

# Soil Health and its Management

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The BHU Future Farming Centre

Permanent Agriculture and Horticulture Science and Extension

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# 1. Introduction

This report is based on a booklet written for the Irish Organic Association [www.irishorganicassociation.ie](http://www.irishorganicassociation.ie).

The health of soil and its management by farmers, growers and all land managers is at the heart of many of the global challenges humanity faces such as climate change, biodiversity loss and nutrient pollution of water ways. Soil is a critical part of how planet earth's life support systems work. Some 60% of all living species, including everything in the oceans, make soil their home - so it is the most important and biodiverse ecosystem on the planet (Anthony *et al.*, 2023). It has key roles in the water (hydrological), nitrogen and carbon cycles, with soil being the second biggest store of biological carbon after the oceans. Soil is also vital to the provision of many ecosystem services (Figure 1).

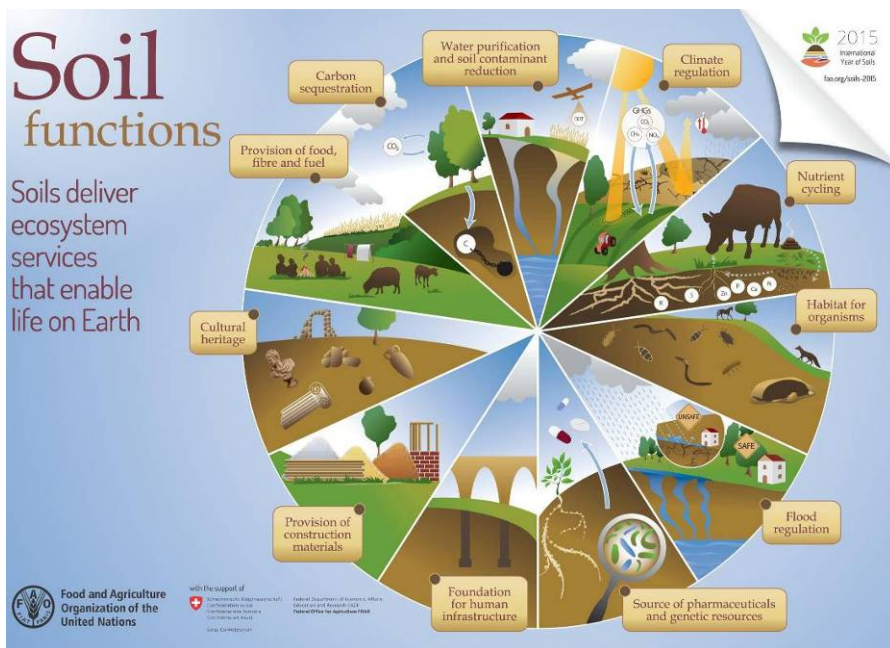


Figure 1. Soil function that deliver ecosystem services. Source FAO.

Soil in poor health cannot support these services anywhere near as well as a healthy soil.

Soil is also the literal foundation of farming and thus civilisation - food grown in or on soil (livestock) still represents almost all the food we eat. Food is the third most vital resource for people after air to breathe and water to drink. Thus, farming - feeding ourselves - is therefore the only truly essential activity human's undertake. Without healthy soil, agriculture functions poorly putting civilisation at risk of collapse.

Soil health is also key to farm productivity. Soils in poor health simply cannot grow as much pasture or crops as healthy soil. They are also more at risk of erosion by water and wind. As soil is the primary capital asset of a farm it's loss is effectively capital value washing away. So protecting soil health also makes excellent financial sense.

Thus if we are to successfully address the global challenges, farmers, growers and all land manager need to better look after their soil.

Since the turn of the millennium there has been a revolution - a paradigm shift - in soil science especially in the areas of soil biology / ecology and the formation of organic matter. This has in a large part driven by new technologies (e.g., the many forms of genetic (DNA) analysis, CT scanning and synchrotron particle accelerators) developed for other fields such as medicine, which have allowed soil scientists to study soil in ways that were previously impossible. Modern soil science has reached the point of considering the soil itself to be a living thing, not just a habitat for living things (Minami,



2021). For farming the most important part of this revolution is the formation of organic matter. This has moved from organic residues such as plant foliage, manure and compost to the exudates from living plant roots. This has massive implications for how soil should be managed to maximise its health and thus how we should farm.

This report therefore brings together the key knowledge required by farmers, growers and all land managers to understand the soil science revolution and how to manage their soils so they are healthy. The good news is despite soil being the most complex things humans manage, the 'rules' to successfully manage soil health are surprisingly simple, even if they can be practically more of a challenge to implement.

## 2. The soil health scientific revolution

The concept of soil health has in the past been a contentious issue within soil science, with some arguing the concept is meaningless. However, the majority of soil scientists now agree with the concept. A common definition is

“the continued capacity of a soil to function as a vital, living ecosystem that sustains plants, animals, and humans” (Doran & Zeiss, 2000)

More simply we can think about in terms of our own health: are you fit and eat a well balanced diet or are you sedentary and eat a lot of junk food? A healthy soil is one that functions as it would under natural vegetation, e.g., a woodland.

As soil is a living thing, the key to understanding soil health are its processes. Living things are divided into two main groups: autotrophs i.e., plants which get their energy from sunlight and make complex organic compounds like sugars, proteins and fats from carbon dioxide and water, and heterotrophs (e.g., animals and fungi), that consume the complex organic compounds made by autotrophs and break them down to release energy, carbon dioxide and water. This is life's foundational cycle of photosynthesis and respiration.

For soil, it is plants that capture the energy of sunlight and carbon dioxide from the atmosphere and then directly transfer it to the heterotrophs living in the soil via 'root exudates'. This is the core part of the revolution in soil science, that it is **not** dead residues like compost, manure and plant foliage that 'feeds' soil life, it is mostly exudates from living plant roots that drives the soil ecosystem.

### 2.1. Soil organic matter formation pathways

Figure 2 shows the two main soil organic matter (SOM) creation paths.

#### 2.1.1. Particulate organic matter (POM)

On the left-hand side of Figure 2 is the path that represents the old view of SOM formation. Organic materials such as compost, manure and vegetation are fragmented by larger soil organisms such as worms, then they are decomposed by microbes such as fungi and bacteria to form particulate organic matter (POM). However, instead of being the dominant source of SOM only about 20% of SOM is created through this route. POM is also not resistant to decay, and even the toughest organic material, like lignin (the compound that makes wood) is fully decomposed back to inorganic minerals (such as ammonium and phosphate) in a few years to a few decades at most.

##### 2.1.1.1. Humus does not exist

A key surprise in the soil science revolution is that humus does not exist! Traditionally humus was viewed as complex SOM that resists further decay (is recalcitrant) and for many it was the form of SOM that was the foundation of soil health. View was that it was the supposedly hard to decay materials, like the lignin in wood, that was converted into humus. However, when using new soil



analysis tools looking at intact soil, humus cannot be found. Indeed humus does not really make sense - dead organic matter is broken up by small soil organisms, then decomposed by microbes all the way back to inorganic compounds, and somewhere along this path of the chemistry getting broken down into smaller and smaller pieces, the large humus molecule is created. How does that happen? And what is it about the particular arrangements of carbon, oxygen and hydrogen in humus that makes it recalcitrant compared to all the other organic compounds in soil also made of carbon, oxygen and hydrogen that rapidly decay? Humus is now known to be an artefact of the alkali chemical extraction methods used last century.

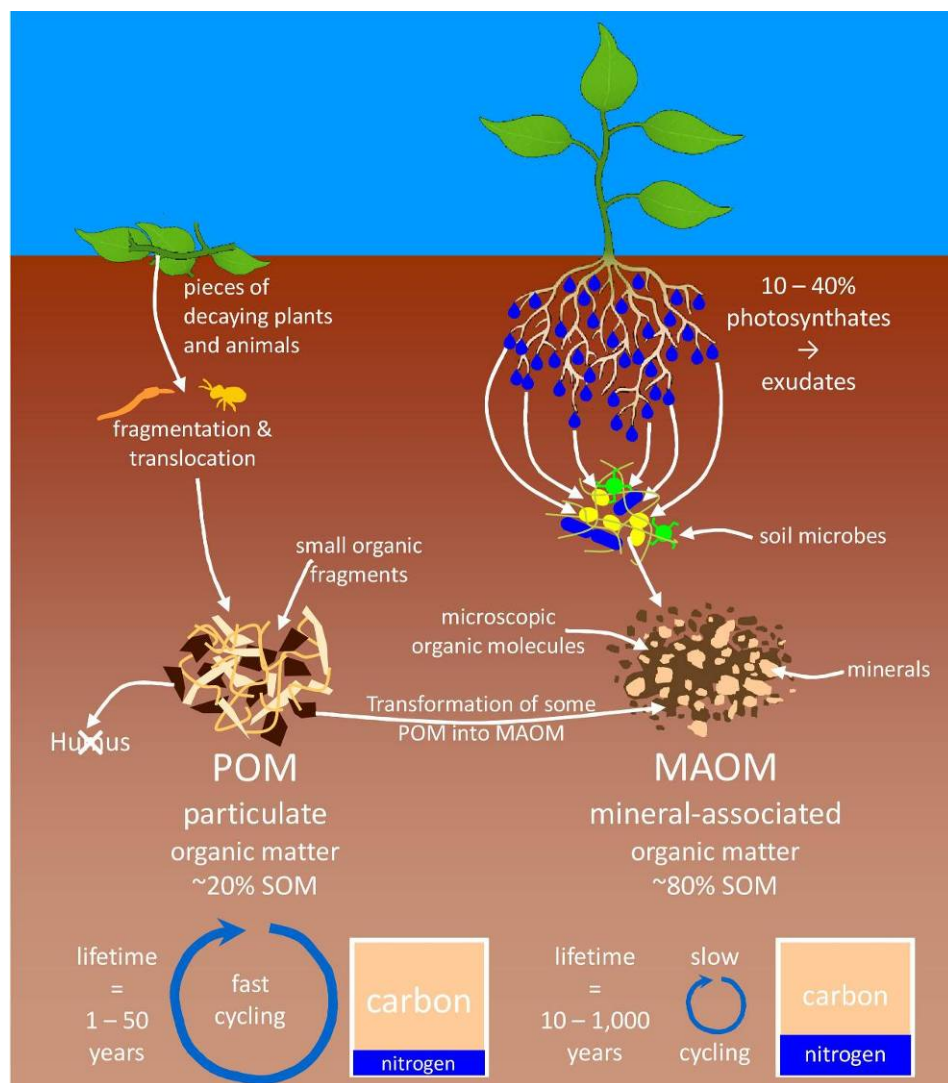


Figure 2. The two main soil organic matter (SOM) formation routes: particulate (POM) and mineral-associated organic matter (MAOM). After Jocelyn Lavalley (Cotrufo *et al.*, 2022).

