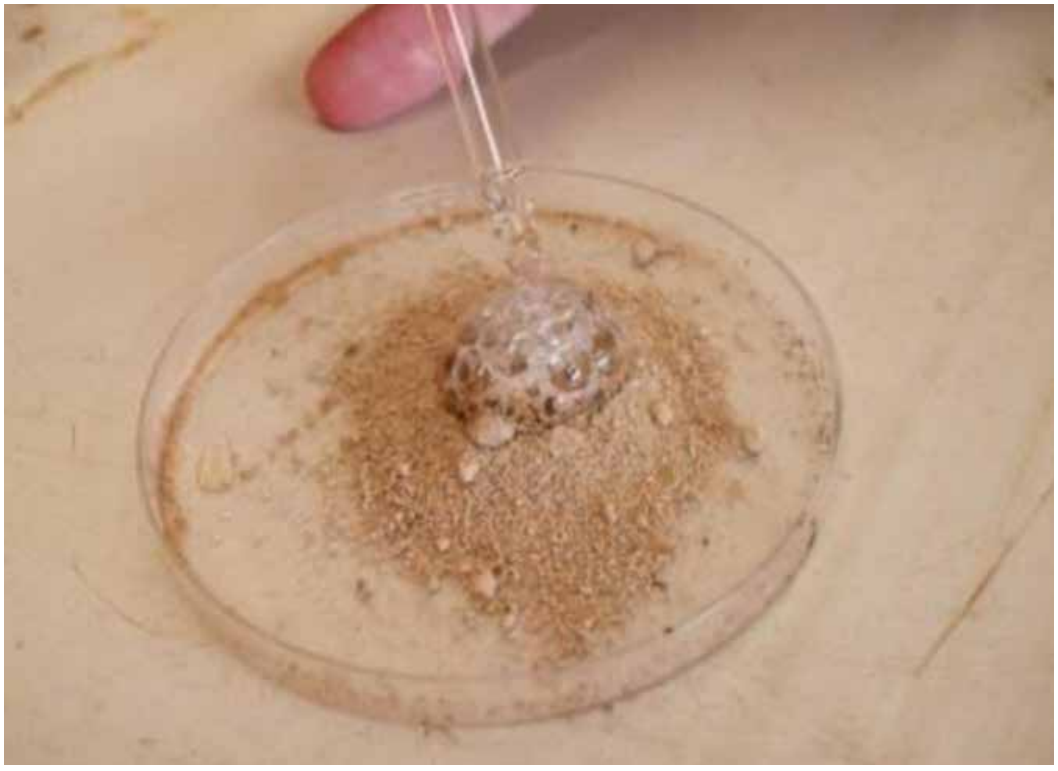


Figure 13. Example of a very high fizz reaction (Maschmedt, 2004).

To make a 1N hydrochloric solution add 100 ml of commercial hydrochloric acid (35.5% w/w) to 1,000 ml of distilled or rainwater.

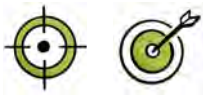
Table 22. Carbonates fizz test (Maschmedt, 2004)

Reaction	Strength of effervescence	Approx. % carbonate
Nil	None	Less than 0.5
Slight	Just visible	0.5 to 1.5
Moderate	Easily visible	1.5 to 8
High	Strong	More than 8
Very High	Strong, bubbles jump up	More than 8

Table 23. Scoring carbonate fizz test

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Carbonate reaction fizz test	Very high	High	Moderate	Nil to slight

Soil structure: pedality

Sampling  **Measure by** 

What

Assessment of the way that aggregates (peds) are arranged.

Soils without aggregates or peds are called apedal and can be due to little or no cohesion between the particles so they are 'single grained' (think of beach sands), or they can stick together but have no regular shape and termed 'massive'.

The most favourable pedal structure are crumbs, polyhedral and blocky (< 5 mm). Prismatic, columnar, and platy structures are unfavourable as they affect root growth and water and air movement.

Why

All soils have structure (the arrangement of solid particles and pores) but not all soils have pedality. Pedal soils are when the aggregates are arranged into defined shapes and these shapes provide a good indication of the physical condition of the soil.

How

Take a shovel full of surface soil or a large handful of subsoil. Observe the way the aggregates break up, look at the size and shape of the peds. When broken down, peds larger than 20 mm indicate poor structure.

Figure 14. Shovel of soil—you can see the soil breaking into small aggregates of crumb pedality [Photo Amanda Schapel].

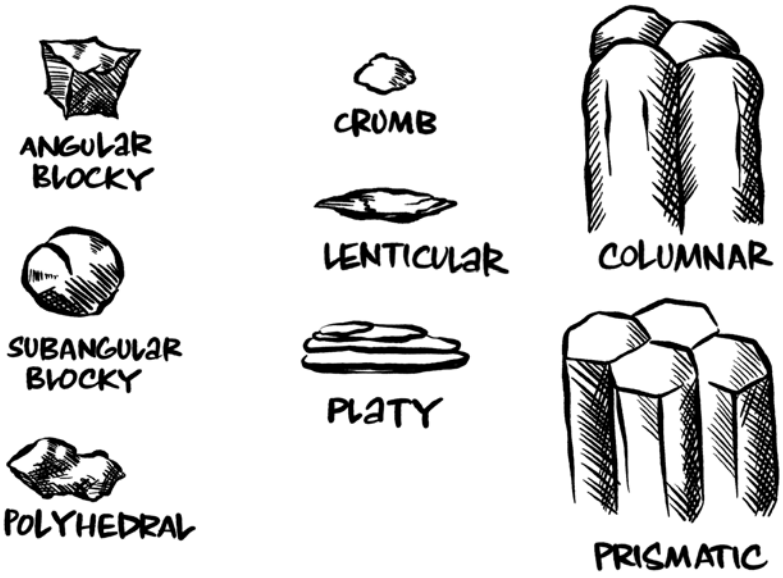


Figure 15. Pedality grades for pedal soils [Maschmedt, 2002].

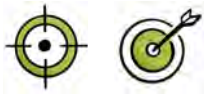
Table 24. Scoring soil structure

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Soil structure	Columnar, prismatic, platy	Lenticular	Polyhedral, blocky (< 5 mm)	Crumb

Further information

- NQ Dry Tropics: **Rapid assessment of soil health (RASH)** videos and manual
- Soil Science Australia: **Soil structure**

Soil aggregate strength

Sampling  **Measure by** 

What

Soil aggregates are clumps of soil particles that are held together by moist clay, OM, exudates from worms, and by fungal hyphae. They range in size from the micro level (< 0.25 mm in diameter) to the macro level (> 0.25 mm in diameter). They can be different shapes and sizes and the areas in-between provide spaces to accommodate air and water, which are all needed for healthy grapevine growth.

Aggregate strength refers to the ability of soil aggregates to keep their structure under stress. Soil aggregates that hold together indicate stable soil structure in good condition.

Why

Good soil structure is important for healthy plant growth, soil aeration, root penetration, and water storage. Poor soil structure can limit root development, the rate of water infiltration, water-holding capacity, and aeration (please refer to the section on **soil penetration resistance and water infiltration**). The deterioration of soil structure occurs via the slaking of aggregates and dispersion of clay particles.

When placed in deep water, soil aggregates will either:

1. **Remain intac**t, or
2. **Slake (aggregate falls apart)**, and/or
   Slaking is the rapid disintegration of macro-aggregates of soil into micro-aggregates by rainwater. Slaking occurs because of a lack of strong organic bonds between soil particles and micro-aggregates.
3. **Disperse (water becomes cloudy)**
   Dispersion occurs when dry soil is wet with rainwater and the clay structures that bind the fine aggregates and large particles (sand and silt) break down. The clay particles then go into suspension in the water. As the soil dries out, the clay particles block the pores between the remaining aggregates. This blockage prevents the flow of water and air through the soil. Dispersion is also a potential indicator of soil sodicity.

How

Take three surface soil (0 to15 cm) and three subsoil samples (30 to 50 cm for a sub-surface sample in the rootzone) from each sampling point along a monitoring transect and select three aggregates about the size of a pea (3 to 5 mm) from each sample. Assess sandy soils when there is moisture in the profile as dry sandy soil will rarely have aggregates.

Place the aggregates in a shallow container filled with rain or distilled water. Alternatively, you can use the vineyard water source to assess the effect it may have on your soil aggregates.

Watch the aggregates closely in the first few minutes and observe whether they float on the water surface or sink to the bottom and the rate that smaller particles break away from the larger sample. After two hours, record if slaking is complete, partial, or absent (or you can also do a quick test over a ten-minute period to assess any initial results).

Leave the same dish untouched for about 20 hours and then assess dispersion. Assess to determine if a cloudy or milky halo has developed around the slaked fragments of the aggregates and partial dispersion has occurred.

Complete dispersion is indicated when the bottom of the container is completely covered with a layer of clay, leaving only a pile of sand where the aggregate was placed.

