ECO VINEYARDS
GROWING RESILIENCE NATURALLY

BEST PRACTICE MANAGEMENT GUIDE

ON SOIL HEALTH IN AUSTRALIAN VINEYARDS
PART B: BIOLOGY

by Dr Mary Retallack, Dr Joseph Marks, Dr Thomas Lines, Mark Tupman and Dr Mary Cole

Wine Australia
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Productive Ecology
AGPATH

ACKNOWLEDGEMENTS

The EcoVineyards series of best practice management guides (BPMGs) and support materials were developed by a team of subject specialists led by Dr Mary Retallack, Retallack Viticulture Pty Ltd for the National EcoVineyards Program.

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Published by Retallack Viticulture Pty Ltd
ABN: 161 3501 6232
March 2024

Cover photograph: Mary Retallack assessing arthropod activity in a soil sample with event participants in the Adelaide Hills wine region [Photo: Janet Klein].
Additional photos: Mary Retallack
Editor: Sonya Logan
Graphic design: Debbie Wood Creative

Citation

Retallack, M.J., Marks, J., Lines, T., Tupman, M., and Cole, M. (2024) EcoVineyards best practice management guide on soil health in Australian vineyards: Part B (biology). Retallack Viticulture Pty Ltd, Adelaide.

Funding

The National EcoVineyards Program is funded by Wine Australia with levies from Australia's grape growers and winemakers and matching funds from the Australian Government.

The program is delivered by Retallack Viticulture Pty Ltd with significant support from regional communities.

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

CCN cloud condensation nuclei

C:N carbon-to-nitrogen ratio

ESP exchangeable sodium percentage

EM effective microorganisms

IPM integrated pest management

MAOM mineral-associated organic matter

OC organic carbon

OM organic matter

RKN root-knot nematode

SOC soil organic carbon

WHC water-holding capacity

FUNCTIONS OF SOIL ORGANISMS

Soil organisms	Function
Arthropods	Decomposition, nutrient cycling, aeration of soil, biocontrol of pest species
Bacteria	Decomposition, nutrient cycling, nitrogen fixation, suppression of plant pathogens
Fungi	Decomposition, nutrient cycling, mycorrhizal association with plants, suppression of plant pathogens
Grazers	Regulation of microbial populations
Microbes	Decomposition, nutrient cycling, suppression of plant pathogens
Mutualists	Symbiotic relationships with plants
Nematodes	Regulation of microbial populations
Protozoa	Regulation of microbial populations

SOIL HEALTH DEFINITIONS

Term	Definition
Actinobacteria	Actinobacteria are a diverse phylum of bacteria that are of great economic importance to humans because they help to decompose organic matter so the molecules can be taken up by plants.
Arbuscular mycorrhizal fungi (AMF)	AMF form mutualistic associations with plant roots, often growing small arbuscules (nutrient exchange sites) within the plant cell wall. The association is beneficial to both fungi and plant as the fungi receive organic carbon from the plant, while the plant is delivered inorganic P, N, and Zn from the fungi. Grapevines form mutualistic associations with AMF.
Arthropods	Arthropods are invertebrates with segmented bodies and jointed limbs. Arthropods, such as mites, springtails, and ground beetles, are important decomposers. They break down organic matter and release nutrients into the soil.
Bacteria	Bacteria are one of the most abundant organisms in soil. They play a crucial role in nutrient cycling, breaking down organic matter and making nutrients available to plants. Some bacteria can fix atmospheric nitrogen into a plant available form and some bacteria are pathogenic and can cause diseases in plants. Examples of bacteria include cyanobacteria (formerly called blue-green algae), actinomycetes (bacteria that give healthy soil its characteristic smell) and *Agrobacterium tumefaciens* which causes grapevine crown gall.
Biotic	Relating to or resulting from living organisms.
EM/bokashi culture	EM means effective micro-organisms. Bokashi is a Japanese term that means fermented organic matter. It is a bran-based material that has been fermented with EM liquid concentrate and dried for storage. Bokashi aids in the fermentation of organic matter.
Endophyte	An endophyte is an endosymbiont, often a bacterium or fungus, that lives within a plant for at least part of its life cycle without causing apparent disease.
Endosymbiont	An endosymbiont is any organism that lives within the body or cells of another organism most often, though not always, in a mutualistic relationship.
Facultative anaerobes	There are a large group of bacteria and yeasts, collectively termed facultative anaerobes, that can switch to anaerobic respiration or fermentation to acquire energy from organic materials when oxygen is limited.
Fish hydrolysate	Fish hydrolysate is a process that uses water as a medium to extract the desired components including oils via fermentation. It is undiluted and is a rich food source for beneficial microbes and especially beneficial fungi in the soil. If you purchase a fish emulsion the oil is removed and as a result the quality of the product is lower.
Functional ecosystem	A 'functional ecosystem' suggests the presence of 'functional biodiversity', that is, a set of species that contribute a range of ecosystem services, both physical and chemical to the overall benefit of the ecosystem.
Fungi	Fungi are an important group of microorganisms in soil. They are essential for decomposing organic matter and releasing nutrients into the soil. Fungi also form symbiotic relationships with plants, helping them to absorb nutrients and water from the soil. Mycorrhizal fungi, for example, form associations with the roots of most plants (except brassicas), enabling them to access nutrients that are otherwise inaccessible and saprophytic fungi decompose dead organic matter.
Grazers	Higher trophic level organisms such as protozoa, nematodes, and microarthropods that feed on lower trophic level organisms including bacteria and fungi.
Healthy soil	A healthy soil supports optimal plant growth and soil biology (which in turn feeds the soil). It will have 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 the provision of plant-available nutrients, infiltration and storage of water, balanced populations for pest and disease suppression, and greater longevity of soil organic carbon.
Hemicellulose	Hemicellulose is present along with cellulose in almost all terrestrial plant cell walls. Cellulose is crystalline, strong, and resistant to hydrolysis. Hemicelluloses are branched, shorter in length than cellulose, and show a propensity to crystallise.

Term	Definition
Heterotrophic	A heterotroph is an organism that consumes other organisms in a food chain. They are primary, secondary, and tertiary consumers, but not producers.
Lignin	Lignin is particularly important in the formation of cell walls, especially in wood and bark, because it creates rigidity and does not rot easily.
Mesophilic	A mesophile is an organism that grows best in moderate temperatures with an optimum growth range from 20 to 45 °C.
Mineral-associated organic matter (MAOM)	MAOM is important for the 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 soil.
Macro-, meso-, micro-fauna	Macrofauna, in soil science are animals that are up to 20 mm long but smaller than an earthworm. Mesofauna have bodies up to 2 mm long. Microfauna are the smallest of the soil fauna and are less than 0.1 mm in size, and need a microscope to be seen.
Mycotrophic	A mycotroph is a plant that gets all or part of its carbon, water, or nutrient supply through symbiotic association with fungi.
Necromass	The mass of dead plant material lying as litter on the ground surface and animal material (including macrofauna and microbes).
Nematodes	Nematodes are microscopic, worm-like organisms that play an important role in the soil food web. They can be classified into three categories: plant parasitic nematodes, bacterial/fungal-feeding, and predatory nematodes. Predatory nematodes feed on other nematodes, as well as other small organisms in the soil.
Organic nutrients	Organic nutrients contain carbon derived from once living organisms, while inorganic nutrients lack carbon.
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.
Pedogenesis	The microbial bioconversion of plant exudates and detritus into stable soil carbon.
Phototropic	Phototropism is the ability of plants to re-orient shoot growth towards a light source.
Physicochemistry	Dependent on the joint action of both physical and chemical processes.
Protozoa	Tiny, single-celled animals, including amoebas, ciliates, and flagellates. Protozoa are single-celled organisms that play a crucial role in the soil food web. They are important grazers, feeding on bacteria, fungi, and other microbes in the soil. Protozoa also help to regulate the population of other microorganisms in soil.
Rhizosphere	The rhizosphere is the zone of soil surrounding a plant root where the biology and chemistry of the soil are influenced by the root. This zone is about 1 mm wide but has no distinct edge.
Root exudates	Root exudates refer to a suite of substances in the rhizosphere that are secreted by the roots of living plants and microbially modified products of these substances.
Soil carbon sponge	By connecting soil carbon with a restored water cycle, it may be possible to induce planetary cooling via evaporative cooling and higher reflectance of denser green vegetation.
Thermophilic	A thermophile is an organism (a type of extremophile) that thrives at relatively high temperatures, between 41 to 122 °C.
Tropic levels	Levels of the food chain. The first trophic level includes photosynthesisers or producers (plants) that get energy from the sun. Organisms that eat plants make up the second trophic level. Third trophic level organisms eat those in the second level, and so on. It is a simplified way of thinking of the food web. Some organisms eat members of several trophic levels.

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 three best practice management guides is a key part of this initiative..

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

- soil health in Australian vineyards,
  - Part A (chemical and physical)
  - Part B (biology) – **this guide**
- 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 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.

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 (Parts 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 '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 in conjunction with the EcoVineyards BPMG on soil health in Australian vineyards: Part A (chemical and physical).

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

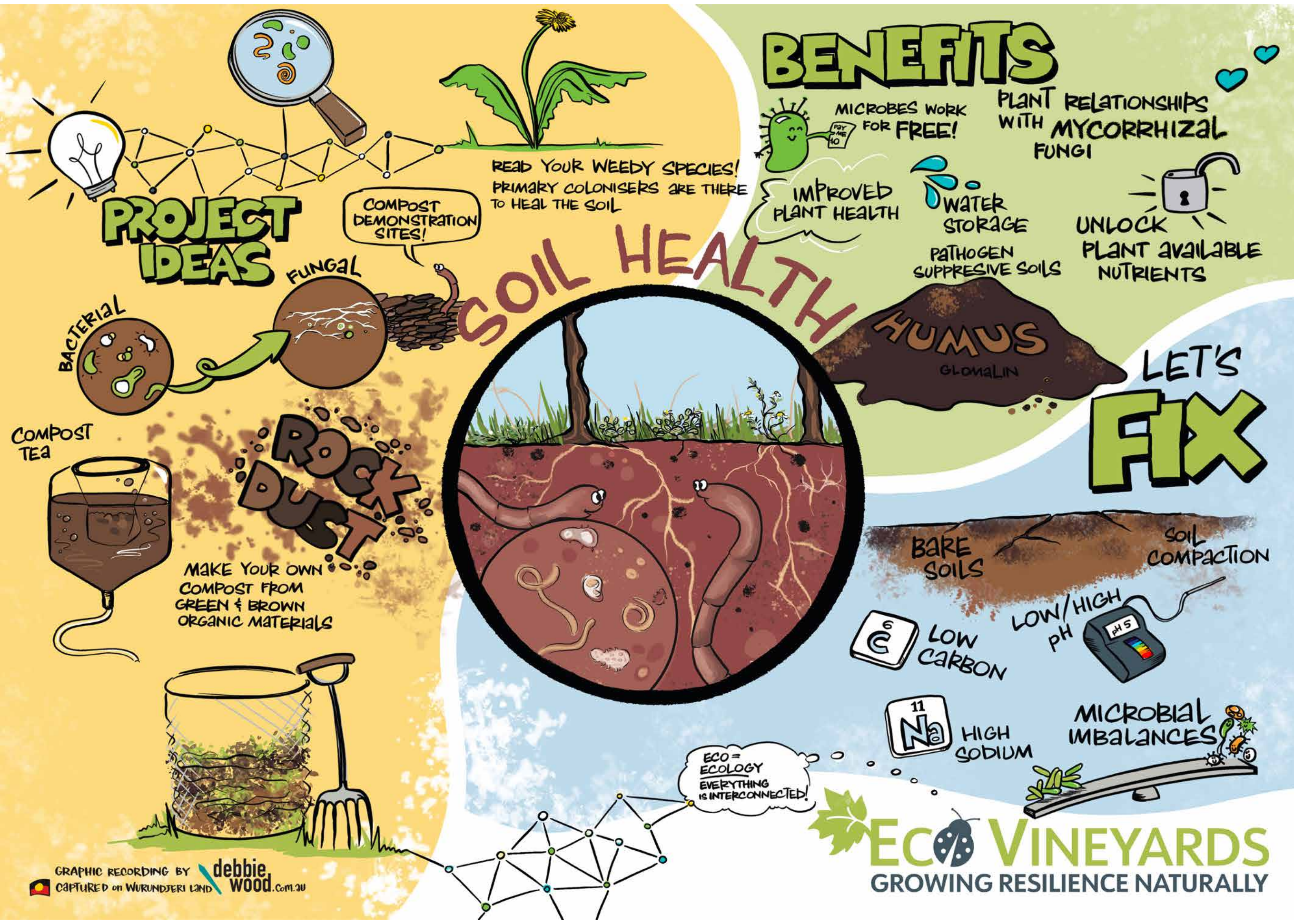


Figure 1. Some of the themes captured within this BPMG on soil health and more broadly in the National EcoVineyards Program [Image: Debbie Wood].

INTRODUCTION

Background

There has been increasing awareness that optimally photosynthesising plants (grapevines and ground covers) are needed to feed soil biology to create healthy soils with integrity and greater resilience in vineyards.

This is important so production systems are better able to respond to changing climate and extreme weather events that impact grape production in Australia and around the world. This best practice management guide (BPMG) presents information that will help wine growers transition to a more ecological approach to viticulture (and wine) production.

An ecological approach

The National EcoVineyards Program focuses on the living components of production systems (including soil biology) as an underpinning pillar along with soil health, ground covers, functional biodiversity, and the interactions between each.

These ecological and biologically focused principles are complementary to existing practices, help break the cycle of intervention (saving time and resources), and can assist wine growers with their environmental stewardship reporting requirements.

There are many ways to describe wine growing practices with terms like conventional, organic, low input, regenerative and sustainable often used. We prefer not to use the word sustainable, as to 'sustain' in our view is a low bar and cannot be maintained - either we are moving forward or backward.

In some cases, maintaining the status 'quo is' is actually moving backwards, given the dynamic nature of knowledge being unearthed in this field and the huge potential to solve some of the urgent challenges currently being faced by growers. We cannot continue to do more of the same and expect a different outcome.

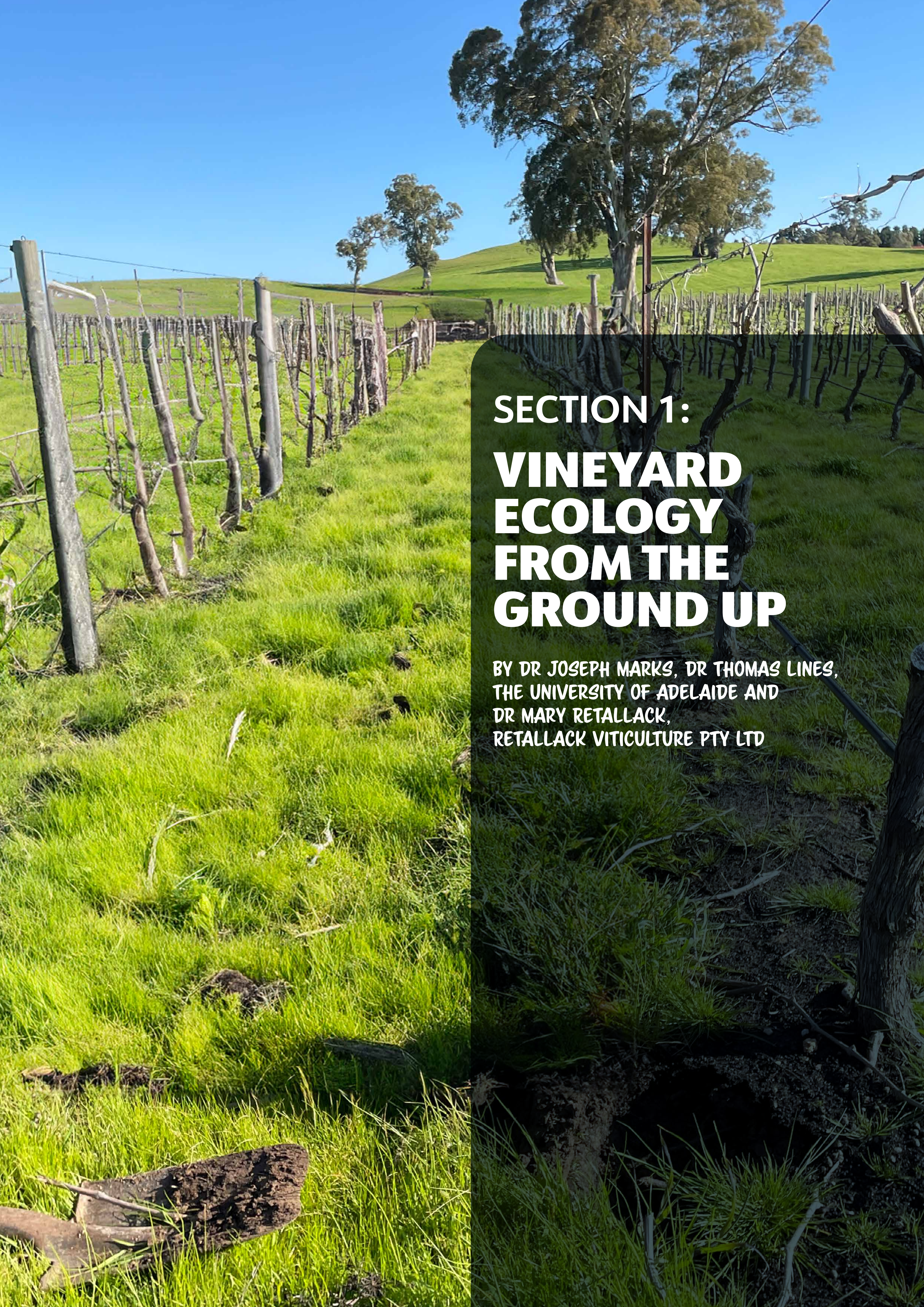
We advocate for making small changes with an ecological and regenerative focus and then scaling up as a grower observes benefits and gains confidence in practices that are suited to a particular location.

We are conscious of the urgent and dynamic need to future proof production and grow resilience in our viticultural landscapes, while focusing on fruit quality, financial security, and environmental stewardship. To do this, we need to regenerate and move our thinking and production practices forward in harmony with nature.

Climatic events of the 21st century and a greater understanding of the impact of conventional agriculture have led to a greater awareness of more naturally integrated methods of land use and agricultural production. Greater understanding of the role of soil as the basis of human, and animal health has become more apparent.

A wholistic approach has the potential to provide greater production and fruit quality benefits over the longer term. The aim of growing in harmony with nature is to minimise synthetic inputs, maximise microbial activity and diversity, optimise plant/vine health, nutritional integrity, photosynthetic capacity, improve fruit quality, reduce water use, improve economics for the enterprise and share the complexity and beauty of nature.

We look forward to exploring each of these concepts with you in more detail.



SECTION 1:

VINEYARD ECOLOGY FROM THE GROUND UP

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APPLYING ECOLOGICAL THINKING TO VINEYARD SOIL MANAGEMENT

As human beings, we've come a long way. As a collective species, we've been to the bottom of the Mariana Trench, walked on the moon and split the atom.

If it can be hypothesised, tested, analysed, sampled, extrapolated, manipulated, dissected, distilled, and perturbed, we've done it. We've certainly done a lot, and yet for all our collective achievements, sometimes, less is more.

It really is difficult to beat 3,500 million years of evolutionary trial and error – of change and refinement so gradual that it has created and nurtured a range of ecosystems so vast and complex we can scarcely fathom. Ecosystems are a product of interaction, both biotic (biological) and abiotic (not biological), and they may be as vast as entire deserts and mountain ranges or as small and unassuming as a desert swale or isolated mountain escarpment.

In each case, the creation of a functional ecosystem requires time for it to reach a steady state – an equilibrium with the capacity for both resistance and resilience in the face of disturbance.

The agroecosystem

In the immediate light of the previous paragraph, it may seem somewhat oxymoronic to view agricultural systems as ecosystems, but in fact they are. In many cases throughout the world – too many cases, in fact – natural ecosystems are devastated to make way for agricultural practices. Footage showing the clearing of rainforest to make way for monoculture cropping or grazing is embedded in our minds as the epitome of human-led disturbance.

Many agricultural systems are thus viewed as the antithesis of functional ecosystems – so why should we entertain the notion of an 'agroecosystem'? Agroecosystems lie on a spectrum of human input and human disturbance and yet within each lies the potential for biotic and abiotic interaction and thus the potential for ecosystem function.

Establishing a functional agroecosystem requires an understanding of several core components:

- The biological requirements of the focal crop, in this case grapevines
- Climatic conditions and seasonal variations inherent to the land in use
- Topography of the land in use
- What lies beneath, namely, soil biology, chemistry, and physical structure.

This last component is of primary importance. The pedosphere – that vast and mysterious matrix beneath our feet – is the primary focus of this management guide.

Understanding both the functions and mechanisms that govern soil biology and physicochemistry (the joint action of both physical and chemical processes) are fundamentally important to establishing a functional agroecosystem.

The reasons for establishing functional agroecosystems are multifarious and rooted in both economic and environmental outcomes yet are also underpinned by social philosophies regarding environmental stewardship through long-term strategies.

A 'functional ecosystem' suggests the presence of 'functional biodiversity', that is, a set of species that contribute a range of ecosystem services – both physical and chemical – to the overall benefit of the ecosystem. A regenerative approach also focuses on the living components of the system and functional biodiversity – the set of species that contribute to ecosystem services in an agroecosystem.

Table 2. Agroecological and conventional management approaches

Agroecosystems (greater resilience and needs less intervention)	**Conventional systems (less resilient and needs greater intervention)**
Biodiversity: Increased plant and soil biodiversity (richness and abundance), leading to functional redundancy in the system, enhanced capacity for soil nutrient cycling, and uptake of nutrients in a plant-available form.	**Biodiversity**: Reduced above and below ground due to less plant diversity (monocultures), introduced species that are not locally adapted and increased reliance on herbicide/pesticide inputs, as well as synthetic salt-based fertilisers.
Soil health and fertility: Enhanced due to optimal plant photosynthesis resulting in the release of exudates nourishing soil microbes, ground covers (including multispecies cover crops), organic matter input and protection, reduced herbicide and pesticide use leading to longer-term benefits.	**Soil health and fertility:** Overuse and over-reliance on synthetic chemical inputs such as fertilisers, herbicides, and pesticides, as well as increased tillage practices can degrade soil over time leading to a breakdown in biological and physical processes, erosion, and runoff.
Chemical input: Reduced synthetic chemical inputs – reliance on biological and ecological processes to conduct nutrient cycling.	**Chemical input**: Often a heavy reliance on broad-use synthetic chemical inputs, increasing economic costs and reducing biological and ecological processes.
Ecosystem services: Enhanced ecosystem services, including biocontrol of soil and plant pests and carbon sequestration leading to improved soil structure, water-use efficiency and reduced run-off and pollution of waterways.	**Ecosystem services**: Highly reduced owing to a reliance on human inputs to control weedy and pest species, fewer plant species leading to poorer soil structure, less fauna found in association and increased potential for run-off and habitat destruction.

THE VINEYARD AGROECOSYSTEM

This best practice management guide is focused on vineyards – specifically, vineyard floor management from a biological and ecological viewpoint. Vineyards often provide ideal settings for the implementation of regenerative and ecological management practices – in effect, they make ideal agroecosystems.

