Soil Stamina –
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Literature Review

The Points

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Network SW Consulting

CHAF Central Highlands Agribusiness Forum

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Introduction

The aim of this literature review is to review the most up to date soil research, reports and findings conducted since 2000, with particular reference to improved soil heath, soil structure, organic content and nutrient performance through changed management practices.

In the course of this review some papers written pre-2000 have been included as they are relevant and particular to the topic.

Literature was selected on where the findings were relevant to agriculture in south west Victoria, in particular to the grazing industry.

It is anticipated that this review will provide the basis for extending research information into the wider farming community.

Soils

Soil is a wonderful, complex substance, made up of decomposing rock, decaying material and living organisms. Soil structure is determined by the mix of these elements and by local conditions such as drainage, the type and age of rock being broken down and climate factors.

Healthy soil is essential for healthy pastures, crops and gardens – it contains the building blocks for life that is air, water, structure and nutrients.

Healthy soils also provide us with a range of 'ecosystem services'. ‘Healthy’ soils support and allow the best plant growth, resist erosion, receive and store water, retain nutrients and act as an environmental buffer in the landscape. Soils supply nutrients, water and oxygen to plants, and are populated by soil biota (micro-organisms), which are essential for decomposition and recycling processes. (Landcare)

Soil Health

The terms ‘soil health’ and ‘soil quality’ are, in a general way, interchangeable. 'Soil quality' is a term generally used more by soil scientists and 'soil health' by others, but they do have different emphasis.

‘Soil quality’ is the capacity of soils within landscapes to sustain biological productivity, maintain environmental quality, and promote plant and animal health.

‘Soil health’ is the 'fitness' (or condition) of soil to support specific uses (e.g. crop growth) in relation to its potential - as dictated by the inherent soil quality.

Both terms link soil to other concepts about health such as environmental health, human health, plant health, and animal health. ‘Soil health’ and ‘soil quality’ represent the capacity of soils to support these other aspects of health. So, just as human health is a functional concept that describes how fit we are to interact with each other and our environment, soil health and soil quality are functional concepts that describe how fit the soil is to support the multitude of roles that can be defined for it. (Department of Primary Industries)

The Healthy Soils for Sustainable Farms (HSSF) project, funded through Land and Water Australia and the Victorian Government (DPI) state that soil health within the context of ecosystem functions, indicates the fitness of soil as a living system, within its natural means;

- to sustainably support biological production and promote plant and animal health,
- maintain the Earth's genomic heritage, and
- act as a living filter or protector of water and air quality. (Aumann & Fisher, Soil Health and Soil Organic Matter Info Leaflet)

What are the indicators of good soil health? This seems to be a question which soil scientists have been grappling with for many years.

When considering which soil properties convey a measure of health or a degree of quality or of general soil fertility, it is customary to compartmentalise them into the three divisions of physical, chemical and biological attributes.

The list compiled under these three headings has remained fairly comprehensive since early attempts to define measures of quality or fertility. A consensus list compiled by the National Resources Institute in UK is given in Table 1. This covers the subject examined by many authors since c.1990.

Soil organic matter itself is often cited but is not included, though the ways in which it influences the other indicators is commented on. (National Soil Resources Institute, 2007)

It should be noted that no one measure is an accurate measure of soil health. It is a combination and balance between physical, chemical, biological and organic matter which results in a truly healthy soil.

Table 1. Soil properties most consistently cited as being useful as indicators of soil health and/or quality since c.1990. (National Soil Resources Institute, 2007)

Type of property	**Indicator**	**Description**	**Interaction with Soil Organic Matter**
Physical	Depth of soil	Depth of soil layer available as a rooting medium.	
	Water holding capacity	Influenced by both texture and structure of soil, the ability of soil to hold sufficient water for plant growth and can determine crop yields.	soil organic matter can influence the water holding capacity of soil through its effects on soil structure as well as being a medium for moisture retention itself.
	Hydraulic permeability and infiltration rate	The ability of a soil surface to accept rainfall and the rate at which water can be transmitted through soil. Impermeable soils are prone to water-logging and erosive surface run-off.	soil organic matter can influence a soil's permeability by its effect on structure and structural stability.
	Structural stability	Both the size distribution and stability of aggregate structural units in topsoil can influence the workability of soil and its value as a rooting medium.	The amount of soil organic matter in topsoil can greatly effect the size of aggregates formed and their degree of stability in water.
	Bulk density and soil strength	Both texture and structure influence the strength of soil, and its degree of penetrability to roots and tillage implements.	soil organic matter can reduce bulk density, but both raise and lower soil strength depending upon its concentration and interaction with structure

Chemical	Cation exchange capacity	A measure of the amount of plant nutrient cations a soil can retain by electrostatic charge.	Soils cation exchange capacity is governed by charged surfaces on clay and soil organic matter particles. These also affect the soils structure.
	Soil pH and base saturation	The pH and ionic environment of plant roots directly effects how well different species grow.	
	Plant available nutrients	A measure of the amount of nutrients a soil can supply (*cf* with retention by cation exchange capacity above).	soil organic matter is a source of plant nutrients via mineralisation processes.
	Soil organic carbon fractions	A specifically defined sub-division of the total soil organic matter. The "light fraction" and "active carbon" fractions are such sub-division fractions.	A measure of the more labile organic matter in the soil, open to biological transformation, these fractions are more sensitive to change than total soil organic matter.
Biological (microbial)	Microbial population indicators	Either indicators of total amount of microbial growth *i.e.* biomass. Or measures of abundance of particular species according to function. Relates to nutrient supply of soil.	Amount and quality of soil organic matter can effect and limit the growth of microbial populations.
	Microbial community indicators	Measures of bio-diversity or range of functional groups of organisms present in a soil. Relates to supply of particular nutrients or environmental regulation in soil.	Quality of soil organic matter is important in controlling the diversity of communities and the ability of functional groups to operate effectively.
	Microbial activity	Measures of decomposition and respiration rates, carbon and nitrogen turnover rates and enzyme activity. The level of activity as well as size and diversity of populations affects a soil's ability to supply plant nutrients.	Microbial populations respond to new (quantity) and more degradable (quality) organic matter by increasing activity for a period. Changes in activity can relate to soil organic matter turnover.
Biological (soil fauna)	Keystone species or ecosystem engineers	A measure of the abundance or biomass of certain micro, meso or macro-fauna species that demonstrate an unambiguous contribution to soil quality or health.	Abundance may be linked to concentration of soil organic matter as a food source.
	Diversity at the taxonomic group level.	A measure of the abundance or biomass of classes of organisms to provide a simple indication of the complexity of a soil community.	As above.
	Diversity at the species level	A measure of the species richness of the soil.	Quality of soil organic matter may have an impact on the number of species it can support.

Soil Type

Texture

Soil texture is the "feel" of the soil when a moist quantity is manipulated between thumb and forefinger. Some soils can be manipulated like plasticine. These differences in properties gave rise, in agriculture, to soils being called clays, loams or sands. Clays stick to your boots, loams are easily moulded but sands are not cohesive at all and cannot be moulded when moist.

Sands hold very little water that would be available to plants and have no ability to hold onto plant nutrients in the way that clays do.

Loam soils contain sand, silt and clay in such proportions that stickyness and non-adhesiveness are in balance - so the soils are mouldable but not sticky. Loams are the "friendliest" soils to cultivate.

Clays can absorb and hold onto large amounts of water because of their sheet structure and large surface area. This property causes the swelling and shrinking of clay soils as they wet and dry.

The texture of soil is considered to be a stable property. To change the soil texture would involve considerable mechanical and financial input. For most land managers, changing the texture of the soil is not a viable option for soil management.

Texture often changes with depth down the soil profile. It is important to describe texture changes that occur within the soil profile. Many of our soils have loamy surface soils and heavy clay subsoils. This arrangement controls the movement of water through the profile, the clay restricts downward drainage and encourages water movement along the top of the restricting layer. This can result in waterlogging of the surface soil, even though the subsoil may not be saturated. (DPI)

Structure

Soils structure is often confused with soil texture. Soil structure is often defined as the size, shape and arrangement of aggregates and the spaces or pores in between at a given time.

From a functional point of view in terms of soil as a habitat and the activities of the inhabitants, it is more meaningful to focus on the pore space system which can be described in terms of total porosity, pore size distribution and continuity of the pore systems. Pore size distribution differs according to soil type, thus offering habitats for a diverse range of organisms. Clay soils provide better habitats for bacteria because of higher micro-porosity, so there are more micro-niches than sandy soils (Chan, 2004) . Soil water is held at different energy levels, depending on the pore size, so that water in smaller pores is held more strongly than that in larger pores.

Soil structure determines the abundance, diversity and activity of the soil biota and therefore biological fertility of the soil. On the other hand, soil biota can modify soil structure by stabilising as well as creating soil structure. The interactions of soil structure and soil biota determine all the three aspects of soil health, physical, chemical and biological. (Chan, 2004)

At the microscopic level, a healthy soil will probably have less than half of its volume as solids. The rest is a complex arrangement of pores and channels. It is these pores and channels, which enable soil functions;

- Water, air, nutrients and organic materials can all accumulate and be stored here, so that bacteria, fungi, microorganisms and tiny animals can grow and multiply.
- Roots can grow readily into and through the soil
- Rain water can be stored and excess water can drain to the groundwater systems.

The better the range of sizes, the condition and the stability of the soil pores, the more productive the soil.

The living component of the soil (roots, fungi, macro and micro-fauna) and the dead, decaying and humified organic materials influence soil structure. Roots growing in soil leave semi-permanent channels (pores) enriched with organic matter when the roots die and decay. These pores provide conduits for air and water and for successive new root growth. The surface of the live root produces mucilages and gums which assist in stabilising the mineral surface of the pore and provide a source of food for soil dwelling micro-organisms.

The relationship between soil structure and management is extremely important. Management affects the type, amount and frequency of organic matter additions to soil, has a direct influence on soil chemistry, and determines the ways by which a soil might be compacted or loosened. Management can therefore influence density, aggregate stability, aggregate size, and pore size distribution. (Chan, 2004) (DPI)

Further discussion about farm management strategies are later in this document.