Assessment tools

A shallow, clear, and open container (or a small paint pallet), rain or distilled water, smartphone (to record time and take photos) and a recording sheet.

Table 25. Scoring soil aggregate strength

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Slaking (%)	More than 70	20 to 70	Slight slaking around the edges of aggregate	Aggregate remains intact
Dispersion	Strong dispersion (cloudy water)	Moderate dispersion	Slight dispersion (cloudy water around aggregate edges)	No dispersion

Tips

Use a bigger container and more water if salinity is suspected as salt prevents dispersion which will give you a false 'no dispersion' result.

Further information

- Bragato Research Institute: DIY Soil Health Tests
- EcoVineyards: Soil health indicators for Australian vineyards
- CRCV: Vineyard activities 5: Assessing soil structure
- FAO: Visual soil assessment – vineyards
- NQ Dry Tropics: Rapid assessment of soil health (RASH) videos and manual
- Soil Health Institute: SLAKES: A free smartphone app to measure aggregate stability

Soil sodicity: Exchangeable sodium percentage (ESP)

Sampling  **Measure by** 

What

The exchangeable sodium percentage (ESP) is another way to measure soil aggregate dispersion.

How

Samples collected for the slaking and dispersion test, or soil collected for topsoil or subsoil chemistry analysis can be sent to a laboratory where exchangeable cations will be measured, and cation exchange capacity and exchangeable sodium percentage calculated.

Assessment tools

Shovel (or dig stick if chemical analysis), tape measure, plastic bag, marker pen.

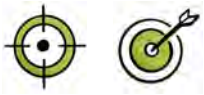
Table 26. Scoring exchangeable sodium percentage (%)

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Exchangeable sodium percentage	> 15	6 to 15	2 to 6	< 2

Tip

Where high levels of sodium chloride are present, a pre-wash of the sample should be requested to get a more accurate result.

Water infiltration

Sampling  **Measure by** 

What

An infiltrometer measures the rate at which a fixed volume of water soaks into the soil and provides an indication of how effectively water enters the soil during a rainfall event.

Why

By storing moisture in the soil (rather than in dams above ground) it will be available at depth in the soil profile when the plants need it. The water-holding capacity of the soil is related to its texture, structure, and ground cover. The better the soil structure and level of organic matter, the better the infiltration, water-holding capacity, and capacity of water to percolate through the soil profile. This leads to greater volumes of plant-available moisture at depth and increased capacity for soils to sustain populations of soil microbes throughout the year.

How

The rate of water infiltration is measured by pouring a volume of water into an infiltrometer ring installed in the ground to a sufficient depth of a few centimetres to prevent leaks.

Assess when the soil is moist or wet the soil with 1 to 2 L through the infiltrometer prior to assessing to reduce preferential flow through soil cracks.

Place a ruler on the inside of the infiltrometer. Pour the water gently through an open hand into the infiltrometer ring and record the start height (you may wish to fill the infiltrometer to the top of the cylinder). Start your stopwatch and record how much water in millimetres is absorbed into the soil over a six-minute period.

You may wish to compare between bare ground or wheel compaction zones or an area with ground cover to compare the difference. As a minimum, assess the water infiltration at a single location along your point-to-point transect or measure at three to five separate locations and calculate an average of the results. If you are testing an area where there are ground cover plants, trim the vegetation close to ground level and test. Be consistent with your approach from year to year.

Multiply the result (drop in water in mm from the start to finish point) by 10 to determine the infiltration rate in millimetres per hour (i.e. 48 mm over 6 minutes x 10 (to convert from minutes to an hour) = 480 mm per hour).

Assessment tools

Stainless steel soil water infiltrator (100 mm diameter x 300 mm long) or PVC ring (160 mm diameter by 160 mm long) with a hardwood board and mash hammer for installing the PVC ring with a bevelled bottom to make it easier to push into the soil, ruler, mobile phone (with a stopwatch), and 1 to 2.5 L of water per assessment (depending on the diameter and water-holding capacity of your infiltrometer).

Table 27. Scoring water infiltration rate: estimates by soil texture

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Sand	0 to 20	20 to 150	150 to 250	More than 250
Sandy loam	0 to 10	10 to 40	40 to 80	More than 80
Loam	0 to 2	1 to 10	10 to 20	More than 20
Clay loam	0 to 1	1 to 7	7 to 15	More than 15
Clay	0 to 0.2	0.2 to 2.0	2 to 5	More than 5
General	0 to 25	25 to 100	100 to 250	More than 250

Variation to monitor change in structure as well as infiltration rate

Tracking the number of 'steps' and the length of time that water is 'held up' and monitoring change over time can indicate a change in soil structure.

Establish the infiltration ring as above but the depth of water is recorded every 30 seconds for ~7 to 10 minutes and then every 1to 2 minutes thereafter for 20 to 30 minutes.

To graph the data: the water infiltration recording sheet can be used to account for differences in starting water depths; calculate the millimetres of water moved by subtracting the value from the time 0 value.

The 'steps' can tell us where restrictions to water movement occur. Tracking the number of steps and the length of time that water is 'held up' and the change in this over time can indicate a change in soil structure.

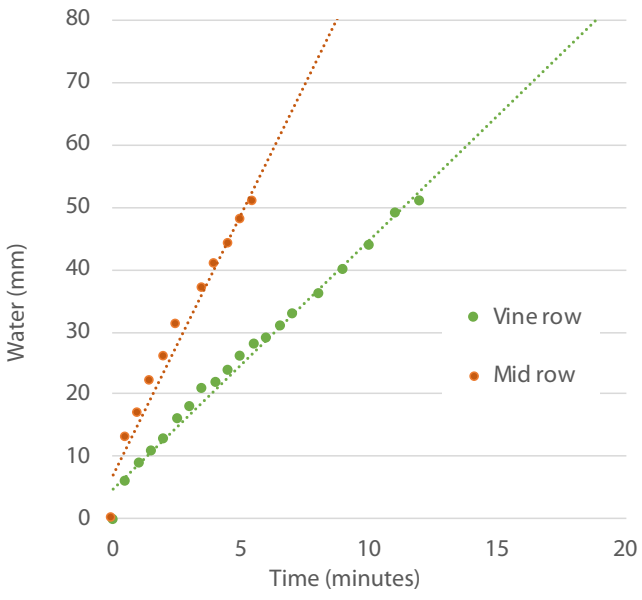


Figure 16. Water infiltrometer test and graphing the rate of water infiltration [Photo and Figure: Amanda Schapel].

Tips

If a lot of plant material is present, you can trim the plant matter to within 1 cm of the soil surface without disturbing soil to make it easier to read the ruler.

Knock the core into the soil at least 5 cm to best ensure that water is moving down into the soil rather than spreading horizontally.

Cutting a piece of plastic to lay at the bottom of your ring can make it easier to pour the water in without disturbing the soil and to make sure that water doesn't start infiltrating the soil before you start the timer.

If soils are dry, run 1 to 2 L of water through prior to measuring to get the soil moist otherwise you will get preferential water flow through the cracks rather than pores. Or you can take duplicate measures to see if there is a change in results. If they are similar, you have water infiltrating in a steady state.

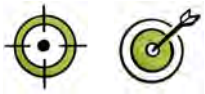
Use roughly the same volume (or depth) of water each time you monitor as different volumes create different pressure heads which influences water movement.

Further information

- CRCV: Vineyard activities 8, **Measuring the infiltration rate of water into soil**
- EcoVineyards: **Soil health indicators for Australian vineyards**
- Masters, N.R. (2019) **For the love of soil, strategies to regenerate our food production systems**. Printable Reality, New Zealand.
- Soil Care: **Northern Rivers Soil BMP Guide, Perennial Horticulture, Best Management Practices for Soil Health**

For a ready to use Excel spreadsheet on graphing the rate of water infiltration please see **EcoVineyards data recording and water infiltration.**

Water repellence

Sampling  **Measure by** 

What

Soils where waxy residues of broken-down plant material coat sand particles can make it water repellent.

Why

Water repellence results in uneven soil wetting where water either sits on the surface or moves around until it finds a point of entry. This can cause patchy and poor plant growth and staggered emergence, low soil moisture and increased susceptibility to erosion.

How

Take three surface (0 to 5 cm) and three subsurface samples (5 to 10 cm) from each sampling point along a monitoring transect. Leave the soil to dry naturally (a few days to weeks depending on the moisture content and ambient temperature).

Once soil is dry, place 1 to 2 drops of rainwater to the soil sample from about 1.5 cm height. Observe if the drop forms a spherical shape on top of the soil (indicates water repellence) and record the length of time it takes to penetrate into the soil. If water takes longer than 10 seconds, place 1 to 2 drops of ethanol on the soil and record if it takes longer than 10 seconds to penetrate the soil.

Assessment Tools

Shovel or trowel, plastic bag, marker pen, tape measure, water, ethanol/methylated spirits solution, dropper, container for assessment (e.g. a paint tray).