Here are some reasons why:

- **Longevity of land-use:** Unlike broadacre systems, vineyards are perennial in nature, at least in terms of roots, trunks, and cordons. In this, they are generally subject to long-term management strategies ranging from several decades to over a century in some situations. Implementing regenerative and ecological management practices requires longer-term strategies to allow ecosystem service providers time to reach a steady state. Often, positive results can be seen within a season or two.
- **Lack of disturbance:** Vineyards are far less prone to disturbance through annual tillage compared to many broadacre systems. A lack of soil disturbance is not only ideal for building abundance and diversity in soil microbiology but also crucial for maintaining it.

Moreover, disturbing soil through tillage and/or promoting bare earth can lead to rapid oxidation and metabolism of soil organic matter and the creation of a compacted hard pan, which creates anerobic soil conditions and a physical barrier to root growth.

- **Ground cover:** Vineyards provide ideal spaces to increase above-ground biodiversity through the planting of ground covers. Due to their perennial nature, vineyards can support a range of plant species in the mid-row and indeed the under-vine area. The positive influence of ground cover biology on vineyard soil will be enumerated further.
- **Carbon sequestration:** As previously mentioned, the relative lack of soil disturbance in vineyards makes them ideal systems to build soil organic carbon (SOC). Where a lack of soil disturbance protects SOC, having increased above and below ground biomass in the form of native grasses and forbs, cover crops or volunteer swards actively help to increase SOC. Again, SOC will be discussed further.
- **Pest management:** Vineyards offer the potential for integrated pest management (IPM) strategies where ecological intensification, including the use of supplementary flora, has provided niche habitats for select predator species, which in turn provide biocontrols against pest species both above and below ground.

The ecological intensification of a vineyard requires ecosystem service providers to perform integrated functions that might otherwise be undertaken by human intervention. The primary purpose of this best management practice guide (BPMG) is to synthesise knowledge around soil biological and ecological processes that can be integrated into vineyard systems.

It is, therefore, necessary to identify those soil processes (biological, chemical, and physical) that are important to vineyard and grapevine function. The following sections of this BPMG will cover soil biological, chemical, and physical processes that are inherently important to vineyard and grapevine function. These will be discussed through the integrated use of biological agents and ecological processes to achieve functional outcomes.

VINEYARD SOIL BIOLOGY: AGENTS, MECHANISMS, AND CHEMICAL PROCESSES

Take a single gram of healthy soil – about one quarter of one teaspoon – and within it will exist over a billion single organisms. Most of these are bacteria, in fact, vastly so. However, you will also find fungi, protozoa, nematodes, arthropods, and viruses, often in their thousands.

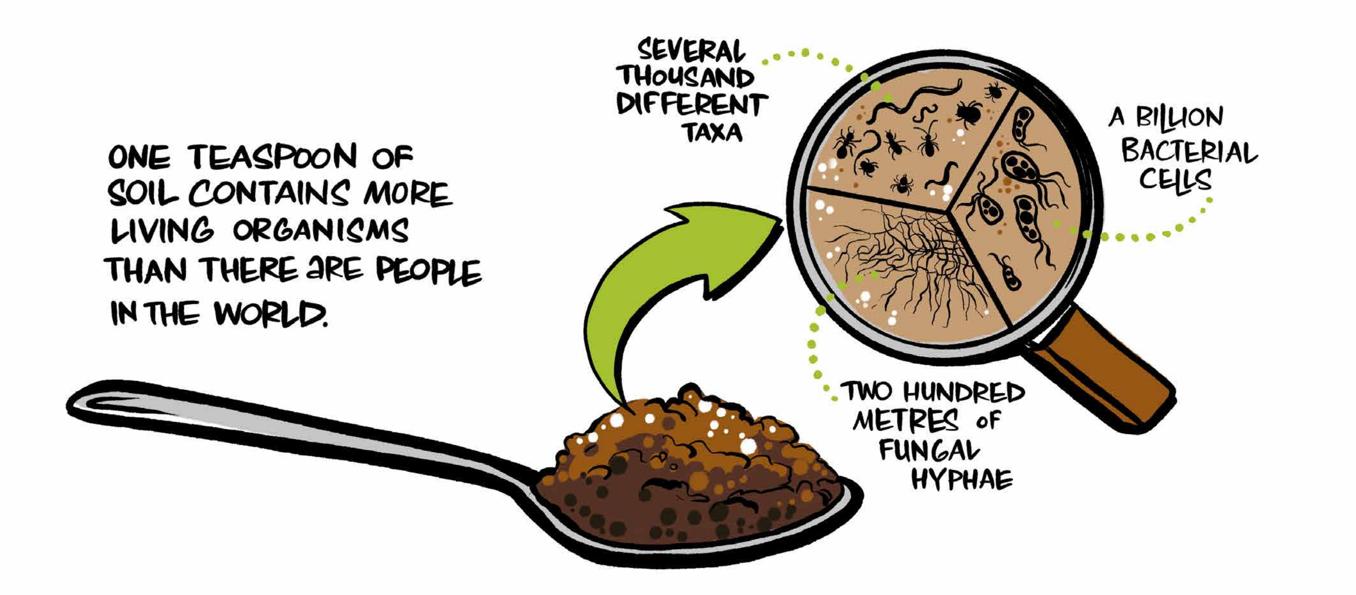


Figure 2. Healthy soils teem with an abundance of life.

The pedosphere (the soil sphere) truly is a world within a world. It is also a busy world – one of many mechanisms and processes vital to the formation of soil structure and the function of plants. Many of these are highly beneficial to agroecosystems, others are inconsequential, while some are wholly detrimental.

To better make sense of those soil organisms fundamentally important to soil health and fertility, let's begin by listing each of these groups, providing examples of those that perform essential roles:

Bacteria:

- **Nitrogen fixation:** Bacteria such as *Rhizobium* and *Azotobacter* can fix nitrogen from the atmosphere and convert it into a plant-available form of nitrogen, ammonium.
- **Decomposer bacteria:** Groups of bacteria, such as those from the phyla Actinobacteria, can decompose some of the more resistant organic compounds, such as cellulose and lignin.
- **Nutrient mineralisation:** Several groups of bacteria – along with fungi – are responsible for the breakdown of organic matter and the subsequent release of plant-available nutrients, while others can oxidise or reduce certain molecules into forms that are plant-available.

Bacterial dominance can predispose soils to weedy species. In ecological terms we call them early succession coloniser or pioneer plants, which are nature's way of filling a void if there is bare soil or an underlying imbalance.

Fungi:

- **Mycorrhizal fungi:** One of the most important soil organisms is the genus *Glomus*. Fungi from this genus can form mutualistic associations with plant roots. Through this association, the fungus can access nutrients such as phosphorus, nitrogen, and zinc, transporting them to plant roots in exchange for plant-assimilated carbon (sugars).

  They can also produce a 'soil super glue' called glomalin which can store greater than three times more soil carbon than humic acid (USDA, 2002).

- **Decomposer fungi:** Perhaps even more important to primary decomposition than bacteria are fungi which play a pivotal role in decomposing plant matter and contributing to soil nutrient cycling.

Perennial plants including grapevines benefit from a fungal-dominated environment as well as abundant populations of all soil biology.

Protozoa:

- **Predatory protozoa:** Consume bacteria, help regulate bacterial populations, and contribute to an ecological balance. Consumption of bacteria also leads to bacterial nutrient cycling.

Nematodes:

- **Plant-parasitic nematodes:** Due to their parasitic nature certain nematodes, such as *Meloidogyne* spp., root-knot nematode; *Xiphinema* spp., dagger nematode; *Tylenchulus semipenetrans*, citrus nematode; *Pratylenchus* spp., root-lesion nematode, and *Criconemella xenoplax*, ring nematode, can have a detrimental effect on grapevine root growth and vigour when they build up to damaging levels. This is an indicator that the system is out of ecological balance.
- **Predatory nematodes:** Most nematode species take the role of biocontrol agents, consuming pest species in healthy ecological systems.
- **Bacterivorous nematodes:** Like protozoa, the consumption of bacteria by nematodes also leads to bacterial nutrient cycling (Wang and McSorley, 2005).

Arthropods:

- **Predatory arthropods:** Many arthropods (insects, spiders, and mites) act as biocontrol agents against soil-borne pests and predators including ground beetles, assassin bugs, wolf spiders, centipedes, earwigs, scorpions, predatory mites contribute to biocontrol of pest insects close to ground level.
- **Decomposer arthropods:** Better known as detritivores, some species of arthropods are considered primary decomposers, breaking down larger organic matter, such as leaves, into smaller sections (e.g., slaters, springtails, cockroaches, termites, millipedes, beetles).

Bacterial-feeding nematodes have a higher carbon-to-nitrogen (C:N) ratio requirement than bacteria, so in consuming bacteria they take in more N than necessary for their body structure. The excess nitrogen is excreted as ammonia.

For example, if nematodes have a C:N ratio of 12:1 and bacteria have a C:N ratio of 4:1, then a nematode will need to consume three units of carbon to maintain its requirements (12/4 = 3) but only needs one unit of nitrogen, therefore, the other two units are excreted in a plant-available form and this is a simple example of how nutrient cycling works.

Earthworms:

- **Soil engineers:** Improve soil structure, improve water movement, improve porosity and aeration, promote organic matter breakdown, the release of natural bio-stimulants and create vertical channels for root movement. To find out more about the important work of earthworms visit '**soil health indicators for Australian vineyards**'.

Viruses:

Viruses can be deleterious to grapevine health and function but are also part of functioning ecosystem.

The figure below provides a snapshot of some the most important biological agents (and their functions) in maintaining soil physicochemical health and fertility in vineyards, and indeed all agroecosystems.

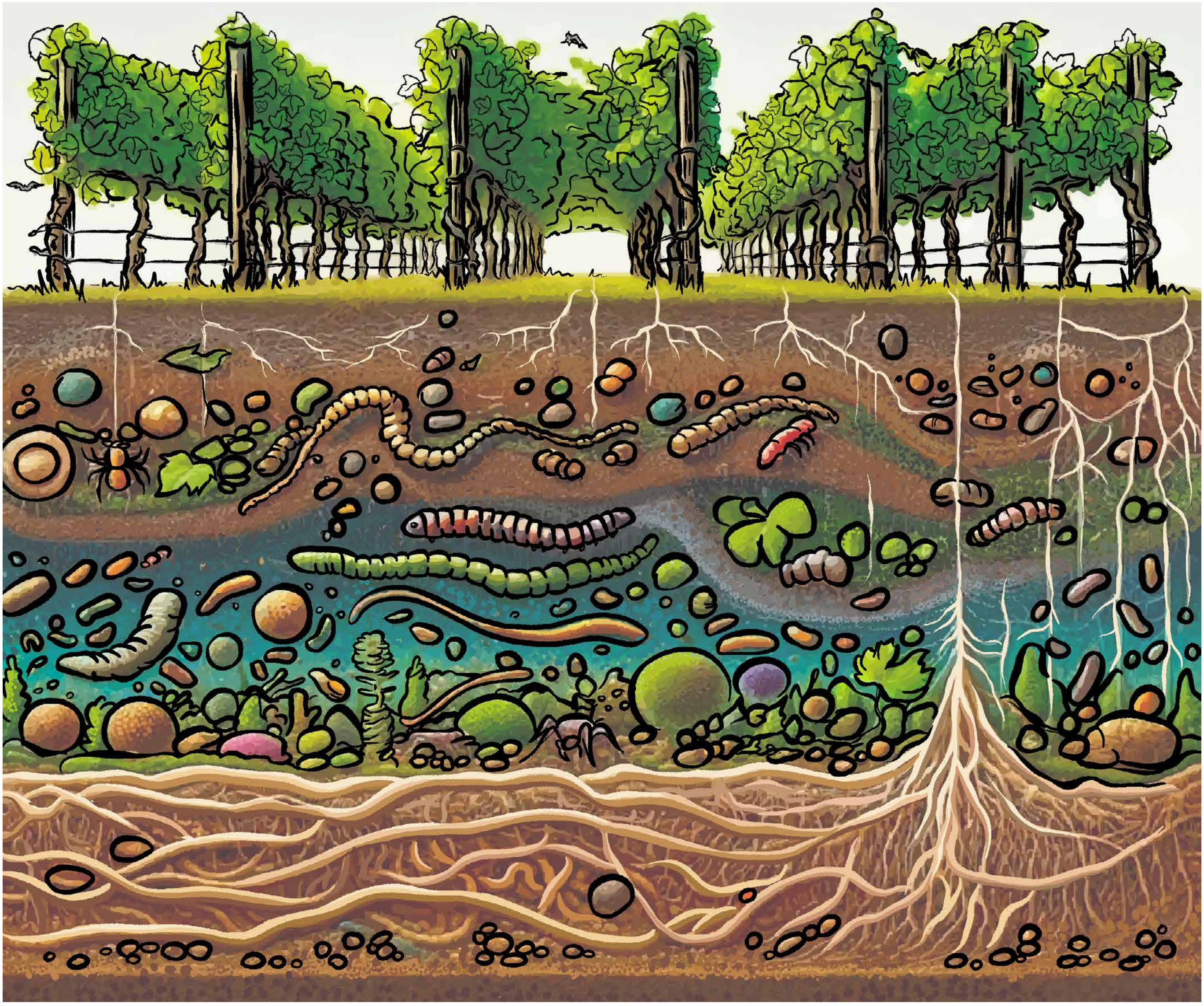


Figure 3. Artistic rendering of a vineyard soil profile showing 'healthy soil', complete with fungi, bacteria, arthropods, and earthworms.

Perhaps most importantly – and from a practical perspective – the question hereafter is: How can we manage the vineyard floor to ensure soil biological agents are both present and performing effectively?

Understanding the roles of these biological agents is necessary; however, their presence and activity is never in isolation – they are all functioning together within the agroecosystem. In a practical sense, we are now discussing these organisms ecologically, in interactional terms.

The following sections will discuss the mechanistic role of these biological agents in more detail, while also highlighting vineyard floor management practices that can help to encourage their existence, function, and stewardship. Some of these management practices are active, while others are passive, and many will overlap as practices whose outcomes affect more than one biological agent. Indeed, many biological agents will also perform more than one role in maintaining soil health and fertility.

Bacteria: Nitrogen-fixation, nutrient mineralisation, and decomposition

The Haber-Bosch process was one of the great turning points in agricultural industrialisation. Founded in the early 19th century, it allowed humans to synthesise plant-available ammonium $[NH_4]^+$ from atmospheric nitrogen (N_2). Although it was a revolution in synthetic fertiliser production, it came at a cost. The source material must be heated to 500 °C and squeezed to 350 atmospheres of pressure – in short, it requires a high energy input. Bacteria do it with ease, every day, all the time, no problem!

Of course, that's not all they do. Bacteria also play a critical role in both the decomposition, mineralisation and cycling of plant-available nutrients. Specific bacteria can produce enzymes that can decompose particulate organic matter. As members of a food web, they often perform the latter-stage decomposition after larger decomposers (worms, vertebrates, fungi, etc.) have eaten, cut, and shredded larger debris, exposing greater surface area. Certain bacteria contribute critical mineralisation tasks, making available to plants inorganic forms of sulfur, iron, and other nutrients.

Moreover, plants use a significant amount of their photosynthetic energy to convert synthetically applied nitrate to plant-available amino acids and proteins. It is reported that a plant requires three times more water to convert nitrate to amino acids compared to ammonium (Kempf, 2020).

Soil strategies to promote bacterial nitrogen-fixation

Plant leguminous cover crops:

Planting leguminous cover crops (mid-row and under-vine) can increase soil nitrogen to the benefit of the grapevine. Legumes form mutualistic associations with nitrifying bacteria, promoting a net release of plant-available nitrogen in the soil profile. Here is a list of some options for leguminous cover crops:

- ***Medicago* spp., medic** is a genus of legumes that are popular with growers in warm, dry climates owing to their ability to thrive in less irrigated vineyards, provided winter rainfall is adequate. Medics tend to be self-seeding annuals or short-lived perennials. Summer dieback aids in reducing competition for water with grapevines. Species used as cover crops include *Medicago trunculata*, barrel medic and *M. polymorpha*, burr medic.
- ***Trifolium* spp., clover** is a genus of legumes not dissimilar in nature to medics, with both genera contributing a significant seed yield, encouraging self-perpetuation in the vineyard. Ensuring sound establishment may require some soil amendment prior to seeding, therefore, it is prudent to conduct some soil testing to identify any nutrient deficiencies. Clovers often work well in combination with other cover crop species.
- ***Vicia* spp., vetch** are annual legumes and can generally tolerate a wide range of climates. Vetch are highly effective at increasing soil nitrogen and thus should be monitored to ensure excess nitrogen does not produce overly vigorous grapevines. Species of vetch include *Vicia villosa*, hairy vetch and *V. sativa*, common vetch.

However, white clover can also harbor insect pests such as *Epiphyas postvittana*, light brown apple moth (LBAM), when planted as a monoculture (Begum et al., 2006).

Figure 4. Rhizobium root nodules [Photo: Frank Vincentz, CC BY-SA 3.0].

The leguminous clover forms mutualistic associations with the rhizobium bacteria from which excess soil nitrogen is released, thus allowing the fescue grass to grow without depleting soil nitrogen.

There are many more cover crop options for nitrogen-fixation, with options that can suit a variety of soil types, management practices, outcomes, and climates.

For specific information on selecting the correct cover crop and bacterial strain for inoculation, please refer to CSIRO: cover crop candidates fact sheet **and the** EcoVineyards soil health indicators for Australian Vineyards booklet **to find out more about assessing legume nodulation.**

The process of rhizobium-root inoculation

Chemical signals emitted by plant root attract bacteria	→	Root hair curls around bacteria → bacterial thread infects root	→	Root cell forms white nodule → bacteria enter root cell	→	Bacteria changes shape and begins to fix nitrogen

Inoculating cover crop seeds:

Prior to sowing legume cover crop seeds, it is often best practice to use a commercial rhizobium inoculant to ensure that germinating seeds are both infected adequately with the most suitable strain of the bacteria to suit the cover crop species or cultivar.

Although many Australian soils are adequately populated with diverse strains of rhizobia, it is difficult to know exactly how well-established these populations are. Moreover, Australian soils in higher rainfall areas are often prone to acidity, with pH < 5.5 producing soil environments less than suitable for naturally occurring rhizobia.

To ensure cover crop seeds form infections and nodules it is prudent to inoculate prior to sowing.

Inoculants come in varied forms:

- **Powdered inoculants:** As the name suggests, these inoculants come in a powder form and, as such, have a long shelf life but can be dusty when applied. Generally, they are effective but often require the combined use of an adhering agent for application to seeds. These are widely used and commercially available.
- **Liquid inoculants:** These inoculants consist of rhizobia strains suspended in a liquid solution. These are generally regarded as being highly effective and adhere to seeds well. Liquid inoculants require storage in cool, dry places away from sunlight and typically have a shorter shelf life than dry inoculants. Seeds are coated with the liquid inoculant prior to sowing. As with powdered inoculants, these are widely available.
- **Granular inoculants:** These are like powered inoculants yet may require some specialised equipment to dispense. Instead of being applied to the seed, granular inoculants are applied to the soil furrow or as a broadcast application at the time of seed sowing.
- **Coated seeds:** Rhizobium bacteria are applied to the seed coating by the manufacturer. These are easier to use yet can be more expensive. Perhaps not quite as available as powdered or liquid inoculants; however, for common crop types they are becoming more commercially available.

If a grower has a perennial legume cover crop and isn't sure if it has been adequately inoculated with the correct strain of rhizobia prior to planting, rather than trying to inoculate the seed by spraying freeze dried rhizobia prior to a rainfall event (which can be very hit and miss), carry out an inoculation assessment and check the nutritional status of the soil i.e., phosphorus, potassium, zinc, iron, molybdenum are needed by legumes to ensure optimal conditions for nitrogen fixation

Fungi: plant nutrient acquisition and decomposition

Fungi are considered of paramount importance to the health and fertility of agroecosystems. As ecosystem service providers, they play numerous roles in the vineyard, both physical and chemical. Maintaining abundant fungal diversity in a vineyard requires soil cover and minimal disturbance and will be discussed at length further on.

Figure 5. Micrograph of a plant root colonised by arbuscular mycorrhizal fungi (AMF). The yellow rings highlight AMF hyphae growing through the root cell walls, while the red circle shows AMF mature vesicles [Photo: Matthias Salomon].

The following list emphasises the importance of soil fungi for maintaining a productive vineyard.

Symbiotic relationships with plants (nutrient acquisition):

- Mycorrhizal fungi (AM), or arbuscular mycorrhizal fungi (AMF), are one of the most important organisms on earth. It is thought that approximately 80% of terrestrial plants form associations with AM or AMF to assist in the acquisition immobile nutrients (phosphorus, nitrogen, and zinc specifically).

  Like rhizobium, AMF form mutualistic associations with plant roots, often growing small arbuscules (nutrient exchange sites) within the plant cell wall. The association is beneficial to both fungi and plant, as the fungi receive organic carbon from the plant, while the plant is delivered inorganic P and Zn from the fungi.

Grapevines are mycorrhizal, that is, they form mutualistic associations with AMF.

Decomposition and nutrient cycling:

- Fungi play a key role in decomposition and nutrient cycling, even more so than bacteria, though it is important that both are functioning in tandem and maintaining a functional ratio of abundances.
  - **Complex decomposition:** Fungi can break down more complex molecules than bacteria. Utilising specialised enzymes and enlarged surfaces areas, fungi can metabolise and break down molecules such as lignin and cellulose.
  - **Mineralisation and nutrient cycling:** Through the breakdown of complex organic molecules, fungi release net amounts of inorganic compounds that are available to plants and soil organisms.

Soil structure and water dynamics:

- Fungi also plays a critical role in improving and maintaining soil physical structure. They also contribute greatly to improving soil aeration, water-holding capacity, and soil organic carbon sequestration.
  - **Glomalin glue:** Perhaps one of the more underappreciated roles of fungi is in their production of an important glycoprotein called glomalin. Glomalin is excreted by arbuscular mycorrhizal fungi (AMF). The name 'glomalin' refers to the genus *Glomus*, of which AMF are a member.
  - Glomalin production assists AMF hyphal networks, creating a barrier and allowing AMF hyphae to grow and network. Glomalin is a glue-like substance that can adhere to soil micro-aggregates, gluing them together to form stable micro and macro-aggregates. Soil aggregation contributes not only to soil structure but also to the protection of organic matter from microbial degradation.

Glomalin accounts for 27% of the carbon in soil and is a major component of soil organic matter compared to humic acid which contributes only about 8%, that is a difference of 3.4 times (Wright and Nicolson, 2002).

  - **Hyphal channels:** Fungal hyphae help to stabilise soil through vast, interconnected hyphal networks. These networks not only help to bind and stabilise soil aggregates but also create vast channels throughout the soil. Hyphal channels improve soil porosity, aeration, and the ability for water to infiltrate through the soil profile to the root zone. They are often referred to as the 'wood wide web' (www), a term used to describe the underground network of fungi that connect the roots of trees, vines, and other plants.
  - **Water-holding capacity (WHC):** This is an important physical property of soils and will be discussed again. It is important to note that fungi play a key role in improving WHC both through their creation of stable aggregates and pore spaces but also through the accumulation of stable organic matter.

Soil carbon is also an important aspect of future proofing vineyards.

For every 1% increase in soil humus (a stable form of soil carbon) it is possible to store an additional 160,000 L/ha of water every time it rains (Morris, 2004).

