CHAPTER 2

SOIL FERTILITY IN ORGANIC AGRICULTURE

Namibian Organic Association
Enabling Sustainable Organic Agriculture

IFOAM SOUTHERN AFRICAN NETWORK

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DEUTSCHE ZUSAMMENARBEIT

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SOIL FERTILITY IN ORGANIC AGRICULTURE

2.1.Soils in organic agriculture

Organic farming methods conserve and grow soil, maintain water quality and use water efficiently and responsibly.

Organic farmers and gardeners:

- Minimise the loss of topsoil through minimal tillage, contour ploughing, crop selection, maintenance of soil plant cover and other management practices that conserve soil
- Take measures to prevent erosion, compaction, salination, and other forms of soil degradation
- Use techniques that conserve water, such as increasing organic matter content of soil, timing of planting and the appropriate design, efficiency and scheduling of irrigation practices
- Apply water and inputs in a way that does not pollute water by runoff to surface water or leaching into ground water
- Plan and design systems that use water resources responsibly and in a manner appropriate to the local climate and geography
- Use organic management plans that anticipate, address and mitigate impacts on water resources, including but not limited to the application of manure, stocking densities, application of soluble fertilisers, and effluent from processing and handling facilities
- Respect sustainable resource management and the common good

2.1.1. Soil quality, health and fertility

Soil health is the key principle to successful organic farming.

More than 50% of soils in Namibia have relatively low fertility with fewer patches of higher fertility. As a result, Namibian soils, with some localised exceptions, are not suited for crop production. Even soils considered to have high fertility status in the comparative Namibian context, are rated soils of low fertility in the global context. *(Pre-study on the adaptation to climate change in agriculture for the improvement of livelihoods in the north of Namibia – Manjo Smith & Edith Kalka, 2013).*

Poor soil results in poor plants, more pests and diseases, and poor yield. The key to successful soil health is the build-up and correct management of organic matter. This gives the soil an open friable structure to aid both drainage and water retention and buffers the pH of soils that naturally tends to acidity or alkalinity. It also creates large complex organic molecules that allow mineral ions to be adsorbed – or stick to – for later use by the crop. This is very important in areas that are inundated with periodic heavy rainfall as these organic carbon molecules prevent the mineral ions from leaching, keeping nutrients on the farm for later use by crops and preventing eutrophication of water catchments downstream. The stable forms of organic matter such as humus and charcoal act as a storagebank and buffer for these minerals. Humic, fulvic, ulmic acids and other organic acids such as carbonic and acetic acids formed by the decay of organic matter, help make locked up minerals available for use by plants by changing them into forms that plants can use. The term for this is that the minerals are bio- available.

Another important function of organic matter is to encourage the growth of and provide shelter for beneficial soil microorganisms that make minerals such as nitrogen, phosphorous, potassium and trace elements bio-available. They also provide a host for beneficial fungi such as *Trichoderma spp.* and *Penicillin spp.* which help control pathogens such as *Rhizoctonneia, Phytophthora, Armillaria* and *Pythium*.

A whole-systems approach to soil management is required to achieve high yields, including using a complete analysis soil test (e.g. Albrecht Soil Test) to assess the mineral balance of soil. It is important that the soil has sufficient plant available nutrients in the correct balance to ensure that the crop is not deficient and can achieve its maximum genetic potential. The correct balance of minerals is essential to the health of crops and microorganisms that help maintain the soil food web to produce healthy crops.

A benefit of this kind of total nutrition is that healthy plants are more robust in adverse conditions such as drought and heavy rain and are more resistant to pests and diseases.

2.1.2. Soil organic matter – the key to productive farming

Soil organic matter is one of the most neglected yet most important factors in soil fertility, disease control, water efficiency and farm productivity.

Soil organic matter has largely been ignored by most of non-organic agriculture. Instead, they prefer a hydroponic model of nutrition, where plants are fed directly from dissolved mineral ions in the water of the soil. This combination of dissolved mineral ions in the soil water is known as the soil solution. Plants absorb these dissolved minerals when they take up the soil solution into their roots to obtain water. In most agronomy literature, it is regarded as the only model for plants to absorb nutrients, making the role of organic matter in the soil irrelevant.

However, this can be likened to force-feeding and has been clearly linked to metabolic disturbances in plants, which results in increased pest and disease attack. *(Francis Chaboussou: Healthy Crops – A new agricultural revolution, 2004).*

But absorbing minerals through the soil solution is just one way to provide a significant amount of minerals that plants need. Research shows that plants also obtain significantly high levels of nutrients from ion exchange. Ion exchange is a process whereby plants absorb larger organic molecules like chelates and amino acids from direct symbiosis with microorganisms through the action of plant root enzymes and the stomata in their leaves. Several of these critical areas of plant nutrition are clearly linked to the organic matter cycles in soils.

To understand plant nutrition at this level, it is crucial to understand what constitutes organic matter, and more importantly, what constitutes soil organic matter (SOM).

2.1.3. What is soil organic matter?

Soil organic matter is derived from the decaying parts and excretions of plants, animals, insects, microorganisms and all biotic forms of life.

Soil organic matter is intricate and scientists and researchers are only starting to understand this complexity. Current research shows that it is composed of two main fractions that are part of two cycles that merge and overlap continuously.

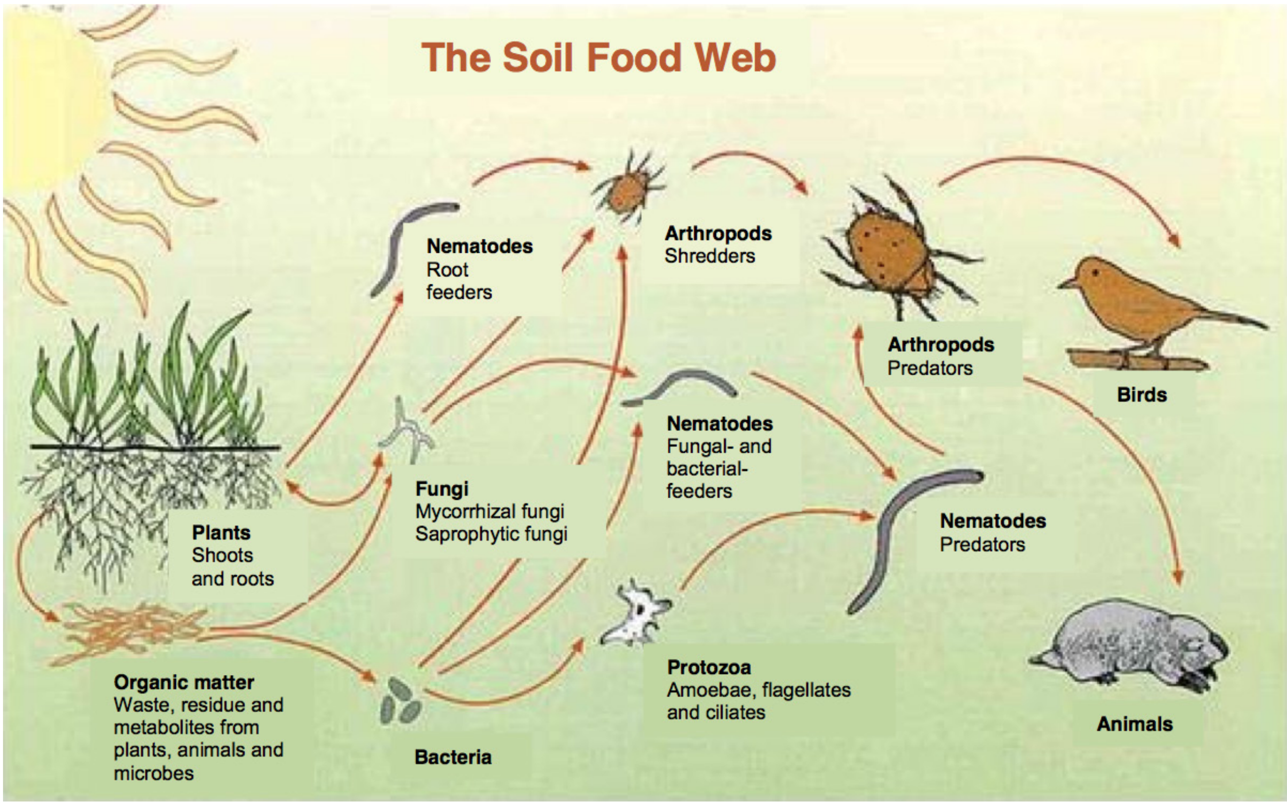
These main cycles are the labile or volatile fraction and non-labile or stable fraction.