Table 28. Time taken for water to penetrate the soil (Maschmedt, 2004)

Time	Interpretation of water repellence
< 1 second	Nil
1 to 10 seconds	Very low
10 to 50 seconds	Low
50 to 260 seconds	Moderate
> 260 seconds	Moderate to severe

Table 29. Scoring of water repellence

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Water repellence	Water > 50 seconds Ethanol/methylated spirits > 10 seconds	Water 10 to 50 seconds Ethanol/methylated spirits < 10 seconds	Water 1 to 10 seconds	Water < 1 seconds

Tips

- Methylated spirits at a concentration of 24 ml to 200 ml of water can be substituted for (Maschmedt, 2004).
- A shallow paint or ice cube tray can make it easy to keep your samples separate.

Figure 17. Water repellence test showing distinctive spherical droplet not penetrating soil (left), a paint pallet can be handy to keep samples separate when you are testing (right) [Photos: Amanda Schapel].

Bulk density

Sampling **Measure by**

What

Bulk density calculates the weight of dry soil in a given volume. The density of the soil can provide an indication of soil structure, the amount of pores (porosity), strength (the bonds between the aggregates) and is valuable for converting nitrogen or carbon concentrations to amount in tonnes or kilograms per hectare.

Why

High bulk density values highlight soils with fewer pores which affects air and water movement and reduces root and biological growth.

How

Take a minimum of three samples from 0 to 15 cm and 15 to 30 cm (only take the subsurface sample if interested) to account for variability within your transect of interest.

Soils with gravel contents > 15% (w/w) are not recommended for this method unless you are an experienced sampler as corrections for the gravel need to be included in the calculations.

Use a shovel to create a flat surface at the depth you want to sample. Use a wooden block to hammer the ring into the soil (be careful not to push the ring in too far to avoid compaction). Carefully excavate the soil around the ring (be careful not to loosen the soil in the ring). Remove the ring from the soil (flat plastic or steel paddles slightly larger than the ring can make this much easier, especially in dry soil). Remove excess soil or plant roots (a flat knife is good in sand and a longer fishing knife is good for cutting clay). Pour the soil into a labelled bag and seal.

Weigh an ovenproof container (aluminium foil takeaway containers are ideal for the oven but use glass or similar in the microwave). Record the weight in grams (W1). Place the moist soil into the container and dry (10 minutes in a microwave or in an oven at 110 °C) until the weight of soil does not change. Record the dry weight of the soil and container (W2).

The dry soil weight (g) is calculated by subtracting W1 – W2

Measure the volume of the ring using a ruler (record in cm but measure to the nearest mm, e.g. 7.2 cm) and record the height (H) and diameter. Divide the diameter in half to get the radius (R).

Soil volume (cm^3) = radius squared x height x pi or volume = R^2 x H x 3.14 cm^3

To calculate bulk density (g/cm^3) = Dry soil weight (g) divided by soil volume (cm^3)

If gravel is present: using a 2 mm sieve (kitchen sieve is often suitable) sift the soil and record the weight of the gravel (Wg). Calculate the gravel concentration by Wg divided by dry soil weight x 100.

To adjust bulk density if gravel is present = bulk density x (100-gravel concentration)

For example, my soil had a dry weight of 350 g, soil volume of 207 cm^3 and gravel content of 10%

Bulk density = (350/207) = 1.69 g/cm^3

To adjust for gravel – 1.69 x (100-10) = 1.52 g/cm^3

Assessment tools

Steel ring (tin or hard pipe) about 7 cm in diameter and 10 cm tall, shovel or trowel, wooden block, hammer, flat paddles, flat knife to make soil flush with steel ring, plastic bag, marker, oven, ovenproof dish, scales, calculator.

Figure 18. Collecting a soil sample to assess bulk density [Photos: Amanda Schapel].

Collecting and preparing bulk density samples is laborious so the benefits of measuring it must be clear.

Table 30. Bulk density for soil texture classes (adapted from Hazelton and Murphy, 2007)

Texture	Critical bulk density (g/cm^3)
Sand	1.8
Sandy loam	1.7
Loam and clay loam	1.6
Clay	1.4

Bulk density can be misleading as a predictor of root growth restriction as roots can grow into a dense soil when moisture is present, or they can follow cracks or old root channels past the restriction.

Table 31. Scoring of bulk density (g/cm^3)

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Bulk density	> 1.8	1.6 to 1.8	1.2 to 1.6	< 1.2

Tips

- If samples are wet, you may want to air dry the samples to remove most of the moisture before the final drying stage.
- Air dry by leaving the samples in a sheltered, ventilated place for several days/weeks depending on the soil moisture and ambient temperature.
- Bulk density in soils with strong shrink/swell properties (due to clay mineralogy) varies depending on the soil moisture and hence the amount of cracks (air) present. For consistency, sample these soils when at field capacity.
- Topsoil with high quantities of OM can have densities as low as 0.5 g/cm^3 and the domes (top of) of the clay in a sodic soil can exceed 2.0 g/cm^3.

Further information

- Soil quality fact sheet: **Bulk density measurement**

Soil porosity

Sampling **Measure by**

What

Soils need pores for adequate aeration and good drainage. Total soil porosity is related to bulk density.

Why

Soil management can change the porosity of a soil. Tillage and trafficking, particularly of wet soil, can destroy macro and mesopores while cover crops and mulches can maintain and stabilise these pores.

The density of the solid particles (particle density) is generally taken to be 2.65 t/m^3. Care and corrections may be required for soils with significant quantities of dense minerals (e.g. iron segregations) or light materials (organic soils).

How

Total porosity can be calculated using the bulk density value.

Total soil porosity (%) = 1 – (bulk density of the soil)/(density of the solid particles) x 100

For example, calculations for soils with a bulk density of 1.52 g/cm^3 and 1.24 g/cm^3

- Soil 1 total porosity (%) = 1 – (1.52/2.65) x 100 = 43%
- Soil 2 total porosity (%) = 1 – (1.24/2.65) x 100 = 53%

Soil strength: penetration resistance

Sampling  **Measure by** 

What

The amount of resistance a plant root encounters in the soil can be estimated by using a penetrometer, which measures the resistance to vertical penetration. Push a penetrometer into the ground to feel how dense the soil is.

Does it slide into the soil easily or does it take some effort? If there are compacted layers, it will take more pressure to break through these layers, similarly a plant root may encounter greater resistance to growth.

Why

Soil strength or penetration resistance is measured in megapascals (MPa). Soil strength is influenced by soil water content, texture, and structure. As the soil dries out, the soil strength increases, and more force is required to break apart soil aggregates.

Grapevine root growth is reduced at 1 MPa and severely retarded beyond 2 MPa (2.5 MPa or 2,500 kPa is considered a critical point).

Fine-textured clay soils stick together more readily than sandy soils. Soil compaction is a result of compressed structure which results in less available air, water, and root spaces. Therefore, there is less area for water storage, the total volume that a soil can hold is reduced and soil dries out sooner and can't hold as much water when recharged. Similarly, water penetration is slower and more will run off in a heavy downpour.

How

The best time to carry out a measurement of soil strength is when the soil is at field capacity, which normally occurs approximately 24 to 48 hours after a soaking rain event. Assess soil that will potentially impact on root growth and water penetration. For example, compare the soil strength in the under-vine area, where there is a wheel compaction zone and in the midrow area for comparison. Assess the amount of resistance and the depth that you can push the rod into the ground before encountering resistance (or how far you need to push through a compacted zone).

Assessment tools

A hydraulic penetrometer (soil compaction probe with a steel cone on the end of a shaft and a pressure sensor at the other end) or handmade rod using modified pot plant hanger.

Grower solution

You may wish to use a screwdriver or fashion a handmade penetrometer from a 50 cm plant hanger instead of purchasing an expensive hydraulic penetrometer. Cut the round hook off the bottom, sharpen to a point, and use a file to create 10 cm markers along the side of the steel rod and you are ready to start assessing soil resistance by feel (without a pressure sensor).

Figure 19. Soil penetrometer (left and middle) and a handmade penetrometer without pressure gauge (right) [Photos: Mary Retallack].

Table 32. Scoring of soil penetration resistance

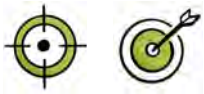
Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Soil penetration resistance (MPa)	Greater than 3	2 to 3	1 to 2	Less than 1
Soil penetration depth classes where strength is 2.5 MPa	Less than 15 cm	15 to 30 cm	30 to 45 cm	Greater than 45 cm

Aim to keep the soil strength below 2 MPa to ensure optimal conditions for grapevine root growth (2.5 MPa is considered a critical point).

Further information

- EcoVineyards: Soil health indicators for Australian vineyards

Soil strength: consistence

Sampling  **Measure by** 

What

The strength between aggregates and of the soil can indicate physical condition.

Why

High soil strength may be natural or induced through compaction and can cause issues for root growth or difficulty in the use of or wearing of machinery implements.