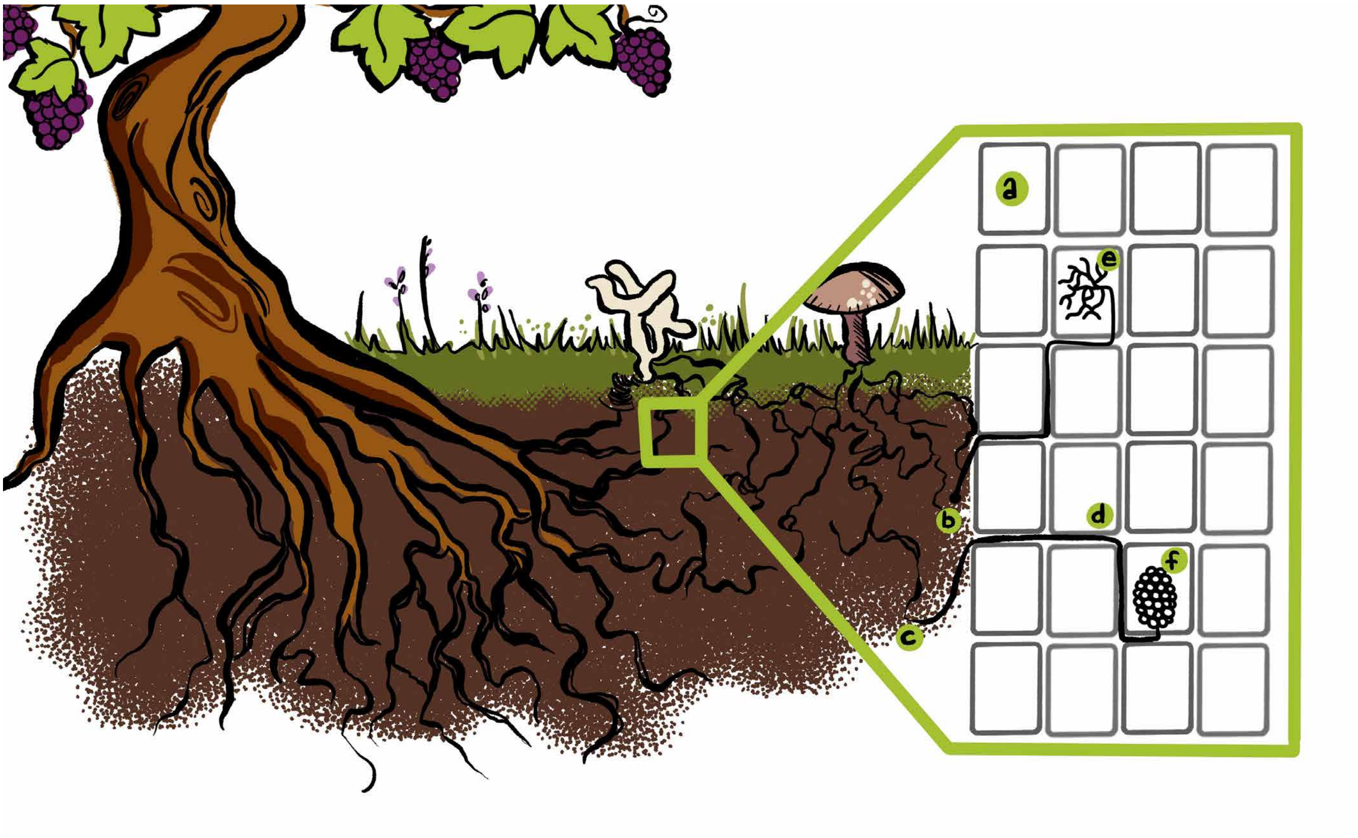


Figure 6. Diagram representing arbuscular mycorrhizal fungi (AMF) hyphae forming mutualistic associations with tree roots.

The symbols in Figure 6 represent the following:

a. individual plant root cell

b. active AMF spore with growing hyphal strand

c. active hyphae – both spores and hyphae can be active sources of colonisation

d. hyphal thread moving between root cell wall and cytoplasm

e. mature arbuscule – outside the cellular membrane but inside the cell wall – this is the active site for carbon and nutrient exchange between plant and fungus

f. mature vesicle – this is a storage organ used by the fungus to store lipids and nutrients used by fungus and plant.

Strategies to promote beneficial soil fungi

Plant mycotrophic cover crops:

- Most ground cover plants (except brassicas) will form mycorrhizal associations with AMF but to ensure that plant roots have reached maximum colonisation it may be prudent to include mycotrophic species as a part of a multispecies mix.

  Mycotrophic species (or cultivars) are plants that are obligate hosts to AMF – that is, they require high levels of colonisation to acquire nutrients. The proportion of the plant root that becomes colonised by AMF varies between species – most will form AMF associations; however, some will become more colonised that others.

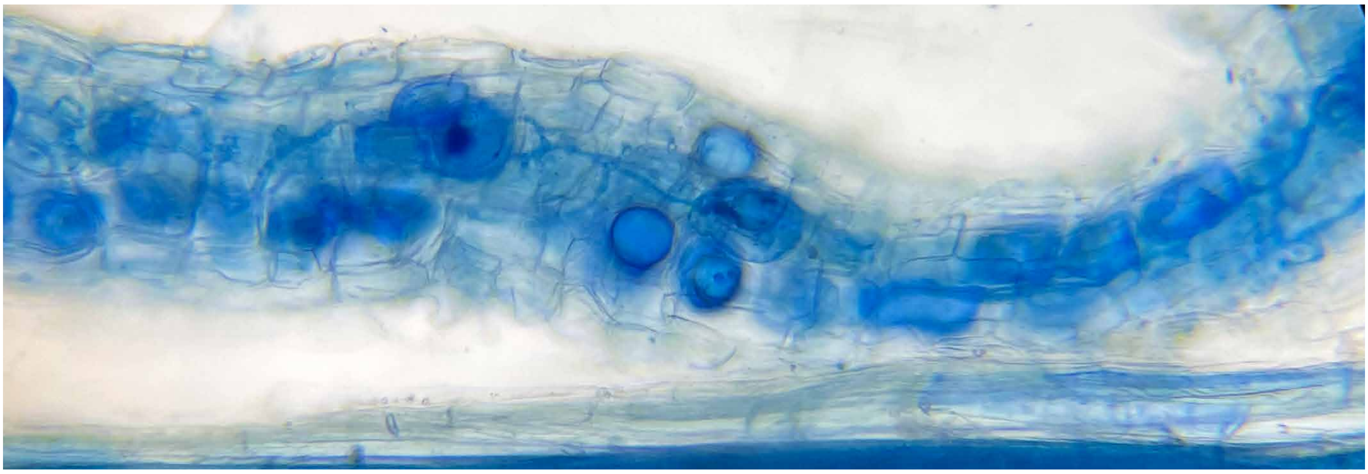


Figure 7. Mature arbuscules (stained in blue) represent the active sites for carbon and nutrient exchange between plant and fungus [Photo: Mary Retallack].

Table 3. Examples of mycotrophic and non-mycotrophic cover crops

Mycotrophic cover crops		**Non-mycotrophic cover crops**	
Legumes	*Medicago* spp., medic	**Brassicas**	*Raphanus sativus*, radish
	Trifolium spp., clover		*Brassica napus*, canola
	Vicia spp., vetch		*Brassica oleracea*, kale
	Pisum spp., pea		*Brassica* spp., mustard
Grasses	*Lolium* spp., ryegrass		
	Festuca spp., fescue		

Although many of the non-mycotrophic cover crops may be poor at promoting AMF in the vineyard, many are useful for other roles, such as biofumigants. Additionally, to promote fungal abundance and diversity, it is often prudent to plant different cover crops in combination to promote microbial diversity.

Aside from planting mycotrophic cover crops to increase AMF colonisation, it is also beneficial to maintain cover (living or dead) to promote fungal abundance. Maintaining cover improves infiltration and water retention and prevents soil surfaces from drying and cracking. Moreover, ground covers improve organic matter deposition in the soil. All these factors are holistically beneficial to promoting soil fungal abundance and diversity. AMF need to colonize a living plant rootr to survive.

Aim for 100% functional ground cover (and living roots), 100% of the time where possible

Reduce soil disturbance:

One of the most important management strategies to promote and maintain fungal (and bacterial) abundance and diversity in the vineyard is practising minimal disturbance.

- **Physical damage:** Tillage and cultivation break soil aggregates, expose fungi to light and oxygen and break up hyphal networks. Breaking hyphal networks damages the ability of fungi to reproduce, transport nutrients, and form symbiotic relationships with plants.
- **Fungicide use:** Fungicides applied to vine leaves, as well as subsequent spray drift, can damage fungal populations in soil. Though foliar applications of fungicides are a vital tool in a viticulturist's arsenal, it pays to be conscious of the collateral damage that spraying them can cause to soil fungal populations. Alternatively, healthy soil and optimal plant nutrition can help to improve leaf brix and reduce the susceptibility of grapevines to airborne pathogens and insect attack (Datnoff et al., 2007).
- **Rapid loss:** Soil disturbance breaks soil aggregates and affects soil porosity that fungi have often taken years to create. This also exposes organic matter to increased oxidation and decomposition, leading to rapid loss of water-holding capacity and nutrients that would otherwise be equilibrated with soil organisms and plant uptake.
- **Microbial communities:** Become altered and affected by disturbance regimes, leading to changes in community composition and loss of diversity. Microbial diversity is important as different functional microbes perform specific tasks. Moreover, changes in microbial communities may favour resilient microbes, leading to an imbalance in the system.

A soil that is dominated by bacteria is usually tilled or disrupted and has higher soil pH and nitrogen available as nitrate, which is the perfect environment for weedy species (Ingham, 2000).

Practicing zero soil disturbance is often simply not practical or possible. Replacing old grapevines with young ones or changing grapevine varietals are all part of managing vineyards. Sowing or replacing cover crops is also a realistic practice that will lead to some form of soil disturbance – it's unavoidable.

In this sense, the best management practice should aim to minimise the frequency of disturbance, direct drilling, or the planting of every second row. This requires long-term thinking and adherence to long-term strategies with regard to vineyard management. Understanding and linking commercial aims, soil properties, climatic conditions, and logistical constraints can inform viticulturists to make the best decisions early so that the requirement for soil disturbance is reduced to a decadal scale.

Reduce/monitor soil phosphorus requirements/additions:

Phosphorus is the main limiting nutrient that plants derive from mycorrhizal fungi. In the case where vineyards have been over-fertilised with phosphorus – either as a single addition or as part of an N, P, K addition – this can result in reduced fungal colonisation (Abbott et al., 1984; Smith et al., 2011; Van Geel et al., 2017). This occurs because the plant has sufficient P from the fertiliser addition and so has less need to allocate energy and resources to fungal colonisation – why exchange carbon for phosphorus when you don't need to?

NEMATODES: FRIEND OR FOE?

Approximately 95% of nematodes are from functional groups that assist with nutrient cycling and/or biocontrol.

- **Biological control:** Nematodes may exist in the vineyard as either beneficial predators (i.e., predatory nematodes) or detrimental pests (i.e., root parasitic nematodes). The former relates to nematodes that function within a soil ecosystem and in equilibrium with other biological agents. These actively prey on other nematodes (including pest species) and also bacteria and protozoa. In doing so, beneficial nematodes function as biological control agents, maintaining a top-down equilibrium.
- **Root-knot nematodes (RKN):** Plant parasitic nematodes are the bane of many vineyard managers. Parasitic RKN (i.e., *Meloidogyne* spp.) live in soil where they can enter grapevine roots and feed on plant-acquired nutrients, resulting in characteristic galls.

  Their impact on grapevine health can be extremely detrimental. Losses from nematodes are estimated to be 5 to 15% in Australia and badly infected vines will show poor vigour, have stunted growth, reduced fruit quality, and yield poorly (Penfold and Collins, 2012). Other damaging species, including citrus, root lesion, and ring nematodes do not result in prominent galling on feeder roots.

In addition to causing crop losses directly, plant parasitic nematodes can act indirectly as virus vectors and may combine with other nematode species or fungal pathogens to exacerbate root malfunction.

The compounded effect of root-knot nematodes, which block grapevine water and nutrient uptake from soil, may cause a production loss of up to 60% depending on the host susceptibility status of a cultivar (Rahman et al., 2012).

Strategies to suppress root-knot nematodes (RKN)

- **Resistant rootstock:** One option for guarding against RKN is to graft to a nematode-resistant rootstock in much the same way as one would graft to a phylloxera-resistant rootstock. However, this is no guarantee of long-term control as some rootstocks (1103 Paulsen) which were initially recommended as being resistant to root-knot nematodes were subsequently found to have higher susceptibility to certain species, including *Meloidogyne javanica* and *M. arenaria* (Walker, 2008).
- **Cover crop rotations:** Another method that may assist in suppressing RKN is to use different cover crops throughout the vineyard. Certain crops are less suitable hosts for RKN, and their use may help to suppress populations. Additionally, certain cover crops of the brassica family are known to emit natural biofumigants that can be detrimental to RKN.
- **Brassicas (e.g. mustard, radish, canola):** Produce bioactive compounds that act upon nematodes in a process called bio-fumigation. It is reported that the Nemfix cultivar of *Brassica juncea*, Indian mustard, when grown in the mid-row and then side-thrown under-vine provides a 13-fold reduction in root-knot nematode populations in the vine row, 36 weeks after treatment (Rahman and Somers, 2005).
- **Balanced ecosystem:** Maintaining a balanced and healthy soil ecosystem can promote the presence of beneficial fungi and certain predatory nematodes that are capable of acting as biocontrol agents against RKN (Khan and Kim, 2005).
- **Nematicides:** Are biodegradable and, thus, a resurgence of nematodes occurs after a certain period. Nematicides also kill other non-target beneficial nematodes, potentially unbalancing soil biological systems (Rahman et al., 2012). There have been no chemical nematicides registered for use in vineyards since 2015.

Figure 8. Photographs of NSW vineyard employing brassica species cover crops as a biofumigant against RKN (left) [Photo: The University of Adelaide and Wine Australia] and a microscopic image of a root knot nematode (right) [Photo: Penfold and Collins, 2012].

Arthropods and earthworms in the vineyard

"It may be doubted whether there are any other animals which have played so important a part in the history of the world as have these lowly, organised creatures."

Charles Darwin on the importance of earthworms to soil, plants, and crop production.

It really cannot be understated just how important arthropods and earthworms are to soil health, structure, fertility, and so much more. They are the great biological engineers of the pedosphere.

- **Decomposition and nutrient cycling:** Decomposition and nutrient cycling are processes that require a succession and combination of organisms. Arthropods and other soil macro-fauna are essential primary decomposers. Their consumption of larger debris breaks down organic matter into smaller constituent parts, increasing surface area and allowing smaller organisms (fungi and bacteria) to further reduce and mineralise nutrients into their inorganic, plant-available forms.
- **Soil structure:** Earthworms and certain arthropods are highly beneficial to soil structure, aeration, porosity and, subsequently, water infiltration. Burrowing through the soil profile helps to create pores and channels which improve aeration and allow roots to move freely. Channels and pores also improve water infiltration from the surface to the root zone. Small arthropods and earthworms are important in their creation of soil aggregates, improving structure.
- **Biocontrol agents:** Certain arthropod species, such as spiders and predatory beetles, prey on pest species that would otherwise be detrimental to grapevine leaves and fruit. Further to this, parasitic wasps play an important role in vineyards by laying their eggs directly inside pest species where there is a species-specific, host-parasite relationship. This action both kills pest species but also helps to proliferate the beneficial wasp species.

Figure 9. *Tasmanicosa godeffroyi*, garden wolf spider consuming a lynx spider (left), and *Nabis kinbergii*, Pacific damsel bug (right) [Photos: Mary Retallack].

Strategies to promote beneficial arthropods and earthworms

- **Mulch, compost, cover crops:** Increasing surface cover and the incorporation of organic matter is highly beneficial to creating an environment where arthropods and earthworms can exist and proliferate. The presence of mulch and compost increases organic matter but also provides cover from the drying effects of direct sunlight. Moreover, they improve water retention in the soil and prevent surface evaporation.

  Planting a variety of ground covers, including native cover crop species, promotes a diversity of arthropods throughout the season. Retallack (2019) found 38 different morphospecies (visually distinct species) of predatory arthropods in wallaby grasses.

  Flowering cover crops further increase arthropod diversity by attracting a range of predatory arthropods and pollinators. Placing an emphasis on planting insectary plants, especially locally adapted insectary plants, is highly beneficial to improving beneficial arthropod diversity and abundance. Moreover, these may be planted sporadically throughout the vineyard in combination with multi-species cover crop plantings.

- **Reduce soil disturbance:** Like maintaining fungal health and diversity, reducing soil disturbance is also beneficial to maintaining macro-fauna abundance and diversity in the vineyard.

- **Reduce pesticide use:** In promoting beneficial arthropods as biocontrol agents, it is important to reduce the application of synthetic pesticides (including copper and sulfur) that are detrimental to non-pest species as well as, or use alternative chemistry. Adopting an integrated pest management (IPM) strategy is one option for reducing the need for pesticides.

  Please refer to the pesticide toxicity table in the **EcoVineyards fact sheet: The impact of agrochemicals on natural enemies** for more information.

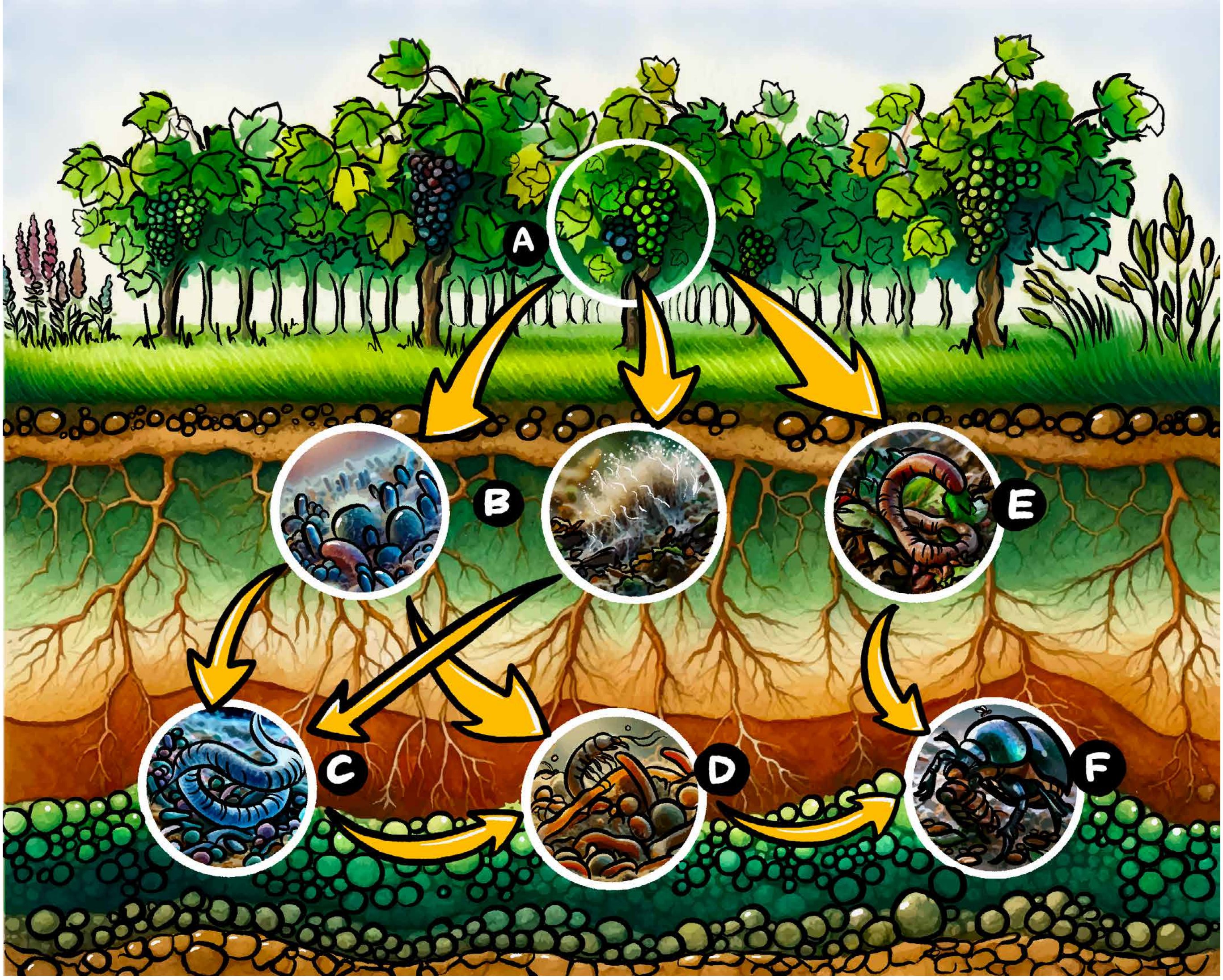


Figure 10. Example of a soil food web.

Food webs are conceptual representations of recycling within an ecosystem and the figure above highlights some of these trophic levels and relationships.

- **First trophic level (photosynthesisers/plants):** Grapevines and ground cover plants produce organic matter (foliage and/or fruit) and root exudates (sugars, amino, and organic acids) via the process of photosynthesis (A).
- **Second trophic level (decomposing mutualists, pathogens, parasites, root feeders):** Bacteria and fungi engage in decomposition of organic matter (B).
- **Third trophic level (shredders, predators, and grazers):** Nematodes and protozoa consume bacteria and fungi (C and D) and release nutrients back into the system.

  Detritivores (earthworms, slaters etc.) and larger beetles also engage in decomposition (E and F) and help to maintain equilibrium in the system.

At each descending level, organisms become larger but also fewer in number – a sign of an equilibrated ecosystem. Additionally, at each level of consumption, metabolic processes release carbon dioxide and deposit soil organic carbon, some of which will remain in the soil for weeks or months, while other carbon molecules may become bound within the soil matrix for year or decades.

SOIL STRUCTURE, SOIL WATER AND SOIL ORGANIC CARBON

Where the previous section focused on soil biological agents and their various roles in decomposition, mineralisation and nutrient cycling, this section will focus on vineyard floor management to improve soil structure, water efficiency, and organic carbon.

We've touched on the role of soil biological agents – namely, bacteria, fungi, protozoa, nematodes, arthropods, and earthworms – and their ability to contribute to improved soil aggregation, structure, water dynamics, and organic matter deposition. Maintaining the physical structure of soil is crucial to nutrient exchange, water dynamics, carbon sequestration and, of course, plant growth. In this sense, we can view the various elements of vineyard soil management as holistic or inextricably linked, each affecting the next.