Labile or volatile fraction

The labile fraction comprises decaying organic matter. This is the most crucial part of the soil organic matter cycle. It is where microbes break down residues of crops, leaves, twigs, branches, root excretions, animal manures, animal remains and release minerals, sugars and other compounds into the soils to feed plants and other microorganisms. This complex process is known as the Soil Food Web.

The key to this cycle is that it needs to be continuously fed with organic matter to ensure that it remains active.

Some models look only at this cycle and pay little or no attention to the soil organic matter



Soil food web

cycles. These models assume that all the carbon in organic matter has to be completely decayed into carbon dioxide (CO_2) for all the minerals in the soil to be released as nutrition to plants.

In natural eco-systems and under good management, some parts of the decaying organic matter form stable soil carbon and soil organic matter fractions.

Non-labile or stable fraction

The most stable organic matter fractions are humus, glomalin (from fungi) and charcoal (char). Research shows that humus and char can last in soil for thousands of years. Other fractions are less stable (labile) and can be easily volatilised – or converted – into CO_2. Bio-chars (charcoals from living sources) are now being promoted as a stable form of soil carbon for the benefits that they bring to soil and to crops. While bio-chars do have several benefits, the multiple benefits of soil humus are significantly greater.

Humus improves nutrient availability:

- It stores 90 to 95%of the nitrogen, 15 to 80% of phosphorus and 20 to 50% of sulphur in soil
- It has many sites that hold minerals and consequently dramatically increases the soil's Total Extractable Cations (TEC - the amount of plant available nutrients that the soil can store)
- It stores cations (positively charged ions), such as calcium, magnesium, potassium and all trace elements
- It can store significantly higher amounts of anions (negatively charged ions), such as nitrates, sulphur and phosphorous than clays
- The complexity of humic acids help make minerals available by dissolving locked up minerals
- It prevents mineral ions from being locked up
- It prevents nutrient leaching by holding on to them
- It encourages the growth of a range of microbes that make locked up minerals available to plants
- It helps to neutralise the pH of soils
- It buffers the soil from strong changes in pH

Humus improves soil structure:

- It promotes good soil structure which creates soil spaces for air and water
- It assists with good/strong ped formation (Soil is made up of particles and small aggregates, these can clump together to form larger aggregates – peds – which are the 'building blocks' of the soil)
- It helps prevent soil erosion
- It encourages the presence of soil macro-organisms such as earthworms and beetles that borough and till the soil

Humus directly assists plants:

The spaces made by the humus in the soil allow microorganisms to turn the nitrogen in the air into nitrate and ammonia.

- Soil carbon dioxide contained in these air spaces increases plant growth
- It aids plant and microbial growth through growth stimulating compounds
- It facilitates root growth by making it easy for roots to travel through the soil

Humus improves soilwater relationships:

- The open structure increases rain absorption
- It decreases water loss from runoff
- Humus molecules soak up to 30 times their weight in water
- Water is stored in the soil for later use by the plants
- Improved ped formation helps the soil stay well drained

Humus and soil nutrients – ion exchange:

Ions are charged atoms or molecules of minerals. Positively charged ions are called cations and negatively charged ions are called anions. In standard agronomy texts, ions are dissolved in the soil solution and when plants absorb water through their roots, they absorb the dissolved ions as nutrients.

Many of these ions are also adsorbed to the charged sites on humus and will not be dissolved in the soil solution. This prevents the ions from leaching out and causing environmental problems, especially in rivers and seas.

Plants use a process called ion exchange whereby they separate water into the required charged ions. These are the positively charged hydrogen ion and the negatively charged hydroxyl ion.

The charges on these ions will displace the ions adsorbed by humus to allow them to be absorbed by the plant roots *(Handrek, K & Black, N. 2004. Growing Media for Ornamental Plants and Turf. Univ. of New South Wales Press ISBN 0 86840 333 4).*

Humus can store significantly higher amounts of both cations and anions than clays due to the presence of more absorption sites for ions to stick to. These sites have positively and negatively charged electrostatic sites that work like magnets to attract the ions. Ion exchange is a significant process in the nutrition of plants in organic systems with high levels of humus in the soil organic matter.

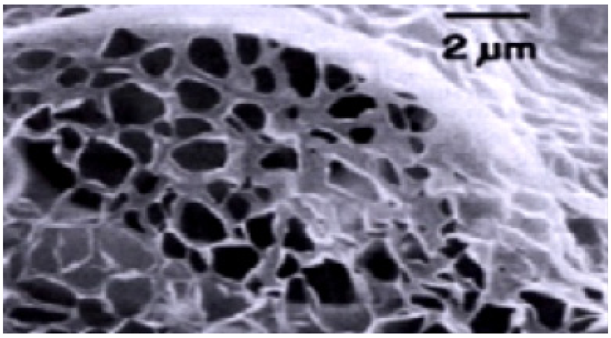
Building long lasting soil organic matter:

Humus is the longest lasting component of soil organic matter. It can last in soil for several thousand years. Over time, bio-chars will be turned into humus and/or CO_2 depending on the soil management systems.

Humus is generally very resistant to microbial breakdown; however, a combination of synthetic nitrogenous fertilisers and oxidation through poor tillage practices causes it to decline rapidly. Soil erosion is the other major cause of humus loss, as the top layers of the soil have the highest percentage of humus.

The exact nature of humus is still being researched. It is a complex structure that has been formed from the lignins, oils and waxes in decomposing plants rather than from the other main organic compounds such as cellulose, sugars and starches.

Under an electron microscope, humus looks like a sponge – it is a sticky substance with numerous porous holes with high levels of holding and locking capacity. This is why it can store up to 30 times its own weight in water and why it holds on to soil nutrients and prevents them from being leached away.



Humus under an electron microscope (source - Rodale Institute)

The critical issue when building up humus is to allow ground covers, green manure crops, and stubble to mature to the point where they have formed lignins. The structures of most plants are composed of cellulose and lignin. Cellulose is the part that makes wood and paper. The lignins are like strong flexible fibres that glue the plant structures together to give them both flexibility and strength.

Young fresh plants tend to have few lignins as they are mostly cellulose, sugars and starches. These are readily consumed by the microorganisms as food sources – feeding the labile cycle of the Soil Food Web.

Cellulose takes longer to break down. Cellulose is formed in plants by building chains of glucose. It is very stable, not water soluble and resistant to being degraded. Various microorganisms, especially fungi can digest it. They use enzymes such as cellulase that breaks down cellulose into glucose and water. Ruminants and termites also have symbiotic microorganisms in their digestive tracts that break down cellulose. This is why termites can thrive in arid areas. They get their water and glucose from breaking down the cellulose in wood and dry, mature grasses.

Lignins tend to be the last parts of the plants to be consumed by microorganisms. They can be converted into humus and humic acids, provided that the correct species of microorganisms are available and that negative farming practices are avoided.

The best way to ensure that plants are rich in lignins is to let them mature and become coarse and woody. It is the lignins that turn tender plants into tough plants. Where possible, let green manures reach full maturity before recycling them into the soil.

Young, fresh green manures are a good source of sugars and nutrients such as nitrogen for microorganisms in the soil. However, they will not produce as much humus as mature lignified organic matter.

Without regular inputs of organic matter, soil organic matter levels can fall over time as the sugars and starches of remaining organic matter in the soil are consumed by the soil food web.

Soil organic matter tends to volatilise into CO_2 in most non-organic farming systems. However, the correct management systems can continuously increase both the non-labile and labile fractions. Research conducted by Dr Christine Jones showed that the majority of the newly increased soil carbon was in the stable fractions. *"78% of the newly sequestered carbon is in the non-labile (humic) fraction of the soil rendering it highly stable" (Jones, 2011).*

Research conducted over a period of more than 100 years at the Rothamsted Research Station in the UK and at the University of Illinois 'Morrow Plots in the USA, showed that the total soil carbon levels can steadily increase and then reach a new stable equilibrium in farming systems that use organic matter inputs. This means that good organic management systems can increase and maintain the labile fractions as well as the stable fractions.