How

Take a dry aggregate about 20 mm in diameter (roughly the size of a golf ball) from each layer in your characterisation hole. Using your thumb and forefinger, press on the aggregate to see if it can be broken. If the aggregate is too hard, place it on a flat surface and apply pressure with your foot (or the head of a hammer if required). Record the ranking of consistence on your sheet.

Assessment tools

Shovel or trowel.

Table 33. Soil strength assessment (adapted from McDonald et al., 1998)

Degree of strength	Amount of force required
Weak	Can be crushed with thumb and forefinger easily
Moderate	Can be crushed with thumb and forefinger with firm force
Strong	Can't be crushed with hand but can be crushed underfoot on a flat, hard surface with little effort
Very strong	Crushes underfoot when using all of body weight
Rigid	Cannot be crushed by foot but can be with a hammer

Table 34. Scoring of soil consistence to indicate soil strength

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Consistence	Crushed underfoot using all body weight	Crushed underfoot with minimal effort	Crushed with firm force with thumb and forefinger	Crushed easily with thumb and forefinger

Tips

- This test is complementary to the slaking and dispersion test
- If the soil is moist, dry the clods by placing them on labelled paper or by leaving the plastic bag open and out of direct sunlight.

Further information

- CRCV: Vineyard activities 7, **Measuring soil strength** and Research to Practice: **Measuring soil strength**
- Soil Care: **Northern Rivers soil BMP guide, perennial horticulture, best management practices for soil health**
- The Australian and New Zealand Grapegrower and Winemaker: **Understanding, measuring, and ameliorating soil compaction in vineyards**

CHEMICAL INDICATORS

pH: acidity and alkalinity

Sampling **Measure by**

What

pH measures the amount of free hydrogen or hydroxyl ions in the soil, more commonly known as acidity and alkalinity. Soil pH is measured on a log scale from 1 to 14, where 7 is neutral, below 7 acidic and above 7 alkaline. Samples can be tested at a laboratory as a 1:5 soil: solution in water or calcium chloride. pH_{CaCl_2} is the preferred test for acidic conditions. A field pH kit can be used on-site and is like the pH_{water} test results. pH_{water} results can be 0.5 to 1.2 units higher than pH_{CaCl_2}.

Why

Soil pH affects the availability of plant nutrients and biological processes. Under strongly acidic conditions, aluminium can be released from the soil in toxic levels, stunting root growth and affecting nutrient uptake.

How

Samples can be collected with a normal 0 to 15 cm and 15 to 30 cm soil chemical test but if acidity is suspected it is prudent to dig a few holes to at least 30 cm and assess pH in smaller increments (0 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 30 cm).

Field test: use a pH field testing kit available from most hardware or garden stores. Field test kits are equivalent to pH_{water} and provide a reasonably accurate result. To estimate pH_{CaCl_2}, subtract 0.8 pH unit from the result. Care needs to be taken when the field kit indicates values around 5.5 pH.

Collect samples and place on a sheet or tray or you can test directly in the hole. Wet the soil with the indicator solution as it should not be sloppy. If the soil is water repellent, mix with the provided stick. Puff the white barium powder to the soil surface (do not mix). Leave for about one minute then assess the colour against the provided chart. Record the result.

Figure 20. Using a field kit to assess soil pH [Photos: Amanda Schapel].

Assessment tools

Shovel or trowel or soil corer, tape measure, field pH kit, container for soil.

Laboratory test: Laboratories offer pH testing and can be analysed by itself or in a suite to assess for fertility and other properties. Ideally, pH_{water} and pH_{CaCl_2} should be measured.

pH_{water} can be used for alkaline soils. Soil pH_{CaCl_2} gives a more accurate result in neutral to acid soils and has less variability during seasons than pH_{water}.

Table 35. Soil acidity and alkalinity (Hazelton and Murphy, 2007; Proffitt, 2014; B Hughes *pers. comm.*, 2024)

Degree of acidity/alkalinity	pH in $CaCl_2$	pH in water (also field test kit)
Strongly acidic	< 5.0	< 5.5
Moderately acidic	5.0 to 5.9	5.5 to 6.0
Slightly acidic	6.0 to 6.9	6.0 to 6.5
Neutral	7.0	6.5 to 7.4
Slightly alkaline	7.1 to 7.5	7.4 to 7.8
Moderately alkaline	7.6 to 8.3	7.8 to 8.5
Strongly alkaline	> 8.4	> 8.5

Note: issues for grapevine and pasture growth occurs at the strongly acidic and alkaline scales. When soil is strongly acidic you may see stunted shoot and root growth. Some elements including phosphorus, calcium, magnesium, and molybdenum may have limited availability and others, including aluminium and manganese, may become available at toxic levels.

When soil is strongly alkaline, the availability of iron, manganese, copper, and zinc can be low whilst sodium, boron, and salt can be an issue. Some soils are inherently (naturally) acidic, and it can be cost prohibitive to manage them to reach neutral. A target in the moderately acidic range is suitable for these soils. A target in the slightly acidic to slightly alkaline range is the target for soil not naturally strongly acidic. There is little that can be done to manage soils in the moderately to strongly alkaline range.

Table 36. Soil pH scoring guide (NQ Dry Tropics, 2019)

Scoring guide	Poor	Moderate	Good	Very good
Score	**0**	**1**	**2**	**3**
pH_{water} and Field pH kit	Under 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.5
	Above 8.5	8.0 to 8.5	7.5 to 8.0	
pH_{CaCl_2}	Under 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 7.5
	Above 8.5	8.0 to 8.5	7.5 to 8.0	

Organic carbon

Sampling  **Measure by** 

What

Organic carbon is a laboratory measure to indicate soil organic matter content and makes up about 58% of OM with the remaining mass consisting of other nutrients, such as nitrogen, phosphorus, and sulfur.

Why

Organic carbon has an essential role in soil function, and with incorporation into the soil it affects aggregate stability, water infiltration and movement, nutrient holding and buffering capacity and is a food source for soil biology. It is a good indicator of soil structure, fertility, and biological activity.

How

Soil samples collected for chemical analysis 0 to 15 cm and 15 to 30 cm if interested in distribution down the soil profile. Targeted or point sampling can be used to investigate differences.

Assessment tools

Shovel or soil corer, bucket, plastic bag, marker pen.

Table 37. Rating levels for soil OC to assess soil functions

Soil OC (%)	Interpretation	Reference
< 1%	Value below which the soils capacity to perform key functions is constrained	Kay and Angers, 1999
1 to 2%	Will improve the structural stability, pH buffering capacity, water-holding capacity, and soil nutrient levels (especially nitrogen)	Hazelton and Murphy, 2007
> 2%	Considered to have very good structure, high buffering capacity and have sufficient OM to decrease bulk density and improve water-holding capacity	Hazelton and Murphy, 2007

Table 38. Interpreting topsoil OC concentration (%) Walkley and Black OC test in relation to soil condition for different soil textures (Schapel et al., 2021) and general from Proffitt (2014)

Texture	Low	Moderate	High
Sand	< 0.5	0.5 to 1.5	> 1.5
Loamy sand	< 0.7	0.7 to1.8	> 1.8
Sandy loam	< 0.9	0.9 to 2.3	> 2.3
Loam	< 1.1	1.1 to 2.5	> 2.5
Clay loam	< 1.2	1.2 to 2.3	> 2.3
Clay	< 1.0	1.0 to 1.9	> 1.9
General	0.4 to 1.0	1.0 to 1.8	1.8 to 3.0

Table 39. Scoring topsoil OC concentration (Walkley Black test %)

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
Sand	< 0.5	0.5 to 1.0	1.0 to 1.5	> 1.5
Loamy sand	< 0.7	0.7 to 1.2	1.2 to 1.8	> 1.8
Sandy loam	< 0.9	0.9 to 1.6	1.6 to 2.3	> 2.3
Loam	< 1.1	1.1 to 1.8	1.8 to 2.5	> 2.5
Clay loam	< 1.2	1.2 to 1.7	1.7 to 2.3	> 2.3
Clay	< 1.0	1.0 to 1.4	1.4 to 1.9	> 1.9
General	< 1.0	1.0 to 1.8	1.8 to 3.0	> 3.0

Tips

- To estimate OM multiply the OC concentration (%) by 1.72.
- Sample the area under the vine and mid-row separately if they are managed differently.
- If swards or cover crops are grown in the mid-row, OC values are often higher than the vine-row and can be used as an indicator of the OC capacity of the vine-row.

Carbon ratios

Total carbon to total nitrogen ratio

Table 40. Carbon-to-nitrogen ratio predicts the rate of breakdown of organic residues (Hazelton and Murphy, 2007)

C: N	Interpretation
< 25	Decomposition may proceed at the maximum rate possible under environmental conditions
> 25	Decomposition slows unless nitrogen is added as N will be tied up in soil biology decomposing the organic material and will not be available to plants.

Carbon fractions stable or active carbon as an index of total OC

Assessing the more stable, mineral-associated carbon or more active or labile carbon concentration in relation to the total OC is thought to provide an indicator of the stability of OC in the system. This information could be used to identify practices that encourage an accumulation of or an increased efficiency in stable OC which benefits soil aggregate stability, pedality, nutrient, and water storage.