Chemistry

Chemical properties of soil affect soil structure primarily through influence on charge of clay and oxide surfaces and their consequent flocculation or dispersion. There is a relationship between soil sodicity, electrolyte in the soil, and clay dispersion. Soil chemistry thus modifies soil structure by influencing bonding between soil particles.

Aggregates

An aggregate is a group of soil particles that bind to each other more strongly than to adjacent particles. If the internal binding forces are robust and unaffected by outside influence, the aggregate is said to be stable.

Aggregates have the characteristics of:

- size,
- shape,
- distinctness and
- stability

A well structured soil has pores in-between the different aggregates and with-in the aggregates. These pores are important for the housing of soil life and for the movement of gases, water, nutrients, soil organisms and plant roots. Large pores allow for the exchange of oxygen and other gases into the atmosphere, while small pores hold plant available water and dissolved nutrients. A range of pore sizes in a soil, enhanced by a well aggregated soil, is important for the health of plants and soil biota.

Soil aggregates can be broken down by rainfall, cultivation, livestock and vehicle traffic, wind and water movement. Aggregates with weak bonds break down quickly and then the pore spaces can fill with particles of soil. This restricts the movement of gases and water and the ability for plants roots to move through the soil. Soil aggregates with strong bondscan also break down with disturbance such as mechanical cultivation.

Some of the impacts of poor soil aggregation are

- Limited ability to hold water
- Inability to retain and release nutrients all soils
- Capping, crusting of soil surface (sodic and silt soils)
- Compaction due to structure collapse
- Waterlogging

Sandy and silty soils (with low clay content) have very weak electrostatic attractions between particles and are usually poorly aggregated. High levels of organic matter input are required to build aggregation in such materials. High clay soils have strong electrostatic attraction between particles which can result in strong aggregation.

Dead plant materials and root exudates are the primary source of organic matter in soil. Living organisms might only comprise 1 – 5% of total organic matter. Good levels of organic matter give strength to soil aggregates.

Soil aggregation is a transient property and aggregates are continually being formed around decomposing SOM. Soil aggregation has been shown to protect and isolate SOM from soil fauna and microorganisms through physical protection. Reduced soil disturbance concentrates organic matter in macroaggregates (aggregates, >0.250 mm), but as these are broken apart (i.e. by tillage, wet-dry cycles or natural attrition), previously protected SOM is exposed to new environments and different types of soil organisms. (Aumann & Fisher, Characteristics of non-living Soil Organic Matter Info leaflet)

Soil pH

Acidity and alkalinity in any solution is measured as pH. The pH of soil indicates the strength of acidity or alkalinity in the soil solution which bathes soil constituents, plant roots and soil micro-organisms. Soil is neutral when pH is 7, it is acid when pH is less than 7 and alkaline when it is greater than 7. The pH scale is logarithmic, so a difference of a unit is a tenfold difference in acidity or alkalinity (eg. pH 5 is ten times more acid than pH 6).

Most soil pH measurements in Australia are made by shaking soil samples for an hour in either a 1:5 soil to water suspension (pHw) or a 1:5 soil to 0.01M calcium chloride suspension (pHCa) and using an electrode to measure the pH of the resultant mixture. (Upjohn, Fenton, & Conyers, 2005)

The pH measured in calcium chloride is on average 0.5 to 0.8 less than pH measured in water, although the difference can vary from nil to 2.0 for different soils.

Soil pH was mapped across Victoria using a statewide soil chemistry data set based on samples submitted from farms, vineyards and orchards between 1973 and 1994. Each sample was a composite of 20 to 30 cores representing the 0-10, 0-15 or 0-30 cm depth of soil taken from the main soil type in each paddock. Samples from national parks, urban land and sport and recreational turf were excluded from the data. Collated data included nearest location and pH (1:5 soil:water). (DPI)

A map was generated by applying geo-statistical techniques (‘kriging’) to the mean pH of the locations. It indicates the geographic trends in the acidity and alkalinity of surface soils across Victoria's agricultural land. This map cannot indicate soil pH at the paddock scale and it should only be used as an indicator of likely pH at a regional scale. Considerable variations in soil pH will occur within a region. This map does not substitute for a soil test and can be found at http://www.dpi.vic.gov.au/dpi/vro/map_documents.nsf/pages/surf_ph.

Basically it shows that soils in south west Victoria are acid soils. This is confirmed by the new Caring For Our Country federal funding program which has identified this area as a priority for funding for acid soils. (www.nrm.gov.au)

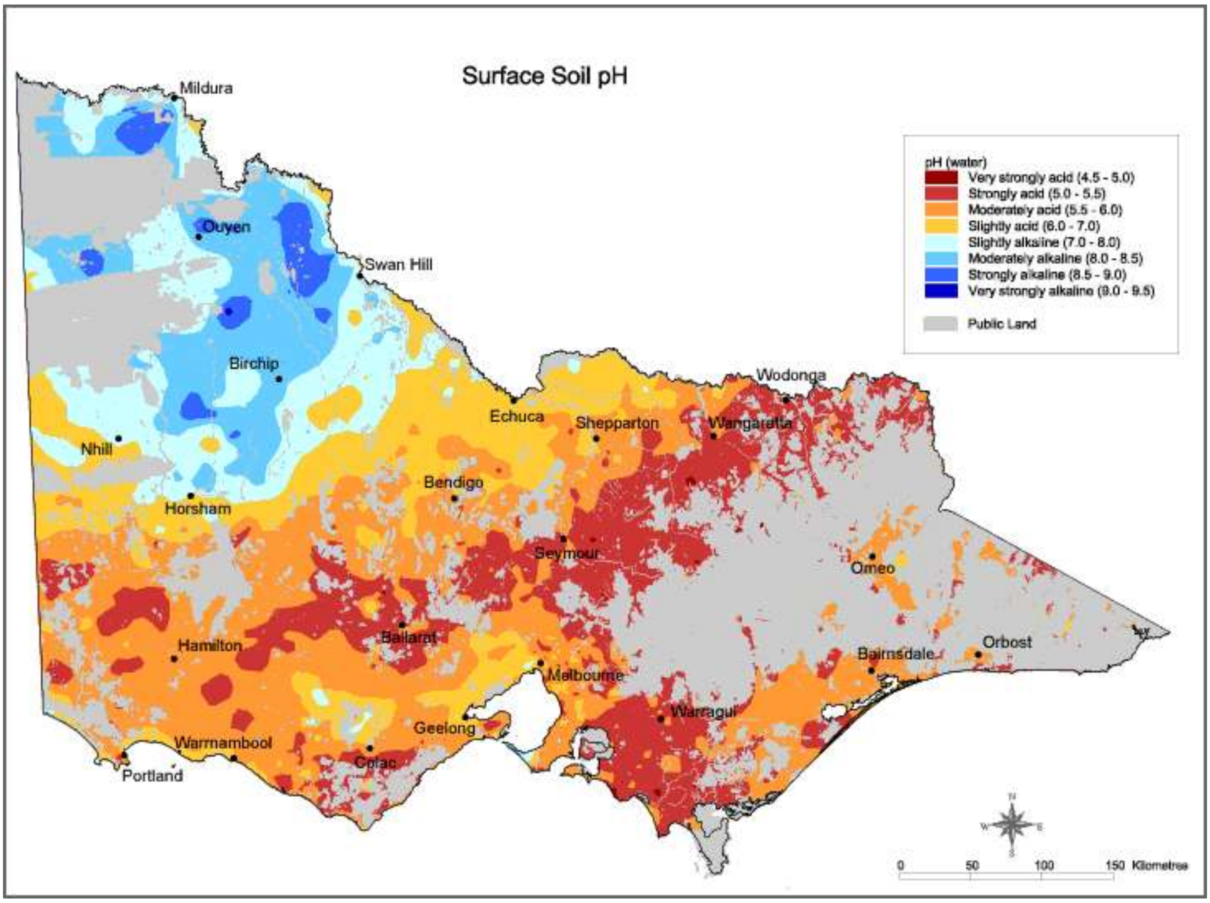

Fig. 1. Surface Soil pH

Acidification of the soil is a slow natural process and part of normal weathering. Many farming activities cause an increase the rate of acidification of the soil. Changes in soil pH under agricultural use are measured in tens or hundreds of years rather than thousands of years as in the natural environment.

Agricultural practices have acidified soils. For example; soils under subclover based pastures, leguminous crops such as lupins, and where ammonium fertilisers are used. Management practices can be used to reduce the impact of acidification. These include use of perennial and deep rooted species (eg. phalaris) and avoiding acidifying fertilisers. Ultimately, application of lime will be needed to combat acidification. (Department of Primary Industries)

Soil pH affects the availability of soil constituents to plants and soil micro-organisms. For most plants, the ideal soil pH (water) test result is pH 6 - 7.5, although many will tolerate pH 5.5 - 8.5. However, the tolerance to extremes in pH varies between plant species and within species. Some plant species have quite different preferred pH ranges (eg. lucerne 6.0 - 8.5, celery 6.0 - 7.0, potatoes 5.0 - 6.0). Therefore, consideration of the need for soil amelioration will depend on individual circumstances.