2.1.4. Water management

One consistent piece of information emerging from many studies is that organic agriculture outperforms non-organic agriculture in adverse weather events, such as droughts and intense rains.

Organic systems use water more efficiently

Research shows that organic systems use water more efficiently due to better soil structure and higher levels of organic matter, particularly humus. The open structure allows rain water to quickly penetrate the soil, resulting in less water loss from runoff.

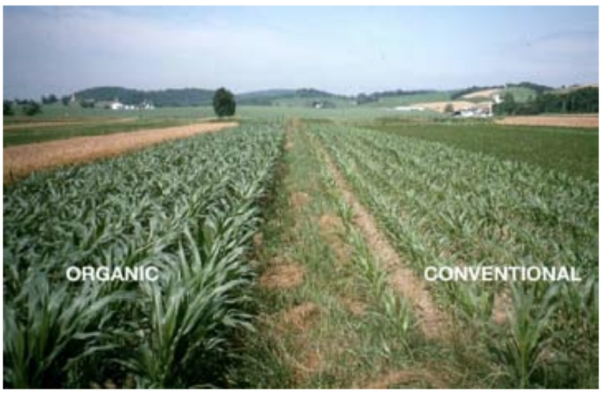
Humus is one of the most important components of organic matter. It stores up to 30 times its weight in water so that rain and irrigation water is not lost through leaching or evaporation and remains available for later use by plants *(Handrek, 1990; Stevenson,1998; Zimmer, 2000; Handrek and Black, 2002)*.

The scientific review by Cornell University into the 22-year long Rodale Farm Systems Trial field study, a direct comparison between organic farming practice and conventional production methods, found:

- The non-organic crops collapsed during drought years
- The organic crops fluctuated only slightly during drought years, due to greater water holding capacity in the enriched soil
- When these fluctuations in yields were averaged out, the organic crop had yields equal to or greater than the non-organic crops *(Pimentel et al., 2005)*

The Rodale Farm Systems Trial showed that the organic systems produced more corn than the non-organic system during drought years. *"Average corn yields in those 5 dry years were significantly higher (28% to 34%)in the two organic systems: 6938 and 7235 kg per ha in the organic animal and the organic legume systems, respectively, compared with 5333 kg per ha in the non-organic system" (Pimentel, 2005).*

The researchers attributed the higher yields in dry years to the ability of soils on organic farms to better absorb rainfall. This is due to the higher levels of organic carbon, making the soils more friable and better able to capture and store rain.



Better water infiltration, retention and delivery to plants helps to sustain yield during drought.

(source - Rodale Institute)

According to the authors, *"This yield advantage in drought years is due to the fact that soils higher in carbon can capture more water and keep it available to crop plants" (LaSalle and Hepperly, 2008).*

The Rodale Institute has just published their 30-year study edition (2014) of 'The Farming Systems Trial', which supports and substantiates the above findings.

The importance of organic matter for water retention

There is a strong relationship between the levels of soil organic matter and the amount of water that can be stored in the root zone of a soil. The table below should be taken as a rule of thumb, rather than as a precise set of measurements. Different soil types will hold different volumes of water when they have the same levels of organic matter. Sandy soils for example, will as a rule, hold less water than clay soils.

The table gives an understanding of the potential amount of water that can be captured from rain and stored at the root zone in relation to the percentage of soil organic matter.

Volume of water retained/ha (to 30cm) in relation to soil organic matter (SOM):

0.5% SOM	80 000 litres
1% SOM	160 000 litres
2% SOM	320 000 litres
3% SOM	480 000 litres
4% SOM	640 000 litres
5% SOM	800 000 litres

There is a large difference in the amount of rainfall that can be captured and stored between the current SOM level in most non-organic farms and a good organic farm with reasonable levels of SOM. This is one of the reasons why organic farms do better in times of low rainfall and drought.

Soil can act as the largest reservoir of water if it has good levels of SOM. This water is stored at the crop root zone is and used as needed.

1 000 hectares of farmlands with just over 3% SOM would be storing 500 mega litres of water in its soil. This is an enormous saving if one takes into account that the water would have had to be purchased or that farmers would have had to pay for building a dedicated 500 mega litre dam and irrigation system.

How organic matter improves water use efficiency

Soil organic matter increases water retention in several ways. As stated before, humus, one of the major components of organic matter, stores up to 30 times its own weight in water. This is achieved through building up soil with an open sponge-like structure where water is efficiently captured and stored in its numerous pores.

Good soil needs to be able to hold a lot of water, air and nutrients. Air is essential for roots to breathe because plants, like animals and humans, need oxygen to survive. In most cases, the roots have to get oxygen directly from contact with the air. Some wetland plants such as water lilies, reeds and mangroves have special air tubes (aerenchyma) that can conduct air from the leaves on the surface of the water to the roots. However, the majority of plants need to have their roots in direct contact with pockets of air in the soil. Too much water can fill these air pockets and suffocate the roots, killing the plant. Air is also essential for aerobic soil microbial activity. Too much water also creates anaerobic (no air) conditions that kill the beneficial microorganisms and favour the growth of microorganisms that cause disease.

Well-developed organic soil is composed of crumbs. These crumbs are call peds. When good quality peds are gently squeezed between the thumb and fingers they crumble away to smaller peds. This gives soil numerous pores of different sizes. Some sizes are better for holding air while others are better for holding water.

Most importantly, the open structure of soil ensures good capture of rain and irrigation water while compacted soils and those with crusts on the surface, have very few spaces for water to infiltrate, resulting in much of the water from rain or irrigation either running off the surface or evaporating.

Building good quality peds

Organic matter, calcium, clay, microorganisms, air, moisture and plant roots are needed to build peds. They have interrelated roles and it is difficult to build good soils without them.

Clays are needed as binding agents. Nearly all soils have some clay component, including the sandiest soils.

The regular addition of small amounts of clay - ideally through the composting process - will improve sandy soils. Without organic matter though, these clays can be dispersed through the pores in the sand, stopping infiltration and tightly binding to water. Pure clays hold more water –and very tightly - making it difficult for plants to access.

Microorganisms are the key to building peds and have numerous roles, including turning organic matter into humus. Humus is made from phenolic polymers and is very sticky, which is one of the reasons why they are good at holding soil nutrients and stopping them from leaching out of the soil. They act as the soil glue, making various particles of clay, silt and sand stick to it.

Calcium plays a keyrole in the formation of building good quality peds. It helps in the aggregation of various components that make up the soil to form peds. The best analogy is that calcium acts like the mortar between bricks. Over time, microorganisms assemble various soil particles into peds using humus as the glue and calcium as the mortar. This gives soil the combination of strength and flexibility. Soil fungi further hold it together with their hyphae (fungal filaments) and by secreting substances like glomalin.

Glomalin is a stable carbon polymer that forms long strings act as reinforcing rods in the soil. Research shows that glomalin has a significant role in building a good soil structure that is resistant to erosion and compaction. The structure also facilitates good aeration and water infiltration.

Plants also hold other significant key. The carbon shed by the roots feeds the microorganisms that produce the bulk of the organic matter used for building humus and soil health. The roots also work as reinforcing rods and deepen the soil over time.

As a result, a good living soil will recover easily from compaction caused, for example, from the moderate use of motorised farming equipment - over a period of time.

2.2. Soil fractions and their roles in fertility

2.2.1. Physical

Soils generally have 3 layers or horizons. These are called the Topsoil or A horizon, the Subsoil or B Horizon and the Parent Material or C Horizon.

The most important area is the topsoil as this is the most fertile zone. It is the area where most of the nutrients reside and where the majority of the crop's feeding roots will be found. The topsoil is formed from the subsoil by the action of crop roots and other parts of plants that deposit organic matter that feeds the soil biology that form soil.

The subsoil, or B horizon, is usually a lighter colour as it does not contain the same levels of organic carbon as the topsoil and because of this, does not have the same level of fertility.

In many soils that have been due to poorly managed, there is either no topsoil or very little difference between the topsoil and subsoil. These are usually soils of poor structure and fertility except for some soils of recent volcanic or glacial origin.