At this stage there are no guides but watch this space!

Carbon to macronutrient ratios C:N:P:S 10,000:833:200:143 in stable OC

There are some constant ratios for total macronutrients and carbon. It is known that to produce 1,000 kg (1 tonne) of stable mineral-associated organic carbon, you need to supply 80 kg of nitrogen, 20 kg of phosphorus and 14 kg of sulfur (Kirkby et al., 2011) above what is required for normal plant growth to feed microbes. A lack of these nutrients is a key limiting factor to why active carbon is not being converted to stable carbon.

Further reading

- CRCV: Vineyard activities 4, **Measuring soil organic carbon in soil**

Salinity

Sampling  **Measure by** 

What

Salinity measures the amount of soluble salts (particularly sodium chloride) in the rootzone as high levels can adversely affect plant growth.

Why

Salts can be naturally occurring in soil, added through irrigation water or from a rising saline water table. Salinity is made worse in soils that have little to no ground cover as water evaporates from the surface, concentrating salts in the rootzone.

How

From soil collected for chemical analysis 0 to 15 cm and subsurface layers (e.g. 15 to 30, 30 to 45 cm), targeted monitoring or point samples. As irrigation water can be a source of salts, be mindful of where you collect the sample from in relation to the dripper. Use the same distance and depths when repeat sampling.

The sample is analysed in a laboratory using a 1:5 soil:water solution and results are expressed as decisiemens per meter (dS/m).

Assessment tools

Shovel or soil corer, bucket, plastic bag, marker pen.

Table 41. Soil salinity texture conversion factors for 1:5 soil:water when weighed (Wetherby, 2006)

Soil texture	Conversion factor
Sand to clayey sand	14.0
Sandy loam to clay loam	9.5
Clay	6.5

If EC 1:5 values exceed 0.15 dS/m in sands, 0.18 dS/m in loams or 0.30 dS/m in clays a sample should be tested using the saturation extract method.

Table 42. Salinity hazard for grapevines using EC of the saturated extract or estimated for EC 1:5 with texture conversion factor (Cass, 2002; Proffitt, 2014)

Salinity hazard	ECe (dS/m)	Effect on vine growth
Non to saline	0 to 2	Little effect
Slightly saline	2 to 4	Own rooted vines begin to be affected
Saline	4 to 8	Some rootstocks tolerate
Very saline	8 to 16	Severely affected
Highly saline	> 16	Vine die

Table 43. Scoring salinity: EC saturation paste or converted EC 1:5 values (dS/m)

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
General	> 8	4 to 8	2 to 4	< 2

Tips

- Where EC 1:5 values are in the slightly saline to saline range, it is sensible to get the EC of the saturation extract and chloride measured for a more accurate assessment of salinity.
- Be aware when samples are collected as salts that build up during the season can be leached by winter rain.
- Depending on dripper spacing, sampling 15 to 30 cm away from a dripper in the vine-row will provide a generalised view of salinity. Sampling closer to drippers will often result in higher salt readings.

Further reading

- CRCV: Vineyard activities 3, Measuring soil salinity
- GWRDC: Salinity management interpretation guide
- GWRDC: Sustainable salinity management in your vineyard
- Wine Australia: Sustainable salinity management in Australian vineyards

Cation exchange capacity (CEC)

Sampling  **Measure by** 

What

CEC is a measure of a soil's capacity to hold cations (calcium, magnesium, potassium, sodium, aluminium) on the colloidal (clay particles and OM) surface. As the cations can be knocked off the surface of the colloids by other cations in solution, they are said to be exchangeable.

Why

CEC is an indicator of the potential fertility of soil. Higher CEC has the capacity to hold onto more cations.

How

From soil collected for chemical analysis generally from the topsoil 0 to 15 cm; send the sample to a laboratory for exchangeable cations and CEC.

Assessment tools

Shovel or soil corer, bucket, plastic bag, marker pen.

Table 44. Range of CEC values (cmol+/kg) commonly found in different textured soils (Hughes, 2005)

Soil texture	Cation exchange capacity (cmol/kg)
Sands	1 to 4
Sandy loams	7 to 12
Loams	12 to 20
Clay loams	15 to 25
Clays	20 to 60

Table 45. Scoring cation exchange capacity (cmol/kg)

Scoring guide	Poor	Moderate	Good	Very good
Score	0	1	2	3
General	< 5	5 to 10	10 to 15	> 15

Soil nutrients

Sampling  **Measure by** 

What

Chemical analysis measures nutrients, those required at high concentrations (macronutrients N, P, K, S, Ca, Mg, Na, and Cl) and lower concentrations (micronutrients Cu, Zn, Fe, B, Al and, Mo) in the soil.

Why

Nutrients strongly influence grapevine growth and production and an oversupply or undersupply in soil can affect vine growth and toxicity or deficiency can occur. Soil analysis can be used to indicate potential problems. As the vine can actively exclude or include nutrients, it is possible to have a soil test that indicates nutrient deficiency or toxicity with no effect on plant growth. Macro and micronutrients can often be better identified from foliar symptoms or tissue analysis.

How

Soil samples collected for chemical analysis 0 to 15 cm and subsurface (if assessing micronutrient toxicity) collected and sent to a laboratory.

Assessment tools

Shovel or soil corer, bucket, plastic bag, marker pen.

Table 46. Interpreting commonly analysed soil nutrient results (mg/kg) in relation to wine grape production (extracted from Proffitt, 2014)

Nutrient	Deficient	Marginal	Adequate	High	Toxic
Nitrogen – nitrate (NO3)	< 1	1 to 2	2 to 10	> 10	
Potassium (K)	< 50	50 to 100	100 to 250	> 250	
Phosphorus (P)	< 25	25 to 35	35 to 80	> 80	
Sulphur (S)	< 10				
Copper (Cu)	< 0.1	0.1 to 0.2	0.2 to 0.4	> 0.4	> 2
Zinc (Zn)	< 0.5	0.5 to 1.0	1 to 2	2 to 20	> 20
Manganese (Mn)		< 2	2 to 4		
Iron (Fe)			> 4.5		
Aluminium (Al)					> 100
Boron (B)	< 0.1		0.2 to 1.0		> 3

Analytical methods: Colwell bicarbonate extractable P and K; DTPA extractable Cu, Zn, Mn, Fe; Ammonium chloride extract Al; hot water extract B.

Tips

The pH of soil affects the availability of soil nutrients so making sure soil is in the slightly acidic to slightly alkaline range will help plants access required nutrients.

More information

- Government of SA, DEW: Soils of southern South Australia
- GWRDC: Managing grapevine nutrition and vineyard soil health
- GWRDC: Assessing soil quality and interpreting soil test results

SECTION 4:
ACTION PLAN

PLANNING

Assessing a soil's health starts with:

- **Identifying what soil health and function is for a particular location**
- **Identifying the soil type and its limitations**
- **Selecting soil health indicators suited to the soils, available time, and budget**
- **Understanding what can be changed and what can't**
- **Modifying the expectation, management practice or soil**
- **Monitoring key soil, plant, and economic attributes to measure soil function**
- **Reassessing the system – is it working?**

How to measure soil health on your vineyard?

- Define what soil health means for your property and business and write it down.
- Identify the main soil types on your property.
- List the limitations to production for each soil type

For example, deep sandy soils have low water-holding capacity, are low in nutrients, CEC, and are susceptible to compaction and water repellence.

- Choose soil health indicators that will measure the suspected limitations in your main soil types, that you have the time and budget to measure.
- Due to how soils are formed, their chemical, physical, and biological properties vary across the landscape. As so many factors influence soil function, a soil's health is best evaluated against a local reference with similar capacity.
- Select a block that is performing well and use it as your yardstick measure. Make sure when you compare sites that they have similar soil texture, soil colour and depth to clay or rock to provide the context to the measured parameters. Your sites can be grouped by these key characters and used to identify your soil's upper capacity.
- Measure the vine-row and mid-row separately.
- The groups and comparisons will be very important for monitoring change in soil health over time. Consistency in the selected test or method, soil depth and time of sampling will ensure data is accurate and comparable.
- Choose the soil health function and assessments that are important for your property.
- Create a recording sheet (see **Appendix 1: EcoVineyards soil data recording and water infiltration**).
- Collect the equipment you will need (make a list) and don't forget your phone/camera.
- You are ready to take your samples.

Assessing your soil health

- For the soil health indicators you have chosen, use the standards to check if you are within the desired range.
- For any that are outside of these areas, make a note as this will help you develop an action plan to ameliorate or adjust management practices.
- For each site, add the values from the scoring guides. The score provides an arbitrary value. Use this to monitor change over time.

Make a list of actions for identified areas

- Compare the score to the score of the reference 'healthy' site you selected. Are they different?
- Select ameliorants to change an indicator (e.g. lime to adjust acid soils).
- Review and adjust management practices for a health indicator – for soils low in OC, consider application of compost or other waste to improve OC.
- Determine the frequency of future soil health sampling.