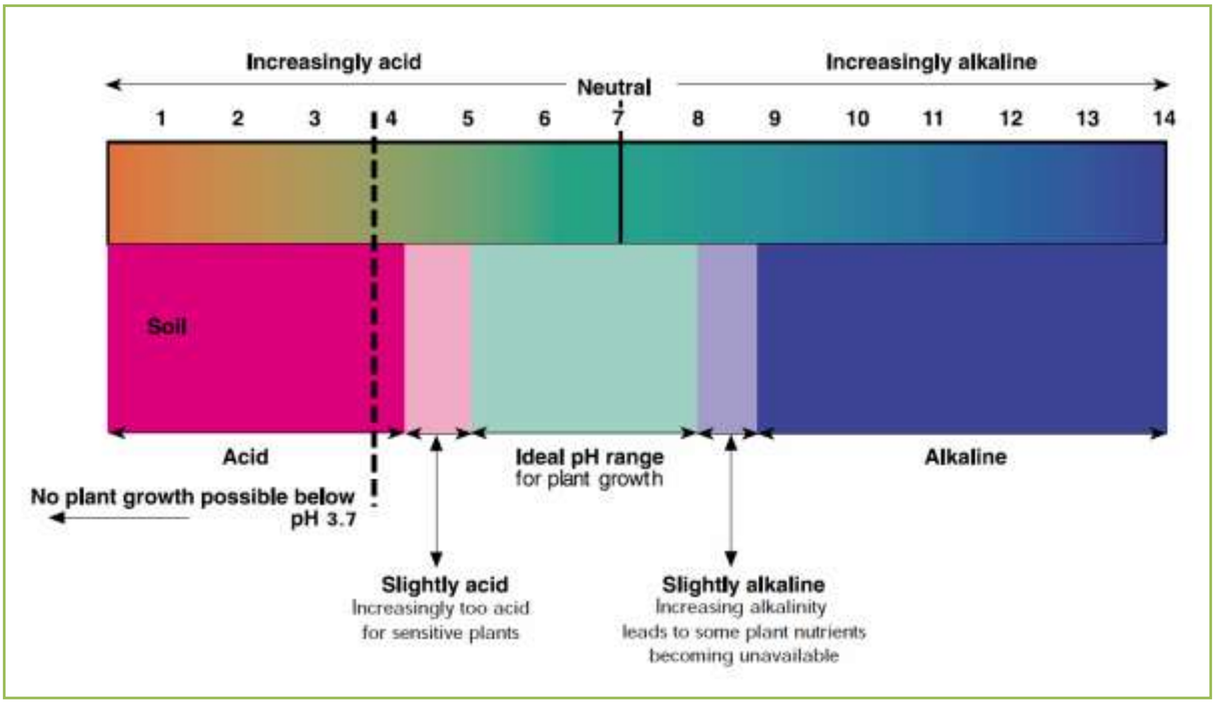

Fig. 2. Plant growth and pH scale
Source: Understanding Soil pH, Acid Soil Management, NSW Acid soils action program

A soil pH(CaCl2) of 5.2 to 8.0 provides optimum conditions for most agricultural plants (Figure). All plants are affected by the extremes of pH but there is wide variation in their tolerance of acidity and alkalinity. Some plants grow well over a wide pH range, whilst others are very sensitive to small variations in acidity or alkalinity.

The pH of the surface soils in Victoria ranges from pH 4 to pH 10. In south west Victoria, the soils are more prone to acidity. These extremes in alkalinity and acidity present problems for the production of many agriculturally important plant species and their symbiotic rhizobia. Due to the complexity of soil chemistry, it has often been difficult to confidently identify the cause of poor plant growth or nodulation. However, aluminium and manganese toxicities and molybdenum and phosphorus deficiencies are probable causes of poor production in many strongly acid soils.

Microbial activity in the soil is also affected by soil pH with most activity occurring in soils of pH 5.0 to 7.0. Where the extremities of acidity or alkalinity occur, various species of earthworms and nitrifying bacteria disappear. Legume root colonising bacteria (Rhizobia) vary in their sensitivity to soil pH and have preferred ranges in which they are effective. In some crops and pastures (e.g. faba beans and lucerne) the Rhizobia specific to these plants are more sensitive than the plant itself.

Soil pH affects the availability of nutrients and how the nutrients react with each other (Figure 2). At a low pH, beneficial elements such as molybdenum (Mo), phosphorus (P), magnesium (Mg) and calcium (Ca) become less available to plants. Other elements such as aluminium (Al), iron (Fe) and manganese (Mn) may become more available and Al and Mn may reach levels that are toxic to plants. The changes in the availability of nutrients cause the majority of effects on plant growth attributed to acid soils. Sensitive crops such as barley and lucerne can be affected by small amounts of exchangeable aluminium. (Lake, 2000)

Soil's with a low pH (less than pH 5) result in chemical imbalances such as aluminium toxicity and deficiencies of phosphorus and trace elements such as calcium and molybdenum. Very low pH (less than pH 4) leads to soil physical breakdown where the clay structure of the soil is broken down. Acid soils also impact on soil biota, reducing earthworm numbers and making Rhizobia less effective. (Hollier, 2006)

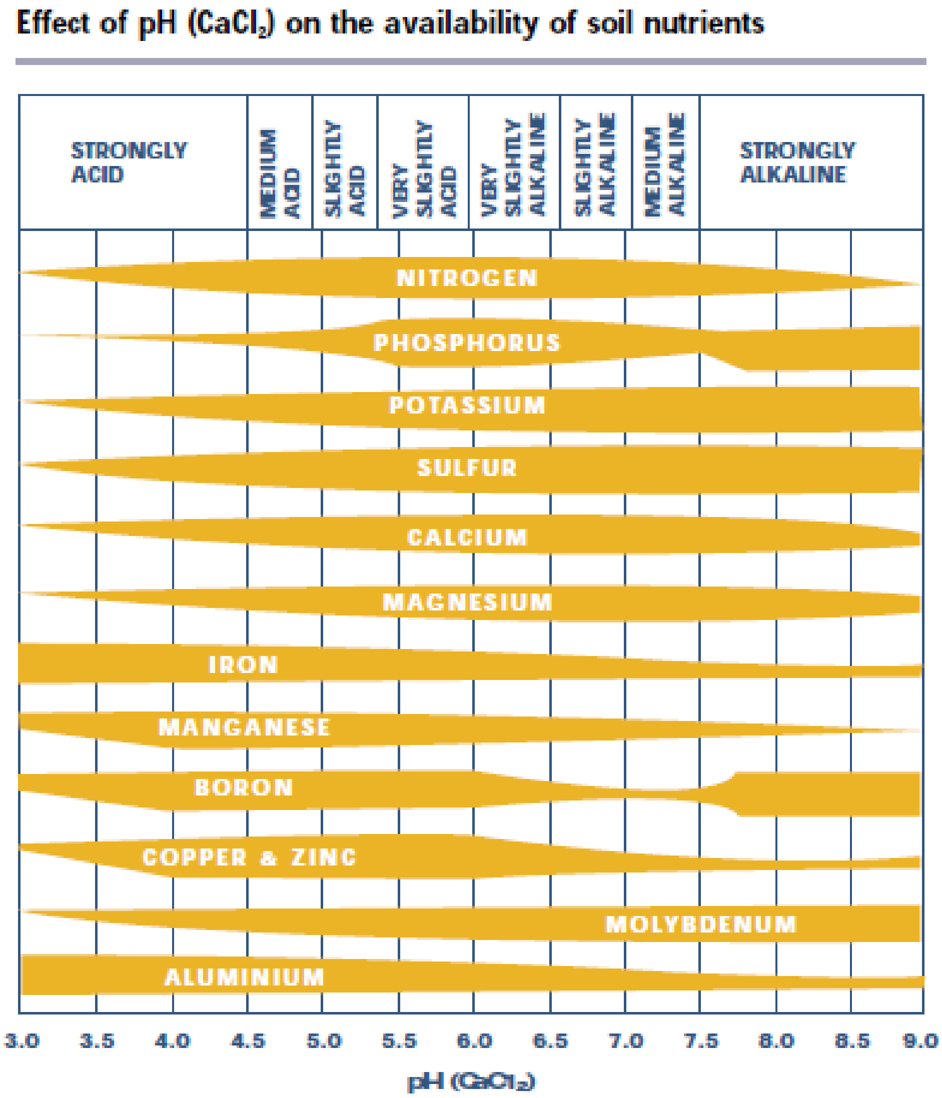

Fig 2. Effect of Ph on the availability of nutrients
Source: Understanding Soil pH, Acid Soil Management, NSW Acid soils action program (Lake, 2000)

Aluminium (Al+++) and sodium (Na++) cations are not plant nutrients, so are not wanted by the plant. Aluminium is not present as a cation when soil pH (CaCl2) is over 5 because it is precipitated out of the soil solution. It is only at pH (CaCl2) levels below 5 that it may become available as a cation, and under 4.5 may become available in toxic levels, displacing other cations from the clay or humus colloids. This is one reason why it is important to maintain pH levels at 5.0 or more. (DPI)

Four main causes of soil acidification

According to (Schumann, 1999), and a further study by Upjohn et al, the four main causes of soil acidity are:

- removal of product from the farm or paddock
- leaching of nitrogen below the plant root zone
- nitrogenous fertilisers
- build up in organic matter (Schumann, 1999) (Upjohn, Fenton, & Conyers, 2005)

Removal of product.

Obviously the main aim of any agricultural production system is to produce saleable products. However most agricultural products are slightly alkaline so their removal from a paddock or farm leaves the soil slightly more acidic. The degree of acidification will depend on how alkaline the product is and how many kilograms of product are removed. Where little actual product is removed from the farm, such as in wool production, the system remains largely in balance. The most acidifying forms of agricultural production are operations such as lucerne hay cutting. For instance the removal of one tonne of lucerne hay requires 70 kg of lime to neutralise the resulting acidity.

Cutting and removing large quantities of hay, especially lucerne, will increase soil acidity, unless balanced by lime use If the produce is sold off-farm, regular liming is the only way to maintain pH. The effect on soil acidity of removing hay will be greatly reduced if the hay is fed back in the paddock where it was cut.

Leaching of nitrogen.

Leaching of nitrogen in the nitrate form is a very important factor in soil acidity. Nitrate is a major nutrient for plant growth. It is supplied either from nitrogenous fertilisers or atmospheric nitrogen fixed by legumes. When there is more nitrate than the plant can use, the nitrate is at risk of draining - leaching - below the plants roots and into the ground water system. This leaves the soil more acidic. Leaching of nitrate can happen through inappropriate use of nitrogen fertilisers and is more common in intensive production like horticulture - or because the plants are not at a suitable stage of growth to use the available nitrogen. Pastures based on annual species, the use of long fallow in crop rotations and heavy applications of nitrogen fertilisers are examples of practices that may increase the risk of nitrate leaching.

Use of nitrogenous fertilisers.

The amount of acid added to the soil by nitrogenous fertilisers varies according to the type of fertiliser. The most acidifying are ammonium sulfate and monoammonium phosphate (MAP), followed by diammonium phosphate (DAP). Less acidifying are urea, ammonium nitrate and anhydrous ammonia. Fertilisers such as sodium and calcium nitrate are not acidifying. Superphosphate has no direct affect on soil pH. However, its application stimulates growth of legumes and clovers which fix nitrogen. This increases the amount of nitrate nitrogen in the soil increasing the potential for leaching and consequent soil acidification.