The Parent Material or C horizon is composed of the "decomposing" or "weathering" rock material that forms the basis of the soils above. In some cases, this parent material has been deposited by volcanic eruptions as lava or ash, as ground rocks and rock dust from retreating glaciers or by recent sedimentary events such as flooding rivers, lakes and sea sands.

Other soils have come from the "weathering" of harder rocks of igneous, metamorphic or sedimentary origin over longer geological periods. Standard geological and soil textbooks state that these rocks were weathered by normal physical events such as extremes of heat and cold, wind and running water or by chemical weathering such as weak acids to produce their respective soils and can be applied to limestonnee and dolomite. Most acids and alkalis, however, have little effect on the silicates that form most rocks, especially the very dilute organic acids that are formed in normal soil processes. Glass is very pure silica and because of its high level of resistance, strong acids and alkalis are stored in glass containers in a laboratory environment.

Similarly, the extremes of atmospheric weather such as abrasive winds, very hot or freezing cold temperatures and fast flowing water rarely reach the C horizon of the soil and do not have enough impact to cause major weathering at this depth.

These types of weathering are now being seriously questioned as the most significant parts of the weathering processes that form soils.

Biological weathering

A large body of scientific research shows that a major part of the rock decomposition process that forms soils is biological, rather than mechanical or chemical.

Scientists studying these rocks have found a wide range of microorganisms, higher animals such as worms as well as plant roots that mine them for specific minerals.

These microorganisms produce various enzymes that will extract their desired mineral or minerals from the parent rock. Three very important outcomes occur in these complex biological processes of mining rocks for minerals:

The orphaning of other minerals

When the biological agents extract the mineral that they want (for instance potassium), they will "orphan"release the other mineral or minerals that it was attached to (for instance silica). These orphaned minerals can be taken up by other organisms or combined with other minerals to form new compounds outside of the parent rock

Causing rock to decompose

The gradual loss of minerals that hold parent rocks together, causing them to crumble into smaller particles and start the process of forming the physical basis of the soil type

Feeding the soil foodweb

The initial microorganisms that mine the minerals continuously die and are consumed by other microorganisms to form a food chain through the soil food web. This results in some of the newly mined minerals being taken up by plant roots.

The process of the soil biology mining the Parent Material for new minerals is the key to maintaining a fertile and productive soil. This can be achieved if there is active and healthy soil biology and the key to healthy soil biology is to feed it with organic matter!

In 1840, Professor Justus Von Liebig showed that plant roots could extract the minerals directly from rocks. Charles Darwin conducted similar experiments later in the 19th century that showed the ability of plant roots to extract significant amounts of minerals and in the process, weather rocks. Darwin also showed how smaller rock particles were weathered when they went through the digestive tracks of worms and how these minerals were bio-accumulated in the worm casts in the topsoil or A horizon!

At this stage, there is limited scientifically verified data on specific microorganisms that can be used in farming to improve the availability of soil mineral for crops. There are many companies and organisations making claims about their proprietary microorganisms, however few have had these claims verified in scientific literature.

The ability of microbes to extract significant amounts of minerals from the parent rock has been successfully used for commercially viable mining operations to collect minerals such as copper and gold. Mining companies have isolated specific microbes that they can use to inoculate the rocks to extract the required minerals in commercially viable quantities.

Another critical element in weathering rocks is deep rooted plants. The cropping system needs to include species of plants that can send their roots down to the Parent Material in the C horizon and extract minerals. These plants also have another important role of deepening the soil with their roots by opening up the subsoil to allow the infiltration of air and water as well to deposit organic carbon that is shed by roots.

Ideally, a farming system should not be "exporting" more nutrients from its soil by sending crop harvests to market, than can be replenished from the parent rock by the farming system. If there are more nutrients being exported than can be naturally replenished, it is critical to look at two key areas of intervention:

- Firstly, to improve the soil biology so that it can replenish minerals at the same rate as they are being exported, and
- Secondly, to bring these required minerals to the farm where the natural system is not replenishing it

If neither of these is done, then the land management system is degrading the soil.

Soil composition

Soils are made up of more than minerals. Soils also contain air, water, organic matter and most importantly, soil biology. Soils are very different from inert mineral dusts such as ground basalt or sands. Most of the parent rocks of soil, finely ground into a powder, will barely support plant growth when used as potting media. When organic matter with living biology such as fresh compost is added, they support good plant growth. Organic matter and its biology is the key to turning dirt into soil.

In typical textbooks, soil is described as containing around 45% minerals, 25% air, 25% water and around 1 to 5% organic matter. The soil biology is found throughout; however, it is concentrated in the organic matter and particularly in the zone around the roots.

Soil colour

Black and dark/chocolate brown colours indicate organic matter levels. The blackness comes from high levels of organic carbon that occurs in organic matter.

Reds come from the two most common elements in soils; namely, iron and aluminium oxides. Oxides form due to the presence of oxygen in the air and reddish subsoil is usually a sign of good aeration – which usually indicates good drainage.

White soil can come from silicates such as sand, pure kaolin clays and from excess salt. High levels of salt indicate levels of sodium and chlorine that are toxic for plants.

Very white sands or clay soils indicate soils that are critically low in nutrients and will need a lot of building up with organic matter and other amendments to be able to grow viable crops.

Soils with grey to blue subsoil show poor drainage or regular water-logging in the wet seasons of the year. These soils generally need a range of work and inputs to remediate them. This type of soil or farm remediation is not in the scope of this manual.

Soil texture

In classical soil manuals, the texture of the soil is determined by the proportions of three distinct particle elements. These are sand, silt and clay.

- Sand is defined as particles of silica from 2.0mm to 0.02mm
- Silt is defined as particles of various sources from 0.02mm to 0.002mm
- Clay is defined as platelets of aluminium silicate of less than 0.002mm

The critical areas for clays are the colloidal clays in the range from 0.0005mm to less than 0.00002mm. Humus is also found in colloidal form.

Colloidal particles such as clay and humus are very important as they have the most sites for exchanging nutrients to plants via ion exchange. This means that soils with high levels of these types of colloids can store more nutrients that can be made available for plants.

The texture of a soil is classified by the percentage of each of these particle elements that is found in the soil.

This can easily be assessed by finely crushing the soil, mixing it with water in a clear glass jar with straight sides and letting it settle out until the water is clear. The largest and first particles to settle are the sand particles, followed by the silt and finally the clay will settle on the top. The colloidal particles of clay and humus will be the last to settle.

Some of the organic matter will float to the top, other bits will settle on top of the clay and some of it will disperse through all the layers.

Once all the layers have settled it is then quite easy to measure each of these with a ruler and work out their relative percentages. This is then used to work out the type of soil.

Standard approaches state that soil on a farm cannot be changed and will always maintain its current state, for example, if the farm has a heavy clay soil it will always have a heavy clay soil and if it has a light sandy soil it will always have that type of soil. However, contrary to this stance, the regular addition of organic matter will move a sandy soil towards a sandy loam and a clay soil towards a clay loam. Loam soils are regarded as amongst the best and are another reason why building up soil organic matter is so important.

2.2.2. Minerals

Professor Von Liebig's research, and a substantial amount of further scientific research, has determined that plants need a range of minerals to grow healthily. Several of these - macro nutrients - are needed in major quantities and others, although still essential to growth and yield, are needed in trace amounts.

Consequently, minerals are divided into macro nutrients and micro nutrients (or trace elements).

The science behind the multiple roles that minerals have in numerous biochemical functions continues to expand annually and shows that there is far greater complexity than we fully understand.

New minerals are being added to the list all the time and some of them that were previously ignored, such as silica, clearly show the faults in original scientific methodologies that were used to determine which minerals are essential to crop yield. Other minerals were thought to be non-essential - that crops will grow without them - however these crops will not reach their full genetic potential of high yields, or will be more prone to damage from pests, diseases and weed competition in these mineral's absence.

A number of nutrients, such as cobalt, may not be directly needed by the plant but are essential for symbiotic microorganisms such as Rhizobium bacteria that fix nitrogen in the root nodules of legumes. The critical issue is that plants need the complete range of minerals to function well. As Von Liebig's Law of Minimums shows, maximum crop yield will be determined by the level of mineral/minerals that is/are deficient.