Some soil health properties will change quickly and can be re-assessed in 1 year (nutrients, OC, salinity aggregate stability, macrofauna and microbial abundance and diversity) whilst others will take several years for changes to occur (generally anything that changes the physical properties (e.g. soil strength, bulk density). As seasons and inputs change, the aim is to pick up the trend over time to understand if a stable change is occurring in the direction you want it to go.

Management plan

Managing OM and soil structure is key to soil health. You can't have good structure without OM and you can't grow good OM without good structure.

Soil biology is a key to both OM and structure and change won't occur without it.

Soil biology is a key driver of soil health, soil type and texture and the production system (e.g. vineyard, vegetation) defines the limits of what can be expected.

Therefore, soil health management needs to optimise soil structure and OM and create a favourable environment for soil biology and plants to grow. Different management practices will be needed for different soil types and production systems (in many cases the vine and mid-row are treated differently, and management plans are likely to be different).

Aim for management practices that:

- minimise disturbance (maximise structure)
- maximise soil cover
- maximise OM inputs
- maximise diversity (of OM sources and soil biology) and create a favourable environment for soil biology and plant growth.

1. Optimise soil structure for air and water movement

- Minimise soil disturbance through tillage to protect soil aggregates. Weigh the benefits of using tillage to the loss of soil structure through breaking down soil aggregates (availability and movement of air and water), exposure of OC to decomposition by microbes (decrease OC) and increased risk of erosion (losing OC and soil structure). Reducing soil disturbance encourages the growth of beneficial fungi whose hyphae binds soil particles into aggregates (especially important for sandy textures) and can access water in micropores unavailable to plant roots.
- Be mindful of machinery weight and access by grazing animals when soils are susceptible to compaction (destroy macropores, reducing air and water movement, root, and biological growth).
- Encourage diverse vineyard floor plantings to explore more of the soil through deeper root growth and different root structures (architecture) to create root exudates to feed the biology that produce the glues to improve aggregate stability.
- Encourage vineyard floor plantings that provide as much ground cover as possible for the climate and irrigation parameters of your system. Ground cover minimises the risk of wind and water erosion, raindrop impact on aggregates, regulates soil temperature, minimises soil evaporation and creates an environment where plant roots and soil biology can thrive and seek resources. If a living cover isn't possible because of competition for water, mulches provide a good alternative.

2. Optimise OM as a food source for soil biology

- Grow OM on the vineyard floor to provide food for soil biology. Diverse plants create diverse root architecture that explore the soil and provide a buffet of root exudates, resulting in diverse soil biology with their associated functions (improve soil structure, increase nutrient cycling, disease suppression, and the potential to increase OC).
- Where it is difficult to grow sufficient on-site OM or to extend the length of OM inputs, external sources, such as composts, manures, and mulches, can be an option depending on budget. Sources are varied and will provide different nutrition, longevity, and potential contaminant issues so they need to be assessed prior to use.

3. Optimise nutrient supply for biological and plant growth

- Be aware of the soil texture and biological activity and the ability of the soil to capture, convert, and store nutrients (CEC, OC).
- Determine the nutrients within the system e.g. decomposition of OM on the vineyard floor and be aware if there is a nutrient that may be limiting turnover e.g. nitrogen.
- Assess if, and when external inputs are required if there are deficiencies.
- Provide well-considered fertiliser applications that encourage root-microbe associations and increase microbial conversion to stable OC.
- Ensure mid-rows and vine-rows are within a desirable pH range for plant and biological growth.

4. Understand the boundaries

- Soil type and texture sets the capacity of the system.
- Be aware of limitations and work within the boundaries.
- Consider if soil improvements are required to remove production constraints, such as liming and rootzone leaching for salinity.
- Set realistic expectations and push the boundaries if possible.

ORGANIC AMENDMENTS

Organic amendments are made from organic matter and their application can improve a soil's ability to supply and hold nutrients, retain soil moisture, and increase biological diversity. There are many forms of organic amendments and include compost, mulch, manure, biochar, and clay.

- **There is no 'one size fits all' approach to using organic amendments. Consideration is required of the desired outcome from their use, soil types and their limitations, rainfall, and availability of suitable products.**
- **On sandy soils, organic amendments increase water and nutrient-holding capacity.**
- **On clayey soils, organic amendments improve soil structure by creating aggregates that improve the flow of air and water into and through the soil.**
- **Chemical analysis of amendments is essential to determine the proportions of available nutrients, to identify benefits and risks, and determine an appropriate rate to apply.**
- **Fertilisers derived from organic sources are often nutrient-rich but variable in composition. Nutrient content is highly dependent on the source and quality of amendments.**
- **Biochar produced from manure, greenhouse waste, and grasses are better at providing nutrients than wood-based products that are better for carbon sequestration. Pre-loading biochar with nutrients may prevent the adsorption of herbicides and pesticides and provide a source of nutrients whilst increasing the nutrient use efficiency of subsequent fertiliser applications.**

Organic amendments that are more susceptible to microbial decomposition (lower C:N ratio), such as composts, will increase OC (~10 to 20%) at relatively low rates. If an amendment was applied at rate of 10 t/ha, such a product may increase OC by 1 to 2 t/ha or around 0.1%. Therefore, adding or removing small amounts will have a small yearly effect and may take 5 to 10 years before changes to OC are measurable.

Organic amendments that are not as susceptible to decomposition (higher C:N ratio), such as biochar or clay, will have a much higher rate of conversion to OC but will only make small contributions to soil fertility or structure.

To find out more about organic amendments including compost and biostimlants please refer to the EcoVineyards BPMG on soil health in Australian vineyards: Part B (biology).

Further information

- Murraylands and Riverland Landscape Board: Farm-scale biochar production
- Murraylands and Riverland Landscape Board: On-farm production of biochar for improved soil health

SECTION 5:

PRACTICES TO IMPROVE ORGANIC MATTER AND STRUCTURE

MANAGEMENT PRACTICES TO IMPROVE SOIL ORGANIC MATTER (OM)

Management practices can:

- optimise inputs into soil by growing more biomass (roots and shoots), providing a continuous 'in situ' source of OM) and/or add from elsewhere (e.g. manures, composts)
- decrease losses of OC from the soil by maximising stabilisation within aggregates attached to the surface of minerals or in mineral complexes, improving soil surface cover and minimising erosion.

Changes in management practices need to be carefully considered in relation to what is practical, economical, and appropriate for the long-term goals of the enterprise.

Improving OM and OC can be a slow process with significant annual variation. Climate change and patterns of seasonal variability will affect OC inputs and outputs. Changes in management practices can result in a trade-off between increased OC return to the soil and higher OC losses from increased microbial activity and OC decomposition.

Management practices to increase OC inputs or reduce losses

Table 47. Management practices to improve organic carbon

Optimise OM inputs	**Minimise SOC loss**
Add more OM	**Decrease SOC loss**
• Grow more shoots • Retain more biomass • Grow more roots and exudates • Grow more soil organisms • Add OM from elsewhere	• Maintain OM inputs • Minimise soil erosion • Minimise CO_2 loss from decomposition of OM • Maximise stabilisation of SOC • Maximise production of MAOC
Adjust management	**Adjust management**
• Address soil limitations to production where possible • Optimise nutrition • Grow green plants for longer periods • Optimise plant diversity • Consider growing perennial instead of annual plants • Encourage root growth • Minimise bare ground	• Provide OM inputs to maintain or improve OC • Minimise bare ground • Minimise soil disturbance • Maximise soil particle surface area for capture and stabilisation of MAOC • Find ways to optimise decomposition conditions to reduce release of CO_2.

Abbreviations: organic carbon (OC), organic matter (OM), carbon dioxide (CO_2), mineral associated OC (MAOC)

INCREASE ORGANIC CARBON INPUTS

Grow more shoots (solar panels)

Practise good agronomy: optimising the supply and balance of nutrients and the effective control of pests, weeds, and diseases is important for maximising the growth of desired plants.

Low OC levels (below 1% for sands and 2% for heavier clay soils) reduce a soil's capacity to mineralise nutrients therefore nutrients from synthetic or organic sources are required. Improving soil nutrition improves plant growth and biomass production. Higher OM inputs into soil increases microbial populations and activity, potentially increasing the amount of decomposition and loss of OC as CO_2 gas. However, improved nutrition assists in the microbial conversion of particulate (active) to mineral associated (more stable) OC which improves soil and plant health.

Grow a diversity of plants

Within season (where possible) or across seasons to improve resilience to seasonal conditions and climate variability. Different plants have different proportions of carbon and nitrogen in their physiology, resulting in different rates of breakdown and nutrient release.

A plant's root structure (architecture) can modify soil physical limitations (such as water infiltration) and associate with specific microbes, such as rhizobia or fungi. Different species can extend the length of the growing season, remaining green and actively growing for longer periods, supporting microbial activity and the benefits they provide.