Build-up of organic matter.

Over the last 50 years the regular use of fertiliser and improved pastures, particularly subterranean clover, has increased the amount of organic matter in the soil. While organic matter has many beneficial effects including improving soil structure, the increasing amount of organic matter may make the soil more acid. However, organic matter will not build up indefinitely, and when an equilibrium is reached the acidification process stops.

The acidification caused by a build up in organic matter is not permanent and can be reversed if the organic matter breaks down. However, there will be a permanent change in the acid status of the soil if the topsoil containing the organic matter is eroded or removed.

It is important to differentiate between a natural build up in organic matter and the build up that occurs by adding organic material from another site. Where organic matter build up occurs due to transported material the increased organic matter generally increases pH (less acid). (Schumann, 1999) (Upjohn, Fenton, & Conyers, 2005)

Effect of soil acidity on the micro-organisms that affect plant growth

Sometimes the effect of acidic soils on the growth and production of crops and pastures is not direct but rather through the effect on soil micro-organisms that in turn affect plant growth.

Acidity reduces the survival of Rhizobia and the effective infection of legume roots. The sensitivity to acidity varies greatly between species. When a Rhizobia sp is affected by soil acidity it shows as poor nodulation and results in reduced nitrogen fixation. Often Rhizobium bacteria are more sensitive to soil acidity than the host plant, for example lucerne and medics.

Lime pelleting of inoculated legume seed is used to protect the inoculum against drying out and contact with fertiliser. Sowing into bands of lime-super also creates an environment suitable for survival of the inoculum in an acidic soil. (Upjohn, Fenton, & Conyers, 2005)

Managing soil acidity with limestone

According to Upjohn et al, application of finely crushed limestone, or other liming material, is the only practical way to neutralise soil acidity. Limestone is most effective if sufficient is applied to raise the pHCa to 5.5 and it is well incorporated into the soil. Where acidity occurs deeper than the plough layer, the limestone will only neutralise subsurface soil acidity if the pHCa of the surface soil is maintained above 5.5. Liming to increase the pH of the surface 10 cm significantly above 6.0 should be avoided as it may induce deficiency of other plant nutrients such as zinc, boron and manganese in well weathered soils.

The liming materials most commonly used are agricultural limestone and dolomite, but other materials are available.

The neutralising value (NV) of a liming material is its capacity to neutralise acidity. The higher the NV the more pure is the product. Pure calcium carbonate (pure limestone) is taken as the standard with an NV of 100. The neutralising value of commercial limestone is usually between 96 and 98.

The finer particles in a liming material react more quickly in the soil as they have a greater surface area to react with acids. Secondly they will be better distributed through the soil after incorporation. Most lime crushers strive to produce a lime that has a particle size where 90% passes through a 150 μm sieve. Lime where 99% is less than 75 μm is highly reactive but requires special machinery to spread. Particles larger than 500 μm react only very slowly with the soil. (Upjohn, Fenton, & Conyers, 2005)

Apply limestone before the most acid sensitive crop or pasture in a rotation as it gives the best economic return. If the limestone will not be effectively incorporated due to reduced tillage, then apply the limestone a year before the most sensitive crop and apply it at a slightly heavier rate. These two actions will enhance lime movement into the top soil. The time of the year when lime is applied is not important.

Limestone begins to become effective as soon as the soil is moist and reaches its major impact after 12 to 18 months. Applying limestone to permanent pastures is often not economic as there is no incorporation of the limestone and the pasture species are generally acid tolerant and will give only a limited response. In sandy soils and where the annual average rainfall is greater than 600 mm, limestone applied to the surface may move to 10 cm depth in 2–3 years. As the clay content in the soil increases, or the rainfall decreases, there is less movement of limestone down the profile. A rapid response to surface applied limestone is most likely caused by release of molybdenum or improvement in legume nodulation, and the release of nitrogen from organic matter.

Table 11. Limestone required (fine and NV > 95) to lift the pH of the top 10 cm of soil to 5.2.

Colour codes group limestone rates to the nearest 0.5 t/ha

Soil test ECEC (meq/100 g)	Lime required (t/ha) to lift the pH of the top 10 cm:			
	from 4.0 to 5.2	from 4.3 to 5.2	from 4.7 to 5.2	from 5.2 to 5.5
1	1.6	0.8*	0.3*	0.2*
2	2.4	1.2	0.5*	0.4*
3	3.5	1.7	0.7	0.5*
4	3.9	2.1	0.9	0.6
5	4.7	2.5	1.1	0.7
6	5.5	3.0	1.2	0.8
7	6.3	3.3	1.4	1.0
8	7.1	3.8	1.6	1.1
9	7.9	4.2	1.8	1.2
10	8.7	4.6	1.9	1.3
15	12.5	6.7	2.8	1.9

*It is recognised that low rates of lime are impractical to apply, but over-liming can cause nutrient imbalances, particularly in these light soils.

KEY: Limestone rates per hectare

0.5 t/ha	1.0 t/ha	1.5 t/ha	2.0 t/ha	2.5 t/ha	3 to 4 t/ha	Split applications advised

Table 2. Limestone required to lift the pH of the top 10cm of soil to 5.2
Source (Upjohn, Fenton, & Conyers, 2005)

Cation Exchange Capacity

Cation exchange capacity (CEC) is the capacity of a soil for ion exchange of positively charged ions between the soil and the soil solution. A positively-charged ion, which has fewer electrons than protons, is known as a cation. Cation exchange capacity is used as a measure of fertility, nutrient retention capacity, and the capacity to protect groundwater from cation contamination. (Wikipedia)

Cation exchange capacity is a useful indicator of soil fertility because it shows the soil's ability to supply three important plant nutrients: calcium, magnesium and potassium.

What CEC actually measures is the soil's ability to hold cations by electrical attraction. Cations are positively charged elements, the positive charge indicated by a + sign after the element symbol. The number of + signs indicates the amount of charge the element possesses.

The five most abundant exchangeable cations in the soil are calcium (Ca++), magnesium (Mg++), potassium (K+), sodium (Na+) and aluminium (Al+++).

Cations are held by negatively charged particles of clay and humus called colloids. Colloids consist of thin, flat plates, and for their size have a comparatively large surface area. For this reason they are capable of holding enormous quantities of cations. They act as a storehouse of nutrients for plant roots.

As plant roots take up cations, other cations in the soil water replace them on the colloid.

If there is a concentration of one particular cation in the soil water, those cations will force other cations off the colloid and take their place.

The stronger the colloid's negative charge, the greater its capacity to hold and exchange cations, hence the term cation exchange capacity (CEC). (DPI)

Soil pH is important for CEC because as pH increases (becomes less acid), the number of negative charges on the colloids increase, thereby increasing CEC.

CEC varies according to the type of soil. Humus, the end product of decomposed organic matter, has the highest CEC value because organic matter colloids have large quantities of negative charges.

Clay has a great capacity to attract and hold cations because of its chemical structure. Sand has no capacity to exchange cations because it has no electrical charge. This means sandy soils such as podzolic topsoils have very low CEC, but this can be improved by adding organic matter.

You can improve CEC in weathered soils by adding lime and raising the pH. Otherwise, adding organic matter is the most effective way of improving the CEC of your soil. This can be done with permanent pasture, regular slashing, green manure crops, leaving crop stubbles to rot, rotating crops or pasture, and the addition of mulch and manure. (DPI) (Loveland P.J.and Webb, 1997)

Soil Organic Matter

Schwenke cited from Baldock and Nelson (2000) who derived the following definition of soil organic matter (SOM) from several eminent sources: (Schwenke G. , 2004)

'Soil organic matter is the sum of all natural and thermally altered biologically derived organic material found in the soil or on the soil surface irrespective of its source, whether it is living or dead, or stage of decomposition, but excluding the above-ground portion of living plants.'

More simply put, soil organic matter is everything in the soil of biological origin, whether living or non-living.

Organic matter is the fraction of the soil made up of anything that once lived, including plant and animal remains, cells and tissue, plant roots and soil microbes. It is a dynamic, changing resource that reflects the balance between addition of new organic matter and loss of organic matter already in the soil.

Soil organic matter is one of the most important components of a soil, influencing a wide range of physical (e.g. soil structure and water holding capacity), chemical (e.g. cation exchange capacity and nutrient supply) and biological (e.g. nutrient turnover and microbial activity) properties. (Carter, 2001)

Soil Organic Matter (SOM) is composed of both living and non-living components. The living component comprises only a small fraction of total SOM.