## 2.1.2. Mineral associated organic matter (MAOM)

The right-hand side of Figure 2 shows the new SOM formation pathway that has been discovered as part of the soil science revolution. Through photosynthesis plants capture the energy in sunlight, and take carbon dioxide out of the atmosphere to create sugars. These are then transformed into all the other organic compounds i.e., carbohydrates, proteins and lipids. Then between 10% to 40% of these photosynthates are translocated down to the plants' roots and pushed out into the soil as 'root exudates'. These feed a vast density and biodiversity of beneficial microbes (e.g., bacteria, archaea and fungi) that live in a thin layer of soil around the roots called the rhizosphere. The microbes return the favour by helping the plants access water and nutrients and help protect the plant against pests and pathogens. Plants can even change the type of compounds they excrete to favour particular species of microbes when they need their specific help, for example fungi getting water in dry



condition. Different plant species also put out different kinds of exudates which feed different species of microbes. Thus to maximise soil biodiversity we need to maximise the diversity of plant species growing together, i.e., intercropping.

The microbes are themselves then consumed by other organisms and get killed by viruses, so the energy and organic chemistry in the exudates gets cycled through the soil ecosystem. Eventually the organic matter gets broken down into such small pieces that it ends up inside soil mineral particles, especially clay minerals. This is called mineral associated organic matter (MAOM). Some 80% of SOM is in the form of MAOM. Being inside the soil minerals protects the MAOM from further decomposition, resulting in MAOM potentially lasting from centuries to millennia. Thus MAOM derived from plant root exudates is the most important form of SOM, knocking humus off its throne. Hence the aphorism 'humus is dead — long live MAOM'!

Therefore maximising the creation of MAOM is vital to maximise soil health. Thus it is living plants via their root exudates that drive soil health, not plant residues, compost, manure and other organic residues. Indeed not only are plant root exudates directly feeding the majority of soil microbes, they are the primary source of energy for all soil biology / ecology, as it is only plants that capture the energy of sunlight.

### **2.1.3. Turning the standard view of plants upside down**

The standard view of plants is therefore upside down. That view is that plants take up water and nutrients from the soil and use that to build their foliage. However, plants are around 45% carbon, 45% oxygen, and 6% hydrogen, with nitrogen, phosphorous, potassium and all the other nutrients only being 4% of plant dry weight. All of the carbon and quite a bit of the oxygen are taken directly out of the atmosphere by plants. The rest of the oxygen and all the hydrogen comes from water - H<sub>2</sub>O - which also comes out of the atmosphere as rain (precipitation). Thus the vast majority of plant biomass comes directly or indirectly out of the atmosphere not the soil. Then 10% to 40% of the photosynthates are transferred into the soil as root exudates. Thus plants mostly push organic chemistry and energy into the soil rather than taking nutrients up from the soil, the opposite of the standard view.

### **2.1.4. Living roots year round not compost, manure and plant residues**

This revolution also kills the idea that dead organic mulches, compost, manures and other organic residues (e.g., foliage from cover crops) are the drivers of soil health. All of these end up as POM, so only represent some 20% of soil organic matter which decomposes quickly. None of the microbes that need root exudates to survive - which is many of them - are 'fed' by dead organic matter. Thus soil under dead organic mulches with no living plants is not healthy at all, it is literally dying.

This scientific revolution has been key for regenerative agriculture and is the origin of the saying 'a diversity of living roots year round'. To maximise soil health requires healthy soil biology, particularly microbes, and it is a diversity of exudates from a diversity of plant species, maximising photosynthesis and thus the amount of exudates that maximises the soil's microbial ecosystem and thus soil health, hence the regen mantra of 'a diversity of living roots year round'.

Therefore the focus of soil management needs to shift from organic residues like compost and manure to ensuring that there is as large a diversity of living plants, maximising photosynthesis and thus root exudates at all times. This is why regenerative agriculture has something of a fixation on cover crops and multi-species mixtures to maximise root exudate production. Indeed it is not the foliage from incorporated cover crops that provides the most benefit to soil health it's the exudates from the roots while the cover crop is alive, that provide by far the biggest benefit.



### **2.1.5. The soil health scientific revolution conclusions**

The soil science revolution has really important implications for land management. It clearly shows that having a diversity of plant species growing in mixtures (intercropping) and maximising the amount of foliage to maximise photosynthesis, which in turn maximises the amount of root exudates, is key to maximising soil health.

## **3. The three soil healths - physical, chemical and biological**

Building on the foundation of the new science of how soil functions, soil health is commonly split into physical, chemical and biological / ecological healths. Physical health is primarily about soil structure - how the pores and aggregates are arranged and the amount of compaction from the likes of livestock and machinery. Chemical health is focused on pH and nutrients - the chemical element that living things require. Biological / ecological health is focused on the organisms within soil, from viruses, then microbes such as bacteria and fungi, through invertebrates like worms, springtails, mites and nematodes to vertebrates such as moles, and how they interact, i.e., their ecology. Increasingly the flow of energy through the soil ecosystem - all of which originates from photosynthesis and is mostly delivered via root exudates - is increasingly viewed as another important way of understanding soil processes, and reinforces the point that soil is a highly dynamic, not a static, system (Wacha *et al.*, 2022).

While soil and its processes are incredibly complex actually managing soil health is surprisingly straightforward.

### **3.1. The three legged stool of soil health**

While viewed separately in terms of their management the three soil healths are all interlinked, with the metaphor of a three legged stool demonstrating that interdependence with each leg being one of the three soil healths. A three legged stool only works if all three legs are the same length and are firmly attached to the seat. The seat can be viewed as the energy flowing through the soil system and holding the legs together. For example, if one leg of a three legged stool is short, it can be fixed by shortening the other two legs to the same length, but now the stool is lower so its not as good a stool - the metaphor is that if one soil health is lower than the rest, lowering the other ones makes soil less healthy overall. Neither can a short leg be compensated for by making the other legs longer - you now have a wonky stool. The metaphor is that if, for example, biological health is poor it can't be compensated by trying to increase chemical health. All three soil healths support each other, chemical health supports biological health, which supports physical health, which supports chemical health. Therefore all three healths have to be equal to have a healthy soil overall.

## **4. Physical soil health**

Physical soil health is about soil structure, i.e., that soil is well aggregated with an open crumbly structure with lots of well connected pores Figure 3. An analogy is that soil should be like a sponge - a whole lot of tubes of different sizes all joined up together that make soil 'pores'. The pores are what allow air and water to percolate though the soil and help it hold more water. Around half of the volume of soil should be pores in a healthy soil. The stability of the aggregates - the crumbs of soil that surround the pores - are also key measure of overall soil health.



The opposite of a physically healthy soil is a compacted dense soil. The key things that damages physical soil health are:

- Compaction from livestock and especially machinery like tractors.
- Tillage / cultivation.
- A lack of living plants.



Figure 3. Examples of healthy (left) and unhealthy (right) silty loam soil. In the healthy soil note the darker colour, the crumbly structure, and good numbers of roots and earthworms. In the unhealthy soil note the paler colour, the platy blocky structure and few roots and earthworms.

## 4.1. Compaction

The damage done to soil from compaction and tillage (cultivation) have been known for centuries if not millenia. Farming inevitably causes harm to soil as livestock have to graze fields and machinery is needed to undertake field work. Even without machinery people walking on soil will still compact it. Compaction occurs the most when soil is moist or worse wet. Avoiding having livestock on fields and operating machinery and especially cultivating when the soil is too wet is essential.

### 4.1.1. Livestock surface compaction of macropores

There is increasing scientific and practical evidence of livestock causing a loss of macropores in the soil surface. Confusingly macropores are soil pores larger than 0.075 mm (75  $\mu\text{m}$ ) / 0.0029" which to a non-soil scientist is pretty small and about the same width as a human hair! The macropores are key to allowing the soil to 'breathe' i.e., exchange oxygen, carbon dioxide, water vapour and other gasses with the atmosphere. Without good macroporosity soil becomes anaerobic which is unhealthy. This happens far from the kind of very wet conditions that cause soil to liquefy, i.e., become slurry like, due to stock or machinery pugging soil, at which point soil structure has been completely destroyed and will take years to fully repair.

Even small livestock like lambs will compact - 'squish' - macropores when the soil is too moist. The heavier the animal the deeper the compaction will be, reaching as deep at 20 cm / 8" for cattle. If the surface compaction is present when soils dry out the compaction gets 'locked in' as the biological processes that create new macropores only functions slowly, if at all, in dry soil. Using tillage to break up the surface compaction is an option, but, machinery creates deeper compaction as discussed



below. Thus the use of stand-off pads, sheds / barns so that livestock can be kept off fields when conditions are wet, is of increasing importance to protect soil health and productivity over the longer term.

#### 4.1.2. Machinery compaction

Machinery, particularly tractors and heavy trailers, cause significant compaction. The increase in soil density (loss of pore space, crushing of aggregates) is mostly determined by tyre pressure with higher pressures causing the greatest increase in density. The weight of the machine mostly determines how deep the compaction goes. Under average soil moisture levels a Massey Ferguson 135 weighing in at just under 1.5 tonnes / tons with around 400 kg / 900 lb per rear tyre will compact to a depth of over 30 cm / 12", i.e., the bottom of the plough layer / topsoil - subsoil horizon. A four tonne tractor with 1000 kg / 2,200 lb per wheel will compact to nearly three quarters of a meter / 30", large tractors with 3000 kg / 6,600 lb per wheel will compact to a meter / 40" and a half loaded combine at 8,000 kg / 17,600 lb to over 1.5 meters / 60" Figure 4.

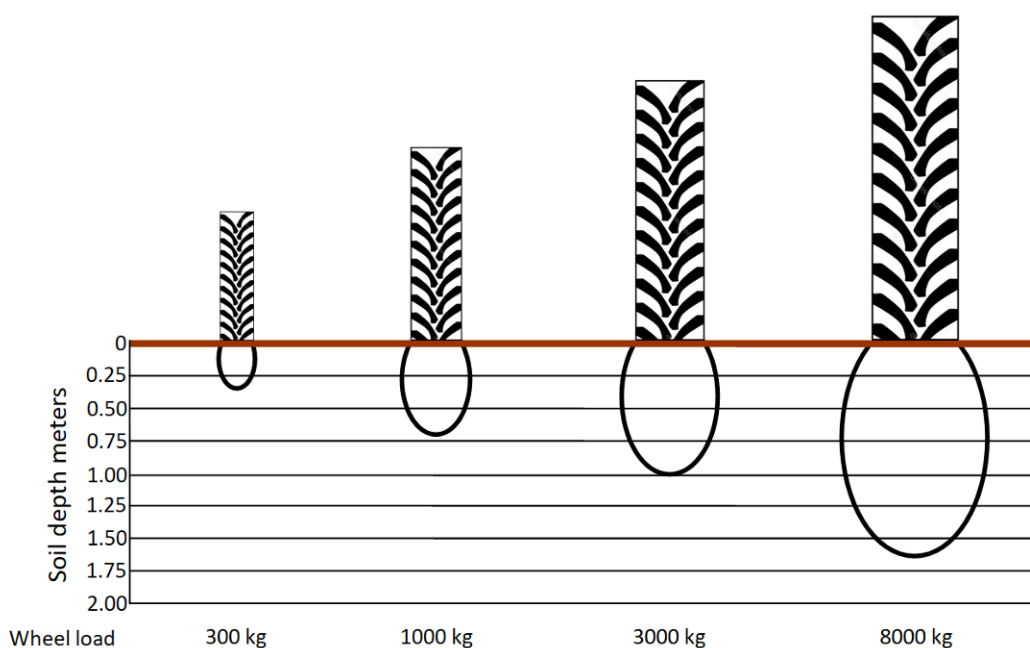


Figure 4. Depth of compaction for four different wheel loads ranging from very small tractor (~1.5 tonne) to half full combine harvester. Sources (Davies *et al.*, 2001; Keller *et al.*, 2025).