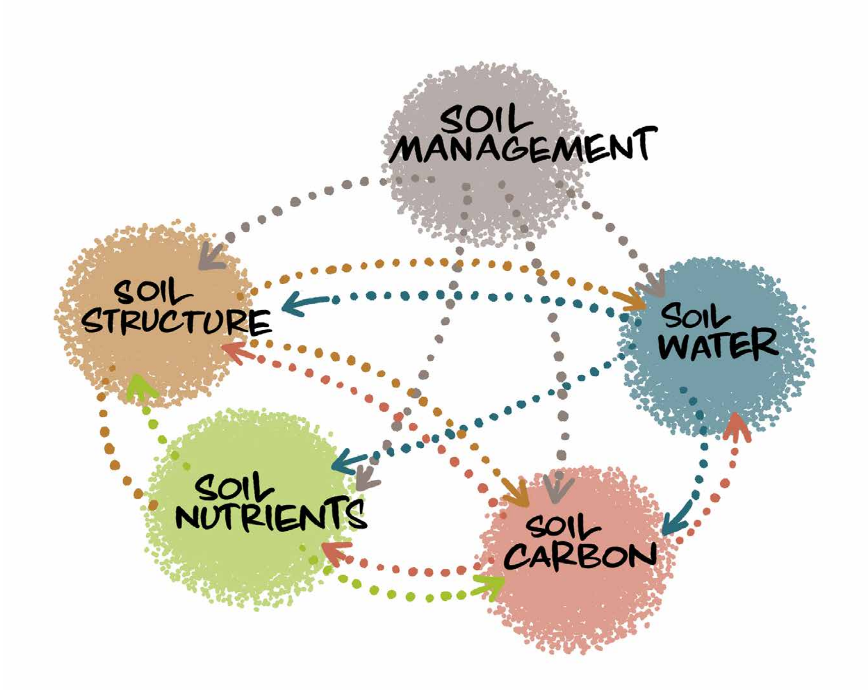


Figure 11. Diagram demonstrating the interrelated nature of each of the main soil properties covered in this section.

This schematic highlights the importance of viewing vineyards as ecosystems. Each property functions both in and of itself, but also in relation to every other property. The altering of one will influence the functionality of the others. The term 'soil health', although somewhat nebulous, is perhaps most apt when discussing the ecological interaction of these properties within the vineyard system.

Cover cropping in vineyards: Improving soil physical structure and water dynamics

The use of ground covers, including cover crops, has been mentioned several times throughout this BPMG and for good reason. Research from Australia, France, Spain, Italy, the United States, and further has all concluded that the use of ground cover plants in vineyards has the capacity to improve soil structure, aeration, porosity, and certain water dynamics, namely, water-holding capacity and infiltration.

Note: Cover crops imply a crop that has been selected and sown for a particular purpose. Often vineyard managers will allow volunteer swards to grow in lieu of a selected cover crop. In this BPMG, we will discuss ground covers (including cover crops); however, volunteer swards can have very similar effects.

- **Soil structure:** Ground cover plants improve soil structure in several ways.
  - Root penetration breaks up compacted subsurface soil layers, reducing compaction and improving structure and reducing strength.
  - Root exudates and the microbes found in association also help to bind smaller soil aggregates, creating larger stable aggregates that contribute to improved structure.

- **Soil aeration:** Root channels created by ground cover plants improve the passage of air throughout the soil, especially into the deeper layers.
- **Soil porosity:** Ground cover plants increase soil organic matter and help create stable aggregates, both of which contribute positively to soil porosity.
- **Water-holding capacity:** This refers to the amount of water a soil can hold and is a function of many things, most importantly soil texture (the ratio of sand, silt, and clay).

  Organic matter also improves water-holding capacity, as does soil aggregate structure and porosity. Ground cover plants help to improve water-holding capacity by positively affecting these soil properties.
- **Water infiltration:** Plant root pores greatly improve infiltration rates by creating vertical root channels, allowing water and air to move to the root zone quickly and at depth.

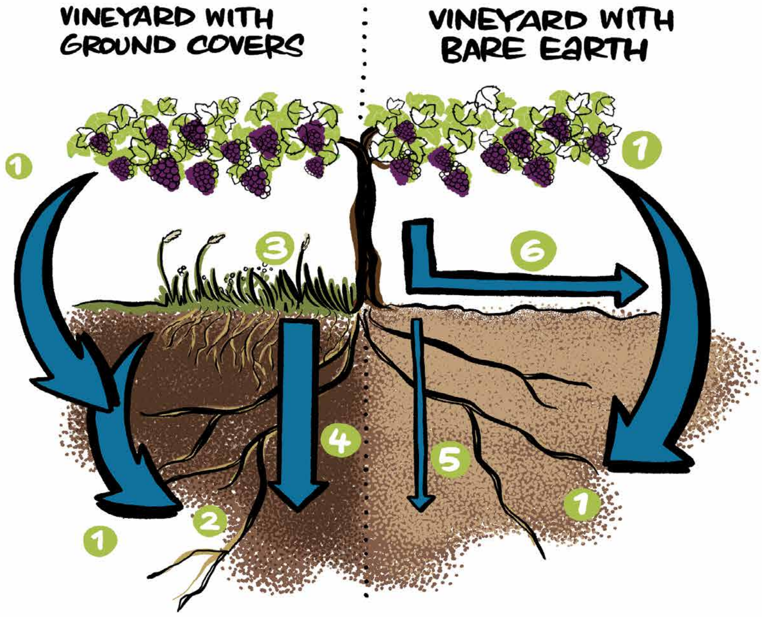
Strategies to improve soil physical structure and water efficiency

Ground covers:

Research from Italy and Spain has shown that planting cover crops on sloping vineyards can significantly reduce erosion and topsoil loss. Field trial experiments have shown that ground cover plants have several distinct functions in preventing erosion.

- Above-ground cover (shoots) protect soil from the dispersive energy of raindrops, preventing direct contact with the soil surface and diminishing raindrop energy.
- Increased vertical porosity from cover crop roots allows surface water to infiltrate the soil quickly, rather than pooling on the surface, potentially leading to runoff and erosion. Research has shown that water infiltrates significantly faster in cover crop-managed soil versus bare earth. This is both a function of vertical root pores assisting water movement and a lack of impenetrable surface crust which is often associated with bare earth.
- Increased organic matter from cover crop associations helps to stabilise subsoil, increasing aggregate stability, improving soil structure and water-holding capacity at depth (Ruiz-Colmenero et al., 2013).

In summary, ground covers act in a multifunctional way to improve soil structure, infiltration, soil dispersion, and erosion-prevention. Additions of organic matter are increased under cover crop use, increasing water-holding capacity and soil aggregate stability. Vertical root pores assist with water infiltration to the root zone, while above-ground biomass reduces the dispersive impact of raindrops. Reduced ground cover limits infiltration rate, allowing surface pooling and the potential for runoff and erosion, leading to topsoil loss which impacts on soil structure and organic matter retention.



1. Organic matter accumulation via grapevine-derived biomass
2. Organic matter accumulation via cover crop derived biomass
3. Increased photosynthetic cover AND erosion prevention by raindrop dispersal and soil stabilisation by ground cover root systems
4. Improved vertical porosity by ground cover roots, leading to improved infiltration rates
5. Reduced vertical porosity leading to reduced infiltration
6. Lack of cover allows soil dispersion by raindrop impact and reduced infiltration promotes pooling and run-off, leading to increased erosivity

Figure 12. Diagram showing the differences between vineyard floors managed with ground covers versus those without.

Mulch and compost:

- **Compost:** Comes in many different forms depending on the organic material from which it derived. Additions of compost can help to increase organic matter over time, as well as enhance microbial activity.
- **Mulch:** Can differ between parent material but is usually derived from organic matter that is hardy and difficult to breakdown. Straw mulch may last for several years at a time and offers both a source of surface organic matter and a surface protection. Using both materials in combination can often have a noticeable effect on organic matter, soil structure, soil biology, and water dynamics.

  Research has shown that additions of mulch and compost can boost surface organic matter. Moreover, both materials function as surface protection, trapping moisture and reducing evaporation. Research has found that both macro-fauna and micro-fauna (microbial) abundance increases under treatments of mulch and compost.

Figure 13. Photographs showing a fresh application of a municipal compost under-vine (left), and straw mulch (right) [Photos: Thomas Lines].

- **Side-thrown mulch:** The main drawback with mulch and compost is cost and frequency of application. Cost is generally high – often far greater than a once-sown cover crop. One option to mitigate this is to sow a tall cover crop in the mid-row during autumn and throughout winter.

  During budburst or before veraison, the tall cover crop can be mown and side-thrown so that stubble and mulch remain both in the mid-row and under-vine. This allows the cover crop to regrow during autumn and recycle the process annually.

  However, some wine growers sow their ground covers (including winter cover crops) up to the butt of the vine so there is no demarcation between the mid-row and under-vine area and mow the crop 'in situ' in preference to side throwing.

SOIL ORGANIC CARBON

Carbon is the stuff of, well, living and dead stuff. Every living organism is constructed of long chains – polymers – of carbon and hydrogen (plus a few other elements thrown in). Plants are primary consumers, fixing atmospheric carbon into useable forms of carbohydrates used to power cellular function and keep pretty much everything on the planet alive.

Through the power of photosynthesis and carbon fixation, plants can kick start the great carbon cycle – a process that accounts for the movement of carbon from atmosphere to biosphere, hydrosphere, and pedosphere. The latter of these two spheres are the greatest sinks (or repositories) of atmospheric carbon. The pedosphere is, of course, the protagonist in this narrative, and it is here where this section will focus.

We've discussed organic matter throughout this BPMG, now we will discuss organic carbon or, to be more specific, soil organic carbon (or SOC).

A note on SOC vs SOM:

The terms are often used interchangeably, but what is really meant is that organic matter (SOM) comprises many elements, roughly 57% of which is carbon (SOC). Therefore, a soil containing 1.6% SOM contains approximately 1% SOC.

The amount of SOC in a soil can vary drastically and differs between ecosystems and soil textures. It should be noted that SOC has a limit in every soil system, whether that be 2.2% or 12% (or another amount altogether) and it is important to understand that limit when regarding the overall health and fertility of a soil.

Above all else, it should be noted that SOC is transient, and highly prone to rapid loss. It can take many years of diligent soil management to build SOC to its upper limit and yet very little time to destroy it. Management, with regard to SOC, is critically important.

Why build and retain SOC? Here are some practical reasons:

- **Soil structure:** Building SOC improves soil structure by creating binding sites where certain chemical elements can bind and create micro-aggregates.
- **Soil water:** Organic carbon improves aggregate stability and increases soil absorptive properties which increases soil water retention.
- **Cation exchangeability:** Increased organic carbon provides additional negative binding sites for positively charged elements (cations) to bind and exchange with plant roots.
- **Soil biology:** Organic carbon is metabolised by microbes, providing early-stage food webs for soil organisms, as well as habitat in carbon-stabilised aggregates.
- **Climate stability:** Capturing and storing more atmospheric carbon in soil is environmentally beneficial.

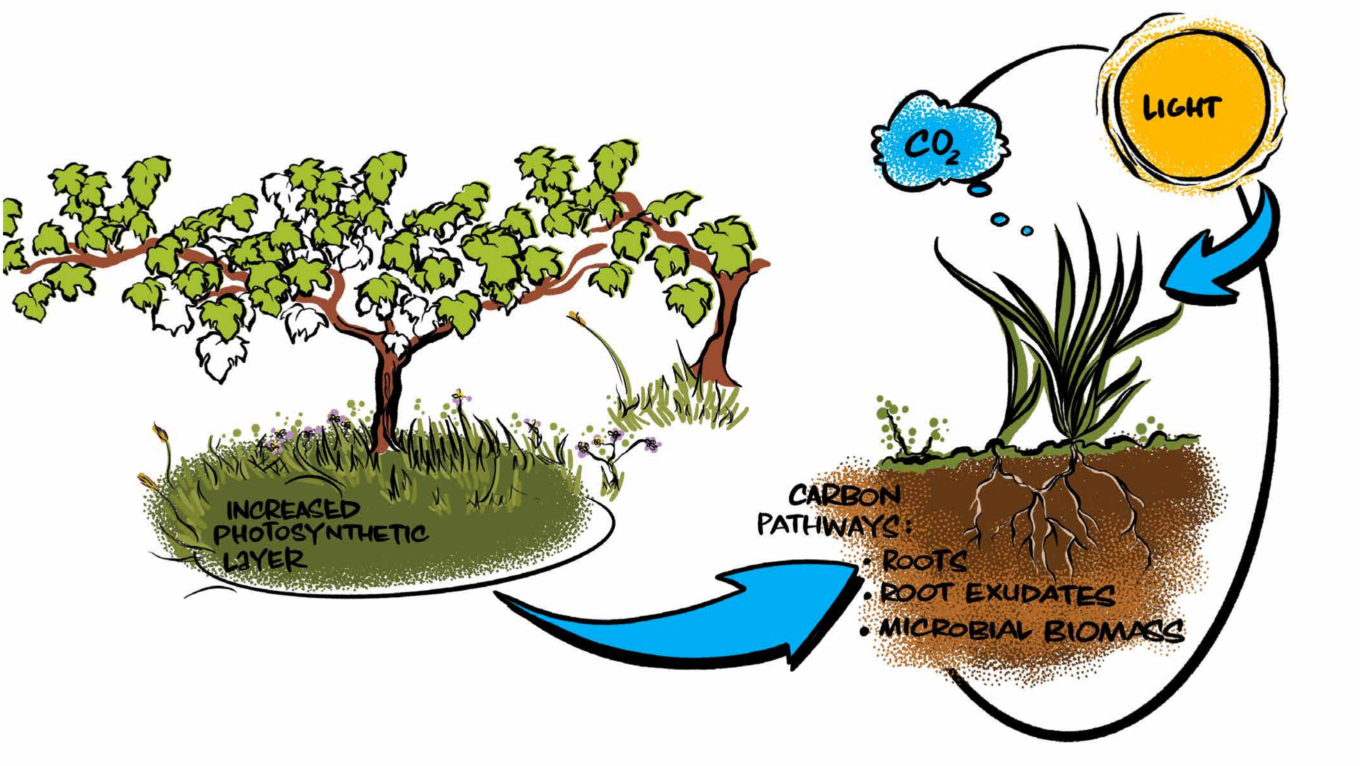


Figure 14. Some of the ways vineyard ground covers can contribute to increasing soil organic carbon concentrations in the soil.

Strategies to build and retain SOC in vineyards

- **Ground covers:** Whether the aim is to build SOC in a vineyard or to retain it, planting ground covers can be useful tools to achieve the desired outcome.
- **Building SOC with ground covers:** Ground covers including cover crops are plants that are sown and grow adjacent (or beneath) a grapevine and are not generally intended for consumption.

  In simplest terms, plants grow by fixing atmospheric carbon into useable carbohydrates via above-ground photosynthetic pathways. Assimilated carbon is then translocated to all regions of the plant to grow biomass (shoots, roots, leaves, flowers, fruit, etc.). Some of this carbon enters the soil via several pathways including senesced roots, microbial biomass, root exudates and above-ground detritus.

Translocation of 'liquid carbon' or root exudates (plant sugars) from leaves (source) to roots (sink) represents one of the most important pathways for soil organic carbon sequestration. Via this pathway, carbon enters the soil both through exudation and microbial biomass as microbes metabolise simple plant-derived sugars (Jones, 2008).

- **Retaining SOC with ground covers:** On the other side of the same coin, one may wish to plant ground covers as a means of retaining SOC in a vineyard. As mentioned previously, a great deal of research has been conducted on sloping vineyards in regions where erosion has been a concern. Ground cover plants not only assist in building SOC but also help to retain it by anchoring the topsoil. Root systems of varying sizes can bind topsoil on sloping vineyards.

The primary pathway of photosynthesis feeds microbial biomass and kickstarts the soil food web.

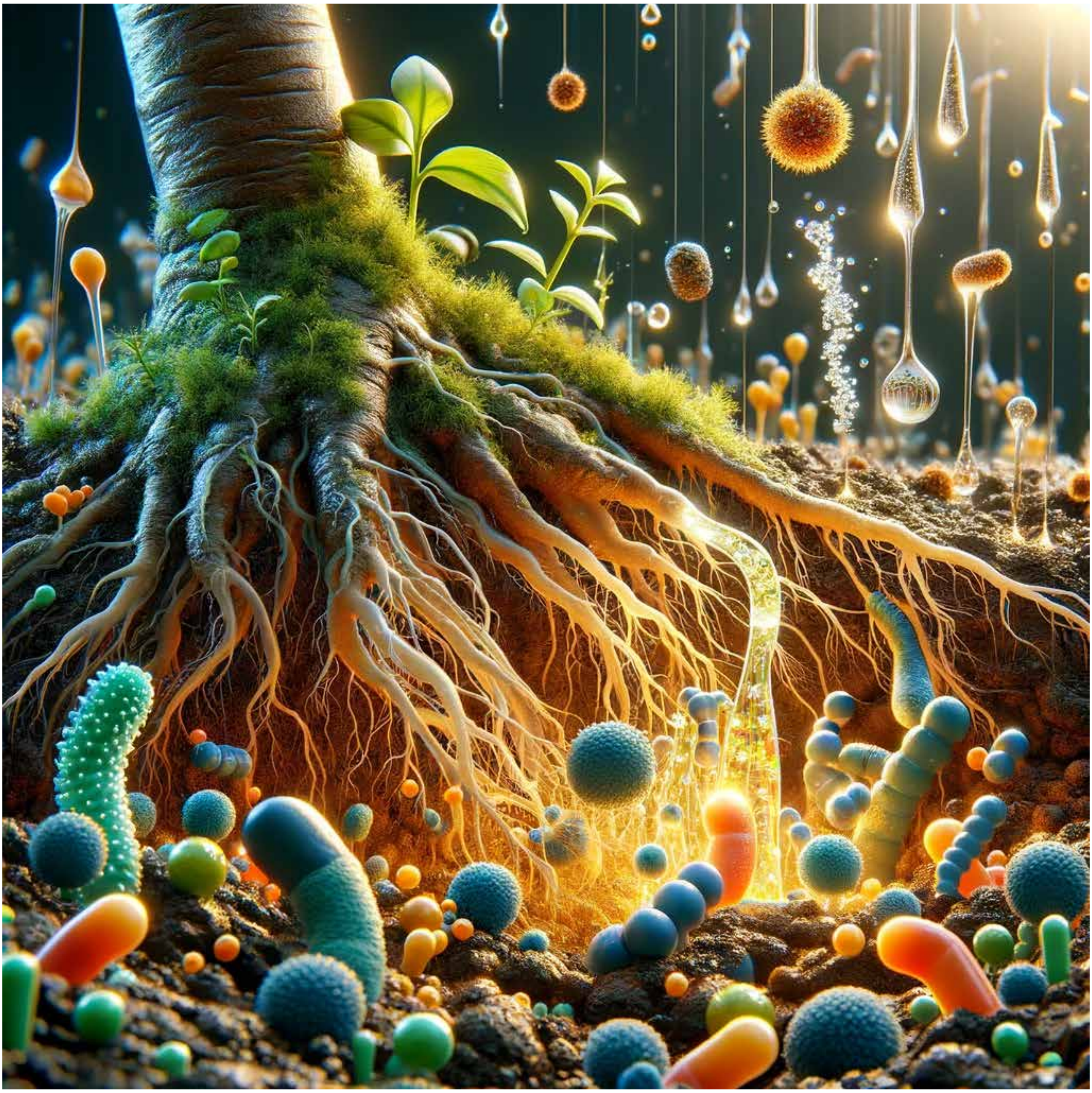


Figure 15. Artistic representation of plant-derived liquid carbon (root exudates) providing a food source for soil microbes.

Recent research by Marks et al. (2022), from the University of Adelaide, found that ground cover-managed soil under-vine sequesters up to 23% more soil organic carbon (SOC) than the traditional, herbicide practice over a five-year period of growth and microbial activity increased by more than double in soils with ground cover present.

Selecting the right ground cover:

Ground cover selection is important, and options can vary with climate, rainfall, desired outcome, grapevine variety, etc. It is important to spend some time conducting research into which ground cover is best suited to a specific terroir. In terms of suitable ground covers for increasing organic carbon, there are many options, with each providing a source of carbon and cover.

Grasses often produce the most biomass (above and below-ground), with below-ground biomass contributing the greatest source of organic carbon. High biomass grasses can be vigorous, thirsty, and require high levels of nitrogen to grow – all of this can produce a soil deficit that may be unfavorable to the grapevine.

Research has shown that ground cover plants grown in combination with a range of species or functional groups are often beneficial. Ryegrass is a less vigorous species of grass yet contributes high biomass to soil. Growing it in combination with leguminous medic can be beneficial as the medic provides free nitrogen to the grass, reducing the likelihood of a net decrease in nitrogen. Additionally, in cooler, wetter climates a more vigorous grass, such as a fescue, may function well, reducing excess soil moisture to the benefit of the grapevine.

Reduce disturbance: One of the best and more passive ways of maintaining SOC in the vineyard is to adopt a no-till approach. Tilling or ripping the soil can destroy aggregates, increasing surface area and exposing organic carbon to oxidation and microbial metabolism.

Figure 16. Photographs of under-vine cover crops: fescue x clover (left), and medic x ryegrass (right) [Photos: Thomas Lines].

Fescue is highly vigorous and better suited to cooler, wetter climates, while ryegrass is less vigorous and suited to warm, dry climates where water may be limited.

SAMPLING AND TESTING VINEYARD SOIL

Sampling: The great trade off in agricultural studies – and indeed all sample studies – relates to sampling. The truth of what actually exists in a vineyard soil system is out there and, theoretically, we could find it. However, to do so would require hundreds or even thousands of samples and analyses and this would be extremely time consuming and fantastically expensive. Therefore, to mitigate cost and sample as close to the truth as possible, we must sample and analyse intelligently and representatively.

The following are suggestions and recommendations on sampling regimes in the vineyard and can be applied to soil biological testing, nutrient analysis, and soil organic carbon testing, among much else.

- **Where?** Sampling can be divided in several ways. In a vineyard setting, it is important to sample both in the mid-row and the under-vine space. Additionally, topography (slope, aspect, etc.) can make a difference in soil properties. In a vineyard with highly contrasted topographies, one may opt to divide sampling between the sloping section and the flat section, analysing each separately.
- **How?** Samples from the under-vine and mid-row should be analysed separately as they may tell a different story. Samples can be taken using an auger or simply a shovel, remembering to sample from the same depth throughout (0 to 10 cm or 0 to 30 cm is typical). The number of samples analysed depends on the budget. One intelligent way of sampling is to take composite samples.
- **When?** Sampling should be conducted at the same time of the season every one to three years to understand changes in the system and to construct a baseline of vineyard soil fertility. Sampling prior to making any changes is also useful to understand whether those changes are having a positive effect.

  If you are sampling to assess soil biology, do this during autumn to early spring when soils have been moist for several weeks prior to taking the sample and repeat subsequent samples at the same time of the year.

E.g. Take X-number of samples along row A (say, 10 samples, evenly spaced), mix those samples together in a bag and then take one subsample for analysis. This saves on cost and provides an average result for row A. The same can be done for the under-vine. A composite could be taken based on topography instead, combining all samples taken from the sloped mid-rows.

Testing for soil bacteria:

Testing for soil bacteria is perhaps less important than testing for soil fungi because bacteria vastly outnumber fungi in soil systems. Nevertheless, soil bacteria can be measured – both in abundance and diversity of species – via several methods.

The most comprehensive method is by DNA sequencing and high-throughput analysis. These methods require rigorous adherence to clean sampling procedures so as not to contaminate DNA between samples. It should be noted that this method is very expensive and requires expert analysis and interpretation of results. One sample may yield thousands of species of bacteria, but only certain families or genera (the levels above species) are considered 'functional' to vineyard soil health (see previous section on bacteria).