The majority of SOM is non-living (95% by weight), and can be divided into distinct fractions or pools. A particularly useful SOM classification scheme separates SOM into four fractions. These fractions and their comparative SOM pools are listed as follows:

- dissolved organic matter (DOM, active and slow pools),
- particulate organic matter (POM, active and slow pools),
- humus (HUM, passive pool) and
- inert organic matter(IOM, recalcitrant pool) (Aumann & Fisher, Characteristics of non-living Soil Organic Matter Info leaflet)

SOM is an diverse mixture of components with proportions in any given soil sample differing enormously depending on climate, parent material, soil texture, vegetation, animals, microorganisms, topography and land management. Because there is such a range of components encompassed in SOM, components are often grouped on the basis of their typical breakdown rates in soil and their biochemical makeup. The main groups are stable SOM and active SOM (Schwenke G. , 2004) as shown in the figure below

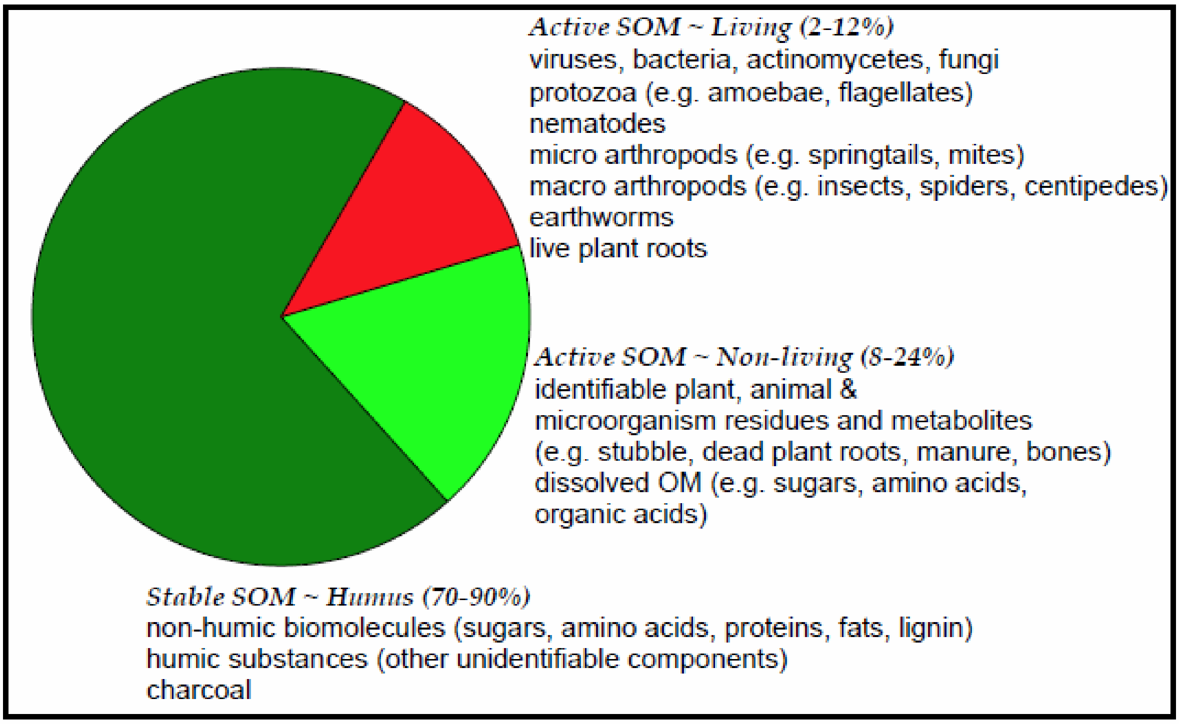

Fig 3. The main groups of Soil Organic Matter
Source (Schwenke G. , 2004)

Stable components of SOM, known collectively as humus, are either chemically or physically stabilised. Chemically stabilised compounds are highly decomposed compounds of high molecular weight that few microbes can degrade. Physically stabilised compounds are those bound inside soil aggregates where microbes cannot reach. Carbon dating and isotope abundance techniques have shown that the residence time of humus in soils ranges from decades to centuries. Some compounds such as charcoal are practically inert. Chemical compounds within humus are a mixture of identifiable (non-humic substances) and more complex organic molecules (humic substances) (Schwenke G. , 2004).

Active or labile SOM is so named because its components break down over periods ranging from days to years.

Once an area is converted from a natural system to a cropping or grazing system the level of organic matter in the soil changes. Typically, farmland experiences organic matter decline of up to 60%. (Schwenke & Jenkins, 2005)

Loss of soil organic matter is usually related to the loss of topsoil through erosion. Organic matter is also lost by microbial oxidation, in which soil microorganisms use organic matter in the soil as a food source during their normal metabolism. Management practices that add little organic matter to the soil or increase the rates of organic matter decomposition (such as summer fallowing and excess tillage) lead to reduced levels of organic matter in the soil.

Because organic matter is rich in nitrogen, phosphorus, and other nutrients, loss of soil organic matter reduces a soil's fertility and its capacity to produce crops. Organic matter holds more water per unit weight than mineral matter and is needed for a well-aggregated soil structure. Its loss also reduces the soil's capacity to accept, store, and release water for plant growth. (Batie & Cox)

When perennial species are used, especially lucerne, they enable the capture of water from the deep subsoil that may have drained beyond the reach of crop roots, thus improving the hydrologic performance of the system. (Kirkegaard, 2004)

Bauer & Black (1992) found that available water capacity (AWC) remained essentially constant in sandy soils as organic C increased from 0.74 to 1.49 %. They concluded that the decline in productivity from soil erosion was not caused by a reduction in AWC, but by a decline in nutrients and biological activity. (Loveland P.J.and Webb, 1997)

It has long been known that additions of, or increases in, soil organic matter can benefit soil properties. Improved plant nutrition (N, P, S, micronutrients), ease of cultivation, penetration and seed-bed preparation, greater aggregate stability, lower bulk density, improved water holding capacity at low suctions, enhanced porosity and earlier warming in Spring have all been commented upon (Loveland P.J.and Webb, 1997)

To build up organic matter in the soil, you need or maximise the addition of new organic materials and minimise losses from the soil. (Schwenke & Jenkins, 2005)

Activity	**Adds organic matter**	**Reduces loss of organic matter**
Grow healthy crops and pastures		
Rotate crops		
Grow green manure crop		
Use pastures in rotations		
Apply animal manures, recycled organic waste		
Retain crop residues		
Grow plants more resistant to microbial breakdown		
Reduce periods of bare fallow		
Reduce tillage and erosion		

Table 3. Activities which increase Organic matter or decrease loss of organic matter
Source: (Schwenke & Jenkins, 2005)

Management factors that can influence the amount of organic matter returned and retained in the soil include:

- Quantity - the more litter or organic material (plant and animal remains, waste products and roots) entering the soil means higher SOM levels. In contrast removal of the above ground OM results in less carbon input.
- Quality - generally when high quality organic materials (i.e. C:N < 20) or those containing highly available C and N are added to the soil, there can be an increase in SOM (soil carbon) levels.
- Intensive tillage - generally results in a decrease in soil carbon due to the accelerated loss or turnover of soil carbon from microbial respiration and erosion. In contrast reducing tillage can lead to increased soil carbon retention and SOM levels. SOM levels are usually higher under forest and pasture soils. (Aumann & Fisher, Soil Health and Soil Organic Matter Info Leaflet)

Total soil organic matter has long been recognised as a key factor in the stability of soil aggregates in water (Loveland P.J & Webb, 2003) which in turn is an important indicator of soil health. An unstable structure in the surface soil will quickly lead to slumped surfaces, reduced infiltration and the resulting erosion and compaction problems

The role of soil organic matter in crop production was considered vital because it was the main source of N for crop production. It was also considered to increase the availability to plants of many essential micro-nutrients, as well as substantial amounts of phosphorus and sulphur.

Long-term trials (20-120 years) comparing manuring and inorganic fertiliser application (Edmeades D. C., June 2003,) have shown that manured soils had higher contents of SOM and numbers of microfauna than fertilised soils, and were more enriched in several plant nutrients. (Schwenke G. , 2004)

Techniques to build organic matter

Grow healthy crops and pastures

Growing more plant biomass will increase the input of organic material to help balance the continual loss of organic matter through decomposition. As organic matter levels decline, the storage and supply of major plant nutrients such as nitrogen, phosphorus and sulfur diminish. This reduces the potential for plant production. When plant production declines, there is less organic matter available for soil organisms, so their activity declines, leading to a downward spiral of production.

Rotate crops

The level of soil carbon is affected by the quantity and quality of the plants grown. The quantity of plant residue can be changed by;

- growing crops of different biomass
- improving the nutrition of and disease status of following crops through a beneficial rotation
- growing crops with different rooting patterns that alter soil structure.

The quality of crop residues can be improved by growing plants that are easy for microbes to decompose. Plants with high nitrogen levels are easier to break down than woody plants with high lignin levels. Legumes have the potential to bring nitrogen into the system from the atmosphere and can be grown as either a cash crop or green manure.

Grow green manure crops

Green manure crops are rotation crops that are ploughed in (or sprayed out) rather than harvested, to provide organic matter for the following crop. For instance, a crop will need less nitrogen if it follows a legume crop. The costs of green manure crops need to be assessed carefully, especially in terms of water use, since there is no direct financial return. Organic matter gains tend to be short-term, especially as the input of immature crops or legumes provides an easily decomposed biomass.

Use pastures in rotations

Pastures increase organic matter in the soil. A mix of grasses and legumes provides more organic matter than legume pastures such as lucerne or medic. The grasses have greater root biomass, and legumes are easily decomposable so their beneficial effect is soon lost.

Apply animal manures, recycled waste

Organic amendments such as animal manures or recycled organics (eg foodwastes and composts) are usually added to supply plant nutrients. Addition of organic matter is generally a secondary concern. Recycled organics provide more carbon in the soil than manures or crop residues, because much of recycled product’s easily decomposed carbon has already been lost to the atmosphere as CO_2 during composting. Applying manures in excess of plant requirements increases potential for serious environmental damage from runoff or leaching.

While large additions of recycled organics or animal manures should increase SOM rapidly, improvements in cropping and pasture systems may take five years or more to register an increase in an OC soil test. Increases occur firstly in the smaller active SOM fraction with benefits to soil structure and microbial diversity, then later in the stable SOM. (Schwenke G. , 2004)

Retain crop residues

Carbon management in soils must focus strongly on inputs. Retention of crop residues is a key management option currently available for farmers. Retaining crop residues produced onsite by crops is more cost effective than bringing in materials.

Reduce tillage and erosion

Reducing or stopping cultivation altogether has several direct and indirect effects on organic matter. The residence time of carbon added to soil can be nearly twice as long under zero tillage than under intensive tillage.

When crop residues remain on the soil surface, and the soil surface is not disturbed, rainwater infiltrates rather than runs off, so the soil is protected from erosion. All processes aimed at increasing organic matter are futile if the soil itself is lost.

After erosion, the main process for carbon loss from soil is microbial decomposition. The physical disturbance of ploughing brings crop residues into the soil where conditions for microbial decomposition are more favourable than for residues left on the surface.

As well, cultivation breaks up soil aggregates held together by organic matter and exposes the organic matter in the aggregates to decomposition by microbes.

A less well-known direct effect of tillage is the degassing of CO_2 that naturally builds up within the soil air from microbes and plant roots.