When machinery makes multiple passes in the same wheelings it is the first pass that causes most of the compaction - about three quarters. Therefore trying to spread compaction out by driving different paths across a field is worse for compaction than sticking to the same wheelings. This is the basis for 'controlled traffic farming' (CTF) where all, or at least most of the main machinery is set up to use the same set of wheelings leaving most of the field untrafficked and thus uncompacted Figure 5.

Having a clear strategy on minimising compaction from machinery is essential. Key aspects are:

- Minimising the use of machinery on fields - e.g., single-pass cultivators, min-till and no-till.
- Using the lightest (smallest) machine possible.
- Using as low a tyre pressure as practical / safe.
- Sticking to the same wheel tracks / using controlled traffic farming.



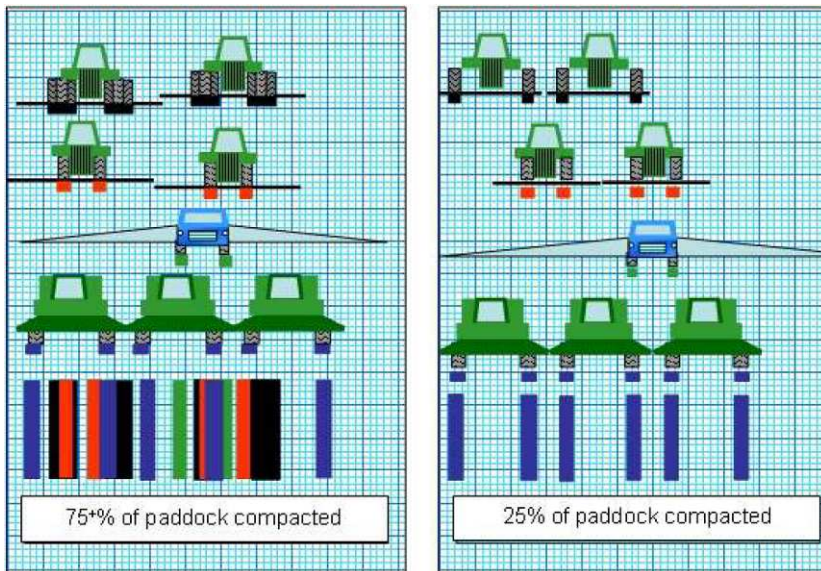


Figure 5. Left: uncontrolled traffic. Right: controlled traffic. Source (Bloomer & Powrie, 2013).

## 4.2. Tillage (cultivation)

All tillage (cultivation) harms soil health. Therefore all tillage should be kept to a minimum, e.g., minimum-till or no-till (direct drilling). The more power used in tillage the more energy is put into the soil and therefore the more damage done. Typically draft operations, e.g., harrowing, use less power than PTO powered machines, e.g., rotovator or power harrow, so draft operations cause less damage. Ploughing, while a draft operation, uses a lot of power (particularly full depth vs shallow ploughing) and causes a lot of soil disturbance particularly inverting the soil profile, so is also highly damaging. However, where soil has been significantly damaged, e.g., compacted or pugged, initial use of tillage can be valuable to give soil biology (including plant roots) a leg up to fix the damage. Fundamentally damage cannot be repaired by tillage alone, only biology can actually fix damaged soil and make it healthy again.

## 4.3. Aggregate stability

As noted above aggregate stability is a key overall measure of soil health. An example of the importance of soil health as measured by aggregate stability comes from a study of New Zealand arable farms where crop yield was directly related to aggregate stability Figure 6. This clearly shows the linkage between soil health, yield and therefore profit.

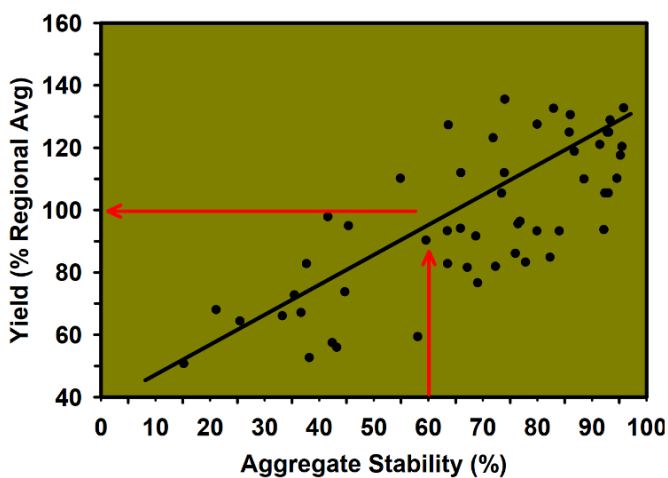


Figure 6. Relationship between aggregate stability and relative yield of grain, forage and process vegetable crops in Southland, New Zealand. From (Beare & Tregurtha, 2004).

To find out more about measuring aggregate stability see section 7.3.



## 4.4. Physical soil health conclusions

While some compaction and damage from tillage is unavoidable when farming, huge differences in the amount of harm done exist between best and standard practices. Along with insufficient nutrients, poor physical soil health is the biggest killer of yield. As Figure 6 shows from the poorest physical health (measured by aggregate stability) to the best, yield nearly quadruples! There is a lot of profit to be made from good physical soil health!

## 5. Chemical soil health

Chemical soil health is having the optimum levels of nutrients and pH for plant growth - not too little and not too much - i.e., in the 'Goldilocks zone'. See (Merfield, 2015) for a deep dive into nutrient testing. This report gives an overview of the key concepts from the perspectives of:

- Stoichiometry - the ratio of the chemical elements of life.
- Global nutrient cycles.
- The law of the minimum and Liebig's barrel.

This moves beyond the basic approach to nutrient management centered around soil nutrient testing and where nutrient levels are sub-optimal, of topping them up with nutrient sources such as mineral fertilisers such as urea and phosphate or organic fertilisers such as compost and manures. Global challenges such as climate change and nutrient pollution are directly tied to soil nutrient management, so this approach looks at the bigger picture, and which also provides an explanation for processes such as composting and nutrient cycling on farm.

### 5.1. Stoichiometry - the ratio of the chemical elements of life

All living things, bacteria, fungi, plants and animals, are made up of approximately the same ratio of nutrients - the chemical elements. All life, including humans, is mostly carbon, oxygen and hydrogen with a few percent of all the other nutrients. This means all living things need nutrients in the same proportion as their makeup. Table 1 lists the essential and beneficial plant elements / nutrients and the percentage of the essential elements.

Table 1. The essential and beneficial plant nutrients.

Essential Element	Percent	Essential Element	Percent	Beneficial Element
Carbon	45%	Sulphur	0.1%	Aluminium
Oxygen	45%	Iron	0.01%	Cobalt
Hydrogen	6%	Chlorine	0.01%	Sodium
Nitrogen	1.5%	Manganese	0.005%	Nickel
Potassium	1.0%	Boron	0.002%	Selenium
Calcium	0.5%	Zinc	0.002%	Silicon
Phosphorus	0.2%	Copper	0.001%	
Magnesium	0.2%	Molybdenum	0.00001%	

#### 5.1.1. Essential vs beneficial plant nutrients

Compared with other biological sciences, plant science has taken a very strict definition of 'essential plant nutrient' requiring that plants will die if they are absent (Brown *et al.*, 2022; Nunes da Silva *et al.*, 2022). However there are nutrients that are not essential by this definition but still produce a plant growth response, thus they are not essential but still beneficial. This strict definition has flowed through to legal definitions of what can be sold as a fertiliser, such that only essential nutrients can be sold as fertiliser. However, more than half of the elements in the periodic table are known to occur in



plant tissues (Brown *et al.*, 2022). Thus there is increasing scientific evidence that non-essential / beneficial nutrients may be limiting crop growth and thus applying them as fertilisers will boost crop growth and health.

In addition, animals (including humans) have a larger number of essential nutrients, which they need to get via plants, e.g., selenium. So for livestock and humans to get enough of these non-essential plant nutrients they need to be in the soil in sufficient amounts for plants to take up. It is thus as important to apply the animal specific nutrients to cropland as pasture so the crops have enough of these nutrients to ensure the people eating them are healthy.

For legumes the symbiotic bacteria and archaea that fix nitrogen need the non-essential plant nutrients cobalt or vanadium as these elements are at the heart of the nitrogenase enzyme which fixes the nitrogen. Soils that are deficient in cobalt or vanadium will grow legumes but there will be little nitrogen fixation occurring. Nitrogenase also contains iron, sulphur and nitrogen so deficiencies in these nutrients also results in low nitrogen fixation. Nitrogen fixation is also very energy intensive so requires considerable amounts of ATP (Adenosine triphosphate), the energy-carrying molecule for all living things) which has phosphorous at its core, so legumes need larger amounts of phosphorous than non-legumes.

To check if legumes are fixing nitrogen, cut open some root nodules where the symbiotic bacteria and archaea live and look to see how pink / red they are, or if they are white. The red is due to haemoglobin which 'mops up' oxygen which 'poisons' the nitrogen fixation process. White indicates no fixation, and the deeper the red the more fixation.

### **5.1.2. Stoichiometry, atmospheric and lithospheric nutrients**

Plants need to take up their nutrients in about the same ratio as their makeup. The most important nutrients, carbon, oxygen and hydrogen are taken up by plants directly from the atmosphere as carbon dioxide (CO<sub>2</sub>) and oxygen gas or as water that come from the atmosphere as rain. They are therefore classed as 'atmospheric nutrients'. All the other nutrients except nitrogen and to a small amount sulphur (e.g., phosphorous, calcium, potassium etc.) do not form atmospheric gasses so they are stored in the soil and only taken up by plant via their roots are thus classed as 'lithospheric nutrients' i.e., they come from the lithosphere - the rocks that make up earth's crust. While sulphur does form a gas - sulphur dioxide - it is only a small proportion of the amounts that plants need and are taking out of the soil, so for simplicity it is grouped with the lithospheric nutrients.

Thinking about nutrients in terms of their origins and cycles gives valuable insights into nutrient management. For example, it is fortunate that the around 90% to 95% of living things are composed of atmospheric nutrients which are cycled back to the farm for free via the atmosphere, because if all nutrients were lithospheric nutrients the same weight of fertiliser would have to be put back on fields as the dry weight of crops and livestock removed from the fields in harvest!