Perennials increase the amount of biomass grown above and below ground over time and their roots and shoots continue functioning when annual species have died. Grazing of cover crops removes biomass from the site, decreasing inputs into the soil, but controlled grazing of pastures can stimulate prolific root growth and exudate production and improve SOC inputs directly to the soil.

Address soil limitations: many viticultural soils have physical and chemical limitations that need to be rectified before plant production and biological processes can be improved.

Identification of soil limitations affecting soil function and restricting productivity is the first step. Limitations need to be divided into those that can be overcome and those that are impractical or uneconomic to address. Soil limitations, such as acidity, sodicity, compaction, or hard setting layers, can be treated.

Soil structure: soil aggregates enable more water and air movement in soil. OM plays a key role in soil structure by providing the 'glue' between particles that maintain pore spaces between silt and sand particles.

OM feeds soil biological activity whose secretions and fungal hyphae are important for soil aggregation. The amount and type of clay and the amount, shape, and size of sand grains affects the way soil particles pack together. In sands, fungal hyphae are more important for structure than microbial secretions as they cross-link sand grains in the aggregates. They are also important for accessing moisture stored in micropores.

Grow more roots and exudates

Plants provides food for microbes through root exudates (plant rhizodeposition). Microbes can colonise roots and assist plants to take up nutrients and protect them from soilborne pathogens. Increased root biomass, root exudates and sloughing of cells increase soil OC through what is termed the liquid carbon pathway. The availability of root exudates encourages microbes deeper into the soil and can improve the conversion of POC to MAOC at depth.

Roots contribute 2 to 6 times more OC than shoot residues, mainly because microbes are unable to break down roots that are bound in soil aggregates and the presence of more lignin in roots is more resistant to decomposition.

Plant growth stage and root architecture affects the amount of exudates produced. The production of plant roots exudates cannot be directly controlled but can be influenced by management practices.

Address soil limitations: target practices that enhance water infiltration and storage, the availability of nutrients (pH and deficiencies) and improved soil structure.

Plants can utilise more nutrients in moist soil thereby improving plant productivity and SOC. Strategic tillage can overcome physical limitations, such as compaction, high bulk density, and natural hard pans. This often leads to improved root growth, OC storage and productivity. However, initial tillage can cause losses of 20% of OC stock in topsoils as aggregates are broken up and OC is exposed to microbial decomposition, particularly in sandy soils.

Retain more shoots

Keeping as much OM on the soil surface as possible aids rainfall infiltration, reduces evaporation of soil moisture, moderates soil temperatures and provides food, enhancing conditions for microbial activity. Soil (and OC) losses from erosion are also reduced. Retaining plant residues and preventing grazing animals from baring out or denuding rows of vegetation are measures that will retain more OM.

Increase number and type of soil microbes

Microbes consume and produce OC so have a role in both mineralising and stabilising SOC.

Decomposition of OM by microbes releases nutrients, water, and CO_2. Microbes also secrete substances that act as glues, binding soil particles together into aggregates. As microbes die, they become part of the stabilised MAOC pool. POC and MAOC are bound into aggregates and are protected from further decomposition unless the aggregates are broken apart by soil disturbance. Fungal hyphae in sandy soils particularly rely on soil aggregation to function so are very vulnerable to soil disturbance e.g. tillage.

Import OM

Where it is not possible to grow extra OM in the vineyard or there are additional needs (e.g. nutrition), obtaining and applying OM from beyond the property is feasible. It is better to apply materials formed from waste products and not from a productive area of land otherwise it is increasing OM inputs on one site at the expense of reducing inputs at the other. Large amounts of OM are required to contribute to a measurable change in SOC stores and inputs will need to be maintained and managed to sustain SOC stocks.

REDUCE ORGANIC CARBON LOSSES

Soil OC constantly cycles from one form to another as microbes and other soil organisms decompose and convert carbon from OM into CO_2. Changes in management practices that decrease OM inputs or increase the rate of loss of CO_2 from soil affect SOC.

Minimise soil disturbance and soil erosion

Soil disturbance breaks apart soil aggregates, damages plant roots, destroys fungal hypha, and leaves soil susceptible to erosion.

Reducing the number of tillage operations and using narrow points or discs on seeding machines minimises soil disturbance. Keeping pasture residues and managing them to ensure they do not wash or blow away reduces the risk of soil erosion. Time soil disturbance activities, such as ripping for compaction, to minimise the length of time soil is left bare to reduce erosion risk.

Minimise CO_2 loss on decomposition

Recycling of dead microbes (such as in composted products) diminishes the release of CO_2 during decomposition. Selection of OM inputs and encouragement of microbes that process OM without releasing as much CO_2 are in early stages of development as management practices.

Maximise stabilisation of SOC

Protecting SOC: the location of OC in soil strongly influences whether it will be stored or broken down.

OC in the top 10 cm of soil is more likely to be broken down and cycled by microbes favoured by high inputs of OM through shoots and added residues. However, at depths greater than 10 cm it is more likely that OC will be stored in soil as there is much less biological activity. However, a supply of diverse OM forms encourages a diverse community of microbes that are likely to be more carbon efficient.

Stabilisation of SOC: depends on many factors including clay concentrations, clay mineralogy, and the formation of stable aggregates.

Chemical stabilisation improves aggregation and can limit the access of microbes to SOC. Chemical stabilisation can occur through the binding of SOC to hydroxyl groups of iron and aluminium in acidic soils and the forming complexes with calcium carbonate in alkaline soils.

Maximise production of HOC

Microbes require nutrients to efficiently turn OM into stable OC and nutrient deficiencies can limit the transformation of particulate (POC) to mineral-associated OC (MAOC). Where there are not enough nutrients in the soil, the provision of additional nutrients might be required.

For every 1,000 kg of humus, 80 kg of nitrogen, 20 kg of phosphorus and 14 kg of sulfur are required to enable biological processes to occur.

Further information

- AWRI Fact Sheet: Vineyard management practices to improve soil health
- AWRI information pack: Soil health
- Barossa Australia: Using composts and mulches to improve undervine soil health and increase the environmental sustainability and profitability of vines in the Barossa and wider Australian wine industry
- Barossa Australia: BGWA demonstration vineyards trials, undervine mulch trials
- Barossa Australia: The use of compost and mulch in vineyards. A case study from Torbreck Vintners, Barossa Valley
- CSIRO: Compost as mulch for vineyards
- Government of SA: Carbon farming roadmap for SA
- Sitos Group: Biochar application demo in vineyards

CASE STUDIES / VITICULTURAL INFORMATION

Australian viticulture and regenerative agriculture

In his 2020 Nuffield Australia project report, Richard Leask examined the tenets of Regenerative Agriculture and how this could be integrated into the Australian wine industry.

He believes that *"increasing the capacity of soils through understanding, building and managing soil carbon levels and the soil microbial network with the use of plants and their diversity is the key to arresting the decline of soils around the world."*

A selection of his recommendations is shown below:

- Rethink the use of cover crops in the vineyard mid-row zone. Increase plant species diversity and consider both winter and summer sowing to have living roots year-round.
- Utilise living plants in the under-vine zone as a cost saving and soil health-building alternative to cultivation and herbicide application.
- Explore the potential beneficial role of the soil microbial network in established horticultural crops as a way of delivering reduced inputs and cost savings to the industry.
- Maximise the benefits of livestock with infrastructure to allow planned rotational cell grazing techniques.
- Develop insectary plantings and beneficial habitats for predator insects in non-productive areas for ecosystem pest and disease control.
- Undertake regular soil testing for nutrition and soil biology. Set baselines and track changes over time with management changes.
- Have an open mind about how vineyards need to look and how common jobs are done. In regenerative agricultural systems, there may be ways to add value to the vineyard system and reduce detrimental impacts on soil structure and ecosystems.

Reference

Leask, R. (2020) **Is being sustainable enough for Australian wine? Regenerative agriculture can redefine what is best practice viticulture.** Nuffield Australia Project No 1916. Wine Australia, Adelaide.

Does soil management affect grapevine yield and quality?

Native species as cover crops

The research team investigated the use of native plant species to replace exotics as the main cover in vineyards at Nuriootpa, Coonawarra, Loxton, Kingston-on-Murray, and Swan Hill.

Species used: *Rytidosperma richardsonii*, wallaby grass and two chenopods *Atriplex semibaccata*, creeping saltbush and *Enchylaena tomentosa*, ruby saltbush.