- **Total and active bacteria:** Laboratory analysis can be carried out to determine the presence of bacteria under a microscope as a total plate count; an estimation of the total number of microorganisms in a material reported as colony-forming units, or qualitative assessment; a fast evaluation based on a visual scan of populations tells you whether bacteria are present in excellent, good, adequate or poor numbers, total bacteria or active bacteria. A quantitative biology test or a qualitative test is carried out by using a microscope.

Testing for soil fungi:

There are several tests that can be conducted to understand soil vineyard fungi. Tests can determine the suitability of a soil for fungal growth, the abundance and diversity of soil fungi and the mycorrhizal colonisation of plant roots (% of plant root colonised).

- **pH testing:** pH testing can determine how acidic or alkaline a soil is and, therefore, its suitability for fungal growth. Testing pH can be done simply using a pH meter, or can be conducted by commercial soil testing laboratories, among a suite of other tests. The ideal soil range for mycorrhizal fungi is between 5.5 to 7 pH.
- **Nutrient testing:** Testing for phosphorus concentrations can be an important indicator of mycorrhizal fungi and their propensity to form associations with plants. Too much phosphorus can limit plant-fungi colonisations.
- **DNA testing:** Testing for the abundance and diversity of fungi (and bacteria) can be expensive but can provide a lot of information. Sampling must be carried out with precision, with sampling instruments cleaned between samples so as not to contaminate microbial DNA. These tests can be conducted by professional laboratories that not only provide results but can also provide material for interpreting results correctly.
- **Total and active fungi:** Laboratory analysis can be carried out to determine the presence of fungi under a microscope as a total plate count; an estimation of the total number of microorganisms in a material (fungi, including yeasts) reported as colony-forming units or qualitative assessment; a fast evaluation based on a visual scan of populations tells you whether fungi are present in excellent, good, adequate or poor numbers, total fungi or active fungi; which are currently growing and metabolising and directly nourishing the plants, so the dormant part of the population may need feeding if the activity is low.

  Soil samples must contain roots if mycorrhiza assay is required. A quantitative biology test or a qualitative test is carried out by using a microscope.

Testing for soil organic carbon:

Determining the organic carbon concentration requires sampling, processing, and analysis. Sampling for carbon is relatively simple by excavating soil samples from a certain depth (typically, 0 to 10 cm or 0 to 30 cm). The sample should then be air-dried and sieved to < 2 mm. This process removes any remnant organic matter, such as plant debris, that might otherwise interfere with the organic carbon concentration. Determining the concentration of organic carbon is conducted in a laboratory using either wet chemical analysis or combustion analysis.

However, for those wishing to understand their organic carbon concentration, the most important step is sampling which should adhere to the protocol outlined above. Drying, sieving, analysing, and reporting can all be conducted by a commercial laboratory. Soil organic carbon concentrations will typically be reported as a percentage (x % of your soil contains this much organic carbon).

For more information on OC refer to the **EcoVineyards BPMG on soil health in Australian vineyards: Part A (chemical and physical)**.

Figure 17. Sequential photographs of a sampling regime conducted under-vine in a vineyard trial site in Langhorne Creek [Photos: Joseph Marks].

Sampling is conducted with a 30 cm split core and a slide hammer (top right). The split core gives the sampler the ability to carefully open the sample core and split the core, differentiating between SOC in the top 10 cm of the soil and that in the lower 20 cm (bottom left and bottom right). The ability to differentiate SOC concentrations can be useful because the majority of SOC is sequestered in the top 0 to 10 cm of the soil profile.

In addition to the many benefits of ground covers, living plants are an integral part of the process to restore the water cycle via the soil carbon sponge and small water cycle which we touch briefly on here.

Plants with living root systems help to restore water availability in a degraded system rather than reduce it.

SOIL CARBON SPONGE

A soil carbon sponge is a porous, well-aggregated soil in good health, which is better able to absorb and retain water. This is done through pedogenesis, the microbial bioconversion of plant exudates and detritus into stable soil carbon.

Retired CSIRO climatologist and soil microbiologist Walter Jehne articulated the concept of the soil carbon sponge in his 2017 paper, Regenerate Earth (Jenhe, 2017).

By connecting soil carbon with a restored water cycle, it may be possible to induce planetary cooling through evaporative cooling and higher reflectance of denser, green vegetation.

It has been postulated that improved performance of soil carbon sponges at a global scale could affect the earth's climate mainly through ecohydrology. Soil carbon sponges also serve as carbon sinks.

This can be done by maximising plant growth to:

A. Draw down carbon from the air to fix it via plant photosynthesis and then

B. Minimise how much of that fixed carbon is oxidised back to CO_2 and instead allow it to be

C. Converted via soil fungi into stable soil carbon to restore the Earth's carbon 'sponge'.

This A, B and C process is simple and natural, but what matters is that we do it, now!

To find out more about the soil water sponge and related concepts please visit:

- Biodiversity for a liveable climate: **The soil carbon sponge, climate solutions and healthy water cycles with Walter Jehne**
- Investing in Regenerative Agriculture and Food: **Walter Jehne, stop talking about carbon emissions and focus on restoring the water cycle**
- Regenerate Earth: **How hydrological processes naturally regulate and cool Earth's climate** by Walter Jenhe
- Regenerate Earth: **Presentations**
- Regenerate Earth: **Regenerate earth paper** by Walter Jenhe
- Regenerate Earth: **Walter Jehne's Soil Carbon Sponge ABCD** Regenerative Agriculture Podcast: **Rebuilding the soil carbon sponge with Walter Jenhe**
- The Regenerative Journey Podcast: **pioneering soil microbiology**
- The Wisdom Underground: **Walter Jehne: clarifying climate history to find the right path forward**

SMALL WATER CYCLE: PRECIPITATION RECYCLING

The small water cycle over land is a closed circulation system in which water vapour evaporated from the land falls in the form of precipitation over the same terrestrial environment, just like rainfall after a period of hot weather may cause dewy, misty, or foggy conditions the following morning.

Activities such as deforestation and agriculture accelerate the runoff of rainwater and cause draining of the transformed land. This also impacts the large water cycle.

Coupled with the soil carbon sponge, the small water cycle is driven by transpiration, so for it to function the ground needs to be covered in actively growing plants that release water vapour as they photosynthesise and transpire (this moisture ultimately returns to the ground).

Bare and compacted soil inhibits many naturally occurring processes and heats up the environment in two ways:

- bare ground heats up directly from the sun's radiation, and
- due to the lack of plants transpiring to cool the local environment down.

This results in a breakdown in the small water cycle.

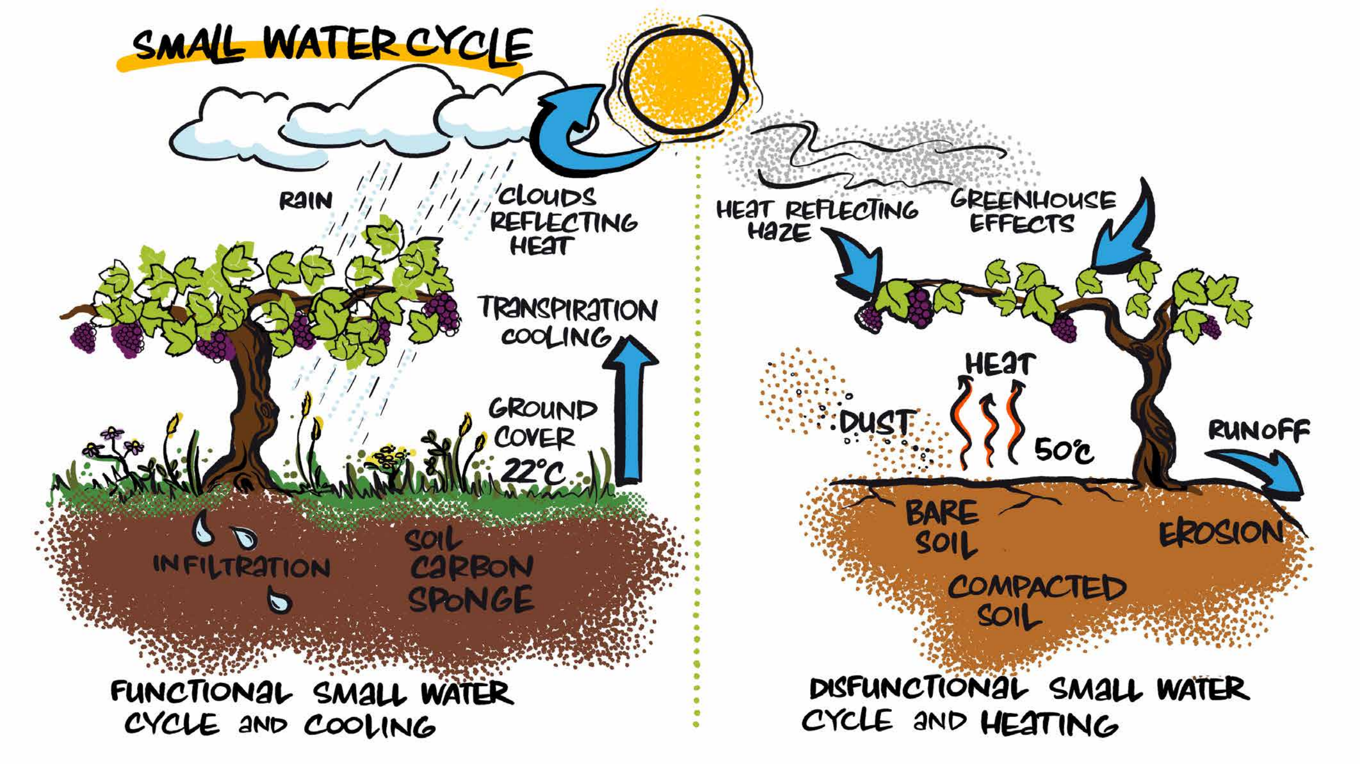


Figure 18. Diagram showing the small water cycle.

Some people may believe that bare soil is caused by a lack of rain, but bare soil causes a lack of rain by breaking the small water cycle. Bare soil is generally caused by poor management and a lack of understanding about soil biology and their intrinsic connection with plants and associated nutrients, water cycles, etc.

Bacteria based water vapour

Another interesting phenomenon is water vapour forms around bacteria activation and cloud condensation nuclei (CCN) and one such nuclei is a special bacterium that becomes airborne through transpiration.

It is this bacteria-based water vapour that seeds the clouds of the small water cycle, leading to rain. When photosynthesis is not optimal transpiration decreases and rainfall decreases.

There is another type of nuclei that water vapour forms about and that is minute airborne particles of dust.

As we plough, leave fields bare and overgraze, the desertification results in more and more dust but it also results in less and less rain.

This dust-based water vapour does not seed clouds in the same way as the bacterial nuclei do. The vapour does not coalesce as easily to form rain drops and the result is this water vapour remains in the atmosphere as a haze – a haze of greenhouse gas (Marlow, 2019).

We can correct the small water cycle by growing plants and ensuring there is 100% plant cover and active root growth, 100% of the time where possible.

CONCLUSION

This BPMG has not sought to define a single-fit-model for vineyard floor management – such a dictation would be foolish and incorrect. Moreover, considering the complexity of ecosystem management, this document has sought to marry notions of ecology with those of viticulture and soil science.

Ecosystems are complex entities that exist on a spectrum of intrinsic and extrinsic variables. Natural ecosystems are delicate and balanced and easily disturbed, with such disturbances not easily corrected.

Agroecosystems – vineyard ecosystems – are, by nature, balanced between the requirements of the grapevine and the spaces in between. The notion of terroir suggests the existence of a microcosm of variables, each of which play some role in reaching the final product.

Vineyards are ostensibly perennial in nature, with grapevines holding their residence for years, decades and often beyond. Therefore, they have a special capacity to become more than simply a space to produce grapes. Moreover, by managing a vineyard in such a way that fosters ecosystem balance, we can benefit the final product and reduce reliance on inputs such as herbicides, pesticides, and nutrient amendments.

Managing vineyard soil is often about doing less than more. Reducing tillage and soil disturbance is a primary step to ensuring soil structure is maintained and soil biological agents, such as fungi, bacteria, and invertebrates, are also maintained in healthy numbers, as well as beneficial ratios. The use of ground covers (mid-row and under-vine) can provide multifarious benefits, such as improving soil structure, infiltration, carbon, microbiology, water retention, and much more.

In this regard, it is crucial for vineyard managers to understand their site variables – precipitation, slope, aspect, depth to bedrock – before deciding on which ground cover plants to select. As much as we revere the natural elements in their dictation of what grape should be planted where, so too is it important to impose the same rigour when deciding what cover to select. By asking a series of reductive questions, a vineyard manager can arrive at a conclusion that will best suit their vineyard, their agroecosystem.

To find out more about ground covers, please refer to **EcoVineyards BPMG on ground covers in Australian vineyards.**

SECTION 2:

THE ART OF MAKING QUALITY COMPOST AND COMPOST TEA

BY MARK TUPMAN, PRODUCTIVE ECOLOGY, TEXT ORIGINALLY PUBLISHED HERE.

FINE COMPOST PRODUCTION

Few things have stood the test of time like the practice of turning organic material into compost that can be used to benefit plant growth. We are continually discovering more about the wonderful properties of good quality, mature compost, and it remains a most important input that growers have at their disposal.

How do we make it?

There is a diversity of micro-organism populations that consume and incorporate dead organic materials or necromass.

In the decomposition process:

1. **organic materials are broken down and inherent nutrients are liberated, making them available to be utilised by biology once again**
2. **free-living, nitrogen-fixing bacteria use energy derived from organic matter to fix atmospheric nitrogen**
3. **organic matter remains are reduced to minute humus fractions that improve soil structure, water retention and nutrient-holding capacity**
4. **microbes release biochemical compounds that stimulate surrounding biology, induce pest and disease resistance, and promote plant growth.**

In natural environments, this is a gradual and ongoing process that is very much dependant on the availability of materials and prevailing conditions. Composting essentially involves the use of certain practices and methods to manage decomposition and effectively turns organic waste into a valuable resource. To make compost, we need to provide the various composting microorganisms with a good balance of food, air, and water that they require and suitable living conditions.

Standard foods include:

- **Carbon-based materials:** Straw, clippings, woodchips, crop residue, shredded newspaper, etc.
- **Nitrogen-rich materials:** Manure, blood and bone, fish emulsion, leguminous matter, etc.
- **Green plant materials:** Greens, fresh prunings, weeds, grass clippings, crop waste, seaweed, grape marc, etc.

Carbon-based materials provide the energy that fuels microbial activity. The cellulose, hemicellulose and lignin content of plant materials may favour certain bacteria, actinobacteria, and fungi profiles.

Nitrogen-rich materials are integral for building the protein required by microbial biomass. Bacteria require large amounts of nitrogen. Over time, resident heterotrophic bacteria can also fix significant amounts of atmospheric nitrogen.

Fresh materials, while not essential, bring a range of active microbes, vitamins, hormones, and enzymes that contribute to the overall diversity and health of the biology in the compost heap.

Volume of organic inputs

For a standard compost mix, 50 to 60% dry carbon-rich materials, 10 to 20% nitrogen-rich materials and 20 to 30% green plant materials, by volume, are reliable amounts to work with.

Other additives that may have useful qualities include rock minerals (basalt, rock phosphate, lime, dolomite, gypsum), crushed seashells, diatomaceous earth, bone meal, trace elements, clay, ash, zeolite, biochar, fish hydrolysate, liquid seaweed, and molasses. These can comprise around 5 or 10%, by weight, of the total materials.

The micro-organisms involved in compost decomposition are generally ubiquitous in the surrounding environment. However, certain species or populations may be introduced at times to favour different types of decomposition. Commonly used examples include EM/bokashi culture, quality compost, biodynamic preparations, manure, etc.

The smaller the feedstock particulates, the greater the amount of surface area the microbes can access. Chopping up vegetative matter or using a mulcher and breaking up clumps of material makes for more rapid decomposition. Conversely, you want to avoid adding too much fine material as it tends to pack down and restrict airflow.

When assembling a compost heap it is important that the different types of materials are layered in repeated sequences and/or mixed well beforehand so that microbes have ready and even access to all the feedstocks. This makes for a homogenous product in a shorter time frame.

Adequate material bulk is necessary when you want to create thermophilic conditions; however, if piles are built up too high, lower layers may get compacted. With such composting, an appropriate height would be in the vicinity of 1.2 to 1.5 metres. Bulk volume is achieved with succinct stacking of rows or piles or the use of a bay or cage to contain the materials.

Hydration is a must for microbial activity and movement, otherwise they go dormant or die. When making compost, dry ingredients should be wetted, and throughout the life of a heap, moisture levels must be monitored and maintained to prevent it from drying out.

On the flip side, if it gets too wet, air supply is compromised, and soluble nutrients are prone to leaching.

Ideally, compost materials should be moist but shouldn't release any release water without applied pressure. Microbes don't fare so well in hard and chlorinated water. If you're going to get serious about making compost and especially compost extract, it might be worth getting your water tested. Always use rainwater where available.

Exposure to extreme weather can be problematic so it's best to locate your compost in a sheltered spot. The use of a protective covering reduces evaporative water loss and generally helps to regulate conditions throughout the heap.

Oxygen is critical for the respiring organisms that participate in the highly active decomposition that takes place when there is a stack of fresh food and adequate air and moisture on hand. However, if oxygen is not replenished as fast as it is used, the inherent oxygen quota can be exhausted, creating less favourable, anaerobic conditions. This is most likely to occur with larger volumes of, or compacted, material as the movement of air to the inside of the heap is somewhat restricted.

If this is the case, maintaining adequate oxygen levels requires active management, especially in the early stages when microbial activity is high. Compost can be systematically turned during this phase to maintain oxygen levels. Another approach is to set up compost systems with physical and/or mechanical components that ensure sufficient aeration throughout the heap without turning.

When the microbes really get going, they burn lots of energy which generates heat. The greater the volume or density of the materials, the longer it takes for heat to diffuse out of a compost heap. When a decently sized compost heap is assembled with suitable feedstocks, it doesn't take long for things to hot up. Thermophilic conditions can be reached within 24 hours (> 50°C), and they can be handy, because if sufficient heat is generated, undesirable pathogens and weed seeds are destroyed.

All material needs to be maintained above 55°C for a minimum of three days to achieve the AS 4454 'Composts, soil conditioners and mulches' sterilisation standard. However, at temperatures above 65°C, many beneficial microbes are destroyed.

The same conditions that predispose compost heaps to restricted gas exchange also leads to higher temperatures, and in this way, the temperature provides some indication of oxygen status.

Most commonly, aerobic thermal compost systems are turned regularly during the thermophilic phase to release heat and replenish oxygen, as well as rotate materials through the hotter centre of the heap. ternative composting methods, such as static aerated, contained environment fermentation and continuous feeding systems, are less conducive to thermophilic conditions.

As the supply of high-energy foods diminishes, activity slows, accompanied by cooler conditions (< 40°C) that eventually stabilise at ambient temperatures.

Over this maturation phase, a broad community of bacteria, fungi, protozoa, and nematodes slowly decompose more persistent organic materials. Strong fungal colonisation is possible at this stage and disturbance should be minimised to avoid damaging their fragile hyphae. When the temperature goes below 30°C, composting worms can be introduced to the heap to further the decomposition process.


Figure 19. Earthworms finishing off compost once it cools down below 30°C (left), worms and worm eggs (right) [Photos: Mark Tupman].

Eventually, all remaining organic matter is broken down into minute fractions that are increasingly resistant to further decomposition. These are the humus fractions that adhere to finer soil particles, forming stable organo-mineral complexes that are the very definition of long-lasting soil carbon.

Regardless of the chosen method, the art of making fine compost lies in our ability to manage these different stages of decomposition so that the various microbe groups can do their thing and turnover a quality product.

The phases of common composting

- In each phase of composting, specific substrate components are degraded, and a varying product quality is achieved
- During the first phase, mesophilic organisms prevail (e.g., acid- forming bacteria and sugar-utilising fungi)
- With the transition to the thermophilic phase, a species change takes place to a less broad range of thermophilic bacteria and actinobacteria and only a couple of thermophilic fungi
- At 65°C, fungi have usually completely withdrawn
- At higher temperatures, the actinobacteria also withdraw; at temperatures in the self-limitation range (at approximately 75°C), the richness in species is very limited and *Bacillus* spp. prevail
- With the decreasing temperatures during the cooling phase, micro-organisms survive through spores and the formation of conidia, or that are introduced from outside, re-colonise the substrate
- During the second mesophilic phase, fungi prevail as they are adapted to the substrate components, which are less degradable, and to the substrate humidity that tends to be lower.

Figure 20. Compost ready to turn (left), and turning the compost in a compost tea round (right) [Photos: Mark Tupman].

To download a list of materials commonly used to produce a compost ring please refer to the **EcoVineyards fact sheet: Preparation for making good quality thermal, aerobic compost for brewing compost tea**.

DIFFERENT TYPES OF COMPOSTING SYSTEMS

Aerobic thermal

This composting system is assembled and managed to ensure materials are subjected to defined temperatures for sufficient periods of time to kill weed seed and pathogens (without getting so hot that beneficial biology is destroyed) whilst maintaining adequate oxygen levels for robust microbial activity.

It is the process used to produce compost suitable for brewing compost tea and involves routine monitoring and systematically turning the heap in accordance with temperature and duration thresholds to maintain suitable conditions and rotate materials through the hotter centre of the heap.

A standard recommendation is to turn within three days at temperatures between 55 to 60°C, turn within 48 hours at temperatures between 60 to 65°C and turn immediately if temperatures go above 65°C.

There is also a requirement to replenish water that is lost as vapour in the process. Large volumes of material can be placed in windrows and handled with suitable machinery, making for the efficient turnover of a product that meets composting standards (please refer the section on the phases of common composting above).

Figure 21. Turning compost windrows with a specialised compost turner [Photos: Dan Falkenberg].

Static aerated

Static aerated compost systems usually involve a structural component that enables good airflow to replenish the oxygen used by respiring microbes during the more active phases of decomposition. Another feature of this type of composting system is that heat generated by microbial activity dissipates at a faster rate, preventing the temperature from exceeding certain thresholds. Because oxygenation and temperature are self-regulated, these systems don't require any turning. The inherent conditions suit beneficial microbial populations, and the lack of disturbance makes for better fungal hyphae colonisation.

Usually, some sort of air channelling is set up, such as through the use perforated pipes, to deliver air through the materials that are often assembled on mesh structures or pallets so that air can get in from the bottom. Mechanical elements, such as fans or exhausts, may also be used to improve airflow.

In some systems, the structural components are removed once they've served their purpose and in others, they remain for the duration of the composting process. On a smaller scale, larger sized organic materials, such as woodchips, straw, and branches, can included and/or succinctly placed to enable better airflow. Static aerated compost systems generally turn out high quality compost, but construction constraints limit the volume of compost that can be processed with each batch.

Figure 22. A Johnson-Su bioreactor (left), and a recently assembled Johnson-Su compost with the air channels that are created once the vertical pipes are removed (right) [Photos: Mark Tupman].

Fermentation

There are a large group of bacteria and yeasts, collectively termed facultative anaerobes, that can switch to anaerobic respiration or fermentation to acquire energy from organic materials when oxygen is limited. Less carbon is lost from organic matter under these metabolic pathways than with respiration, and it favours the formation of stable humus.

Contrary to common compost practice, airflow in fermentation systems is purposely restricted, and moisture is maintained at higher levels. Materials are normally wetted, inoculated with a starter culture, combined, and then contained or covered to restrict the supply of oxygen.