## **5.2. Nitrogen the oddball nutrient**

Nitrogen sits in both atmospheric and lithospheric worlds making it the oddball nutrient. Nearly all the nitrogen (N) on the planet is in the atmosphere which is mostly N<sub>2</sub> at 79%. This is because dinitrogen gas (N<sub>2</sub>) is almost as chemically unreactive as the noble gasses, so it does not partake in the chemistry that makes rocks. As N<sub>2</sub> is so unreactive it cannot be used by living things, instead it has to be converted into 'reactive nitrogen' (N<sub>r</sub>) before it can take part in the chemistry of life (biochemistry). Converting N<sub>2</sub> into N<sub>r</sub> is the process of nitrogen fixation, while the reverse process, converting N<sub>r</sub> to N<sub>2</sub> is denitrification. Thus all the nitrogen in soil originates from the atmosphere, it is fixed into N<sub>r</sub> and is stored in soil as organic matter, as there is no nitrogen in the rocks from which soil forms. It has to be one of evolution's biggest 'mistakes' that while most of the atmosphere is nitrogen plants and all



other organisms, can't directly use it, while in contrast for carbon which is present in the atmosphere at just over four parts per million (0.0004%) as CO<sub>2</sub> which plants take up easily and makes up 45% of their dry weight!

Understanding how nitrogen cycles through the atmosphere and soil is critical to its effective management and avoiding negative effects such as nitrate pollution of waterways.

### 5.2.1. The nitrogen cycle

Figure 7 shows the nitrogen cycle. It may at first look complicated but it is relatively simple. At a high level, starting at the top / in the atmosphere (sky) and going anticlockwise, N<sub>2</sub> gas in the atmosphere is fixed into reactive N<sub>r</sub> by diazotrophs (microorganisms that fix N), natural processes and N fertiliser production (it is exactly the same chemical reactions that makes biological and manufactured N<sub>r</sub>). It is then taken up by plants which return it to the soil as root exudates and when plants die, or they are eaten by animals and they excrete it in urine, dung and when they die. This forms the soil N<sub>r</sub> reservoir in the form of organic matter. Some of the mineral soil N<sub>r</sub> is converted from ammonium to nitrate which can be lost to leaching and denitrification returning the N to the atmosphere.

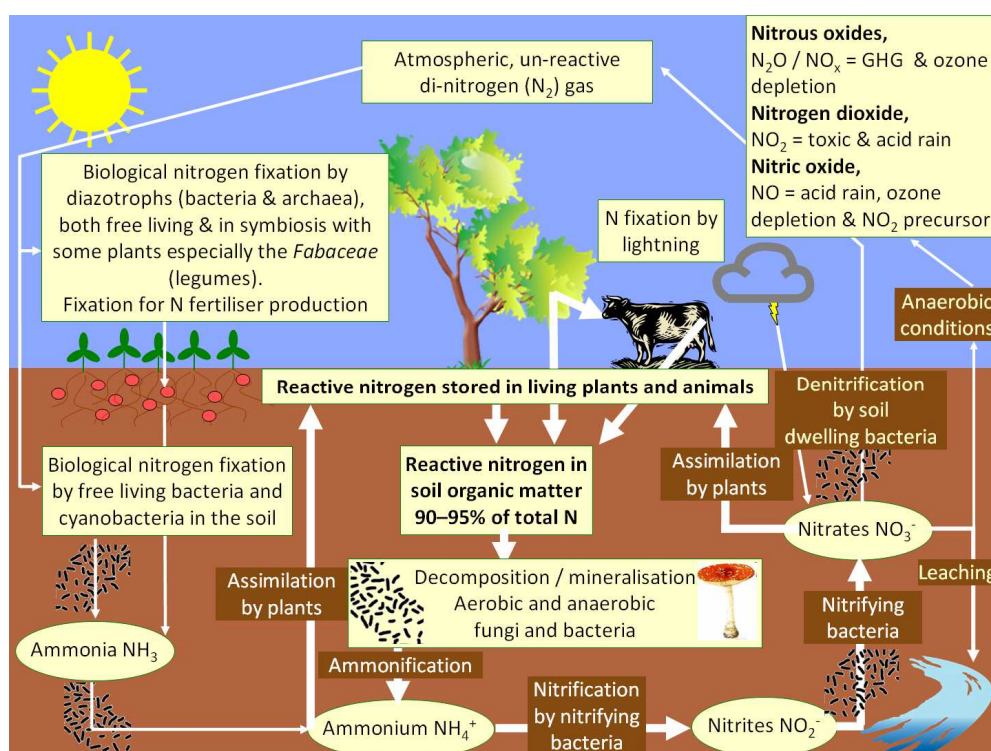


Figure 7. The nitrogen cycle.

### 5.2.2. Nitrogen fixation

In more detail, again starting in the atmosphere and going anticlockwise in Figure 7. Dinitrogen is fixed biologically by a range of diazotrophs which live freely in the soil and also in symbiosis with a range of plant species, of which the legumes are the most important in farming. For plants like clovers that have a symbiosis with the diazotrophs they provide the diazotrophs with a safe environment, nutrients and energy and in return the plants get first access to the nitrogen the diazotrophs fix.

Nitrogen is also fixed in the Haber-Bosch process that is the foundation of N fertiliser manufacture and the main industrial procedure for the production of ammonia.

Fixing nitrogen takes a lot of energy due to the triple chemical bonds of N<sub>2</sub> which require a lot of energy to break apart, both biological and man-made. This is why many N fixing plant reduce the amount of fixation if there is a plentiful supply of soil N, and why the Haber-Bosch process consumes



3-5% of the world's natural gas production which represents around 1-2% of the world's energy supply.

The first reactive nitrogen compound made is ammonia  $\text{NH}_3$  where three hydrogen atoms combine with the three chemical bonds of N. Ammonia is a gas and in soil it is quickly converted by bacteria and archaea into ammonium  $\text{NH}_4^+$ . Ammonium is one of the two forms of inorganic  $\text{N}_r$  that can be taken up by plants, the other being nitrate  $\text{NO}_3^-$ . As ammonium has a positive charge it binds to soil mineral particles and organic matter so it does not leach from soil.

### 5.2.3. The organic nitrogen soil cycle

When inorganic / mineral ammonium is taken up by plants or other soil organisms (mostly microbes) it is converted into organic forms of  $\text{N}_r$  Figure 7. The  $\text{N}_r$  then cycles through plants, livestock and soil biology until it dies and becomes part of the soil organic matter (SOM) pool again. Virtually all N in soil is in the form of organic matter or as mineral forms sorbed onto organic matter particles and inside clay platelets. As nitrogen is not found in the chemistry of rocks there is no nitrogen coming from the soil mineral particles or parent rock material, all nitrogen originates from the atmosphere.

However, plants cannot take up nitrogen (or any other nutrients) in the organic form. They can only take up nutrients, including nitrogen, as a small range of simple mineral (inorganic) forms as larger organic molecules cannot pass through the root surface and/or there are not the chemical uptake pathways for larger molecules. It is these forms of the nutrients that soil tests measure. Therefore to become plant available the organic  $\text{N}_r$  has to be decomposed / mineralised back to inorganic  $\text{N}_r$ . This decomposition is undertaken by a range of soil microbes, mainly bacteria, archaea and fungi. Fungi's 'speciality' is decomposition as they can break down organic compounds, like lignin / wood, that other organisms cannot and the mineralisation of SOM is the main transformation in the soil nitrogen cycle that is not entirely undertaken by bacteria and archaea. The process of mineralising organic  $\text{N}_r$  to mineral  $\text{N}_r$  is 'ammonification' because the primary inorganic form of  $\text{N}_r$  produced by mineralisation is ammonium. The newly created ammonium is then taken up by plants and soil microbes or it can continue being transformed into other inorganic forms of  $\text{N}_r$ .

### 5.2.4. Nitrate - where the trouble begins...

If the nitrogen cycle stopped with ammonium there would be a number of problems that would be avoided, mostly nitrate leaching and hazardous nitrogen gasses Figure 7. Indeed this how nitrification inhibitors work, they block the conversion of ammonium to nitrate. However there are a range of bacteria and archaea that oxidise ammonium called ammonia oxidisers. These first convert the ammonium ( $\text{NH}_3$ ) into nitrite ( $\text{NO}_2^-$ ) which is unstable and then quickly convert that into nitrate ( $\text{NO}_3^-$ ) Figure 7. While nitrate is good in that it is the other form of mineral  $\text{N}_r$  that plants can take up (using less energy to do so than ammonium) it has a negative charge, the opposite of ammonium ( $\text{NH}_4^+$ ), so it can leach from soil when there is drainage, which is bad. Nitrate leaching represents a loss of valuable nitrogen from farmed soils, and worse, nitrate along with phosphate (see below) are the main nutrient pollutants of waterways.

Nitrate is also the main form of mineral  $\text{N}_r$  that is denitrified (by bacteria and archaea) back to  $\text{N}_2$  gas which is another loss of nitrogen from the farm system Figure 7. Worse, under anaerobic soil conditions bacteria and archaea produce nitrous oxides, nitrogen dioxide and nitric oxide which between them are powerful greenhouse gases, causes of acid rain, are toxic and ozone depleters, all of which are very bad Figure 7. As discussed under physical soil health, compaction is a major cause of soils becoming anaerobic as it destroys macropores, so minimising compaction is vital for soil nitrogen management and a key example of physical soil health impacting chemical health.

$\text{N}_r$  is also produced in the very high temperatures and pressures in lightning, which mostly produces nitrate and some ammonia Figure 7. Depending on the frequency of lightning a few kg to a few tens



of kg per ha per year are produced / fall on farmland. There are other atmospheric processes that can create  $N_r$  but the amounts are minor.

### 5.2.5. Availability of soil nitrogen

That SOM has to be mineralised to make the N in it plant available, and that N is lost as nitrate when there is soil drainage has significant implications for soil N availability. To mineralise the SOM microbes need the right temperature and moisture. They cannot function below 'biologic zero' (akin to absolute zero in physics) below which it is too cold for their biochemistry to function, so they are dormant. Biologic zero ranges from about 5°C to 10°C / 41°F to 50°F with an average of about 7°C / 45°F. So below a soil temperature of around 10°C / 50°F little or no mineralisation can occur. Soil also needs to be sufficiently moist for the microbes to have enough water for their biochemistry to function, so in dry soils little mineralisation will happen either. Mineralisation thus occurs the fastest in hot (up to approx. 25°C / 77°F) moist soils, is average in warm to hot, dry soils, and cool, moist soils, and the least in cold, dry soils.

In temperate climatic regions, where there are clear swings between hotter dryer conditions over summer and wetter cooler conditions over winter, the seasons have significant impacts on mineralisation, nitrate loss and plant available N. In spring the soil is at it's coldest and wettest, so there is little mineralisation. It is also likely that there has been soil drainage over winter so nitrate will of leached from the soil, potentially to the point nearly all nitrate has been leached. Quite a lot of the ammonium will also have been taken up by the plants over the winter. This means there could be very low plant available soil N in early spring. However, plants are already starting to grow in spring and thus need soil N, which is why early spring is when plants often show N deficiency if they are entirely reliant on soil N. The judicious use of plant available forms of N, e.g., soluble mineral fertilisers, slurry, farm yard manure (FYM), anaerobic biodigestate, and foliar N fertilisers can be used to address this shortfall.