- They determined that native perennial cover crop species could fit well into a vineyard production system if care is taken to select species that are suitable for each situation.
- When grown in unsuitable situations, the spring and summer active native species can significantly affect vine yield through competition for water. There was a 30% yield reduction of young Shiraz vines in the Barossa but no effect on old, wide-spaced vines in a dry-grown vineyard in the Coonawarra. Prostrate saltbush fit well into the vineyard production system of the warm, dry Riverland and Murray Valley regions but not at Nuriootpa.
- Once established, the native species compete strongly with weeds in spring and summer, negating the need for weed control during that period. However, broadleaf weed control during establishment in the saltbush required a sponge wiper to remove weed competition whereas in the wallaby grass it was manageable.
- There was a significant increase in parasitoid and predatory invertebrate populations in the vineyard as the native species provided a desirable habitat.
- Earthworm abundance increased in the Nuriootpa saltbush treatment.
- Unsurprisingly, after three years there were no measurable changes in soil OC (there is often a lag time of 3 to 5 years after changing a practice to measuring a stable OC change) but there was a trend for increasing microbial biomass carbon in the 0 to 10 cm of the saltbush treatment.
- The saltbush site at Loxton recorded decreased vineyard floor temperatures.
- An economic analysis of establishing the native covers compared to standard annual covers over five years showed that saltbush would be cheaper than an annual cover crop with a similar cost for the native vs annual grass.

Sites were established at Nuriootpa, McLaren Vale, and Langhorne Creek

- Mulch application on the vine row soil surface can have a significant effect on soil moisture retention, potential nutrient availability and vine growth with time response periods for light sandy soils and heavy clayey soils. Vine growth and yield on light soils show an immediate response with a peak in the second vintage which dissipates by the seventh vintage. Heavy soils take more than two vintages to show a response, peaks in the fourth or fifth vintage with some residual effect evident in the seventh vintage.

Mulch application is recommended every six years on light soils and eight years for heavy soils.

Reference

McCarthy, M., Lanyon, D., Penfold, C., Pudney, S., Bhat, V., McDonald, C., Hetherington, R., Howell, C., and Mowatt, D. (2010) **Soil management for yield and quality. Project SAR 04/02**. GWRDC, Adelaide.

Low input under-vine floor management system

As a continuation of some of the findings of the McCarthy et al. (2010) report this project assessed the growth of cover crops below vines which are beneficial to soil and vine while competing with or suppressing weeds.

A bare under-vine strip is recognised as not being in line with best practice. Four sites were established at Nuriootpa, Waikerie, Eden Valley, and Langhorne Creek on different soil types and in different climatic conditions in South Australia.

- Under-vine cover cropping with suitable species can achieve the objective of improving productivity and potentially fruit and wine quality at minimal cost or risk.
- Weed growth was significantly reduced at all sites through suppression by species that competed strongly with weeds or suppressed their germination.
- At Waikerie (sandy soil, hot summer temperature), Kasbah cocksfoot prevented weed growth BUT also reduced grape yield. Whilst there was no yield reduction from the legume and annual grasses, they were not able to suppress some very aggressive summer weeds. Another strategy needs to be devised for the hot, inland areas.
- In the Barossa, the Kasbah cocksfoot and medic/ryegrass mix generated a higher gross margin than the herbicide control and straw mulch.
- At Eden Valley and Langhorne Creek, the medic and medic/ryegrass treatments also maintained or improved yields

Soil OC improved significantly, particularly where legumes and grasses were sown as a mixture. This was achieved at approximately the cost one year's herbicide application.

Reference

Penfold, C., Weckert, M., Nordblum, T., Howie, J., and Norton, M. (2018) **Development of a low-input under-vine floor management system which improves profitability without compromising yield or quality. Project No UA 1301** Wine Australia Final Report.

Adelaide Hills wine region soil health project

As a result of grower concerns about declining soil health under vine rows raised at a sustainability group meeting in 2012, Brian Hughes of SARDI led a scoping study of 13 sites in 2014 and assessed soil and biological health from eight conventional and two biodynamic vineyards.

Key findings included:

- Lower OC (0.5 to 1.5%) under vine row compared to the mid-row for conventional vineyards
- At two sites pH_{CaCl_2} was acidic and at one site low pH resulted in higher OC
- At two sites salinity levels were above 2.5 dS/m ECe and had high chloride levels mainly driven by irrigation water quality. Sodicity was also developing at these sites.
- Soil biology measured by microbial biomass carbon (MBC) was strongly linked to soil OC. MBC was higher where grasses and weeds were growing (including the under-vine area) and lower in bare under-vine areas or where there was salinity, low OC, or sandy texture.
- High soil copper levels did not affect MBC or vine vigour.
- At three sites, topsoil loss (erosion due to the loss of soil structure) in the under-vine area was considered the main factor. Soil was characterised by low OC, clayey surface soil, and poor vine vigour.

Barossa wine region, mulches, composts, and cover crops

A literature review of under-vine soil health benefits for Australian vineyards with a focus on the Barossa, produced by the Barossa Grape and Wine Association (BGWA), provides a good summary of the effects of composts, mulches, cover crops, and bare under vine strips.

Soil health sampling (2021) at several BGWA demonstration vineyards 5 to 8 years post establishment was led by Brian Hughes of SARDI and found:

- Mulch and compost improved the amount of water stored in the profile and decreased bulk density compared to bare under-vine.
- Improvements in pH, nitrogen, phosphorus, and OC were often seen with some changes to copper, zinc, manganese, and boron but was dependent on the compost's origins (e.g. composted manures).
- OC stocks to 30 cm increased (2 to 32 TC/ha) in five out of the six sites with treated compared to a bare under vine strip.
- Mid-row (cover crop) mulch and compost products resulted in some improvements to biological activity and diversity. However, all trials indicated the need to increase general soil microbes and microbial diversity (sampling was done in a dry year; in a wetter year with more soil moisture an increase in biological activity would be expected).
- Higher microbial activity and diversity under-vine with mulch and compost products compared to the control, demonstrating the advantages of organic matter.
- Protozoa, important for nutrient transfer and cycling between soil trophic levels, were more abundant under mid-rows with mulch and compost treatments compared to untreated soil. Most sites had lower bacteria-to-fungi ratios due to an increased amount of OM containing lignin (mostly in the composted-mulch and mulch products).

Reference

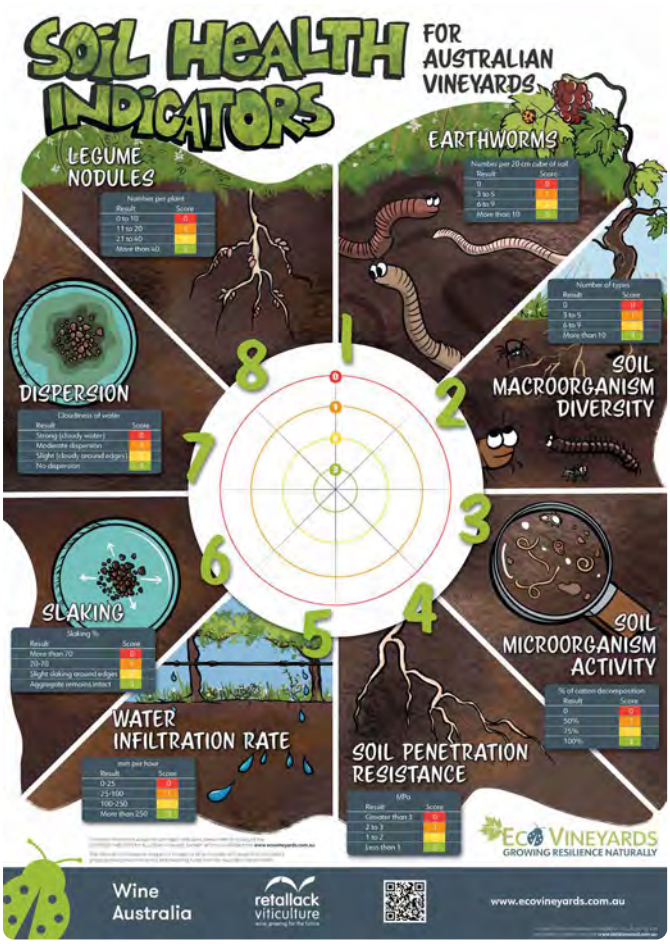
BGWA (2022) **Using composts and mulches to improve undervine soil health and increase the environmental sustainability and profitability of vines in the Baross and winder Australian wine industry.** GWRDC, Adelaide

Further information

- EcoVineyards: Soil health indicators for Australian vineyards
- GWRDC: Assessing soil quality and interpreting soil test results
- GWRDC: Sustainable Viticultural Production: Optimising soil resources
- Nuffield Australia: Is being sustainable enough for Australian Wine?
- NQ Dry Tropics: Rapid assessment of soil health (RASH) videos and manual
- Vidacycle: Soilmentor app allows you to track 10 regen indicators, designed to represent various key aspects of soil health.
- Wine Australia: Soil health – what is it, how do we assess it and how do we improve it?
- Wine Australia: Soil health research summary

To continue your reading on vineyard soil health please visit the EcoVineyards knowledge hub:

- EcoVineyards best practice management guide on soil health in Australian vineyards: Part A (chemical and physical)
- EcoVineyards best practice management guide on soil health in Australian vineyards: Part B (biology)
- Check out the Getting to know the earthworms in your vineyard video series and record your progress on the Soil health indicators for Australian vineyards and Great Aussie EcoVineyards earthworm count posters.



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