Larger volumes of material are best mixed and turned a couple of times to release heat and get the moisture levels right before covering. In the fermentation process, the pH can drop to around 3.5 to 4.5. No further turning is required once assembled and covered and there is little moisture loss as it is a contained environment.

Vermiculture

The principle behind continuous feed vermiculture systems is that you only add small amounts of feedstock material at a time to keep them from getting too hot for worms. Alternatively, larger amounts of material can be partially composted first to get past the thermophilic phase before worms are added.

Materials can be gradually fed to worm farms or batches can be laid out in low rows on permeable fabric. The depth of fresh material in either case is no higher than half a meter high to ensure the temperature doesn't go much above 30°C. Adequate moisture levels must also be maintained for worm habitation.

Some sort of system needs to be in place to enable harvesting of the worm casts without the worms. Mesh bottoms that castings fall through can be used in top-fed systems. In horizontal systems, the castings may be harvested once the worms have finished and moved on to fresher batches of materials or more favourable conditions. By their nature, vermiculture systems are typically designed to take more regular, but lower, volumes of feedstock.

Table 4. The pros and cons of different composting systems

Composting system	Pros	Cons
Thermal aerobic	Heat kills pathogens and weed seed, fast turnover	High management/maintenance, loses a higher amount of carbon and nitrogen
Static aerated	Easy, low maintenance	Doesn't adequately heat all material, low volume, takes longer
Fermentation	Low maintenance, uses less water	Doesn't adequately heat all material
Vermiculture	Can continuously feed, high humus	Doesn't heat sterilise material, slow turnover

COMPOST SLURRY, EXTRACTS AND TEA RECIPES

Well-matured compost and/or vermicast contains a diversity of micro-organisms and bio-chemical compounds that have been shown to promote healthy plant growth, stimulate biological activity, and improve pest and disease resistance.

- A thick slurry made from compost/vermicast can be used to coat seeds before or at planting to support the establishment of a healthy plant microbiome in the rhizosphere.
- A more diluted compost/vermicast extract can be used as a seedling dip, applied in the planting furrow, and sprayed onto the soil or foliage of plants to introduce beneficial microbes and stimulate biological activity.
- Small amounts of compost that were produced using the thermal aerobic method can also be aerobically brewed along with foods to grow a large population of microbes that can then be sprayed over the foliage of plants, fostering beneficial microbiology colonisation on leaf and stem surfaces.

As only little amounts of actual compost/vermicast are used in slurries, extracts, and teas, they are very economical to produce.

Figure 23. Compost with a bolus like putty is a good indication of humification quality (left), and coating seed potatoes with a compost slurry (right) [Photos: Mark Tupman].

Recipes

Compost slurry for seed coating

1. Place 1 kg of finely-sieved compost/vermicast in a bucket.
2. Add 1 level teaspoon of molasses dissolved in 100 ml warm milk, 10 g of seaweed powder and enough water to make a compost slurry with the consistency of a batter.
3. Optional extras: humate powders, clay/micronised minerals i.e. bentonite, rock phosphate, basalt dust.
4. Rhizobia, mycorrhizal fungi, Trichoderma, and other inoculants can be added if required.
5. Slowly add the slurry to the seed in a bucket or cement mixer, stirring as you go until the outside of the seed is lightly coated (approx. 1 L compost slurry per 25 kg seed)
6. Continue mixing until the seed is dry and not sticking together.

Figure 24. Coating seeds with compost extract [Photo: Kate Tarrant].

Compost extract

- Place 2 kg of compost in a 20 L drum of water and agitate vigorously for a couple of minutes to dislodge biology and bio-compounds from the substrate. Pour the liquid off through a fine filter to separate out larger particles. or
- Place 2 kg of compost in a fine mesh bag and suspend over a drum.

Circulate water from the drum through the suspended bag for several minutes to wash biology and bio compounds off the substrate.

Add extract to a tank for application or decant into an airtight container for storage. The biological diversity and activity in an extract is greatest within hours of production.

Application:

1. Extract can be combined with water and applied in the planting furrow with seed or used neat as a seedling dip.
2. It can also be added to a tank with water and applied as a drench over plants and soil.
3. Extract from around 2 kg of compost is recommended per hectare for in furrow or seedling dip application.
4. Higher amounts are recommended for plant and soil drenches.
5. Microbe foods, such as fish hydrolysate, soluble seaweed, and molasses, can be added to the tank along with the extract at rates of 2 to 4 L/ha just prior to application.

Figure 25. The process of creating compost extract [Photos: Mary Retallack].

Compost tea

Three days before brewing, place 2 kg compost in a cardboard box. Mix 100 ml of fish hydrolysate in 200 ml of water and sprinkle over the compost. Keep in a warm environment (20 to 30°C). After 2 to 3 days (depending on air temperatures), the compost will have a cotton wool-like 'fuzz' growing over it – this is the fungal growth. Once this fuzz appears, the compost is ready to brew.

Figure 26. Priming compost with fish hydrolysate to get the fungi growing prior to brewing [Photo: Kate Tarrant].

Brewing instructions:

1. Add 180 L of water to a well cleaned and sterilised 200 L drum (if using mains water which will contain chlorine among other chemicals, turn on the pump and aerate for a couple of hours to drive off the chlorine).
2. Add 800 ml of fish hydrolysate and 400 ml of liquid kelp to the water.
3. Place the 2 kg of compost in a fine mesh bag (can be purchased or made from gauze fabric).
4. Turn on the pump to aerate the water and brew for 24 to 30 hours (the dissolved oxygen content of the water must be kept above 6 ppm for the duration of the brewing process).

Note: In hot weather reduce food and brewing time. When overnight temperatures are above 20°C, brewing will take only 18 hours and the food quantities added should be halved.

Application:

- Add tea to the spray tank at a minimum rate of 50 L/ha and spray out over plant foliage every 10 to 14 days as needed.
- The tea must be applied within two hours of brewing otherwise oxygen levels drop and the microbes start to suffocate.

Figure 27. Brewing compost tea in the vineyard in Margaret River, Western Australia [Photos: Kate Tarrant].

Figure 28. Brewing compost tea in the vineyard in Eden Valley, South Australia [Photos: Dan Falkenberg].

Useful links:

- Gerry Gillespie: Static pile inoculated compost extension (SPICE)
- NutriSoil: WORMinar with agroecologist Nicole Masters
- Leubke Compost: Controlled microbial composting and humus management
- Lower Blackwood LCDC: On farm composting information hub
- Lower Blackwood LCDC: Talkin' composting for farms with Mark Tupman
- RCS Australia: Johnson Su Bioreactor
- Rod Turner: The world's best compost

SECTION 3:

USING BIOSTIMULANTS IN VINEYARDS

BY MARK TUPMAN, PRODUCTIVE ECOLOGY

WHAT ARE BIOSTIMULANTS?

There is an increasing range of inputs being used in primary production to improve plant growth outcomes that do not fall into the established categories used to classify common agricultural or horticultural products. These have been broadly termed biostimulants.

While various definitions for biostimulants have been proposed and there are many products that are widely referred to as biostimulants it is worth noting that at this time there isn't a regulatory framework or legal definition for biostimulants.

In 2019 the U.S. Department of Agriculture offered this definition (USDA, 2019):

"A naturally occurring substance, its synthetically derived equivalent, or a microbe that is used for the purpose of stimulating natural processes in plants or in the soil to, among other things: improve nutrient and/or water use efficiency by plants, help plants tolerate abiotic stress, or improve characteristics of the soil as a medium for plant growth. The characteristics may be physical, chemical, and/or biological. The plant biostimulant may be used either by itself or in combination with other substances or microbes for this purpose."

An important point of difference is that these products are not a fertiliser, pesticide, or soil amendment. It is also yet to be determined if living cultures of microorganisms and non-essential plant elements that can both be used to improve growth should be referred to as biostimulants.

For the sake of common understanding, we will break the definition of biostimulants into its literal components, the operative words being bio and stimulant.

- **Bio:** relating to life.
- **Stimulant:** an agent that produces a temporary increase in the functional activity or efficiency of an organism or any of its parts.

Put simply, a biostimulant could be any agent that increases the activity or efficiency of living things.

When we talk of agricultural/horticultural biostimulants, it is in relation to their application to enhance plant nutrition, abiotic stress tolerance and/or crop quality traits, excluding products that are already classified as fertilisers, pesticides, and soil amendments.

While there is more work to be done on the different components, modes of action, and efficacy of biostimulants, growers are forging ahead and using biostimulants based on the data that is currently available. This is the information we will outline and focus on.

Biostimulants come in a wide range of formulations

Currently recognised constituents of biostimulants include:

- humic substances
- nitrogenous substances including amino acids
- non-essential chemical elements
- seaweed extracts and other plant botanicals
- chitin and chitosan derivatives
- anti-transpirants
- other complex organic materials
- beneficial bacteria
- beneficial fungi
- other non-pathogenic microbiology.

Biostimulant formulations may contain one (e.g. seaweed extract) or a combination of these constituents (e.g. compost/vermiculture).

Figure 29. Preparing a suite of biostimulants for application [Photos: Mark Tupman].

Commercially available biostimulants

Humic and fulvic acid

Humic substances are a product of organic matter decomposition. They are commonly available as the soluble fractions, humic and fluvic acid, that are extracted from leonardite or lignite deposits, and are also naturally present in compost products.

Modes of action:

- Improve soil physical properties
- Improve nutrient retention and uptake
- Hormone-like effects
- Stress response modulator
- Buffering agent
- Chelating/complexing agent

Protein hydrolysates

Protein hydrolysates are usually produced through the enzymatic, thermal or chemical processing of animal or plant wastes. They are commonly available as liquid products, like fish hydrolysate, fish emulsion, and amino acids formulations.

Fish hydrolysate is preferred as the omega 3 fats are retained in the formulation.

Modes of action:

- Upregulation of metabolites
- Hormone-like effects
- Chelating/complexing agent
- Antioxidant activity
- Increase microbial activity

Seaweed extracts

Seaweed extracts are mostly produced through the chemical, physical, and biological processing of brown seaweeds. They are commonly available as a range of liquid and dried seaweed products that have been extracted using potassium hydroxide, or through other methods such fermentation, pressure etc.

Modes of action:

- Plant growth promoting compounds
- Antioxidant properties
- Provides a suite of beneficial minerals
- Regulates stress response, chelating agent
- Detoxification of heavy metals

Chitosan products

Chitosan products are commercially produced from high chitin source materials like shellfish. A limited range of chitosan-based products are available on the market in dry and liquid form.

Modes of action:

- Plant protection
- Tolerance to abiotic stress
- Enhance germination
- Regulate growth and development

Molasses

Molasses is derived from the sugar cane plant. It is a carbohydrate-rich byproduct of refined sugar and a source of B vitamins, enzymes, and trace elements. Molasses is also an ingredient used to make effective microorganism (EM) and bioferment cultures, which are well known DIY biostimulants.

It is important to use molasses that does not contain sulfur if you wish to retain your microbial communities.

Modes of action:

- Increase microbial activity
- Induce pest resistance
- Organic chelation

Silica based products

There are several mineral elements, such as silica, selenium, and cobalt, that, while not classified as essential plant nutrients, are beneficial for plant growth. Of these, the silica-based products are most well-known and prevalent on the market.

They are available in liquid (potassium silicate) and dry forms (crushed silica rich deposits).

Modes of action:

- Increased cell strength
- Plant protection
- Regulate sodium uptake
- Protection against heavy metal toxicity
- Plant hormone synthesis and signalling

Plant growth promoting rhizobacteria (PGPR)

The term PGPRs includes all groups of bacteria that live in the root zone around the plant, colonise root surfaces, and occupy roots. They are usually grown under controlled conditions in a laboratory and then mixed with a dry or liquid carrier for distribution and application.

While there is an increasing range of commercially available PGPRs, the host specific rhizobacteria cultures that are used as an inoculant for various legume species are the most established of the microbial biostimulants on the market.

Modes of action:

- Improve nutrient availability, particularly nitrogen
- Biosynthesis of volatile organic compounds
- Increase abiotic stress tolerance
- Induce systemic immunity
- Promote root development

Fungal inoculants

There are numerous fungi species that have shown to significantly benefit plant growth. Of these, host-specific strains of Mycorrhizae and Trichoderma inoculants are the main fungal species that are being used in agricultural crops.

Propagules are generally cultured in a lab and mixed with a dry substrate for distribution and application.

Modes of action:

- Improve nutrient use efficiency
- Increase tolerance to abiotic stress
- Induce disease resistance
- Growth regulation

DIY or homemade biostimulants

Compost and vermi-castings

Compost is a valuable product made from the managed decomposition of organic materials. The nature of the materials used to produce compost or vermi-castings and the decomposition process confer many biostimulant properties to the finished product. Recognised constituents in compost and vermi-castings include humic fractions, protein hydrolysates, plant extracts, chitosan, vitamins, enzymes, etc. As such, they may directly or indirectly benefit plant growth in a multitude of ways.

For more information about compost and compost recipes (slurry, extract, and tea) please refer to **Section 2: The art of making quality compost and compost tea**.

Figure 30. Humus rich compost [Photo: Mark Tupman].

Bioferments

Certain microbe cultures and organic materials can be used to produce bioferments. Common ingredients used for bio-ferment cultures include facultative anaerobes, molasses, milk, bran, etc. Other materials of animal or plant origin, such as fish or seaweed, and mineral elements can be fermented with cultures under anaerobic conditions to produce specific types of bioferments. Bioferments usually contain several constituents, such as protein hydrolysates, humic fractions, microbes and plant extracts that are recognised as biostimulants and, hence, they potentially have multiple and overlapping modes of action.

Biodynamic preparations

There are several biodynamic preparations that can be made on the farm and could be classified as biostimulants. They are specialised preparations that require knowledge and skill in biodynamics to produce and apply. The parts of various plant and animal species, fresh cow manure, and mineral components such as clay and basalt, are used to make the different preparations. The main two 'preps' are BD 500, which is used to enhance soil processes such as humification and aggregation, and BD 501, which is used to enhance photosynthesis and reduce the incidence of disease. The other BD preps, BD 502 to 507, are used when making compost to enhance the decomposition process.

Fresh plant extracts

The extracts of numerous plant species are understood to have biostimulant properties and can be obtained with low tech methods. Plant species such as aloe vera, alfalfa, nettle, comfrey, and yarrow can be pulverised, squeezed, filtered, and decanted to make a liquid that is applied to growing plants and microbiology to improve plant growth outcomes. As plant extracts can be made from a range of different plant species, their modes of action vary.

Local endophytes

An endophyte is an endosymbiont, often a bacterium or fungus, that lives within a plant for at least part of its life cycle without causing apparent disease. There are numerous naturally occurring endophytic microbes that can be grown 'in situ' on host plants.

Plant endophytes are active on living plants but can survive and spread in dormant states between growing events. Plant parts such as root fragments, seeds, and soil from around plant roots that contain endophyte propagule material can be used to inoculate new growing environments.

Known host plant species can be used to support the growth of various endophytic microbe populations. While the microbial species cultured this way are less controlled, it is nonetheless an easy way to produce broad-spectrum inoculants that are well suited to your growing environment and plant species. Their modes of action are like those of commercially produced bacterial and fungal biostimulants.

Figure 31. Letting a diverse annual cover crop mature so that associated plant endophytes can complete their life cycle [Photo: Mark Tupman]

Application of biostimulants

Biostimulants are designed to stimulate biology. As such, when applying biostimulants it is important to consider what biology we are attempting to stimulate and why?

- We can apply biostimulants to the soil or the plants, but the end goal is always to improve plant growth. Chosen biostimulants may directly elicit a favourable plant growth response or indirectly by altering growing conditions through physical, biological, and chemical mechanisms.
- Plants are part of a living system and the efficacy of any measures carried out in living systems is subject to flow-on effects, positive feedback loops, mutualistic symbiotic interactions, etc.
  - For instance, we may apply a biostimulant that temporarily stimulates plant growth and root exudation. This, in turn, drives extra microbial activity in the soil, which leads to better nutrient acquisition and delivery to the plant roots, furthering subsequent growth, exudation, and so on.
  - Equally, a soil application that stimulates beneficial microbial activity around plant roots, improving nutrient availability, fosters stronger plant growth, an increase in root exudation, etc.
  - In either case, we get a greater overall response than what could be attributed to the application alone. However, if there wasn't much plant cover, or the soil was in a poor state, or there was a lack of moisture, etc, the potential for a beneficial response from a biostimulant application would be limited and short lived.
  - We need to ensure that the necessities of life i.e. nutrition, water, and air, are in place for biostimulants to have any significant and lasting effect.
  - Fundamentals like actively growing plants, soil cover, organic matter, good soil structure and moisture, and nutrient supply are what ultimately determine our success, and while biostimulants can enhance living processes, they are only effective when used in conjunction with good overall management and limiting factors are addressed first.
- By applying biostimulants at planting or, where we have established perennial plants, at the beginning of the growing season, we can get a compounding of the beneficial flow-on effects discussed above.
  - For instance, if we inoculate seed with beneficial bacterial/fungal at planting, we set the scene for a healthy plant microbiome from the start.
  - In this instance, only small amounts of the biostimulant are needed to get things going, from which point on the plants and microbes support each other. In this way, biostimulants can be used as a catalyst for the establishment of a healthy system.
  - Mature plants are generally less responsive to biostimulant applications because larger quantities are required relative to the larger amount of plant mass, older leaf and root tissue is less receptive, competitive microbe populations are already established on and around the plants, and root exudation drops off.
- Putting out biostimulants the right way and in the right conditions is also important.
  - When we apply active microbes in a compost extract, we might do so with water through a fertigation system, or when there is rainfall on the way, as moisture is a prerequisite for survival.
  - For better uptake of a foliar-applied biostimulant like seaweed, it's better to put it out early in the morning or late in the evening, when the leaf stomata are open, and it won't dry out too quickly. On the flip side, we want to avoid heavy rain events so that applications aren't washed off straight away.

A final strategy worth considering is combining compatible and complimentary components in biofertiliser applications. With such formulations, we can get a compounding synergistic effect and more bang for our buck, and time, than we would from applications of individual components.

Useful combinations include:

- applying microbial groups that are known to complement one another (e.g., bacterial and fungal inoculants) together
- applying microbes (e.g., compost extract, beneficial bacteria/fungi) with a source of food (e.g., fish hydrolysate, molasses, humic substances) to support microbial activity
- applying microbes (compost extract, beneficial bacteria/fungi) with growth-promoting hormones and antioxidants (e.g. seaweed extract) to support healthy microbial growth
- applying minerals (e.g. rock phosphate) with microbes (compost extract, mycorrhizal inoculant) to improve nutrient availability and delivery
- applying nutrients (e.g., trace elements) with a substrate that has nutrient-holding capacity and/or chelating properties (humic substances) to improve the retention and/or uptake of nutrients

We can use multiple combinations in a formulation if they meet mixing and application requirements.

Figure 32. Decanting a liquid biostimulant for application [Photo: Mark Tupman].

RECIPES

Organic liquid biostimulant mix

This following mix is a general purpose biostimulant. It contains humic substances, seaweed, organic acids, proteins, carbohydrates, minerals and, with the compost extract, beneficial microbiology.

The biological compounds in this mix are like, and designed to emulate, those that are naturally produced through the activities of plants and microbes in a fertile environment.

It can be used to:

- stimulate plant and microbial activity
- improve retention and uptake of nutrients
- introduce beneficial microbiology
- improve soil characteristics

Recipe

Mix the following ingredients in a container with some water at the following rates:

- 5 L/ha fish hydrolysate
- 4 L/ha fermented (acidic) seaweed liquid
- 4 L/ha molasses
- 400 g fulvic acid powder
- 250 g sea minerals (optional)

Application

1. Add this mix to a spray tank with an adequate volume of water to cover the area of application. It is best applied within 24 hours of preparation.
2. To introduce a biological component, add the extract of 2 kg/ha compost/vermi-castings to the tank mix. Once the compost/vermi-casting extract has been added it must be put out within a couple of hours.
3. Preferably apply in mild conditions during the early part of the day before it warms up, or towards dusk when it starts to cool down.

Note: Due to the nature of different extraction processes, there may be compatibility issues with certain products. If you are unsure, follow the instructions and perform a jar test of the tank mix beforehand.

Use

This mix can be applied to the foliage of plants and soil to support the establishment of healthy plant/soil biological systems. It is very effective when applied earlier in the growing season at planting, post germination, or budburst but can also be applied prior to the growing season to boost microbial activity, speed up the breakdown of organic residue, improve soil structure, etc.

It is widely compatible with many fertilisers and can be used to complex/chelate nutrients in liquid applications. Due to the acidic nature of the ingredients, it is best not mixed with alkaline soluble products.

Making and using bioferments

Culturing facultative anaerobes

There are a large group of bacteria and yeasts, collectively termed facultative anaerobes, that can switch from aerobic respiration to anaerobic respiration or fermentation to acquire energy from organic compounds. They are the predominant type of microorganisms found in environments where the oxygen supply is variable and/or restricted, such as the inside of soil aggregates or the stomachs of earthworms and ruminants where they perform many useful functions.

Facultative anaerobe cultures are easy to make and can be used in several ways, for example:

- to brew liquid fertilisers using animal, fish, plant, seaweed, and mineral/salt nutrients
- to improve the availability of certain soil nutrients
- for the fermentation of various foods and beverages
- as a culture for static composting, i.e. SPICE and Bokashi
- to aid decomposition and humification of organic materials in soil
- to break down wastes and toxins
- for generating fuel by-products from organic matter digestion
- to make probiotic supplements for livestock.

Figure 33. Culturing facultative anaerobes [Photo: Mark Tupman]

Basic cultures

It is a fairly simple process to breed up a population of facultative anaerobes with readily available and affordable ingredients that can then be applied as is or used as a starter culture for different types of bioferments.

Native microbe seed

To make a 200L drum you need approximately:

- 40 kg cereal bran
- 20 kg litter duff that contains visible white fungal growth
- 20 L molasses
- untreated water

Process:

- Mix the dry ingredients on a concrete floor, gradually adding molasses along with some water to moisten, until you reach a uniform consistency. The end product when squeezed in the hand feels moist but not to the point where water drips out.
- Pack all the ingredients into the drum, compressing as you go to expel as much oxygen as possible. Leave a 10 cm gap at the top to allow for expansion. Close off, ensuring it is airtight, and store out of sunlight for at least 30 days before use.

Figure 34. Native microbe seed [Photo: Mark Tupman].

Lab (Lactobacillus) serum

1. Starch wash: Wash some rice or other starchy cereal with water (can also use water left over from cooking potatoes) and then drain the water into a container.
2. Collect the Lab culture: Cover the container with a tea towel/muslin/fine netting and leave in the open, preferably outside so lactobacillus bacteria can find their way to the starchy liquid. It should be ready within a couple of days and have a slightly sour aroma. Siphon or syringe liquid from the middle into a container, avoiding scum from the bottom and top layers, and put in a sealed clean container.
3. Feed the Lab: Combine 1 part LAB liquid with 10 parts milk in a container, leaving a small gap at the top. If your container is fully sealed then slightly undo the lid every day to let gas escape and reseal immediately, or use a container fitted with an airlock.

   In four to seven days (this happens quicker in warmer conditions) the liquid should have separated into two distinct layers consisting of curds and whey. Strain the whey into a sealable container. This is your finished LAB serum. To store for up to a year, refrigerate or mix with molasses at a rate of 3:1. It is best to release gas then reseal a couple of times during the first week of storage, or use a container fitted with an airlock.