As spring progresses into summer soils are warming up but also drying out, so mineralisation initially speeds up, but then slows down again as soils dry. However, as soils are dry there is no drainage and thus no nitrate leaching, so nitrogen that is mineralised is retained in the soil. If irrigation is being used, or it's a wet summer, then mineralisation can occur at high rates. Then as summer turns to autumn soils are cooling down but becoming wetter so there is another pulse of mineralisation which then slows as soils approach biologic zero. Then in winter plants take up available N, if there is drainage nitrate is leached so plant available N reduces to low levels again as spring approaches.

### 5.2.6. The two N cycles

There are thus two main linked N cycles in Figure 7. Around the outside is the inorganic cycle where atmospheric  $N_2$  is converted to inorganic forms of  $N_r$  which cycle through the soil before returning to the atmosphere, mostly as  $N_2$ . Within that at the center of Figure 7 is the organic nitrogen cycle where SOM is converted into ammonium and then nitrate which are then taken up by plants and microbes converting it back to organic  $N_r$  which then cycles through biology before returning to the SOM pool. This highlights the critical importance of SOM as the reservoir of soil nitrogen. Thus soil nitrogen management and SOM management are two sides of the same coin, and another key link between chemical and biological soil healths. Most transformations in soil of the different forms of  $N_r$  are only undertaken by bacteria and archaea making them critically important at farm and planetary level. For a deep dive into nitrogen and farming see (Einarsson, 2024).



## 5.3. Phosphorous and the lithospheric nutrients

Phosphorous is the nutrient required by plants in the largest amount after nitrogen. It's also a proxy for all the other lithospheric nutrients, i.e., everything apart from carbon, oxygen, hydrogen and nitrogen as the nutrient cycles are the same for all of them. There are two main lithospheric nutrient cycles: the soil cycle and the geological cycle Figure 8.

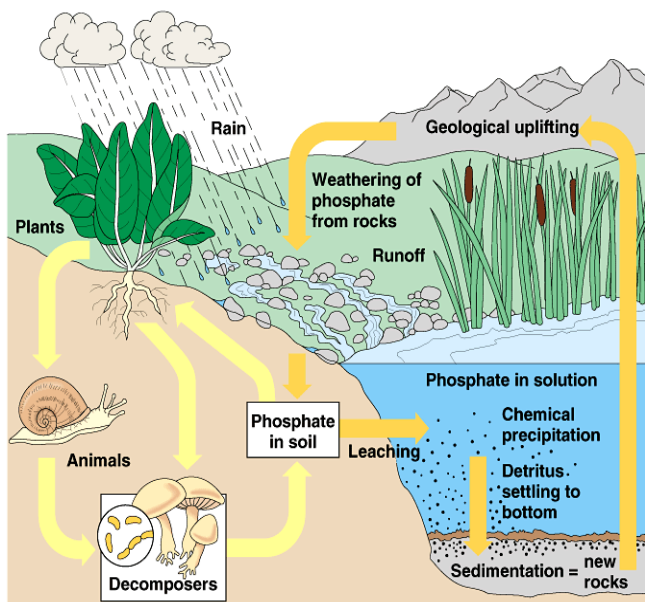


Figure 8. The two phosphorous / lithospheric nutrient cycles: soil and geological. Image from Pearson Education.

In the soil cycle phosphate in soil is taken up by plants and other soil microbes, flows through biology which when it dies and is mineralised returns to the phosphate pools in the soil Figure 8. This is the fast / biological phosphorous cycle. Some phosphate in the soil cycle is lost to waterways, even under natural vegetation, but increases under agriculture. Once in waterways such as streams, rivers and lakes, the phosphate is carried out to the seas and oceans where it falls to the bottom, accumulating as sediments which eventually turn into rocks, which are uplifted by plate tectonics to form new land, which is then eroded releasing the phosphate to re-enter the soil cycle Figure 8. This is the geological / slow phosphorous cycle. Clearly the soil and geological cycle operate at different time scales. An individual molecule of phosphate could complete the soil cycle in a few days, through to centuries. The geological cycle operates at time scales of tens to hundreds of millions of years. Therefore, at human time scales the loss of phosphorous and other lithospheric nutrients from the soil cycle to the geological cycle is effectively a stream - the nutrients are 'lost' to the oceans. Humanities short circuiting of the lithospheric nutrient cycles, particularly phosphorous, is one of the key longer term challenges agriculture faces. See (Merfield, 2024) for more information.

### 5.3.1. Soil phosphorous cycles and pools

The detailed behaviour of the phosphorous (P) cycle in soil is considerably more complex than the high-level soil P / lithospheric cycles in Figure 8. Understanding it in some detail is important to better manage it on farm and also understand the complexities of phosphorous nutrient tests. It is influenced by multiple factors including:

- The nature of the inorganic and organic solid phases.
- Type and extent of biological activity.
- Chemistry of the soil solution e.g., pH, ionic strength, redox (reduction-oxidation) potential.
- Environmental factors such as soil moisture and temperature.



Soil phosphorous exists in a number of different soil 'pools' which interact with each other Figure 9.

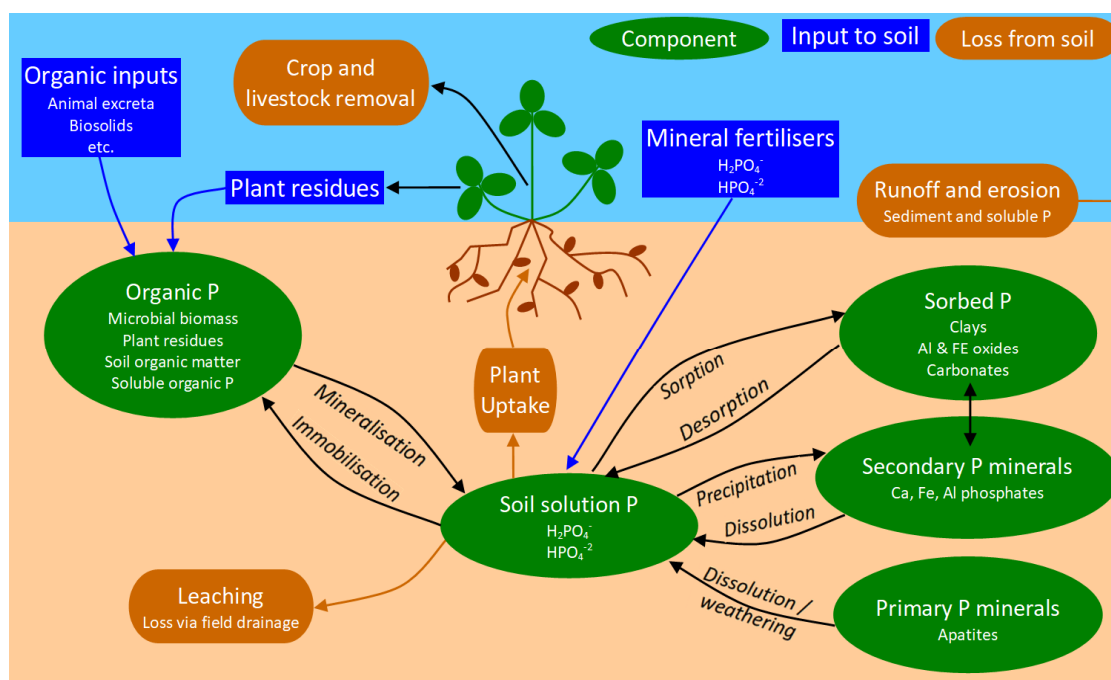


Figure 9. The soil phosphorus cycle and pools. Redrawn from (Prasad & Chakraborty, 2019).

The soil solution P pool is P that is in soluble forms, called orthophosphate, that can be taken up by plants and also leached Figure 9. The concentration of the soil solution is generally very low, such that there is less than 1 kg of soluble P per ha, or 1% of total soil P. The soluble P pool exchanges P with three other soil P pools, the organic, sorbed and secondary mineral pools.

Sorbed P is bound to the surface of aluminium and iron oxides and carbonates. Sorption and desorption are generally quick processes. Soils with bigger concentrations of iron and aluminium oxides have greater ability to adsorb phosphorus than soils with relatively low iron and aluminium oxides. The same applies to clay content. The sorbed P pool is therefore particularly important for replenishing the soluble pool as it is depleted by plant uptake. Plants may have sufficient P or be deficient in P depending on how quickly the soluble pool is replenished from the sorbed P pool.

Precipitation and dissolution, between the soluble P pool and secondary P minerals such as calcium, iron and aluminium phosphates is a much slower process. Metal ions such as Al<sup>3+</sup> and Fe<sup>3+</sup> are dominant in acidic soils and Ca<sup>2+</sup> are dominant in calcareous soils. These react with phosphate ions in the soluble P pool to form minerals such as Al<sup>+</sup> Fe<sup>-</sup>, or Ca<sup>-</sup> phosphates.

The soluble P pool is also very slowly replenished from the primary P minerals in the soil, principally apatites, through physical, chemical and biological weathering of the parent rock material. This is a one way process.

As soluble P is removed, either by plant uptake or leaching losses, it is replenished primarily by desorption from the sorbed P pool and some mineralisation from organic P pools Figure 9. This process also works in reverse; where soluble P is sorbed onto clays, aluminium and iron oxides and carbonates, and soluble P is immobilised into organic P, e.g., through being taken up by microbes. Due to the small size of the soluble P pool compared with the larger amount of P required by plants the soluble P pool needs to be replenished multiple times during the growing season.

When soluble mineral (inorganic) P fertilisers, such as rock phosphate, are added to the soil, they enter the soluble P pool. If enough fertiliser is applied some of the soluble fertilizers P enters the sorbed and secondary P mineral pools, making them unavailable to plants. Some of the soluble P from fertiliser is also immobilised into the organic P pool. When P is added in organic forms (manure,



compost etc.) it enters the organic P pool, so only becomes plant available after it has been mineralised (decomposed).

### 5.3.2. Phosphorous and pH

As noted above, the movement of P between these different pools is mediated by a wide range of both biotic and abiotic conditions, e.g., soil temperature and microbiology. pH is particularly important determining availability to plants Figure 10.

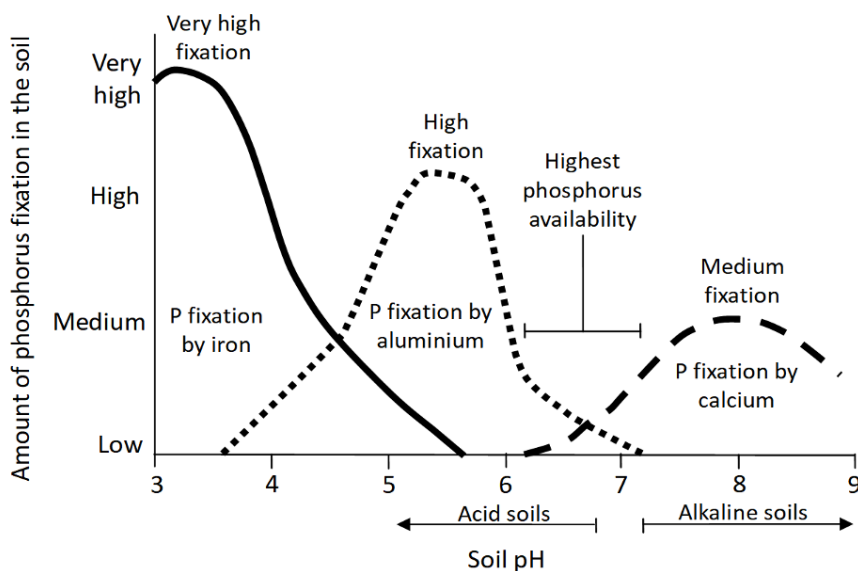


Figure 10. Influence of soil pH on P availability and fixation in the soil. Redrawn from (Plunkett *et al.*, 2019).