Reduce periods of bare fallow

During a fallow period no new organic material is being produced, but carbon continues to be lost from the soil as organic matter decomposes. Summer fallows are worst as the soil stays moist and warm – favourable conditions for decomposition. (Schwenke & Jenkins, 2005)

Incorporating organic matter below the soil

Research has been conducted to demonstrate the effectiveness of incorporating organic matter below the soil. (Gill, Sale, & Tang, 107 (2008)) (Clark, 2007)

Clark et al 2007 carried out a research experiment incorporating a variety of organic materials incorporated in sodic clay

Main treatments were wheat, lucerne and peat in addition to non-amended control. Gypsum was included for comparison as it is a common material commonly used, and still widely used, to ameliorate sodic soils. The additional treatments were canola residue, chickpea residue, chicken manure and sawdust.

The organic amendments, incorporated in sodic clay subsoil, differed greatly in their initial rates of microbial decomposition, as measured by soil respiration.

The incorporation of peat or gypsum had minimal effects on the microbial activity in the soil, This study clearly demonstrates that the incorporation of organic amendments into high clay sodic soil can improve the chemical and biological fertility. In particular, major benefits in the short to medium-term occur with the green crop residues where the benefits for soil fertility are driven by the residue's content of soluble carbon (C) and nitrogen (N). The stubble residues provided much lower initial microbial activity in the soil during this phase. Thus, it may be recommended that 'green' residues or residues with good levels of labile C and N are used for subsoil amelioration, in order to maximize the benefit and, in the short to medium term, justify the expense of using heavy machinery. If crop stubbles are chosen instead of green residues then the effect take a longer time period for the benefit to develop. (Clark, 2007)

In the research carried out by Gill et al 2008, the treatments involved significant mechanical intervention in order to place the high rates (20 t ha) of organic amendment (dynamic lifter or lucerne pellets) and inorganic amendments (gypsum, MAP and coarse sand) at a depth in excess of 30–35 cm, in the upper layers of the B horizon of the soil profile. (Gill, Sale, & Tang, 107 (2008))

Organic amendments produced the largest responses in shoot biomass at flag leaf emergence at both experiments. The dynamic lifter pellets, or the straight lucerne pellets produced the largest responses, almost doubling biomass yields compared to the control plots at the non-lucerne site, with smaller biomass increases of around 70% occurring at the lucerne site.

The marked increases in grain yield that occurred with the deep incorporation of organic amendments indicate that this approach has potential to increase crop productivity.

High grain yields of 11 t/ha and above occurred at both sites in 2005 where straight organic amendments were added to the subsoil prior to the start of the growing season. The highest yields consistently occurred with the dynamic lifter amendment, followed by the use of straight lucerne pellets. The high yields of 11–13 t/ha have not previously been reported for wheat crops in Australia.

These highest yielding treatments resulted in yield increases of 70% and 60% above the control at the non-lucerne and lucerne sites, respectively The lowest yields at both sites occurred on the control and deep ripped plots, while intermediate grain yields were produced with the inorganic amendments, including gypsum, MAP, gypsum plus MAP and coarse sand.

Subsoil amelioration treatments had a major impact on the nitrogen (N) content of the shoots of wheat plants in this study. The most striking effect was the significantly higher ($p < 0.05$) N uptake by shoots from the dynamic lifter and lucerne amendment treatments, compared with the control or the inorganic amendment treatments

The concentration of protein in grains at harvest reflected the N content in the wheat shoots during crop development. Here the treatments could again be generally divided into 3 groups; the organic amendment treatments resulted in the highest grain protein concentrations of 11–13%, the control, the deep-ripped, and the gypsum treatment had the lowest concentrations between 9% and 10%, while the other inorganic amendment treatments had grain protein concentrations between 9.6% and 11%

A further striking result from the organic amendment treatment was the change in water extraction patterns of wheat plants. The change was from a pattern where 60% of the profile water at sowing was extracted from the top 40 cm as occurred with control plants at the non-lucerne site and gypsum plants at the lucerne site to that where 60% of the soil water at sowing was extracted from below 40 cm, as occurred with the organic amendment treatments at both sites. This ability to increase the extraction of subsoil water suggests that this approach to subsoil amelioration has the potential to deliver real increases in water use efficiency. Such outcomes are consistent with the views of Turner (Turner, 2004) who argued that improvements in water use efficiency by crop plants can be achieved if the crop roots are able to extract more soil water from deeper subsoil layers.

Wheat plants with the deep incorporation of organic amendments were able to extract greater amounts of water below 40 cm during crop growth, compared to those from the control treatment. This was a very advantageous outcome as this subsoil water can be used very efficiently by crop plants.

In addition to improving water uptake from the subsoil, the organic amendments in this study also increased N supply to the wheat plants. The increased supply resulted in more than a doubling of N uptake during the growth of the crop, when comparisons are made between the average N uptake for the dynamic lifter and lucerne amendments on the one hand, and the control and deep-ripped treatments on the other

Clearly, the high yielding wheat plants were well supplied with water and nitrogen, enabling this wheat genotype to produce sufficient assimilate at critical stages of growth organic amendments have been shown to increase and stabilize macroaggregates of this dense sodic subsoil (Clark, 2007).

Alternative Soil Treatments

Manures

The medium term experiments conducted by ADAS Gleadthorpe Research Centre in the UK produced results which indicate that repeated farm manure applications have important and measurable beneficial effects on the physical, chemical and biological properties of arable topsoils, acting as a valuable soil conditioner and source of plant available nutrients. Indeed, the most sensitive indicators of soil quality and fertility changes were soil chemical (e.g. increases in plant available P, K and Mg supply and total N) and biological (e.g. increases in biomass N, PMN and respiration rates) properties. The only measureable effects on soil physical properties were on the loamy sand textured soil (at ADAS Gleadthorpe) which had received the highest OC loadings (up to 65t/ha). Changes in soil properties, particularly physical characteristics, only develop gradually and long timescales are needed to fully evaluate the contribution of farm manure applications to soil quality and fertility.

The work has shown that the addition of organic carbon to topsoils via repeated farm manure applications can raise soil organic matter (soil organic matter) levels. This in turn, had measurable effects on selected soil physical, chemical and biological properties, namely: available water capacity (AWC), porosity, bulk density, biomass N, respiration rate and potentially mineralisable N (PMN) (ADAS Gleadthorpe Research , 2002)

In research conducted by (Edmeades D. C., June 2003,) results from 14 field trials comparing the long-term (20 to 120 years) effects of fertilisers and manures (farmyard manure, slurry, and green manure) on crop production and soil properties are reviewed.

In total there were 24 paired comparisons of the effects of manure and fertiliser. Some of the trials also contained a control (no nutrient inputs) treatment.

The input of nutrients as either fertilisers or manures had very large effects (150–1000%) on soil productivity as measured by crop yields. Manured soils had higher contents of organic matter and numbers of microfauna than fertilised soils, and were more enriched in P, K, Ca and Mg in topsoils and nitrate N, Ca and Mg in subsoils.

Manured soils also had lower bulk density and higher porosity, hydraulic conductivity and aggregate stability, relative to fertilised soils.

However, there was no significant difference ($P < 0.05$) between fertilisers and manures in their long-term effects on crop production. In the context of this set of international trials, the recent evidence from the Rothamsted classical long-term trials appears to be exceptional, due to the larger inputs of manures and larger accumulation of soil OM in these trials. It is suggested therefore that manures may only have a benefit on soil productivity, over and above their nutrient content, when large inputs are applied over many years.

The evidence from these trials also shows that, because the ratio of nutrients in manures is different from the ratio of nutrients removed by common crops, excessive accumulation of some nutrients, and particularly P and N, can arise from the long-term use of manures, relative to the use of fertilisers. Under these conditions greater runoff of P, and leaching of N may result, and for soils with low P retention and/or in situations where organic P is leached, greater P leaching losses may occur.

The use of manures, relative to fertilisers, may also contribute to poor water quality by increasing its chemical oxygen demand. It is concluded therefore that it cannot generally be assumed that the long-term use of manures will enhance soil quality – defined in terms of productivity and potential to adversely affect water quality – in the long term, relative to applying the same amounts of nutrients as fertiliser. ((Edmeades D. C., June 2003,)

Compost

According to Stokes et al, increasing organic matter in soils can minimise the impact of cropping on soil health, ensuring the sustainability and profitability of broadacre farming. This can be achieved through the application of processed organic waste materials, such as compost. Compost is a rich source of slow-release nutrients and can absorb up to 10 times its weight in water, resulting in improved soil water and nutrient availability. (Stokes, Cody, & Maheswaran, 2003)

The compost used for this trial comprised of wool scour sludge and timber fines produced from a sawmilling company. Results showed that compost incorporated into the beds has increased soil water retention and reduced soil bulk density.

Increases in soil moisture retention, SOM and porosity can improve conditions for plant development and may result in a reduction of run-off and fertiliser loss. This would benefit both the crop and the environment, since more water and nutrients are available for plant uptake, whilst the decrease in run-off reduces off-site environmental impacts. Generally, the release of nutrients from compost, such as potassium (K), is much slower compared to traditional fertilisers. This can be beneficial for soils that experience excessive loss of K through leaching.

Although there were no significant responses observed for crop growth and yield in 2001, the improvements in soil quality will more likely have an affect on crop yield over the longer term.

Liquid Fertilisers

A CSIRO trial conducted in 2002 demonstrated that liquid fertilisers do not contain sufficient concentrations of plant nutrients, organic matter, or plant growth substances (PGSs) to elicit increases in plant growth when applied as recommended. (Edmeades D. C., 2002)

The results from field trials measuring the effect of liquid fertilisers derived from organic materials on crop yields are summarised and reviewed. Trials comparing the efficacy of 26 specific products and 2 unnamed generic products were identified. Of these 28 products, 15 were derived from seaweed, 4 from fish waste, 5 were of vegetable origin, and 2 were from animal products. Cereals were the most frequently used test crop (328 recorded treatment effects) followed by root crops (227), legumes (88), pastures (59), and vegetables (52). Fifty-three other treatment effects were recorded on crops such as rape (15), peanuts (8), tobacco (6), and miscellaneous other crops (25). The effects of liquid fertilisers on animal performance were measured in 4 trials.