Organic matter is one of the best sources of all these minerals because it is usually made up from the residues of a mixture of plants and materials of organic origin which contain all the required minerals for optimal plant growth.

The critical point that needs to be determined for productive soil is whether there are deficiencies in any of the levels of specific minerals.

The three major nutrients:

Three macro nutrients; carbon, hydrogen and oxygen account for between 95% to 98%of the biomass of most plants. These elements are sourced from the air and water and are combined through photosynthesis into glucose. Through other biochemical processes, cellulose, lignins and most of the other numerous compounds are formed that make up plants.

Carbon

Carbon is the fundamental building block of all plants. It is mostly sourced from the carbon dioxide in the air and combines with hydrogen and oxygen from water and photo synthesis to make simple sugars – glucose and/or fructose.

Glucose is the basic molecule of life. It is the energy source of all cells for plants, animals and man.

Glucose molecules can be combined and slightly modified to build many other sugars such as sucrose (cane sugar), dextrose (fruit sugar), lactose (milk sugar).

Glucose molecules can be combined in long chains to form cellulose which is the basis of paper and wood.

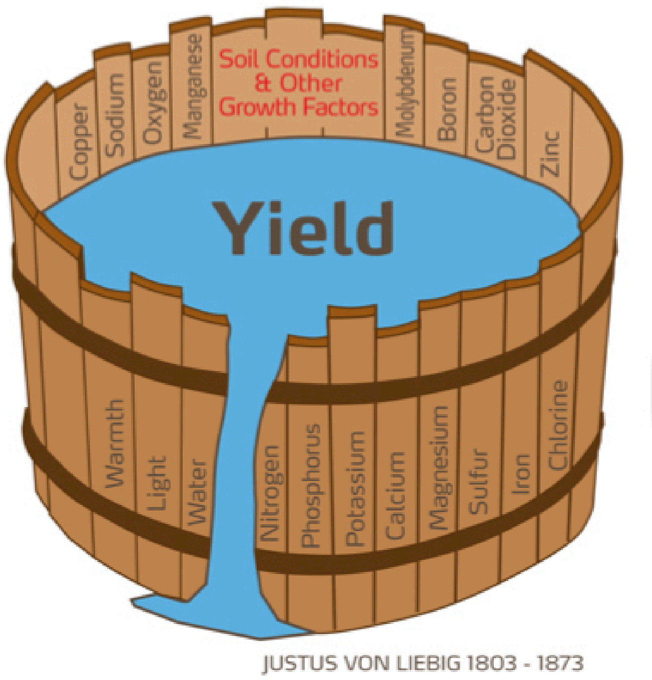
Glucose molecules can be also combined differently to form carbohydrates, or starch, which is the basis of staples such as rice, wheat, potatoes, cassava and mahangu. Carbohydrates can be modified to form hydrocarbons – oils and fats. Glucose molecules can be modified again with the addition of nitrogen and sometimes sulphur to form amino acids – the basis of proteins, DNA and hormones.

Nearly all life on earth depends on the products of photosynthesis either directly or indirectly as in the case of microorganisms, animals and man. We get our sugars, starches and oils from plants or from animals that have fed on plants.

Carbon is a major component of soil organic matter and the vast majority of this carbon

Justus von Liebig's "Law of the Minimum" published in 1873

"If one growth factor/nutrient is deficient, plant growth is limited, even if all other vital factors/nutrients are adequate...plant growth is improved by increasing the supply of the deficient factor/nutrient"



Von Liebig's barrel

comes from CO_2 in the air that has been captured through photosynthesis.

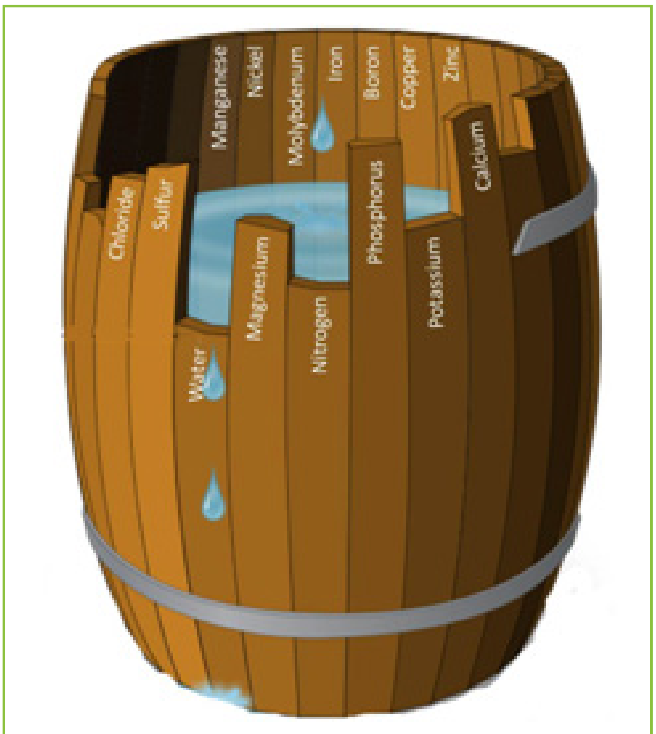
Hydrogen

As stated in the section above, hydrogen is an essential component in sugars and all the other organic molecules in plants. Its primary source is water. Hydrogen ions also have a key role in the electron transport chain in photosynthesis, respiration and other functions in the plant.

Oxygen

Oxygen is the key element for life in most living organism because it is necessary for the respiration of cells. It is also one of the building blocks in most organic compounds that are synthesised by plants.

Plants get most of their oxygen from both water and air. It is critical for most plants that their roots get oxygen from the air in the soil. In anaerobic (no air) conditions, the plant's roots tend to die very quickly, affecting both the water and nutrient uptake from the soil. Plants quickly wilt in waterlogged soils because they are unable to absorb water due to root death from a lack of oxygen.



The remaining 5%or less of nutrients comes from the soil.

While the following list of nutrients usually account for between 2% to 5% of the total biomass of a plant, a deficiency in one of them will limit the yield of the crop. All of these nutrients are important and need to be supplied in the correct proportions.

Primary macro nutrients:

Nitrogen

Plants need nitrogen to build amino acids from glucose. Amino acids are the basis of DNA, RNA, proteins, hormones and numerous other essential compounds in plants. These are some of the most important molecules of life and clearly define the living biota of the planet from non-living structures. This is why nitrogen is regarded as the most important of the soil based macro nutrients.

Standard agronomy texts state that the majority of nitrogen used by plants is in nitrate form, with a smaller percentage in the form of ammonium. However, an increasingly growing body of scientific evidence shows that most plants absorb nitrogen in amino acid form and in some instances; this can be the main form of nitrogen that they use.

Phosphorus

Phosphorus is essential and fundamental to the cellular energy function in plants, animals and humans. It forms a key part of Adenosine-5'-triphosphate (ATP) whose main role is to transport chemical energy obtained from glucose within cells so that they are able to function. ATP is also involved in the synthesis of many other compounds within plants. As a result, every cell in a plant needs a good amount of phosphorus. Phosphorus also has several other key roles that involve enzymes and other compounds within the plants.

Potassium

Potassium regulates the opening and closing of stomata (the breathing holes) on leaves of plants. Stomata absorb oxygen and carbon dioxide that are essential for plant life as well as a significant amount of other nutrients that are carried in the air. Stomata also have a major role to play in minimising the loss of moisture during transpiration during the heat of the day.

One of potassium's most important roles is the building of cellulose, the protective outer covering of plant cellwalls. When the nitrogen to potassium ratio is out of balance and too much nitrogen is present, thinner and longer cell wall structures are built. This can predispose some plants to attacks from pests and disease and also make crops more susceptible to falling over (lodging).

These types of potassium deficiencies can be easily overlooked as the excess nitrogen initially gives the impression of tall, fast growing crops. Many farmers will think that pests, disease or the weather are the cause of crop losses rather than poor cell structure caused by the imbalance in the nutrient supply.

Secondary macro nutrients:

Calcium

Calcium is regarded a secondary macro nutrient in most agronomy texts, while others will rank it higher. Calcium has a key role to play in building healthy soils with good structure. This is critical to achieving high yields of good quality crops because calcium is required by every cell in the plant to assist in the movement of many other nutrients throughout the plant. Not having enough calcium in soil will result in reducing many essential biochemical processes in plants, and could stunted and reduce yields.