In acid soils, P fixation is higher and it is fixed by iron and aluminium. In alkaline soils, P fixation is lower and is fixed by calcium. The least P fixation / highest P availability is between pH 6–7.

### 5.3.3. The complexity of phosphorous nutrient tests

All of this complexity is why there are different soil phosphorous tests, as different tests measure different parts of the multiple phosphorous pools in the soil. See (Merfield, 2015) for a deep dive into nutrient testing. For a full dive into phosphorous and farming see (Merfield, 2024).

## 5.4. All other lithospheric nutrients

All the other lithospheric nutrients apart from phosphorous and oddball nitrogen don't have the same complexity to their cycles and behaviour in soil. They all originate from the soil's parent material, they exist in the soil as available forms that plants can take up and which soil tests measure, and unavailable forms - the parent material and the SOM pool, which the same as nitrogen has to be mineralised to make them plant available. Thus their management is based on soil tests and where they are sub-optimum replenishing them with suitable organic or inorganic fertiliser.

## 5.5. Micronutrient deficiencies

Globally there are increasing problems with micro (trace) nutrient deficiency, such as iron, chlorine, manganese, boron and zinc. There is a common misunderstanding that because micronutrients are needed in much smaller quantities than the macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) they are less important. This is incorrect. Any organism is just as dead if it is deficient in copper that is required at 0.001% than nitrogen at 1.5%. Essential is essential regardless of the amount required.



Organic forms of fertiliser such as manure, compost and guano typically contain a full range of micronutrients due to the source material containing a full range of micronutrients. In comparison, mineral and manufactured fertilisers, such as rock phosphate, superphosphate, ammonium nitrate and urea have low or no micronutrients, particularly the highly refined forms. With the shift in the 1900s from organic to mineral and refined fertilisers, the main input of micronutrients to farmland was lost. Coupled with the focus of soil nutrient testing and fertiliser application on the macronutrients, much farmland has therefore become increasingly micronutrient deficient. It is therefore essential to test for micronutrients (and also non-essential but beneficial nutrients) to determine if any are sub-optimal, and if so, then apply them as an appropriate form of fertiliser.

It is also important to ensure micronutrients are not above optimum as they can become toxic at higher levels. The macronutrients have long and quite flat yield / growth response curves (see Merfield (2015) for details on growth response curves) meaning that sufficient levels of each nutrient are quite wide. In comparison the micronutrients growth response curves are narrower meaning their levels can go from deficient, through optimal to toxic over quite narrow ranges. Copper is the classic example of this, it is an essential nutrient but becomes toxic if levels are too high, and as a chemical element it can't be broken down so it can only be removed in harvest. This is why there is increasing legislative controls (e.g., in the European Union) on the amount of copper and other heavy metals used in farming.

## 5.6. pH

Fortunately managing low soil pH is straightforward. Soil testing, either laboratory or in field with pH test kits, give an estimate of pH, which if below optimum is rectified by adding lime. Rectifying excessively high pH requires expert advice.

## 5.7. Law of the minimum and Liebig's barrel

Liebig's law of the minimum states that an organism's growth is dictated not by total resources available, but by the scarcest resource - the limiting factor. This is visually portrayed as Liebig's barrel Figure 11 where the shortest stave determines the water level.

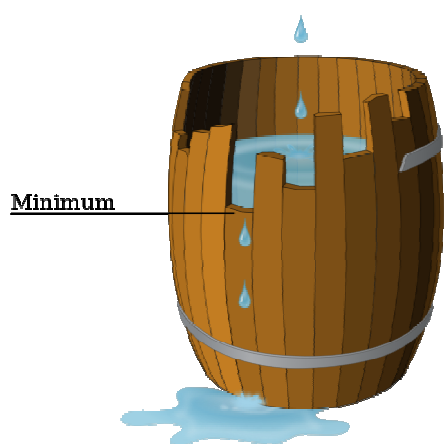


Figure 11. Liebig's barrel. Source By DooFi - Own work, Public Domain, [commons.wikimedia.org/w/index.php?curid=6627159](https://commons.wikimedia.org/w/index.php?curid=6627159).

This is a direct consequence of stoichiometry - that all living things are made up of the same proportions of the chemical elements. All elements / nutrients have specific roles in biochemistry and cannot substitute for each other, e.g., sulphur cannot substitute for phosphorus in ATP. Thus like the three legged stool of soil health needs all the legs the same length, all nutrients, including the micronutrients need to be at optimum levels - have staves the same length - along with pH, if



chemical soil health is to be maximised. This is the primary function of soil nutrient testing - to ensure that all soil nutrients and pH are at their optimum.

## **5.8. Organic nutrients - compost and manure**

There are a number of specific issues when using organic sources of nutrients, such as compost and manure.

### **5.8.1. Balancing nutrients**

The challenge for organic forms of nutrients like manure and compost is they contain a full range of essential and beneficial nutrients but there is little or no control over the proportions of the nutrients. Therefore if a soil is at optimum for some nutrients but deficient in others, organic forms of nutrients cannot bring up the deficient nutrients without over fertilising the ones already at optimum. In this situation straight mineral fertilisers should be used to bring the deficient nutrients up to optimum without over supplying the ones already at optimum. Excessive nutrients are as bad for plant growth, even toxic, and a cause of environmental pollution, especially nitrogen and phosphorous, so over fertilisation must be avoided.

### **5.8.2. Over fertilisation with compost**

The over-application of compost is a case in point, especially on intensive organic horticultural operations. Compost (and any other organic form of nutrients) must only be applied at rates that replace the nutrients removed in harvest. The simple way to picture the amount of nutrients removed in harvest and thus how much compost would replace them is to estimate the amount of compost that would be produced if the harvest was composted instead of sold. The concept of atmospheric and lithospheric nutrients is key here. During composting it is the atmospheric nutrients carbon, oxygen, hydrogen and nitrogen plus water that are 'lost' and return to the atmosphere, completing their cycles. That is why compost reduces so much in volume as most of the material being composted (plants, manure, etc.,) is carbon, oxygen, hydrogen, nitrogen and water. As the lithospheric nutrients don't form gasses they are 'trapped' in the compost heap, so while their total amount does not change, their concentration increases as the atmospheric nutrients and water are lost from the heap.

For light feeders, like salads, that remove few nutrients as they are mostly leaves full of water, a few hundred kilos per hectare / pounds (lb) per acre, per year of compost would be more than replacement. For 'heavy feeders' that can remove a lot of nutrients, e.g., potatoes can remove 100 kg per ha / 90 lb per acre of potassium in a high yield would require a ball-park 30 tonnes per ha / 12 ton per acre of compost to replace the potassium. 30 t/ha of compost spread on bare soil would just be visible when standing. About 100 t/ha of compost would just cover the soil. Some organic horticultural operations are applying compost in layers centimetres thick which would amount to thousands of tonnes of compost per hectare per year. That represents centuries even millennia of nutrient supply and is gross violation of organic principles, even if organic standards do not prohibit it (which they should).

### **5.8.3. Nitrogen losses - compost vs. anaerobic biodigestion**

Between 25% and 75% of the nitrogen in the starting material is lost in the composting process which is partly why compost is not a good source of nitrogen. This is why anaerobic biodigestion, which retains all the nitrogen during the biodigestion process, with a considerable proportion being in the mineral forms of ammonium and nitrate, offer considerable advantages over composting by keeping more nitrogen on-farm and in plant available forms. For example in an organic stockless arable system, harvesting the pasture phase of the rotation and putting it through a biodigester, and putting



the biodigestate on the cereal crops, compared with leaving the cut pasture in-situ, increased cereal crop yields by 27% to 47% (Serdjuk *et al.*, 2018).

For more information on the supply of nitrogen and phosphorous from compost see (Prasad, 2009a, 2009b).

## 5.9. Chemical soil health conclusions

Our understanding of the complexities of how nutrients cycle at the planetary level and behave in soil is now comprehensive. We thus have a very good understanding of these processes and thus how to best manage them, i.e., regular soil nutrient tests, including micronutrients, backed up by plant tissue analysis, informing organic and inorganic nutrient applications based on the results of those tests. So, despite the complexities of how nutrients, particularly nitrogen and phosphorous behave in soil understanding how to manage them is pretty straight forward.

## 6. Biological / ecological soil health

Biological / ecological soil health is about the biodiversity of species in the soil and how they interact i.e., their ecology. As noted in the introduction, soil is the most complex and biodiverse ecosystem on planet earth - far more complex than any tropical rain forest. Most of the life forms are microbial, such as bacteria, archaea, fungi and protists, the majority of which can only be detected through genetic techniques as they can't be grown in the lab, and there are far too many to try and culture them. Figure 12 is a phylogenetic tree showing the genetic diversity of bacteria, archaea, and eukaryota. This gives an indication of the diversity of soil biology and that most of life's genetic diversity exists in the prokaryotes not the eukaryotes even if bacteria and archaea all look the same. Only genetic analysis can measure the diversity of life in soil, the optical microscope techniques used last century are no longer viable.

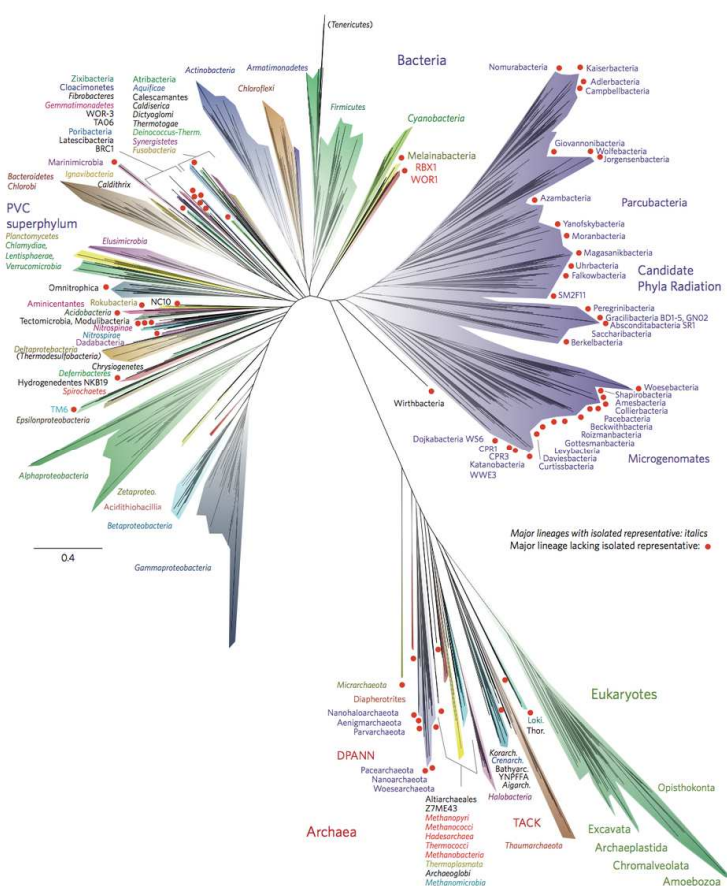


Figure 12. Phylogenetic tree showing the diversity of bacteria, archaea, and eukaryota. From (Hug *et al.*, 2016).