The observed effects of these products on a wide range of crops were normally distributed about zero with an equal number of positive and negative 'responses'. The frequency of statistically significant events, both positive and negative, was consistent with probability theory, assuming that the products are ineffective. The range of observed effects are also consistent with the normal variability associated with field trial experimentation, taking into account the odd intrusion of other experimental errors.

There was no evidence to support the conclusion that at least some product-types or products were effective on some crop-types, crops, or cultivars. Similarly, liquid fertilisers had no effect on animal production when applied as recommended.

This conclusion, based on the field evidence, was consistent with, and could be predicted from, independent evidence showing that these products do not contain sufficient concentrations of plant nutrients, organic matter, or plant growth substances (PGSs) to elicit increases in plant growth when applied as recommended. (Edmeades D. C., 2002)

While the trial focussed on immediate plant growth, it did not focus on any improvement in soil health. Soil health cannot be dramatically improved in a short space of time as it is an intricate living system. Applying liquid fertilisers does not give a ‘quick fix’ in improving soil health. It is possible that soil health would improve with the use of liquid fertilisers which would show an improvement in plant growth over time.

Reactive Phosphate Rock (RPR)

A national Reactive Phosphate Rock (RPR) research project, which investigated the agronomic effectiveness of a series of phosphate rock products on permanent pastures across a wide range of environments in temperate and tropical Australia, was conducted in 1997.

It is concluded that there are areas in the high rainfall pastoral zone in southeast Australia where highly reactive RPRs will become as effective as single or triple superphosphate, after a lag period of three to five years. There are, however some shortcomings to its use, including the need to add sulphur (S) which will reduce cost savings, the likelihood of poor pasture response in winter months, and losses in production on low phosphorus (P) soils during the lag stage. Phosphate rocks of low reactivity are not recommended for widespread use. (Sale, 1997)

Humic Acid

Humic acid or humate products are generally extracts from leonardite or lignite, a mineral similar to brown coal. As with microbial products, increasing SOM measurably with humic acid products is unlikely given the scale of addition advocated versus the background levels in SOM. However, there are many claims and some reports in the scientific literature that adding humic acid products to soils may stimulate plant growth and increase yield, possibly due to mechanisms such as delaying precipitation of phosphorus from mineral fertilisers in certain soil types (Delgado A, 2002). Whether such applications will work and are economical, will be affected by your particular farming system with its unique combination of soil type, climate, landscape, paddock history and economic situation. (Schwenke G. , 2004)

Soil Biology

Soils contain microorganisms (including bacteria, fungi, yeasts; photosynthetic organisms including algae) and macroorganisms (such as protozoa, nematodes, mites, springtails, spiders, insects and earthworms). The functions of this complex array of biota, often referred to as the ‘soil food web,’ are diverse, and include residue decomposition, nutrient storage and release, soil structure and stability, resistance against disease and degradation or immobilisation of pesticides and other pollutants. (Van Zwieten, 2004)

Soil biota influence the availability of nutrients for crop production via a range of activities such as the decomposition of crop residues, immobilisation (microbial uptake) of nutrients, mineralisation (transformation of organic nutrients into plant available inorganic forms), biological nitrogen fixation, and bioturbation.

The soil fauna are crucial for the initial comminution of residues and mixing into the soil, while the microflora have a greater suite of enzymes for chemical breakdown of organic material.

Bacteria and fungi are often considered as a labile pool of nutrients (carbon, nitrogen, phosphorus and sulfur) called the soil microbial biomass that has a pivotal role in nutrient immobilisation and mineralisation. The release of nutrients from the microbial biomass is partly regulated through grazing by the soil fauna. (Bünemann & McNeill, 2004)

Soil organisms (biota) carry out a wide range of ecosystem processes that are essential for crop production, soil resource quality and environmental health in both natural and managed agricultural soils. Production by both crops and pastures is supported and enhanced by soil biological processes. There is a two way relationship between the soil biota and agricultural production. For example, as soil biota play a key role in a number of nutrient transformation processes, crop residues form the essential supply of carbon (energy source) and nutrients for microbial activity. (Roget, 2004)

Soil organisms can be grouped according to their size, morphological characteristics, function and trophic (food) preference. Soil microorganisms are also combined into groups based on their role in specific soil functions (functional groups), irrespective of their taxonomic classification, in order to relate their activities to soil processes. For example nitrifying microorganisms are those that convert ammonia nitrogen into nitrate nitrogen. Soil organisms range in size from microscopic, eg bacteria (two thousandths of a millimetre) to centimetres (earthworms). The four major groups of soil biota, based on their body size, include;

- microflora (bacteria, fungi, algae and actinomycetes)
- microfauna (protozoa, nematodes)
- mesofauna (collembola, mites)
- macrofauna (earthworms, beetles, termites).

In addition, soil animals are also classified into groups based on their principal food source and feeding mode, eg bacterial-feeding, fungal-feeding, plant parasitic or predatory fauna.

In the majority of dryland cropping regions in southern Australia, moisture availability plays a critical role in determining the activity of both microflora and soil fauna.

According to Roget, (Roget, 2004) organic matter in soil is the most important fraction that supports microbial populations, especially the biologically available portion of soil organic matter.

Microbial biomass (MB), the living component of soil organic matter, constitutes 2-7% of the organic carbon in soils. Microbial biomass acts as the engine for organic matter turnover and nutrient release. The size of microbial biomass in the surface soil may range from 250 mg

C/kg in a sandy soil to 1100 mg C/kg in a clay soil rich in organic matter. Microbial biomass carbon may only represent a small portion of soil organic matter (2-7%), but it is dynamic and living and thus is more sensitive to management practices than total soil organic matter.

Microbial biomass is a storehouse of plant essential nutrients. For example, nitrogen levels in microbial biomass range from 15 kg to 150 kg N/ha. Microbial biomass also holds 5-15 kg of sulfur and 10-45 kg phosphorus per ha. Nutrients held in microbial biomass are not prone to leaching, are tied up only temporarily, and are released for plant uptake as a result of predation by microfauna and the death of microbes during soil drying. It is the interactions between microorganisms and organic matter in the soil that largely determine the fertility and overall quality of the soil. Therefore it is extremely important to use farm management practices that maintain organic matter levels, especially biologically available organic matter, in our soils.

In high-yielding eastern Australian agricultural soils, where the level of carbon inputs is not a constraint, it is the composition of specific functional groups of microorganisms that affect plant growth and production.

Plants are the major source of available carbon for biological activity, so soil biodiversity and biological activity depend on the quality and quantity of carbon inputs from plants, through root exudation and above- and below-ground plant residues, and plant-induced changes in soil physical and chemical properties. Pastures are composed of mixtures of plant types (legumes, grasses, C3, C4) so are considered to have a greater potential to influence diverse biological processes. However, the availability of carbon in grazed systems is mediated strongly by grazing management, due to above- and below-ground plant growth in response to grazing. (Roget, 2004).

Chan reviewed the interrelationships between soil structure and soil biota which affect soil functions. He outlines the importance of soil structure on abundance, diversity and activity of soil biota, looks at the effects of soil biota in modifying soil structure, and discusses the importance of soil biota interactions on soil health and the role of soil management practices in harnessing the beneficial functions of soil biota. (Chan, 2004)

The availability of carbon substrates is more important for soil biota than that of nutrients such as nitrogen, phosphorus, potassium and sulphur. Therefore, organic fertilisers usually have greater impact on soil biota than mineral fertilisers. Direct effects of mineral fertilisers on soil biota seem to be variable but perhaps less important than indirect effects. The main indirect effects are a depression of soil biota due to a decrease in soil pH, and an increase in biological activity with increasing plant productivity, crop residue inputs and soil organic matter levels. As Australian soils are generally low in organic matter and nutrient contents, any increase in soil organic matter is desirable in view of the important role of soil biota in nutrient cycling. (Bünemann & McNeill, 2004)

Improving soil biota:

The following are some recommended practices put forward by Hollier for improving soil biota;

- Use appropriate cropping rotations for improved organic matter, disease breaks and more diverse nutrient sources for soil biota.
- Maintain soil fertility: soil test regularly and apply fertilisers according to crop and paddock needs.
- Retain stubble: improves soil organic matter (food source for soil organisms).
- Minimise cultivation: retains a food source for soil biota.
- Lime acidic soils: provides a more favourable pH for soil microbes and earthworms.
- Reduce compaction: limit traffic from machinery and over-stocking. Compaction reduces soil drainage, causing unfavourable soil conditions for biota. (Hollier, 2006)

The frequency of highly productive legume-based pastures in the farming system of the area provides greater inputs of labile carbon and nitrogen to the system, than provided by crop residues, for sustaining microbial activity. (Kirkegaard, 2004)

Worms

Earthworms, termites and ants have been called the soil ‘ecosystem engineers’ because of their ability to modify soil structure. Earthworms are the most effective at ‘turning over’ the soils and in transporting of soil material within the soil profile (Chan, 2004)

By their activity in the soil, earthworms offer many benefits: increased nutrient availability, better drainage, and a more stable soil structure, all of which help improve farm productivity,

Worms feed on plant debris (dead roots, leaves, grasses, manure) and soil. Their digestive system concentrates the organic and mineral constituents in the food they eat, so their casts are richer in available nutrients than the soil around them. Nitrogen in the casts is readily available to plants. Worm bodies decompose rapidly, further contributing to the nitrogen content of soil.

Worm casts release four times more phosphorus than does surface soil. Worms often leave their nutrient-rich casts in their tunnels, providing a favourable environment for plant root growth. The tunnels also allow roots to penetrate deeper into the soil, where they can reach extra moisture and nutrients. Earthworm tunnelling can help incorporate surface applied lime and fertiliser into the soil.

The extensive channelling and burrowing by earthworms loosens and aerates the soil and improves soil drainage. Soils with earthworms drain up to 10 times faster than soils without earthworms. In zero-till soils, where worm populations are high, water infiltration can be up to 6 times greater than in cultivated soils. Earthworm tunnels also act, under the influence of rain, irrigation and gravity, as passageways for lime and other material.

Earthworm casts cement soil particles together in water-stable aggregates. These are able to store moisture without dispersing. Research has shown that earthworms which leave their casts on the soil surface rebuild topsoil. In favourable conditions they can bring up about 50 t/ha annually, enough to form a layer 5 mm deep. One trial found worms built an 18-cm thick topsoil in 30 years.