Magnesium

Magnesium is a key element of chlorophyll molecules that gives plants its green colour. It also has many other important roles, such as:

- Translocating phosphorus in the plant
- Activatingthe enzyme system involved with carbohydrate synthesis
- Facilitating the uptake of potassium when present at optimal levels
- Catalysing some reactions pertaining to nitrogen metabolism

Sulphur

Sulphur is part of several major amino acids, vitamins and has several key roles in the processes of photosynthesis.

Micro nutrients:

Iron

Iron is essential for the formation of chlorophyll pigments and is therefore, necessary for photosynthesis.

Molybdenum

Molybdenum plays a critical role in the enzyme that plants use to add nitrogen to glucose to form amino acids. Without it, plants cannot use nitrogen to build the amino acids that form the DNA in every plant cell, or manufacture hormones and the proteins needed to form seeds such as grain crops or fruit crops. The amount of nitrogen a plant can use is determined by the amount of molybdenum present.

Boron

Boron is required to transport calcium around all plant tissues. As calcium is essential for the transport of many other minerals throughout a plant, a boron deficiency results in multiple other nutrient deficiencies and severely reduces crop yield. The amount of calcium a plant can use is limited by the amount of boron it is able to absorb. It also has several other key roles.

Copper

Copper plays an important role in the bio-synthesis of lignins, the compounds that glue plant cell walls together and give plants strength and flexibility. Lignins are the primary compounds used in building humus, the most important and stable form of soil organic matter. Copper is also necessary for photosynthesis.

Manganese

Manganese is necessary for plant cells to make chloroplasts, the mini engines in plants that perform the task of photosynthesis.

Sodium

Sodium plays numerous roles in plants, however sodium deficiencies are very rare. It can increase growth rates, yields and reduce critical potassium (K) levels. Scientists have labeled elements like sodium (Na) as "functional" nutrients. "Functional"nutrients are those which are crucial to maximising yield or in reducing critical levels of an "essential"nutrient like Potassium (K) by partially replacing it.

Chlorine

Chlorine is needed for plants to transmit nutrients between cells and ensuring that their balance is correct.

Zinc

Zinc has numerous roles in many key enzymes and hormones as well as the building of DNA within plant cells.

New minerals

The following are examples of minerals that rarely, if ever, are given any credit for their role in soil health in older published references in agronomy.

Silicon

Most of the earlier agronomy texts don't have any references to silica despite the fact that it is a major element in many species of the grass family such as rice, sugar cane and bamboo. The hard protective outer coatings of bamboos are made of silica. The itchy hairs on sugar cane and many tall tropical grass species such as guinea grass are made of silica.

Scientific research is discovering a diverse range of functions that silica has in building healthy plants and crops. One of the most important findings is that silica strengthens the defence mechanisms of plants to stop disease and pest attacks.

Nickel

Some plants use nickel to produce an enzyme that allows them to directly use the urea form of nitrogen, rather than the normal route where it is transformed into nitrate by a series of soil microorganisms.

Cobalt

Cobalt is essential for the Rhizobium bacteria to synthesise nitrates that are used by legumes. These bacteria need cobalt to make vitamin B12.

Selenium

Research has found that good levels of selenium in soil increase the protein and amino acid levels in crops, especially grains. It has been found to increase the sulphur based amino acids such as methionine that are regarded as essential to many species of animals and man.

Vanadium

Some plants may require vanadium in low concentrations and in some cases it can be a substitute for molybdenum.

2.2.3. Biological

Von Liebig downplayed the role of humus in plant nutrition and consequently ignored the critical multifunctional roles of organic matter and soil biology in helping plants obtain good levels of minerals. This has had an unfortunate effect on agriculture for around 150 years as most non-organic agriculture systems ignored the key multifunctional roles of the soil biology. This is starting to change as a range of scientists and agronomists have researched it and are beginning to apply it to crop production.

The rhizosphere

The term and concept of the rhizosphere was proposed by the German scientist Lorenz Hiltner in 1904. Hiltner observed that the greatest concentration of soil microorganism could be found in a narrow zone surrounding the roots of plants. He also observed that they were feeding on the sheaths that roots shed as they grow as well as a number of other exudates such as sugars and amino acids.

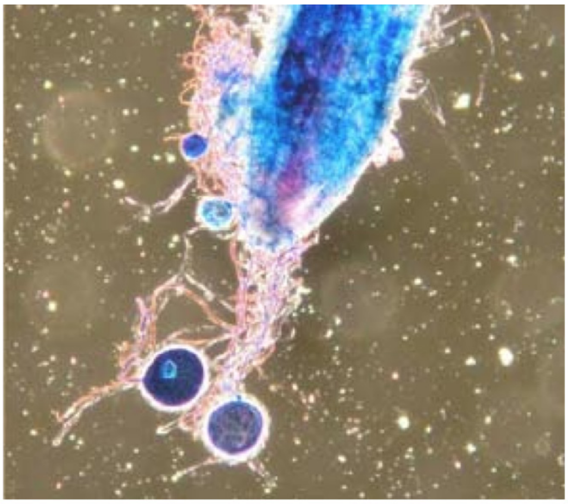
He proposed that the overall health of plants depended on the health of these diverse colonies of microbes because they helped to prevent pathogen attacks and also assisted with the uptake of minerals.

''Based on his observations, he hypothesised that 'the resistance of plants towards pathogenesis is dependent on the composition of the rhizosphere micro flora.' He even had the idea, that the quality of plant products may be dependent on the composition of the root micro flora'' (Hartmann et al., 2008).

Numerous studies show that these microbes produce a range of compounds that plants use for nutrition. The best known are the Rhizobium bacteria that live in and/or on the roots of legumes. These organisms convert nitrogen into forms that plants can use.

Hiltner actively worked on applying his observations to improve the productivity of crops, and as a result, was involved in the first patent on Rhizobium inoculants and developed other microbial inoculants for seed dressings to protect the emerging seedlings *(Hartmann et al., 2008).*

Other examples of groups of beneficial microorganisms are the VAM (Vesicular Arbuscular Mycorrhizal) and related fungi. These fungi live in association with the roots of plants and extend their threads of mycelium into the soil to mine minerals. They exchange these minerals for glucose. They are particularly important for the uptake of phosphorous in many plant species as they have enzymes that can split phosphorous off rocks and locked up molecules such as iron phosphides and tri-calcium phosphates and feed them into plant roots.



Mycorrhizal fungi structures enhance the ability of plant roots to access soil moisture and nutrients, produce stable compounds to sequester carbon dioxide as soil carbon, and slow decay of soil organic compounds.

Mycorrhizal fungi (source Rodale Institute)

Many of these fungi also protect their hosts from diseases as well as helping them with nutrition.

The science around the rhizosphere has now increased significantly, however the complexity of the interactions of the massive biodiversity in the soils around the roots means that it is still not well understood. As a result, it is not being widely applied in most agricultural practice.

One of the critical emerging issues is that high soil microbe biodiversity is essential and that these microorganisms work in symbiosis to fight off pathogens. The most recent study into disease suppressing soils found that more than 33 000 species worked together to suppress diseases.

"Disease-suppressive soils are exceptional ecosystems in which crop plants suffer less from specific soil-borne pathogens than expected, owing to the activities of other soil microorganisms. For most disease-suppressive soils, the microbes and mechanisms involved in pathogen control are unknown. By coupling PhyloChip-based metagenomics of the rhizosphere microbiome with culture-dependent functional analyses, we identified key bacterial taxa and genes involved in suppression of a fungal root pathogen. More than 33,000 bacterial and archaeal species were detected, with Proteobacteria, Firmicutes, and Actinobacteria consistently associated with disease suppression. Members of the Proteobacteria were shown to have disease-suppressive activity governed by nonribosomal peptide synthetases. Our data indicate that upon attack by a fungal root pathogen, plants can exploit microbial consortia from soil for protection against infections" (Mendes et al., 2011).