Despite this vast biodiversity and complexity managing it is again pretty straight forward. As explained in section 2 on the soil science revolution, the start of the soil ecosystem is plants which drive the soil ecosystem by the production of plant root exudates that feed the first tier of soil microbes, which then become food for the rest of the ecosystem. Hence the mantra ‘a diversity of living roots year round’, i.e., maximise the number of species of plants growing in on place, maximise their leaf area to maximise photosynthesis, so they produce the maximum amount of root exudates to power the soil ecosystem and organic matter formation.

As all living things are made of the same proportions of nutrients if soil has the right amount of the nutrients for plants it will have the right amount of nutrients for all soil biology from bacteria upwards. So, good chemical soil health is essential for biological soil health. Likewise, “Soil is a house full of microbes and the architecture of the house influences how the microbes behave” (Andrew Neal, pers. comm.). The architecture is soil structure, i.e., physical health, so good physical health is essential for good biological health. Biological health in turn creates good physical and chemical health hence the three legged stool of soil health.

## 6.1. Measuring soil biology - or not?

With the growing understanding of the importance of soil biology, there is increasing interest within agriculture in measuring it, to help improve its management. Various companies offer a range of tests that purport to measure soil biology. However, as noted above, the vast majority of the important organisms living in soil, excluding plants, are microbes, mostly bacteria and archaea and some fungi. These can mostly only be measured by genetic techniques, which the majority of commercial soil biology tests don’t use. But, even if you did get an analysis of the species diversity in a soil, at a practical farming and growing level the question is - what does it mean? The answer is - we don’t know, or even that it does not mean anything at all. For information to be of value, a farmer or grower needs to be able to make a management decision on that information.

Science has a really deep and broad understanding of the organisms in soil, as Figure 12 shows, and those are just the headlines, not the details, which are truly immense. But in terms of practical soil management there is little or no meaning to have more of one type of organism, or genetic diversity, or functional ecological redundancy, in terms of day to day farm management because it is not possible to make a management decision on that information. This is because the soil ecosystem (as mentioned at the start) is the most complex ecosystem on the planet and one of the harder ones to study, despite literally being under our feet. The number of interactions is so vast, teasing out how they work and the implications is a massive task.

Measuring soil biology is therefore utterly different to measuring soil nutrient levels. With nutrients there is a very substantial body of science that says for a given nutrient level, in a given soil type, for a particular crop, there is a well established probability that if that nutrient is added to the soil (or applied as a foliar fertiliser) a plant growth response will occur. There is a very clear chain of cause and effect, and it is mostly linear - plants are made of nutrients, if there is not enough of one or more, adding them will give plants more of what they need and they will grow more.

The same is completely untrue of soil biology, due to the complexities of the soil ecosystem. The ecosystem is highly dynamic, with many feedback (circular) processes, most being non-linear (chaotic) rather than linear, so it is impossible to draw a simple cause and effect linkage between say, the ratio of bacteria to fungi in a soil and (1) to say what that means and (2) to say what should then be done in terms of farm / soil management based on that ratio. If you want to increase soil biology on farm, orchard, vineyard etc., the science is very clear, ‘maximise a diversity of living roots year round’ based on good physical and chemical soil health! That’s it, it is that simple! What the science cannot say is for any particular measurement of soil organisms you should do X, Y or Z practical action. Thus



commercial soil organism identification tests cannot tell you anything that you can make a management decision on, so are best avoided and your money saved.

However, we do clearly know that in general more soil biology is better than less. How to measure that? The cheapest option are the DIY soil tests outlined in section 17. Because the three soil healths are all linked, a good result for a physical soil test will indicate good soil biology as well. Ditto, for chemical soil health, if your nutrient levels are at optimum, so will soil biology, and vice versa. There is one laboratory measurement of total soil biology that is now very well validated - the 'hot water extractable carbon' test (Merfield, 2023a) and variations on that name. It is a shocker of a name as it describes the test process, not what it measures, as all other soil tests do, e.g., a soil phosphorous test, measures plant available phosphorous, but we are now stuck with it! It simply takes a small amount of soil, soaks it in hot water for around 24 hours and then measures the amount of dissolved carbon in the water, i.e., it dissolves soluble carbon based compounds like sugars and proteins, which are what make up the majority of microbial biomass. There is a large amount of science that shows the results correlates strongly with total soil microbial biomass, i.e., the amount of living biology in your soil. As it is a simple test, it's cheap, so well worth getting done with nutrient analysis, to give you a numerical measure of your microbial biomass you can track over time.

There is also a growing focus at the cutting edge of soil science on what key biochemical processes are occurring, e.g., oxidising ammonium to nitrate, by measuring the amounts of key enzymes and DNA and RNA activity. A list of species is a static snapshot, it does not tell you what soil processes are doing. The key to soil health are the processes and the rate that they are occurring not a static picture. The study of these dynamic processes is therefore where soil science is heading. So if anyone is talking about bacteria to fungi ratios or the amount of nematodes and protists in soil they are still living in 20<sup>th</sup> century soil science and it is best to walk away.

## 6.2. Pasture management for soil health

For pasture systems this means increasing the number of plant species in the pasture, i.e., several species of grass, several species of legumes, and a range of different forbs (herbs) for example, cocksfoot, timothy, brome, tall fescue, white clover, alsike clover, red clover, birdsfoot trefoil, plantain, chicory, sheeps burnett, yarrow, and salad burnett. This also helps wider biodiversity, e.g., insects.

This must be coupled with rotational grazing, i.e., the opposite of set stocking. Set stocking results in livestock eating the most palatable species out of the pasture and keeping it short minimising photosynthesis and therefore pasture and root exudate production, stock growth and profit. Set stocking is so clearly harmful and unprofitable for multiple reasons that it should be avoided at all costs.

Rotational grazing involves moving stock to new pasture on a regular basis - as soon as they have eaten the pasture down to the required height - the residuals - they are moved on. The pasture is then allowed to regrow up to the point that it starts to senesce before being grazed again. Between 20 to 40 days depending on the season. This maximises the leaf area, and therefore photosynthesis, so maximising pasture biomass production along with root exudates. That means more feed, so you can have more stock, fed better, growing faster, producing more milk and thus more profit. It also means stock can't pick the most palatable species out of the pasture so they survive better. They are also forced to eat more 'weeds' like dock, which along with the pasture being more competitive due to the extra species occupying the ecological niches of weeds, crowding them out, means there are less weeds in your pasture. In countries like New Zealand rotational grazing is taken to the extreme of moving stock to new pasture several times a day.

Rotational grazing is also key to minimising soil compaction during wet weather. Stock are put onto new pasture and as soon as they have eaten their fill and want to start ruminating they are taken off



to a stand off pad, lane way or other suitable area. As the stock are hungry going onto the pasture, and it is highly palatable to them (due to the increased plant diversity) they don't wander around looking for interesting plants to eat, they start eating straight away and keep eating with minimal movement until they are full. This means the stock do as little walking on the soil as possible, minimising compaction. This contrasts with the typical endless wandering around that occurs in set stocking due to stock looking for something to eat.

### **6.3. Cropping management for soil health**

Increasing plant species diversity and maximising photosynthesis can be more challenging in cropping (arable and vegetables) than in pasture production. The easy wins are cover crops. When ever soil is going to be bare for more than a few weeks a quick growing, annual, multi-species cover crop should be grown. Leaving soil bare is the worst thing for soil health and is a major erosion risk, particularly over winter. Research in New Zealand has shown that short term cover crops sown between cereal harvest and autumn sown crops statistically increased soil aggregation, which is a key indicator of overall soil health.

Intercropping is the practice of growing two or more plant species together, i.e., the opposite of monoculture. Intercropping was common prior to the advent of the pesticides and intensive agriculture. Intercropping examples include a mix of cereal and beans, undersowing cereals with clovers, or using strip cropping in vegetables (Ditzler *et al.*, 2021; Juventia & van Apeldoorn, 2024).

While intercropping increases plant diversity in space, rotations increase plant diversity in time. Having a more diversified rotation is also a key means of increasing plant diversity to boost soil health.

Cover crops and intercropping are huge topics in their own right. For an introduction and lists of further resources see (Merfield, 2023b).

#### **6.3.1. Annual cover crops vs perennial pasture**

There is a common misunderstanding about the relative benefits for soil health of annual cover crops and perennial pasture (herbaceous) species like grasses, clovers and forbs (herbs). Annual plants have an evolved life strategy of being a seed - they are seeds for most of their lifecycle and a plant only for a few months. Annuals therefore put around two thirds of their biomass into above ground foliage with the primary aim of making lots of seeds. So only one third of their biomass is roots, and as they only grow for a few months as plants before returning to inactive seeds, there is not so much value in feeding soil microbes with exudates. They are thus the fly-by-nighters of the soil microbial world.

In comparison perennial plants could be living in the same piece of soil for years, decades even centuries, so it make sense to look after their microbial 'friends' by producing more exudates, so they can get the maximum benefits the microbes deliver. Particularly for pasture species which have evolved to survive grazing by herbivores, they put some two thirds of their biomass into their roots due to the risk of losing foliage. Thus perennial species produce far more root exudates than annuals. So even though the above-ground biomass of annual cover crops is typically much larger than pasture, pasture is far better at increasing SOM, mainly MAOM and thus soil health than annuals so it makes no sense to rip up pasture to plant annual cover crops in terms of soil health, and also due to the cost and work involved.

### **6.4. Biostimulants and biofertilisers**

With the increasing challenges facing agriculture there is growing interest in biostimulants and biofertilisers, mainly as alternatives to mineral fertilisers. Biofertilisers are biological materials that supply plant nutrients in sufficient quantities to achieve a plant growth response when those nutrients are sub-optimal, for example, fish fertilisers. Technically compost and manure are therefore



biofertilisers, however, commonly biofertilisers are viewed as products bought in bottles. Biostimulants are biological materials that do not contain sufficient plant nutrients to produce a plant growth response but they enhance plant growth by stimulating plant biochemistry. For example, some seaweed based biostimulants contain gibberellic acid which is a plant hormone that promotes vegetative growth, so spraying it onto plants increases their growth, even though no extra nutrients have been applied.