Other starter cultures: kefir, effective microorganisms (EM), fresh rumen contents/manure

Making a bioferment

Ingredients for a 200 L barrel (multiply by five for 1000 L IBC)

Starter culture:

- 40 L fresh rumen contents/manure, or 20 L of native microbe seed/Lab serum/BAM/EM culture or, 10 L recently made bio-fertiliser (you can use any combination of the above, reducing the rates proportionately with the number of different starter cultures you use).
- 4 L molasses
- 8 L milk/whey
- 200 g bakers/brewers yeast (optional)

Optional extras:

- Up to 3 kg micronised rock minerals, diatomaceous earth, micronised guano, etc.
- Up to 2 kg wood/grass/bone ash, soluble seaweed, sea minerals, blood and bone, fishmeal, sea salt, humic substances, ground biochar, etc (place extras in a fine mesh sack/bag and remove after a week).

Process:

1. Put the starter culture in the barrel first.
2. Mix molasses with some warm water, milk, and yeast then add to the barrel.
3. Top the barrel up with water leaving a 20 cm gap. Leave a larger gap if you plan to add subsequent ingredients and foods to the barrel.
4. Insert the sack/bag of optional extras.
5. Seal the barrel. The lid must be airtight and fitted with an airlock so gas can escape but air cannot get in.
6. The facultative anaerobes feed on the milk/whey (protein), molasses (energy) and minerals and go through cycles of growth, reproduction and death, forming spores and cysts when the food runs out.
7. The finished product contains a rich mix of amino acids, chelated/complexed nutrients, phyto-hormones, vitamins, enzymes, etc.

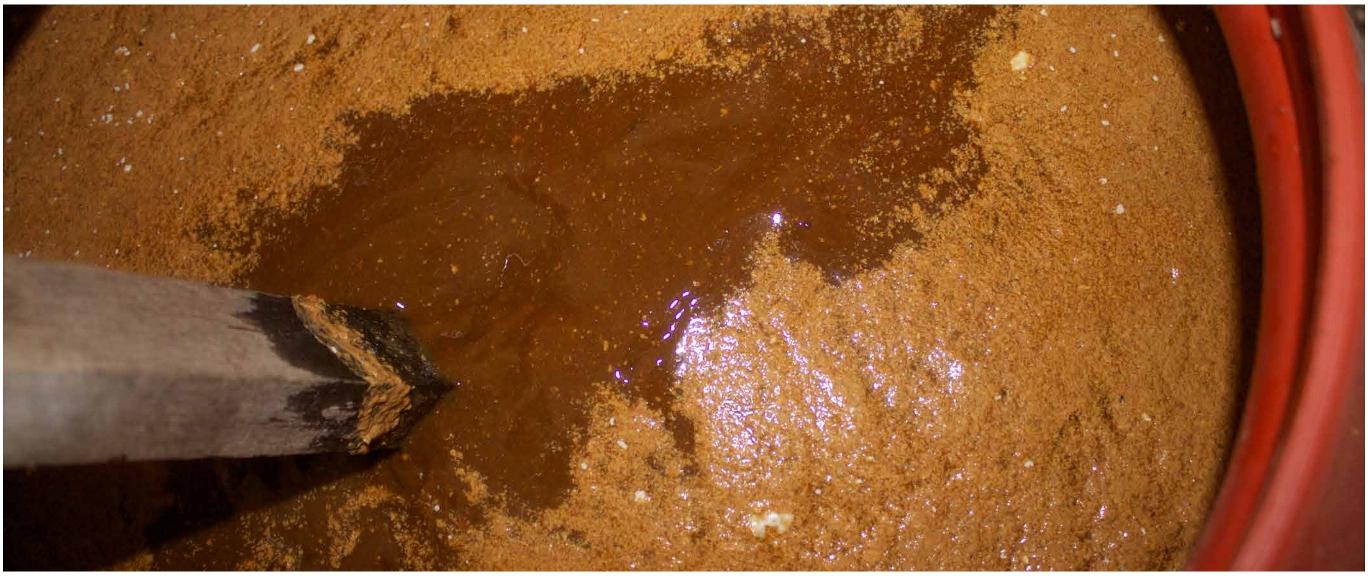


Figure 35. A good looking bioferment brew [Photo: Mark Tupman].

Applying bioferments

- Bioferments can be applied as a foliar spray, through fertigation, or as a soil drench.
- It can be mixed with water at dilutions anywhere between 1:20 and 1:50.
- The usual foliar application rate is between 20 to 30 L/ha for horticulture crops and 10 to 15 L/ha for broadacre crops.
- Sulfate/salt fertilisers can be mixed with bioferments at recommended application rates. The organic acids in bioferments act as reducing and chelating/complexing agents, improving the stability and uptake of inherent nutrients.
- These rates can be doubled if used through fertigation or as a soil drench.

To improve uptake, the following ingredients can be mixed with fermented biofertilisers before application:

- Fish hydrolysate at 0.2 to 0.4 L/100 L, 2 to 4 L/ha.
- Fulvic Acid Powder at 25 to 50 g/100 L, 250 to 500 g/ha.

Include a surfactant/spreader/sticker at recommended rates for foliar spray application.

Fermented biofertilisers are acidic so best not mixed with alkaline inputs. Otherwise, they can be applied in combination with a wide range of products but if unsure, carry out a jar test to check compatibility.

Potassium silicate protective spray

While silica is not classified as a plant essential element, it is nonetheless a very beneficial element for healthy plant growth. It has been shown to increase plant cell wall strength and structural integrity as well as boost plant natural defence systems. Potassium silicate is a liquid form of silica.

Recipe

Mix 2 L/ha potassium silicate in a suitably sized container with water.

The following ingredients are all compatible with and can be combined with potassium silicate to increase the beneficial properties of the mix:

- Alkaline seaweed liquid or soluble powder at recommended rates.
- Concentrated sea minerals 100g/ha.
- Soluble potassium humate at recommended rates.
- Molasses 4 L/ha.

Process:

1. Mix well until all ingredients are dissolved and in solution, adding more water if necessary. Some of the ingredients may settle over time so agitate the mix before application, wait a few minutes then decant through a filter to avoid any insoluble fractions.
2. Micronised lime, dolomite, gypsum, silica, and rock phosphate/guano mineral products can be added to the tank and put out with this mix at recommended rates, but they don't remain in suspension so require tank agitation during application.
3. Trace elements boron and molybdenum, in the form of solubor (500 g/ha) and sodium molybdate (50 g/ha) are also compatible and can be applied with this mix.
4. You can also add the extract of 2 kg/ha compost/vermi-castings to the tank mix, but once this biological component is introduced, it must be put out within a couple of hours to avoid microbial suffocation and die off.

Application

- Potassium silicate is strongly alkaline, so it's best applied at the recommended rate with no less than 750 L/ha water to avoid leaf burn. It is also incompatible with many agricultural inputs so be sure to check before combining with any inputs not listed here.
- Preferably apply in mild conditions during the early part of the day before it warms up, or towards dusk when it starts to cool down.

Note: There is some variability between products on the market so it's always best to read the label and follow the instructions of the products you're using. If unsure, conduct a jar test to check the compatibility of different components.

Use

- This mix can be applied to the foliage of plants and the soil.
- Foliar applications, every few weeks, provide physical and chemical protection against a wide range of pests and diseases. When applied to the foliage of plants, it coats the leaves with a silica layer that provides protection against pathogen attack.
- Some of the ingredients in this mix will temporarily stain foliage and fruit so avoid adding these ingredients if this is an issue. It is best to use on foliage earlier in the season and cease applications at fruit fill.
- It can be applied to soil to increase biological activity and improve soil conditions, root growth, and nutrient uptake.
- Silica is an important component of membrane and transport systems that line plant roots and restrict the excess uptake of potentially harmful elements, like aluminium and sodium, from the soil medium.
- This mix is best applied to the soil at the beginning of the growing season, before, at and after planting or budburst.

Culturing beneficial plant endophytes

1. Organise an annual cover crop seed mix of annual plant species that are known to associate with a wide range of mycorrhizal fungi species, e.g. cereals, legumes, sunflowers, etc.
2. Prepare a garden bed for planting or fill up some sacks or large pots with healthy garden soil.
3. Dust or coat the seed mix with desired endophyte inoculants, e.g. rhizobia, mycorrhizal, and Trichoderma species and plant.
4. Plant and care for the cover crop all the way through to seed set and senescence, avoiding the use of any synthetic fertilisers, herbicides, and pesticides.
5. The endophyte species reproduce prolifically when their host plants start to die as a survival strategy for the non-growing season ahead.
6. When everything has died off, pull out the plants then shake off and collect the soil adhering to the roots as well as the roots themselves which are full of endophyte propagules.
7. This material can be further refined by cutting up and grinding/crushing the dried roots into a powder then putting the soil and fine root material through suitably sized sieves.
8. This refined substrate can be:
   - added to potting mixes
   - dry mixed with seeds before planting
   - mixed into a slurry to coat seeds
   - placed in planting holes around seedlings
   - added to furrows with seed at planting
   - spread over fields, but larger volumes are required and the further away from the root zone it is placed the less effective the colonisation.

Further information on biostimulants

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SECTION 4:
ASK AN EXPERT

BY DR MARY COLE, AGPATH PTY LTD

WE COLLATED A LIST OF SOIL HEALTH QUESTIONS ASKED BY WINE GROWERS AT ECOVINEYARDS EVENTS AT THE START OF THE PROGRAM IN 2023 AND DR MARY COLE HAS KINDLY PROVIDED ANSWERS BELOW.

GENERAL QUESTIONS

What are the different forms of organic matter, how stable are they and which should we be focusing on?

Most literature is carried out on conventional agricultural soils that may already be damaged from excessive cultivation, constant use of synthetic chemistry, erosion, loss of soil water/moisture, and loss of microbial activity in the soil. Any amendment will work on a damaged soil. Any organic matter will provide microbial food although the first decomposition of fresh material increases CO_2 emissions over those that are aged and stable.

Fresh organic material breaks down by bacterial action initially. While heat is generated in the pasteurising process, the resulting material is still unstable and will react with other organic material. Only when the pasteurising process is completed and the temperature of the remaining organic material has returned to ambient can the maturing process begin, and stable humus be formed.

Temperatures of 65 to 70°C is considered the temperature range that will kill weed seeds and potential bacterial pathogens likely to cause human or animal health problems (Insam, 2007). The time required to complete pasteurisation depends on the ratios of the original raw materials, moisture and the size of the compost ring or windrow. It is the stable humus/compost that is the black gold for vine health.

Any organic matter can be composted over time. Rate of composting is related to the size of the material, the availability of moisture and the carbon-to-nitrogen ratio. Nitrogen sources can be manures or any green material. Carbon sources are any brown woody materials.

Table 5. Estimated C:N ratios of common raw materials (Planet Natural Research Centre).

Browns = high carbon	C:N	Greens = high nitrogen	C:N
Ash, wood	25:1	Alfalfa	12:1
Cardboard (shredded)	350:1	Clover	23:1
Corn stalks	75:1	Coffee grounds	20:1
Fruit waste	35:1	Food waste	20:1
Leaves	60:1	Garden waste	30:1
Newspaper (shredded)	175:1	Grass clippings	20:1
Pine needles	80:1	Hay	25:1
Sawdust	325:1	Manure	15:1
Straw	75:1	Seaweed	19:1
Wood chips	400:1	Vegetable scraps	25:1
		Weeds	30:1

Compost contains both stable and labile carbon components. The labile fraction is accessible and easily used by soil microbes and plants. For more information on particulate (also known as labile or active) organic matter and mineral-associated (also known as stable) organic matter, for more information please refer to **EcoVineyards BPMG on soil health in Australian vineyards: Part A (chemical and physical)**.

What are the benefits of plant cover compared to bare earth on different soil types?

Bare earth is not natural in nature except where there has been a disturbance. Bare earth is bacterially dominated and supports fast-growing, primary colonising plants. These plants protect the bare earth from erosion and allow time for perennial plants to emerge and colonise.

Plant cover 100% of the time keeps soil organic matter moist and aids the continual activity of mycorrhizal colonisation of plant roots (Baumgartner, 2005; Gougoulias et al., 2014; Qiu et al., 2021).

Moreover, perennial and permanent ground covers will be fungal dominated because the roots will be infested with mycorrhizal and saprophytic fungal hyphae if the soil profile is not disturbed (Steenwerth and Belina, 2008).

Ploughing or disturbing the plant roots by removing the plant from the ground takes the fungal biomass with the roots. The bare ground remaining is then bacterial dominated until plant cover can be regained. Having a plant cover in the vine-row will allow the soil biota to transition from bacterial-dominated bare ground to fungal-dominated plant cover. The transition from bacterial (bare soil) to fungal (plant cover) population domination in soil is as rapid as it takes plant roots to establish in the area.

This infestation rate is based on the removal of synthetic chemistry, particularly NPK. A healthy soil has a balance of soil biota where each functional group is in balance with all other functional groups. Phototropic soil bacteria are just one of the myriad functional groups in a well-aerated soil (Crouzet, 2019). To remediate a soil, aeration and drainage must be remediated first. Carry out a quantitative biology test by sending a sample off to a soil analysis laboratory or do a qualitative test using a microscope.

How is organic matter improved quickly and cheaply in sandy soils of inland wine regions?

Sand is lacking in nutrients and organic matter. Organic matter needs to be introduced and maintained and this can be done by growing ground covers with active root growth throughout the year to protect and nourish the soil. Permanent ground covers stabilise sand and increase organic matter and nutrients while the consistent flow of plant root exudates keeps the nutrients available in the root zone.

Continual living plant cover is required to maintain and increase organic matter in sandy soils.

Adding compost is useful but expensive, growing it is better. Adding clay to compost before it is spread creates conditions for nutrients to be held in the root zone (Tahir and Marschner, 2017). It is more difficult to maintain organic matter in the root zone of sandy soils, but permanent cover makes this possible.

How can sandy soils be improved?

Sandy soils do not hold nutrients easily so large amounts of organic matter need to be applied over time. Adding clay to sandy soils, or to compost applied to sandy soils, improves nutrient-holding capacity. Adding the clay into compost avoids compaction and carries nutrients when mixed into the sandy soil. Volumes such as 8 to 10 kg/m^3 mixed into compost gives the best result. Progressive applications of compost help to increase organic matter and improves the nutrient-holding capacity of the soil over time. Evidence of this has been shown through personal experience with Dr Cole's work in Egypt and UAE with colleagues producing quality fruit and vegetables in Saharan desert sand using biological and biodynamic methodologies in collaboration with SEKEM.

For more information please refer to Cole and Cavallo (2022), the role of compost in improving plant growth in poor soils.

Why is aeration of soils important and what impact does it have on soil biology and compaction?

Most beneficial soil biota are aerobes. Aeration allows air, water, and nutrients to enter deeper into the soil, allowing plant roots to grow deeper and become more resistant against changes in soil moisture and air temperature.

Compaction is generally caused by excessive equipment use or regular ploughing that causes a hard pan at some depth. Fungal species are all aerobes except for yeasts, so saprophytic and mycorrhizal fungi require aerated soil for healthy population growth (Postma-Blaauw et al., 2010; Rillig et al., 2010; Roper and Gupta, 1995).

How does soil microbiology affect water-holding capacity and soil structure?

Effective and functioning soil biota produce good soil structure through aggregate formation. Increased plant root growth and its accompanying mycorrhizal fungal biomass hold water in the root zone as well as carbon. If the soil is undisturbed and the fungal biomass increases, then the soil structure will remain in good condition.

Ploughing and excessive tilling destroys the fungal biomass, leading to a proportionally higher bacterial biomass and the release of higher amounts of CO_2 to the atmosphere. No till or minimal tillage is recommended for good soil structure (Feeney et al., 2004; Rillig et al., 2010; Steiner et al., 2023).

How do you 'wake up' soils that have had no remediation over time?

Soils respond to aeration with minimal disturbance. Using spiked drums, tines such as the Yeoman's plough or any implement that will open but not turn over the soil, is recommended, causing least disturbance to plant roots and fungal biomass around those roots. Then, applying compost, compost tea or microbial foods such as fish hydrolysate, kelp, seaweed, molasses will stimulate the soil. Cover crops or perennial plants will maintain continual ground cover, leading to increased moisture retention and cooler soil in which vine roots are growing. A dusting of rock dust across the vine and mid-row will provide the slow-release elements that vines, and cover plants need for healthy, balanced growth.

What is the impact of ground covers on nutrient availability?

Ground covers provide soil protection, cool soil, improve water-holding potential, increase fungal biodiversity, and improve plant health overall. Plant cover can be weedy species, mixed crops or native forbs and grasses – any plant that always maintains a cover on the soil. The resultant organic matter (along with root exudates) provides nutrients for soil biota which in turn recycle and mineralise organic matter back to plant-available forms (Bernaschina et al., 2023; Gougoulias et al., 2014; Qiu et al., 2021).

What is the difference between mulch and compost and why is this important?

Mulch is fresh or uncomposed green or brown material. Green materials may be hot because of bacterial activity or brown may be dry plant material. Both are very high in carbon and when applied to soil in a pasture, vineyard, or vegetable garden, can cause nitrogen draw down which is detrimental to vines in a vineyard. As the mulch moistens, microbial activity will begin breaking down the plant material. The only source of biota is in the soil below. Saprophytic fungi and bacteria move from the soil to the mulch/soil interface to commence the breakdown of plant material. This makes nitrogen the limiting factor. This move to a different food source causes a short-term depletion of nutrients, particularly nitrogen, in the vine root area.

To avoid nitrogen drawdown from mulch, first apply a thin layer of finished/matured compost and then lay down the thicker layer of mulch as weed management or just to increase organic matter in the vine-row while cover plants are establishing.

What are the benefits to soil carbon stocks, water storage, humus creation, and humic/fulvic acid differences from the introduction of these methods?

Best biological practice in the vineyard will result in improved water storage via the mycorrhizal fungal biomass around the plant roots. Increased humus can be achieved through the decomposition of roots 'in situ', and the application of organic matter applied as compost.

A progressive increase in carbon storage will occur as the fungal biomass and nutrient status grows with time. Biological farming practices mean that the soil is less disturbed, more plant cover is maintained, and biota populations have time to increase where necessary or stabilise, leading to improved soil and vine health.

Increased carbon can be considered an alternative economic stream but that would need to be negotiated with the carbon trading companies. They are all different.

How are the effects of water logging and compaction reduced and soil structure restored?

Water logging is initially a drainage problem. Determine the cause of the water logging by introducing in-ground drainage pipes, constructing swales to redirect water, and, finally, consider if the area is suitable for growing vines. Compaction results from over-cultivation, overuse, or the use of vehicles when the weather is not appropriate.

Compaction leads to anaerobic conditions in soil and a loss of air pockets that are necessary for earthworm movement and the growth of fungal hyphae. With the loss of fungal activity and increasing anaerobic conditions in soil, there is a parallel loss of soil structure – loss of viable aggregates.

Deal with the reason for water logging; aerate the soil; reduce vehicle use in bad weather; refrain from cultivation; have 100% cover 100% of the time where possible so that soil organic matter continues to increase over time (Steiner et al., 2023).

COMPOST AND COMPOST TEA

How are compost teas prepared and used, how should they be fed, what with and at what rates?

The definition of true compost is the thermal aerobic breakdown of organic matter through pasteurisation followed by a period of maturation to produce humus with high microbial activity (Insam, 2007).

All organic matter will compost over time and return the organic elements that result from photosynthesis back to recycled matter in their inorganic form where they are plant available. Not all compost is equal when considering the product for pest and disease management and soil health.

Compost may be made in small, discrete rings, long windrows, in static piles such as the Johnson Su method, anaerobically in static piles or commercial retorts. Each of these methods produces a product that is high in organic matter and useful as an organic amendment on or in soil. This organic matter then feeds the soil biota, leading to healthier soil, better plant-available elements, better water-holding capacity and improved aerated soil structure.

Compost tea is only as good as the compost from which it is made. Thermal aerobic compost carefully produced to temperature and moisture parameters in a cubic metre ring and matured will provide the greatest diversity and highest population suitable for compost tea and disease protection.

Use may be for foliar spray following pruning: foliar protection following a primary infection notice. Rates depend on the reason the compost tea is being used.

- Is it being used to replace fungicides or pesticides in vine management?
- Is it being used as a post-harvest/pruning vine drench?
- Is it being used as a soil biota remediation?

Compost and compost tea can be applied at almost any rates because neither will cause problems on or in the soil. However, there is a cost of time and resources in making good compost and compost tea. Therefore, in the same way a farmer/grower will have a soil chemistry test or vine nutrient test done before purchasing and applying synthetic chemistry, so should a baseline soil chemistry and biology test be carried out so that the correct recipe can be applied when making the compost or compost tea.

There are many compost tea recipes and Dr Elaine Ingham's YouTube presentations are comprehensive and useful.

Compost and compost tea resources aim to feed the different organism groups. Food resources that feed bacteria may include simple sugars, yeasts, kelp, fish hydrolysate, and fruit pulp. Fungal foods may include simple sugars, kelp and fish hydrolysates, fruit pulp, humic acids, protein meals such as soybean, bran, oatmeal, barley meal, rock dust powder, and yeast.

Bacterial tea

A basic bacterial tea may include 10 kg of bacterial compost, 800 ml of molasses, 750 ml of kelp hydrolysate or fish hydrolysate and fruit pulp can be added.

Fungal tea

A basic fungal tea may include 10 kg of fungal compost, 900 ml of humic acids, 750 ml of kelp hydrolysate, 750 ml of fish hydrolysate and 250 ml of a plant extract, such as yucca.

Yucca extracts contain micronutrients, such as iron, zinc, manganese, and copper. The yucca extracts contain complex carbohydrates that provide slow-release food for many soil-dwelling microorganisms.

The compost must be matured. Water must be clean and not chlorinated. The pump must be strong enough to keep the volume agitated so that the dissolved oxygen stays above 6 ppm, and the volume remains aerobic. Compost tea should be used immediately after it is made and must be kept agitated.

Composts and compost teas made to the specifications dictated by individual soil biology tests carried out for an enterprise are more effective and less wasteful of resources.

How is compost made effectively using windrows, what is involved and how much should be applied?

Compost in windrows requires a tractor with a front bucket to turn the windrow when temperatures reach 65°C. Windrows should be no more than 1.5 m high and two buckets deep (for convenience) and as long as space allows.

Any organic material will compost over time, but rapid composting occurs if the carbon-to-nitrogen ratio is 25 to 30:1 and moisture is 40 to 50% and the materials are around 1 cm in dimensions.

A small but strong chipper is used. Twigs and small limbs up to around 2 to 3 cm in diameter can be mulched. Larger chippers will allow large wood to be processed. Cardboard, paper, and egg cartons are all wood products and can be wetted, pulled apart and form part of the brown (fungal) food. The amount applied is determined by the results from a biology and chemistry test.

What are the economics of compost applications when made on site versus purchased in?

Using all the organic resources from a property that were previously considered waste means a good compost can be prepared at little or no external material cost. All cardboard, paper, food scraps, fallen twigs/limbs, prunings, chicken, or animal manure can be composted by considering the C:N ratio to have a reasonably rapid conversion and access to clean water.

Local chicken enterprises and feed lots must pay to dispose of their effluent and shed waste. This is usually free to collect. Rock dust may need to be purchased but is very cheap if collected and not delivered. The cost of electricity to run a pump may be offset if the enterprise has solar panels. If the pump runs on diesel, then this is a cost. Water should be from a tank, dam or bore so that it is free of chlorine.