Similarly, more as well as different types of free living microorganism species that fix nitrogen continues to be discovered. Most agronomic references only mention Rhizobium bacteria that live in symbiosis in the nodules of legumes. A few more will mention the free living nitrogen fixing organisms such as *Azotobacter,* cyanobacteria*, Nitrosomas* and *Nitrobacter*. However, there are many more that live in the rhizosphere that help plants take up nitrogen from the soil. Researchers are only just starting to discover them. Once again, scientists are finding that there are multiple species that work in symbiosis to achieve this.

Researchers are also finding new nitrogen fixing species in the rhizospheres associated with most species found in hostile environments like mangroves that grow in sea water.

"These findings indicate that (i) other species of rhizosphere bacteria, apart from the common diazotrophic species, should be evaluated for their contribution to the nitrogen-fixation process in mangrove communities; and (ii) the nitrogen-fixing activity detected in the rhizosphere of mangrove plants is probably not the result of individual nitrogen-fixing strains, but the sum of interactions between members of the rhizosphere community" (Holguin et al., 1992).

Soil biology is multifunctional

Soil biology has numerous functions in ensuring optimal crop production. The list below is a summary of some of them.

1. It makes nutrients available

- By decomposing organic matter and releasing nutrients into the soil
- By dissolving minerals from rock
- By chelating and adding to the structure of nutrients and stabilising them

2. It improves soil structure

- Through building peds by disturbing and stirring clay and other particles into open random forms and gluing them together with humus, organic polymers (glomalin) and fungi hyphae
- By enabling macro-organism such as earth worms and beetles to "cultivate" the soil, breaking it into hard pans, moving soil particles around and making large pores for drainage

3. It interacts with the plants

Indirectly:

- Predating pathogens e.g. eating pests and diseases
- Protozoa eating bacteria wilt
- Fungi eating nematodes
- Nematodes eating nematodes
- Producing antibiotics, killing pathogens
- Suppressing pathogens through outnumbering them
- Detoxifying synthetic chemicals and poisons
- Free living organisms such as *Azoto-bacteria* and Cyanobacteria, fixing nutrients like nitrogen from the soil air into plant available forms

Directly:

Plant Health:

- By creating enzymes, vitamins, amino acids, and plant growth factors
- By stimulating plant immune systems

Nutrition:

- *Rhizobia* – Fixing soil nitrogen into plant usable forms
- VAM fungi – Directly feeding nutrients into plants

Soil organic matter is the key to healthy soil biology. The amount of biological activity in a soil is directly related to levels of soil organic matter.

2.3.Soil fertility management in organic agriculture

2.3.1. Soil fertility management principles

Mineral balance

Critical to soil health is to have adequate levels of all minerals. It is important to ensure that there are no mineral deficiencies or large excesses of minerals. Deficiencies in macro and trace elements will limit yield and also predispose plants to disease and pest attacks. Large excesses of nutrients can cause other minerals to be locked up. In effect, they create an artificial deficiency of these locked up minerals.

Von Liebig was the first scientist to show that plant growth is dependent on adequate levels of nutrients in the form of ions – cations and anions and this formed the basis of modern agronomy with water soluble synthetic fertilisers.

Emeritus Professor of Soils at the University of Missouri, Dr William Albrecht, was the first soil scientist to show the importance of having all soil minerals in a balanced ratio along with adequate levels of organic matter.

Whereas Professor Von Liebig felt that organic matter was not important and all necessary plant minerals could be supplied by soluble chemical fertilisers, Professor Albrecht wrote extensively on the importance of organic matter in acting as the primary source for plant nitrogen and as the buffer and storehouse of all the minerals that plants needed along with the importance of the correct soil biology to do this.

Albrecht reintroduced the concept of soil as a living entity and emphasised the fundamental importance of organic matter and soil biology as part of this process.

"Decomposition by microorganisms within the soil is the reverse of the process represented by plant growth above the soil. Growing plants, using the energy of the sun, synthesise carbon, nitrogen, and all other elements into complex compounds. The energy stored up in these compounds is then used more or less completely by the microorganisms whose activity within the soil makes nutrients available for a new generation of plants. Organic matter thus supplies the 'Life of the Soil' in the strictest sense. When measured in terms of carbon dioxide output, the soil is a live, active body." (Albrecht, 1938).

Albrecht also firmly established the link between plant health – particularly the role of soil mineral deficiencies – and the health of animals and ultimately humans who feed on plants and animals.

He showed the direct link between poor quality forage crops and the health of the stock that fed on it. For Albrecht, soil health was the fundamental basis of crop health, good yields and animal and human health.

This clearly fits within the organic paradigm of building a healthy soil to grow a healthy plant, rather than the non-organic farming paradigm of just adding the soluble nutrients for the plant to take up from the soil solution.

The two critical issues that Albrecht wrote about, was to have soils that had adequate amounts of all the minerals that plants need and that these should be in the correct balance or ratios to achieve the highest yields. These ratios are guidelines, meaning that they can and should be modified depending on the environment.

For Albrecht, soil nutrition was not about directly feeding the plant; it was about building a healthy soil that would produce high yields of healthy plants and animals.

Albrecht found that high levels of calcium will form soils with good ped structures, whereas high levels of magnesium will make the peds more compact.

This can be applied appropriately to different soil types. Clay soils need high levels of calcium to open them up and there is research that increasing magnesium on sandy soils will tighten the peds and give better water and nutrient holding capacity.

While Albrecht wrote about calcium being the most important cation, his papers on organic matter clearly state that nitrogen in the form of nitrate (an anion) is the nutrient that plants needed in the largest quantities and insufficient nitrogen was one of the major limitations on yield.

Decades of research shows that soil with low levels of organic matter do not have many spaces in the soil to which nitrate anions along with other anions, can stick or be adsorbed to be stored for later used by plants. Most of the electrostatic charges on clay colloids are negatively charged. This means that they will attract and store cations; however, they will repel the negatively charged anions. This is one of the reasons why anions like nitrate are readily leached from soils with low levels of organic matter. The humus in organic matter has charged sites that will attract and store anions like nitrate.

Albrecht's research showed that for plants to obtain sufficient nitrate, the nitrogen produced in cation form of ammonium had to be turned into nitrate by the soil biology.

"Soil organic matter is the source of nitrogen. In the later stages of decay of most kinds of organic matter, nitrogen is liberated as ammonia and subsequently converted into the soluble or nitrate form. The level of crop production is often dependent on the capacity of the soil to produce and accumulate this form of readily usable nitrogen. We can thus measure the activity that goes on in changing organic matter by measuring the nitrates. It is extremely desirable that this change be active and that high levels of nitrate be provided in the soil during the growing season" (Albrecht, 1938).

The other key issue he wrote about was the stable carbon to nitrogen ratio in soil organic matter. This was the primary source of most plant nitrogen.

Albrecht was the first soil scientist to write extensively on the relationship between nitrogen and soil organic matter and showing that the correct way to maintain sustainable fertility was to have farming systems that recycled enough organic matter to produce the quantities of nitrogen that are needed by the crop.

The other very important role for organic matter that Albrecht researched was the buffering role of organic matter. While Albrecht wrote extensively about the need for the correct percentages and ratio of available cations in soils, he also showed that adequate levels of organic matter would act as a bufferwhere the ratios were not exact and ensure that plants would receive the correct amounts of nutrients. The key is that there are no deficiencies and that there are adequate levels of all the nutrients that plants needed.

Equally important, Albrecht showed that adequate levels of nitrogen, calcium and other minerals were essential to building soil organic matter.

"Bacterial activity does not occur in the absence of mineral elements, such as calcium, magnesium, potassium, phosphorus, and others. These, as well as the nitrogen, are important. Recent studies show that the rate of decomposition is reduced when the soil is deficient in these elements. In virgin soils high in organic matter, these elements also are at a high level, and are reduced in available forms as the organic matter is exhausted. A decline in one is accompanied by a decline in the other".

"... It has recently been discovered that the fixation of nitrogen from the atmosphere by legumes is more effective where high levels of calcium are present in available form (3). Thus, if in calcium-laden soils, excellent legume growth results and correspondingly large nitrogen additions are made, such soils may be expected to contain much organic matter. Liberal calcium supplies and liberal stocks of organic matter are inseparable. The restoration of the exhausted lime supply exerts an influence on building up the supply of organic matter in ways other than those commonly attributed to liming". (Albrecht, 1938).