While there are some biostimulant and biofertiliser products that are backed by good scientific research and work when used in the correct situation (e.g., rapidly rectifying a nutrient deficiency in a crop) there are many products that are not supported by scientific research, or worse science shows they do not work. Many products are promoted as improving soil biology, or similar claims. These should be treated with considerable caution. The volume of living things - the biology - in a hectare of healthy soil is some 30 m<sup>3</sup>. Many of these products only apply a few hundred millilitres or a few litres of microbes of just one or a few species to a hectare of soil. As the biology in soil exists consists of millions if not billions of species of organisms plus viruses, in a massively complex interacting ecology which is highly resistant to invasion, the potential for these products to have any impact on soil biology is exceptionally small. In addition, a hectare of land of healthy growing plants will produce hundreds of kilograms to several tonnes of root exudates a year. The plants and microbes have co-evolved so these root exudates are the 'perfect' food for soil microbes. No amendment, biofertiliser, compost manure is therefore as good a food for soil / soil biology as root exudates, or as inexpensive.

In addition for biofertilisers purchased in bottles the cost per kilogram / pound of nutrient is often orders of magnitude more expensive than compost, manure and mineral fertilisers. As fertilisation is fundamentally an economic activity - you spend money to increase yield to increase income more than you spent on the fertiliser - choosing the cheapest form of fertiliser is generally the most profitable.

For more information on biostimulants and biofertilisers see (Merfield & Johnson, 2016).

## **6.5. Soil biological health conclusions**

Despite the huge complexity of soil biology and ecology, maximising soil's biological health can be summed up in the aphorism 'maximising the diversity of living roots year round'.



## 7. DIY soil health tests

As the old adage goes, you can't manage what you don't measure, and that applies to soil health in spades, literally and metaphorically. While standard lab-based nutrient tests are key to measuring chemical soil health, they are limited in their ability to measure biological and particularly physical soil health. The good news is there are a number of 'DIY' soil health tests that you can do yourselves which will allow you to measure physical and biological health and most cost nothing more than your time and some simple equipment. These have been covered in detail in the publication 'DIY soil health tests V1' (Merfield, 2023a). This section gives a brief overview of the key tests.

### 7.1. Comparing the middle of the field with the fenceline

A very informative approach to all soils tests is to compare the farmed (grazed, cropped) area of a field - 'the middle' - with an unfarmed area - 'the fenceline', e.g., directly under a fenceline, hedge, etc., where stock can't walk or machinery cannot disturb the soil. The 'fenceline' should have the same soil texture as the middle and be in good health as it has not been farmed so makes for a valuable comparison with the middle. This is on the basis that there is vegetation growing on the fenceline rather than a herbicide strip, and that the fence line has had the same nutrients applied as the middle. This comparison often shows up considerable differences, demonstrating the impact of the production system on soil health.

### 7.2. Spade test and Visual Soil Assessment (VSA)

Literally grab a spade and dig a hole down to spade depth or a bit more and then interpret what you see! The first bit is easy, the second part takes a bit of experience! You are looking to see what the soil structure looks like, i.e., is it nice and crumbly and well aggregated or compacted, especially the surface layer by livestock Figure 3. What is the colour like, dark or pale? Does it smell sweet or sour? If it is winter or early spring and the soil is moist, are there lots of worms? How many plant roots are there and how deep do they go? And so on...

The 'full monty' version of the spade test is 'Visual Soil Assessment' (VSA) which is a structured approach to assessing soil health for specific production systems (pasture, cropping, orchards etc.) using a scoring system to give an overall soil health score.

### 7.3. Soil probes and penetrometers



Figure 13. Left: soil probe. Right: penetrometer.



A soil probe, same thing as a tile drain probe, is a round steel rod about 12 mm / ½” thick and meter / yard long on a handle Figure 13. This is pushed into the soil to feel and hear what soil conditions are like, particularly compaction. A penetrometer is a probe with a pressure dial on it to give a numerical value of how hard you are pushing Figure 13. As they are relatively cheap and very robust, probes are a great compliment to a spade test. While digging a hole and having a look takes a minute or few pushing a probe into the ground only takes a few seconds, so many more sample points can be taken in the same time as a spade test. It’s also much easier to get to depth, i.e., up to a meter / yard, with a probe or penetrometer than a spade - a meter / yard deep hole is a big hole!

## 7.4. Ring infiltration test

This uses a metal or plastic ring from around 10 to 30 cm / 4” - 12” wide and 10 to 15 cm / 4” - 6” high, which is hammered into the soil a few centimetres deep and then filled with water Figure 14. The time it takes the water to soak into the ground is the infiltration rate. This is a really good way to measure the porosity of soil and thus the state of the macropores. It also links to rainfall rate. If infiltration rate is 100 mm / 4” an hour then the soil can absorb that rate of rainfall, which is an enormous amount of rain! However, soils with compaction, especially loss of macropores due to livestock, may only have infiltration rates of a few centimetres / inch an hour, which is well within a heavy rainfall rates, meaning that some of the rain would run off the fields potentially causing erosion and nutrient loss to waterways.



Figure 14. Various ring infiltrimeters.

## 7.5. Aggregate stability

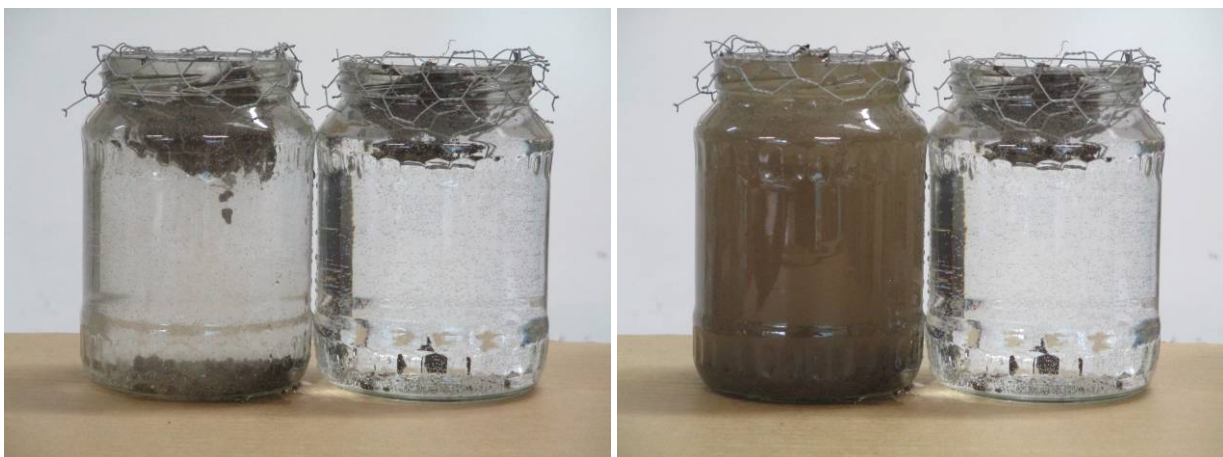


Figure 15. Slake test of unhealthy soil (left jar) and healthy soil (right jar) at start (left photo) after one hour (right photo).

As discussed previously, aggregate stability is key proxy measurement for overall soil health. Dig some soil up without compressing it. Carefully tease out some individual aggregates. If the soil is not dry,



let the aggregates dry out fully. Then place them in some water to see if they hold together or disintegrate, the former is healthy the latter is unhealthy Figure 15

To get a numerical measurement of aggregate stability use the Slakes App from the Soil Health Institute [soilhealthinstitute.org/our-work/initiatives/slakes/](https://soilhealthinstitute.org/our-work/initiatives/slakes/).

## 7.6. DIY soil health test conclusions

All of the tests, and the others described in the main report (Merfield, 2023a), give you different points of view of soil health. Thus no one test will tell you everything, and they have considerably more power when used together to assess the same field - giving you different perspectives that combine into a deeper view.

## 8. Conclusions

Modern soil and planetary science is utterly clear that good soil health is vital for farming, civilisation and our planetary life support systems. Best practice soil management is thus essential in farming and for all land managers. The good news is despite soil being the most diverse, complex and hard to research ecosystem on the planet the fundamentals of good soil management are pretty straight forward:

- Minimise compaction and soil structural damage from livestock, machinery and tillage.
- Ensure all nutrients, essential and beneficial, along with pH are at optimum.
- Maximise the diversity of plant species in space and time, along with maximising photosynthesis to maximise root exudate production.

That's it. No expensive biological products, no need for soil food web analysis, three simple rules for maximising soil health.



## 9. Glossary

**Archaea:** A group of single-celled prokaryotic organisms that have distinct molecular characteristics separating them from bacteria.

**Biogeochemistry:** The science studying how the chemical elements / nutrients cycle through the biosphere and geosphere.

**Biosphere:** The planetary sphere consisting of all life on earth, also called the ecosphere.

**Diazotroph:** Bacteria and archaea that can fix nitrogen, i.e. convert inert diatomic nitrogen ( $N_2$ ) in Earth's atmosphere into reactive / bioavailable compound forms such as ammonium.

**Dinitrogen ( $N_2$ ):** The gaseous form of nitrogen that constitutes 79% of the earth's atmosphere, characterized by its unreactive nature and difficulty in being assimilated by living organisms.

**Eukaryote:** The domain of life of organisms whose cells have a membrane-bound nucleus. All animals, plants, fungi, seaweeds, and many unicellular organisms are eukaryotes, i.e., all organisms that are not prokaryotes.

**Fast or biological element / nutrient cycles:** Where chemical elements / nutrients are rapidly cycling through biological systems (biosphere) over time scales of minutes to millennia.

**Geosphere:** The planetary sphere consisting of all the solid parts of the Earth, i.e., rocks, crust and mantle.

**Hydrosphere:** The planetary sphere consisting of all the water on, under, and above the earth's surface, including all the rivers, lakes, seas, oceans and water in the atmosphere.

**Inorganic chemistry:** A sub discipline within chemistry involving the scientific study of inorganic and organometallic compounds, i.e., chemical compounds that are not carbon-based.

**Intercropping:** Growing two, or typically more, plant species together, i.e., not monoculture.

**Lithosphere:** Is the rigid outermost rocky shell of planet earth, composed of the crust and the lithospheric mantle.

**Macronutrient:** Chemical elements required by living things for their growth and function that are required in larger amounts. The primary macronutrients are nitrogen, phosphorous and potassium (NPK). The secondary macronutrients are calcium, magnesium and sulphur.

**Micronutrients:** Chemical elements required by living things for their growth and function that are required in small amounts. Examples include boron, zinc, manganese, molybdenum, iron and copper.

**Organic chemistry:** A sub discipline within chemistry involving the scientific study of organic compounds, i.e., matter in its various forms that contain carbon atoms.

**Planetary spheres:** The earth systems consisting of the atmosphere, hydrosphere, biosphere and geosphere.

**Prokaryote:** The domain of life consisting of bacteria and archaea, single celled microorganisms that lack a nucleus or other membrane-bound organelles.

**Reactive nitrogen ( $N_r$ ):** is all forms of nitrogen present in the environment except for dinitrogen ( $N_2$ ).

**Slow or geological element / nutrient cycles:** Where chemical elements / nutrients are cycling very slowly through the geosphere via weathering, erosion, and plate tectonics, over times scales of tens of thousands to billions of years.

**Sorbed:** To take up and hold by absorption or adsorption.



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