Research into earthworms in New Zealand and Tasmania found earthworms introduced to worm-free perennial pastures produced an initial increase of 70–80% in pasture growth, with a long-term 25% increase. This raised stock carrying capacity. Researchers also found that the most productive pastures in the worm trials had up to 7 million worms per hectare, weighing 2.4 tonnes. There was a close correlation between pasture productivity and total worm weight, with some 170 kg of worms for every tonne of annual dry matter production. (DPI, NSW, 2004)

Because earthworms do not like soil that is too acid, alkaline, dry, wet, hot or cold, their presence is a good indicator of soil conditions suitable for plant growth.

In agriculture, management practices can have direct effects on soil biota and indirect effects due to changed soil structure. Tillage and associated field machinery traffic destroy habitats of earthworms and result in soil compaction that can render the soil too strong for these ecosystem engineers to survive. (Chan, 2004)

How to encourage earthworms in pasture;

Ensure soil pH (CaCl2) is above 4.5

Earthworms do not like acid soils with pH (CaCl2))* less than 4.5. The addition of lime raises pH and also adds calcium. Earthworms need a continuous supply of calcium, so are absent in soils low in this element. South Australian research found that earthworm numbers doubled when pH(CaCl2) rose from 4.1 to 6.7.

Research undertaken by Dr Guangdi Li et al showed the long-term trend of earthworm population in response to lime application. The total population of earthworms increased linearly from 1994 to 1997 for both limed and unlimed perennial and annual pastures.

From 1997 onwards, the total population of earthworm on the limed pastures decreased gradually, whereas the earthworm population on the unlimed pastures stabilised, fluctuating around 100–150/m2. Lime had little effect on the population of native species before 1999, but had a negative effect after 1999.

In contrast, the numbers of introduced earthworms in the limed soils were consistently higher than those in the unlimed soils. There were no differences in earthworm numbers between perennial and annual pastures. (Guangdi Li, 2006)

Increase organic matter

Earthworms feed on soil and dead or decaying plant remains, including straw, leaf litter and dead roots. They are the principal agents in mixing dead surface litter with the soil, making the litter more accessible to decomposition by soil microorganisms. Animal dung is also an attractive food for many species of earthworms. The following farming practices provide food for earthworms.

Permanent pasture

Permanent pasture provides organic matter as leaves and roots die and decay. Pasture slashings and manure from grazing animals are also good sources of organic matter in pasture.

Keep soil moist

Worms can lose 20% of their body weight each day in mucus and castings, so they need moisture to stay alive. Groundcover such as pasture or stubble reduces moisture evaporation. Decaying organic matter (humus) holds moisture in the soil. In dry times some species burrow deep into the soil and are inactive until rain 'reactivates' them.

Improve drainage

Worms need reasonably aerated soil, so you may need to drain or mound soil in wetter areas to prevent waterlogging.

Reduce soil compaction

It is difficult for earthworms to move through heavily compacted soil, so keep vehicle and animal traffic to a minimum in wet conditions.

Reduce cultivation

Ploughing soil reduces earthworm numbers. Researchers have found that after four years, zero-tilled paddocks had twice as many worms as cultivated soils. However, shallow cultivation may not affect worm numbers.

Protect from climatic extremes

Earthworms are intolerant of drought and frost, and do not like dry sandy soils. They are active only when the soil is moist, and are inactive when it is dry. Organic matter cover helps reduce the effect of climatic extremes, and retains soil moisture. (DPI, NSW, 2004)

Earthworms as a measure of soil health?

Earthworms are often considered as the obvious candidate for a faunal indicator of soil health or quality, not least because they play a direct role in maintaining several other chemical and physical indicators (nutrient supply, structural stability and pore formation) and indirectly several more (microbial populations, rainfall infiltration and transport). They also interact intimately with soil organic matter by being responsible for incorporation of organic residues into the soil and mixing them into close association with physical particles and microbial organisms and the production of key carbohydrate compounds important in structural stabilisation. Indeed their abundance can be linked directly to amounts of organic material applied to soil (manure and straw) (Doube & Schmidt 1997), as well as the performance of surrogate indicators of plant performance such as yield and biomass.

Doube & Schmidt (2004) reviewed many conflicting case histories and concluded that "earthworm abundance cannot be used as a universal indicator of soil health because key agronomic factors which determine plant yield and soil conservation are not those which influence earthworm abundance."

Soil testing

Soil testing is one of the most fundamental tools for understanding soils. However, when considering your soil, it is important to focus on soil function and plant metabolism for a more holistic view encompassing the balances between the integrated components of natural systems.

'*A basic soil audit is the first and sometimes the only monitoring tool used to assess changes in the soil. Unfortunately, the standard soil test done to determine nutrient levels (P, K, Ca, Mg, etc.) provides no information on soil biology and physical properties. Yet most of the farmer recognized criteria for healthy soils include, or are created by, soil organisms and soil physical properties. A better appreciation of these biological and physical soil properties, and how they affect soil management and productivity, has resulted in the adoption of new soil health assessment techniques.'*
National (USA) Sustainable Agriculture Information Service *http://attra.ncat.org*
source: www.tuckombillandcare.org.au

Any soil testing conducted should consider soil structure, available soil nutrients and soil biology to gain a comprehensive picture of the balance of these components

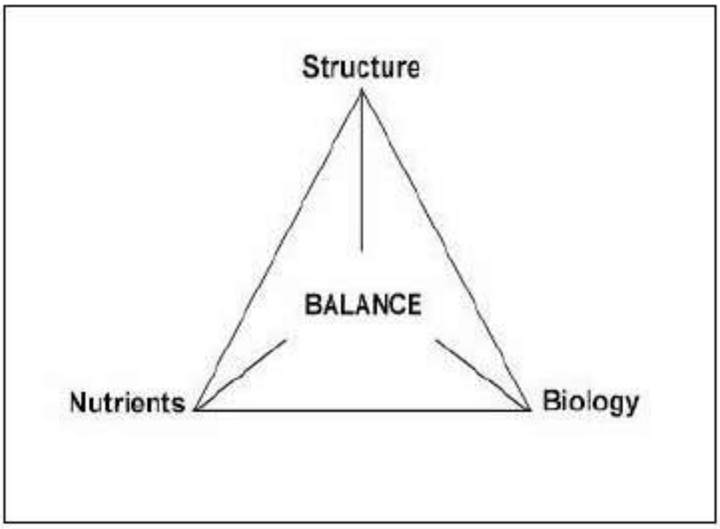

Fig 4. Mikhails Soil Balance System

Research done by Ted Mikhail, showed that a combination of five elements – Calcium, Magnesium, Sodium, Potassium and Hydrogen – work together to determine the functioning and friability of soil. We call this the “Cation Balance” of the soil and it is the first and most important of the three soil components in the Mikhail Soil Balance System.

Lime and Dolomite can react with many fertilisers (especially trace elements) to render them unavailable to plants. Lime, Dolomite and Gypsum need at least six months (more if rainfall is low) to produce their effects on the soil, so that optimum fertiliser efficacy can be assured.

The first step should be the application of any required Lime, Dolomite or Gypsum (for soil structure and function). The application of fertiliser should be the second step, done six months later.

According to Mikhail, the important steps to improve any soil are:

1. Soil test to identify the problem
2. Adjust the Cation Balance first (usually in Autumn)
3. Apply fertiliser six months later
4. Stimulate soil biology after every disturbance
5. Monitor and Adjust

An important aspect of this method is that it leads to progressively reduced inputs, until only small maintenance applications of fertiliser are required each season for both sustainable and cost-effective production. This contrasts with the vicious cycle of applying more fertiliser to increase productivity, but then needing even more productivity to cover the increased cost – requiring still further increases in fertiliser application rates. (SWEP FACT SHEET)

Below is the 5-step process in detail that Mikhail claims will provide a reliable strategy for improving any soil:

1. **Identify the cause of the problem**
   Conduct a comprehensive soil test, including soil biology
2. **Cations first**
   Appropriate applications of materials such as Lime, Dolomite and Gypsum to correct any imbalance, along with the time and moisture needed for the changes to proceed.
3. **Nutrients later**
   For properly balanced plant nutrition, the use of fertilizer should start about six months after correcting the cation balance.
4. **Biology after every application**
   To help get the best results from each of the first two steps, using the appropriate bio-active materials after each cation balance or fertiliser application will speed up the whole process.
5. **Monitor and Adjust**
   The effort and expense of getting your soil working right does not go on and on. Repeating the soil test on a regular basis will let you keep things working properly with only small ‘top-up’ applications, rather than waiting for everything to go back the way it was and starting again. (SWEP Fact sheet)

Conclusion

Soils are a complex web which is yet to be untangled. There is still much to learn.

Although significant research has been conducted into soils, there still appears to be only a few soil scientists considering soil as a holistic system.

Many experiments and research considered only certain soil components or has expected soil change in a short period of time. This is probably as traditionally used fertiliser, such as super, have demonstrated immediate gains in production. However, the gains in plant production are not necessarily improvements in soil health. Also, only a few trials ran for a significant time to demonstrate changes in soil health. This is possibly due to funding constraints and the requirement to deliver results in a short space of time rather than allowing the time to see the effects of the change in practice on soil health.

Soil health needs time to change as it is a complex inter-active system with many components depending on other components to be affective (e.g. highly acid soils affect nutrient availability as well as micro organism abundance and activity which in turn affects soil structure).

Only time, scientific rigour and general community gain in understanding through sharing research and learnings will help to untangle the web.

On farm management seems to be the most effective tool in improving healthy soils. However, it would be debateable as to whether the majority of farmers have a good understanding of their particular soils and the best management practices to create healthy soils. Whilst there is a growing environmental awareness and action by farmers in the general landscape, soils are not generally considered unless there is a problem with plant growth or stock health.

Soils are the basis of all farming. Without healthy soils, production will be low, plant growth will be stunted and lacking in nutrition and stock health will not be at its optimum.

A comprehensive awareness and education program which brings together the current good science and on ground practicality will be the recipe to improving soil health, and productive, profitable and sustainable farming.

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