Can you get to a point where the ground cover area has such good organic matter and biodiversity that there is no benefit to adding compost which uses diesel and compacts soil?

Any soil that is cared for over time will arrive at maintenance point in a couple of years. This time depends largely on the amount of previous damage from synthetic chemistry, over working, overuse of vehicles, weather patterns to provide soil moisture and enthusiasm of the farmer to embrace the regenerative, biological, organic, biodynamic, permaculture paradigm. Applying compost tea then becomes a six-monthly exercise at the change of the seasons, autumn, and spring in vineyards.

What are the benefits of applying compost tea?

When composting to make compost tea for disease management as a foliar spray, then compost with the greatest diversity and population of species is necessary.

Ingham (2016) showed that 70% leaf cover with beneficial microbes will manage and reduce the impact of disease-causing pathogens.

Well-made and finished thermal aerobic compost made in cubic metre rings is shown to change soil microbial composition to eliminate flat weeds, such as cape weed, from pastures and vineyards (Cole 2022).

Applications of compost tea made specifically for soil to be modified are applied at the time of the year depending on the role the tea is to have. For example, if being applied to soil to manage cape weed, it is applied onto the plants before flowering in the first instance. If land is being prepared for use, then compost tea can be part of the preparation because it will be changing the soil biota from bacterial to fungal, thus reducing or eliminating altogether the weedy species. For more information please refer to the **case study compost tea to manage broad leaf weedy species in agricultural systems**

How much and how often compost and compost tea is used is soil dependent. Rhizotron trials amending severely chemically damaged potato soil with 25% and 75% high quality thermal aerobic compost showed an increased germination of maize seeds and change in soil biota populations (Cole 2022).

Microbial activity changes through the seasons so soil tests should be taken at the same time each year to build up a profile of a particular block of land.

Farmers cannot control weather so minimising variables by testing at a particular time of the year can make the microbial data more meaningful. Soil biota can be determined qualitatively by using a simple light microscope and looking at the presence or absence of soil biota, or it can be tested more accurately and given a quantitative analysis from which to begin a remediation program.

Would we be able to use dried seaweed in thermal compost?

Seaweed is low in nitrogen and phosphorus but contains all the trace elements that come originally from the land sand, silt, and clay. Seaweed does not need washing because the sea salts that adhere contain many of the trace elements. As well as trace elements, seaweed contains plant growth hormones such as gibberellin and auxins, all of which are beneficial to soil biota. A useful seaweed tea can be made by steeping the seaweed in clean water for a few days, stirring regularly. It produces a good foliar spray for vines, garden, and orchard.

How much does compost tea cost?

De Bortoli Vineyard in the Yarra Valley makes its own compost and compost tea from resource streams on-site.

- The making of the compost from hay, marc, and wood chips was costed at $13/m^3.
- Compost tea, which was made on site using fish, kelp, molasses, forest floor litter and aloe vera, including electricity, costed out at eight cents per litre, or $80/1,000 L.

One thousand litres of compost tea can be diluted depending on the soil health. At De Bortoli Vineyard, compost tea is applied at 40 L/ha, adding additional fish, kelp costing $32.20/hectare. On their calculation, 1,000L of compost tea covers 25 hectares. To find out more via the case study here

Further information:

- Innovative farmers: **Dr Elaine Ingham compost tea audio**
- Matt Powers the permaculture Student: **Dr Elaine Ingham Soil Food Web compost and compost tea**
- NRCS: **Soil biology primer**

FUNGAL TO BACTERIA RATIOS

Importance of fungal-to-bacterial ratios: should a vineyard be fungal or bacterial dominated?

The recommeded fungal-to-bacteria ratio for perennial plants is 5:1 (Malik et al., 2016) and about 1.6 to 2.0:1 for grapevines (Pearce, 2020).

To increase the fungal population in a vineyard, maintain a 100% plant cover across the vineyard from headland to headland including the vine rows.

Systems that involve ploughing or turning the soil have lower fungal-to-bacterial ratios than non-till systems. This is because soil disturbance damages the fungal hyphal biomass that connects plant roots in soil. High fertilisation rates decrease the C:N ratio favouring bacteria.

As fungal biomass lowers, the capacity of the soil to sequester carbon also lowers (Sinsabaugh et al., 2013). Table 5 shows carbon-to-nitrogen ratios of common raw materials. Grape marc has been used successfully as mulch in vineyards (DeGaris, 2012; Gomez-Brandon et al., 2021). Any material that was once a living plant can be composted.

The speed of the compost depends on the carbon-to-nitrogen ratio in the mix of raw materials. 20 to 30:1 C:N is considered a useful ratio to work with for a time-effective waste reduction (Insam, 2007).

Management techniques that feed the soil biota by way of compost, compost tea and biological foods include rock dust, fish, kelp, and molasses. Balanced vines result from an active soil biota, which helps to express the soil characteristics of the region (Chen, 2020).

When soil health and vine health are balanced, wine quality improves and better expresses the regional distinctiveness of the wine (Chen, 2020). Improved soil and vine health manifests in the quality and vibrancy of the wine. Increased Brix levels can be measured in the photosynthesising plant parts during the season as well as in the fruit towards harvest. As the soil comes into biological balance, so does the vine. The balance is shown in the acid, aroma, and sugar profile coming together at the same time, leading to more consistent fruit quality (Chen, 2020).

Perennial plants require fungal-dominated soils in which to thrive. Detailed explanations of the role of the groups of soil biota are best read from the **Soil Food Web**. If a vineyard has full plant cover in vine rows and windrows, and the use of synthetic chemistry is suspended, then the soil biota will be fungal dominated. Feeding with compost, compost tea if available, fish, kelp, molasses, rock dust, and humates will keep the soil biota in a high, active fungal range. Once synthetic chemistry is removed, and the biological products are applied monthly in the first year, then the change will be rapid.

A baseline biology should be carried out in autumn or spring or both and then again at the same time each year. These data showing the shift in microbial group populations indicate whether the recipe being used is improving the activity and whether the recipe can be amended considering the improved populations. Fungal dominance under-vine increases as the plant population in the vine-row establishes and covers the area with photosynthesis potential and the soil is filled with roots building up an arbuscular mycorrhizal population. Perennial cover crop plants are most appropriate for the mid-row and vine-row because they will create an equilibrium and stabilise the mycorrhizae biomass in the root zone. Bare soil will quickly become bacteria dominated so it is important to maintain a plant cover 100% of the time.

What is the role of phototrophic soil bacteria in soil remediation projects and plant health?

Phototropic bacteria are just one group in the diverse populations that are a healthy soil food web. A well-balanced soil resulting from applications of compost, compost tea, fish, kelp and/or molasses will have the phototrophic bacteria population in the range that it needs to be for the soil type and the season. It is not necessary to purchase any commercial biological products; it is much better to grow the species in the proportions that suit the soil in the vineyard. All the commercial species are like those in soils, but the local soil biota is adapted to the vineyard conditions. They just need the chance to multiply.

How suitable are eucalyptus mycorrhizal communities for vines?

Eucalyptus and Pinus species carry ectomycorrhizal communities but may carry arbuscular mycorrhizae as well. Some mycorrhizal species are not host specific and there is anecdotal evidence that both forms have been found on vine roots. Care needs to be taken if fresh mulch from either of these plant groups is available as mulch, such as from roadside tree management from councils. If this fresh material is available for free, then take as much as can be dealt with and make it into a windrow. Turn as per making compost and when the volatile oils can no longer be smelt, it is safe to use on the soil or as a brown component of compost. The oils are what are distilled as antiseptic Eucalyptus and pine oils. These are antimicrobial so they will be detrimental to the soil biota as well.

PLANT HEALTH

Is it possible to create an ecosystem that is not reliant on fungicides (sulfur and copper)? If so, what steps are involved and are there documented examples of this being done?

Copper and sulfur are the oldest used chemicals in vineyards. Copper is a heavy metal and can accumulate in soil, killing soil microbes that are important in plant health. Sulfur is toxic to beneficial mites and insects (Crisp et al., 2007).

Dagostin et al. (2011) found clay was as effective as copper on leaves and bunches and suggested that yucca extracts, *Salvia officinalis* extracts and the fungus, *Trichoderma harzianum* could be considered as promising candidates to be developed as a part of an IPM program for downy mildew control.

A healthy vineyard has less disease impact. Many biological controls are effective when the disease organism population is low. Milk, whey and Ecocarb were found to be as effective as sulfur in controlling powdery mildew when the disease pressure is low (Crisp et al., 2007).

Manage the vineyard environment in the biological soil health paradigm. Have an effective scouting and monitoring program operating in the vineyard to pick up the primary infections as they occur, and the products mentioned above will be as effective as sulfur and copper and less damaging to the environment.

Apply high quality compost tea throughout the season as a foliar spray to maintain high levels of beneficial organisms on the vines.

How to objectively assess improvements in soil and vine health

The easiest way to assess plant health is to buy a refractometer and use it daily at the same time of the day. Brix is directly related to photosynthesis so choosing a time in the afternoon around 2.30 to 3.00 pm guarantees maximum sunlight. A refractometer and garlic press can be carried in a pocket, although a modified pair of vice grips may be needed to extract juice from grapevine leaves. YouTube is a good source of instruction on how to use a refractometer.

Biological controls within a vineyard

Scale and weevils cause problems under some climatic conditions and are often a symptom of a system that is out of balance. Flocks of guinea fowl, geese, and chickens have all been used in vineyards with mixed results. Vineyards may be fenced against foxes and rabbits. The birds are successful in dealing with the pests but fox-proofing a length of fence over the long term is difficult and mortalities can be catastrophic when they occur. Scale can be a problem of unhealthy vines. Biologically healthy vines harbour less scale because of the diverse biota on leaf surfaces. Eco oils and Neem oils are two product types that could be useful. Compost tea made with an oily fish hydrolysate would smother the scale if applied as a drench.

Applying biological sprays to reduce frost impact

Frost damage can be significant in some regions and in some years. Plants grown in a biological system are stronger and more resilient to changes in temperature. Feeding with biological foods and spraying good compost tea heavy with beneficial microbes over at least 70% of the surface will help to minimise frost and heat damage but is not sufficient alone. It is reported that the application of flavonoids consisting of bitter orange extract (CropBioLife) have resulted in mitigation from heat and frost in grapevines.

MYCORRHIZAL FUNGI AND GLOMALIN

What is the importance of mycorrhizal fungi and glomalin in soil health?

Mycorrhizal fungi are a group of fungi that have a specific symbiotic/mutualistic relationship with living plant roots. This relationship is ancient but is important to plant health today. Some mycorrhizae are mostly external to the plant root (ectomycorrhizae), but most are internal and both external and internal (endomycorrhizae).

Proteaceous plant species and orchids have their own forms of mycorrhizal associations, but all provide the plants with increased nutrients, improve plant growth and yield, and provide moisture when needed (Phillips, 2017). Phosphorus is the major element supplied to plants via the fungal network, but nitrogen is as important.

Grapevine roots carry arbuscular mycorrhizal (AM) species – endomycorrhizae – that have spores out in the soil and arbuscules and vesicles inside the root. Ground cover diversity in the vineyard allows for diversity in the soil. Vine roots are connected by the network of fungal hyphae in the soil, leading to vine health.

Glomalin is a natural exudate of mycorrhizal fungi found by Wright and Upadhyaya (1996) and is now recognised as storing around one third of the world's stored soil carbon (USDA 2002).

It is a glycoprotein that stores carbon in its structure. The fungal biomass around plant roots in a no-till management program improves the water-holding capacity of the soil, leading to some protection against extreme cold and dry conditions. Tilling and the use of herbicides affects the functioning of the soil biota, glomalin and mycorrhizal fungi (Cole, In press; Phillips, 2017).

To achieve a healthy, functioning soil biota that includes mycorrhizal fungi, organic, and non-till agriculture/ viticulture provides the greatest benefit to plants and soil biota.

WEEDY SPECIES

The role of weedy species as early successional pioneer/indicator plants and using non-chemical methods to manage them

Weedy species are present because soil is depleted of biology and bacterial dominated. Deal with the underlying issue which is soil health. Improve the soil so that fungal domination takes over and weedy species become less of a problem, if at all. Good quality compost tea helps to shift the soil biota rapidly. Once the soil biota is fungal dominated then weedy species, especially flat weeds, do not grow because they are out competed by the more vigorous perennials. The poster presentation by Cole and Cavallo (2022) shows the shift in soil fungal populations from bacterial to fungal at the Agpath farm and a nearby vineyard where capeweed is eliminated when fungal-dominated compost tea is applied twice a year.

Understanding weeds within your vineyard

Weeds are primary colonisers. They fill bare patches of soil following a fire or cultivation or some other damage where vegetation is removed from the soil surface. Weedy species can be deep or shallow rooted, but they are fast growing, quick to flower and seed and have highly viable seeds.

Many weedy species are medicinal herbs so have an important role in the ecosystem. Broadleaf weeds tend to indicate an excess of potash relative to available phosphorus (McCaman, 2013).

Soil that is compacted or tight and anaerobic suit grassy species that like tight soil. This type of soil may have excess magnesium relative to calcium, so aeration is essential with applications of compost tea to increase fungal populations. Gypsum is not necessary, but this is a situation where it is often applied to the detriment of the soil biota. Aerate the soil and apply fungal-dominated compost tea (McCaman, 2013).

The pros and cons of using organically certified weedicides to manage weedy species and their impact on soil microbiology

If weedy species are a problem in the vineyard, then the soil biology is out of balance for perennial plants. Deal with the problem, not the result. Look at the soil biology balance. If it is not fungal dominated in the perennial vineyard then change the soil populations to fungal dominated with good quality compost and fungal-dominated compost tea. Weedicides, organic or otherwise, are band aids for a soil imbalance problem. Do not let any unwanted plant flower. Mulch the plant and it will soon die because of a lack of photosynthetic nutrient production. Once the soil is fungal dominated then remove the odd weedy species and make sure the soil has 100% cover 100% of the time.

Weeds are not all negative. Grower understanding of the benefits of some weeds, why they may have certain weeds and how to avoid weeds would be useful.

How to achieve 100% green cover in balance with invasive weed problems

The time taken to improve the general quality of soil and increasing soil biology will result in a change in the plant composition. Applying organic matter – mulch, compost, or compost tea – regularly over time will improve the soil biota, especially if the soil has been previously damaged by synthetic chemistry or over working. How much and how often is dependent on the result of chemistry and biology tests. It is useful for growers to learn how to measure qualitatively their soil biota using a simple light microscope. A soil test will show what elements are locked into the total pool and biology baseline information will show what the biological baseline is and what expected rates would be for that plant species and the time of the year.

MONITORING

How to understand your soil biology, and next steps that can be taken

Understanding soil biology requires training. Online courses are available through the Soil Food Web. Agpath Pty Ltd provides face-to-face courses and a soil testing service for accurate, quantitative soil biota assessments. Molecular biology, direct microscopy and qualitative analysis are methods of determining populations. Farmers are prepared to have soil samples taken before they purchase synthetic fertilisers. They also need to be prepared to have soil tested for microbial populations if they wish to apply organic amendments at the rates at which their soil requires.

Soil testing and assessment protocols / guidelines to assess soil microbiology

There are many methods of assessing soil populations. Molecular techniques are reductive but will provide total population biomass. There are monitors now available that will give an indication of soil biological activity through gas exchange (Doran, 2012; Gyawali, 2019). None of these methods gives a quantitative reading of each of the functional groups. However, they give an indication and are useful to build a trend. The quantitative method developed by Dr Elaine Ingham in her PhD thesis and used by Agpath Pty Ltd is a very accurate method because it uses direct light and fluorescent microscopy (Ingham, 1981).

Understanding what is in your soil or in your brews

A simple light microscope with some important basic features is all that is needed to look at soil biota qualitatively. This skill is taught at the weekend workshops run at the Agpath labs. A basic microscope must have two adjustable light sources and a movable stage with a slide holder clip on the stage. Microscopes now are digital so the image can be seen directly on the screen of a laptop or iPad. Microscope workshops allow growers to learn to recognise different soil organisms. On-line YouTube clips are excellent training for using a microscope. Agpath also has a closed website that contains a large number of soil, compost tea and compost pictures with captions that can be accessed by participants who have attended a small microscope course at Agpath.

Applying compost, compost tea and measuring success

Good quality compost should be sought if it is to be purchased. The volume to be used is directly dependent on the results from baseline chemistry and biology tests. Six or 12 months from the baseline reading, a second reading will show the change in the biota population and diversity. The second data set is used to modify the initial recipe. It takes generally 12 to 18 months to settle a soil into a new biological state. Improved productivity, increased yield, elevated Brix in tissue and change in vineyard floor vegetation (Herrero-Hernández et al., 2022).

Further information:

- Agpath Pty Ltd: **Compost tea ingredients**
- Soil Food Web: **Soil biology for crop nutrition and reduced pathogen outbreaks with Dr Elaine Ingham, Dr Mary Cole and Graham Lancaster**
- Soil Food Web: **The science of returning life to the soil**
- Soil Food Web: **What is the soil food web**
- Soils for Life: **Case studies**

FURTHER INFORMATION

Compost and mulch

- AORA: The use of compost and mulch in vineyards, a case study from Torbreck Vintners
- Compost for soils: Compost and straw mulches, compost for vineyard establishment, compost and nutrients, compost for managing salinity, compost for vineyard regeneration, organic matter for water saving
- EcoVineyards fact sheet: Preparation for making good thermal, aerobic compost for brewing compost tea
- EPA NSW: Using compost for sustainable viticulture
- Murraylands and Riverland Landscape Board: Making farm scale compost, farm-scale vermicomposting, farm-scale biochar production

Native insectary plants

- EcoVineyards: Journal articles on native insectary plants
- EcoVineyards: Regional plant species lists

Redox potential

- 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

Rhizophagy

- Bionutrient Food Association: The rhizophagy cycle, how plants get nutrients from microbes with Prof. James White

Soil biology

- Conservation Tillage and Technology Conference: Quorum sensing in the soil microbiome and Building new topsoil through the liquid carbon pathway with Dr Christine Jones
- DNRET: Soils alive, understanding and managing soil biology on Tasmanian farms
- Dr Christine Jones: Managing the carbon cycle
- EcoVineyards: Soil health indicators for Australian vineyards and the great Aussie Earthworm count poster and videos
- EU: European atlas of soil biodiversity
- NRCS: Soil biology and land management
- Rodale Institute: Types of mycorrhizal fungi
- Soil Food Web: Pathogenic fungi and plant pathogens with Dr Mary Cole
- The teabag index: Citizen science app

Soil carbon sponge

- Soil carbon sponge
  - Biodiversity for a liveable climate: The soil carbon sponge, climate solutions and healthy water cycles with Walter Jehne
  - Investing in Regenerative Agriculture and Food: Walter Jehne, stop talking about carbon emissions and focus on restoring the water cycle
  - Regenerate Earth: How hydrological processes naturally regulate and cool Earth's climate by Walter Jenhe
  - Regenerate Earth: Presentations
  - Regenerate Earth: Regenerate earth paper by Walter Jenhe
  - Regenerate Earth: Walter Jehne's Soil Carbon Sponge ABCD Regenerative Agriculture Podcast: Rebuilding the soil carbon sponge with Walter Jenhe
  - The Regenerative Journey Podcast: pioneering soil microbiology
  - The Wisdom Underground: Walter Jehne: clarifying climate history to find the right path forward

Soil health

- Books
  - For the love of soil by Nicole Masters
  - Holistic management handbook by Jody Butterfield, Sam Bingham and Allan Savory
  - Regenerative soil by Matt Powers
  - Teaming with microbes by Jeff Lowenfells
- GreenCover Seed videos:
  - Secrets of the soil sociobiome with Dr Christine Jones
  - The phosphorus paradox with Dr Christine Jones
  - The nitrogen solution with Dr Christine Jones
  - Cover cropping for carbon capture in vineyards and orchards with Dr Christine Jones
  - Why change? With Dr Christine Jones
- GreenCover: Soil health resource guide
- Lower Blackwood LCDC: Soil Secrets: The fundamentals for building profit, productivity and natural capital with Dr Christine Jones and Profit, productivity, and NPK with Dr Christine Jones
- Podcasts
  - Nutrition farming podcastwith Graeme Sait
  - Quorum sense podcast hosted by Jono Frew
  - Regenerative agriculture podcast by John Kempf
  - Talkin after hours with the Lower Blackwood LCDC
- Regenerative Ag Alliance: Creating a flourishing soil microbiome with Dr Christine Jones
- Soils for Life: Exploring the benefits of bio-amendments in cropping
- Soil Wealth: Biological products database
- The University of Adelaide: Soil carbon under-vine
- Vidacycle: A tale of two approaches: a guest post by Joel Jorgensen (Vinescapes)
- Vidacycle: Soilmentor app allows you to track 10 regen indicators, designed to represent various key aspects of soil health.

Viticulture

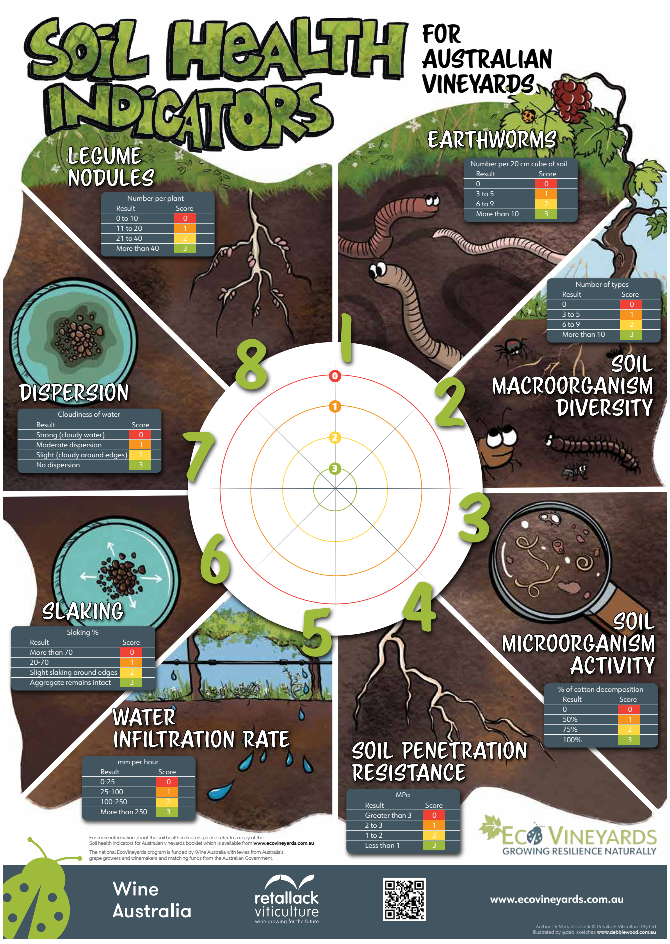
- Advancing Eco Agriculture: Regenerative crop intensive, viticulture

Water cycles

- Climate Farmers: Hydrology panel with Zach Weiss, Nicole Masters and Mark Shepard
- Climate Water Project: The quest to figure out the origin of rain, Part 1 and Part 2
- United Nations: Climate change, the water paradigm

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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The National EcoVineyards Program is funded by Wine Australia with levies from Australia's grape growers and winemakers and matching funds from the Australian Government.

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