2.3.2. Composting

Adding organic matter to the soil is the most effective way to increase soil quality. This can be done in a variety of ways including using composts, mulches, both living and dead as well as green manure cover crops.

Compost is the ideal way to improve soil quality, build up soil organic matter levels and to correct mineral imbalances. The best way to balance soil minerals is to work out the amounts needed through a soil test and by adding these as ground minerals such as rock phosphate, ground basalt, potassium sulphate and gypsum into the compost material when starting a compost pile. The biological processes that form compost will make these minerals readily available to plants in both quick release and slow release forms.

The resulting mineral rich compost is spread around the crops. Periodically, trace elements can be applied. The trace elements can be mixed with molasses and/or compost tea and brewed for several days to make them bio-available. These can be sprayed out over the field. The sprayer ensures an even spread throughout the field. It is the intention that most of the nutrients go into the soil. This system ensures that the soil's biological activity releases a steady flow of all the nutrients needed by the crop to produce a good yield. The complete nature of the nutrition programme ensures that there are no deficiencies.

Composting methods

There are many methods that can be used to make compost and needs to be adapted to the individual situation of the grower, the climate and resources available.

It is important to understand the processes that happen in a compost heap whilst the organic materials break down. We distinguish between the processes of decomposition, humification and mineralisation.

During decomposition, organic matter's essential elements are converted from organic combinations to single inorganic forms with the release of carbon dioxide (CO_2) and ammonia (NH_3). The microorganisms, effecting the decomposition, incorporate the remaining carbon and other essential elements into their cell substance.

In the process of humification – the forming of humus – the biochemical changes, which in total comprise humification, are complex because both degrading (breaking down) and synthetic (building up) processes occur simultaneously.

The minerals released through decomposition need to be trapped in the soil so as not to be lost by leaching and/or oxidation. They can be held onto the clay fraction of the soil in the compost itself or by adding Montmorillonite (bentonneite) clay to the composting process. The organic matter acts as a supply for the essential elements required by the next generation of plants and organisms. Release of these elements or mineralisation depends on the decomposition rate and the demand made by the heterogeneous population of soil organisms.

Decomposition can only happen with a certain degree of moisture. Making compost requires a reliable water source.

Sheet composting

Fresh manure is spread over a cover crop or crop residue and the composting process occurs on the soil. It is usually a requirement of this system that a green manure crop is grown afterwards, which is either slashed or ploughed into the soil. One advantage is very little nutrients are lost through leaching or volatilisation.

If the manure is sourced from non-organic, intensive animal production systems, the risk is that residual chemicals in manure such as drenches, pesticides, atrazine and antibiotics can interfere with the microbial breakdown of raw organic matter and of germination weed seeds. It is important to establish whether the source of the manure complies with the regulation of the relevant organic certification agency.

It is important to note, that for this method to work, adequate water needs to be available for good decomposition. Due to the shallow sheet of compost material on top of the soil, evaporation increases. In a Namibian context, this method is only recommended where there are sustainable irrigation sources available and in some areas, possibly during the rainy season.

Sheet composting

Aerobic compost

The advantage of this method is that it is the fastest way to make compost. The disadvantages are that a lot more labour is required to do the regular turnings and each turning results in the loss of volatile nitrogen, other compounds and moisture. Speed is not necessarily desirable, as very often in this labour intensive process, the compost goes through decomposition and humification processes, but not given the necessary time to mineralise. The effect is that although one feeds the soil with organic matter and quickly available nutrients, the organic matter is not stable and oxidises quickly, especially in harsh African growing conditions.

Some requirements are:

- An ideal carbon to nitrogen (C:N) ratio of 25–35:1
- Has a moisture content of 60% at point of making (when squeezed hard moisture droplets squeezes through the fingers)
- That temperatures reach up to 70°C
- A constant supply of oxygen by turning at least weekly
- That is well mixed
- That it piles up to 2m high with 45 to 60 degrees slump angle
- That it has an addition of high pH rock dusts such as lime and dolomite will cause nitrogen losses (if fresh manure is used) so it needs to be carefully managed. Ideally these rock dusts are added at the turning of the compost

Aerobic compost (Reliance Composting South Africa)

An alternative to the fast aerobic process described previously, is a well built and watered aerobic static compost pile that might only need turning once or twice during its 3 to 6 month process. This creates an organic matter source for fertilisation that is much more stable when added to farm lands.

Anaerobic compost

- Has an ideal carbon to nitrogen (C:N) ratio of 25–35:1
- Has a moisture content of 60% at point of making (when squeezed hard moisture droplets squeezes through the fingers)
- Uses less oxygen which means that it takes more than twice as long before it is ready to use
- Results in less nitrogen loss
- Anaerobic bacteria create a range of low pH organic acids and enzymes that are useful in making mineral rock dusts such as lime, rock phosphate, crushed basalt, dolomite and gypsum bio-available
- Is cheaper to make due to less costs for needed for turning to oxygenate

Sourcing compost ingredients

Compost can be made from any organic matter source. This includes animal manures, grass, bushes, branches, leaves and especially, weeds and overgrown vegetation.

Most farmers become good harvesters of organic materials from diverse sources. Letting the vegetation regenerate around the farm on hillsides, gullies, streams and along the field borders is the best way to ensure a constant supply of organic matter for compost making. This can be regularly managed to prevent it from getting out of control and the harvested cuttings can be used for making compost.

Brown and green sources

Many compost references talk about having materials in an ideal carbon to nitrogen ratio of 25 to 35:1.

There will also be a table of the carbon to nitrogen ratios of many ingredients and examples of how to do the mathematics needed to work out the percentages of each of these to make the ideal ratio when using multiple sources.

Most farmers find this too complicated to use. A more practical way is to think of using a mixture of brown and green organic matter sources. Brown - or dried organic matter sources – is usually high in carbon and low in nitrogen. Green – or fresh organic matter sources – such as freshly cut grasses, usually has high levels of nitrogen in relation to carbon.

Mixing the brown and the green sources will give a good ratio of carbon to nitrogen. Experience will be the best guide to getting a good result.

Time is the important factor. Lower levels of nitrogen will mean that it will take longer to break down into humus-rich compost. This means that farmers should start making compost at least six months to a year before they need to use it.

It is important not to forget to water your compost regularly, especially when you are using the aerobic composting method because a lot of moisture evaporates with the heat build-up in the pile. A cubic metre of compost uses up about 1 000l of water! When there is not enough moisture, especially during the heating phase, there is also the danger of the compost heap catching fire, so check the pile regularly.

Compost benefits

Research shows that good quality compost is one of the most important ways to improve soil. It is important to understand that compost is a lot more than a fertiliser. Compost contains humus, humic acids and most importantly, a large number of beneficial microorganisms that play a major role in the process of building healthy soils – especially humus.

Humus

- Adds organic matter to the soil
- Inoculates soil with humus building microorganisms
- Improves soil structure to allow better infiltration of air and water
- Stores between 20 to 30 times its weight in water and significantly increases the capacity of soil to store water (soil water holding capacity)
- Stores nitrogen and other nutrients for later use by plants

Nutrients

- Mineral nutrients
- Contain a complete range of nutrients of an organic source
- Slow release
- Do not leach into an aquatic environment

Beneficial microorganisms

- Supply a large range of beneficial fungi, bacteria and other useful species
- Suppress soil pathogens
- Fix nitrogen
- Increase soil carbon
- Release locked up soil minerals
- Detoxify poisons
- Feed plants and soil life
- Build soil structure

Lowering greenhouse gases from compost

In some parts of Europe and North America, up to 10% subsoil clay is added to compost to improve its texture. Alternatively, Montmorillonite clay (Bentonneite) as a powder can be added to the pile in trace quantities. Acidic clay will stop the volatilisation of nitrogen as ammonia. Ammonium ions will stick to the clay which lowers the amount of nitrogen based greenhouse gases escaping from the compost.
Similarly, it has been shown that potassium tends to leach out of compost heaps. Clay platelets tend to attract potassium ions that help prevent leaching.

Anaerobic composts can have a carbon to nitrogen ratio of more than 30:1 as the longer time favours more fungi than bacteria. Fungi need less nitrogen to break down raw materials. A higher carbon to nitrogen ratio means that it will take longer for the microorganisms to breakdown organic matter and turn it into humus. It will also reduce nitrogen loss and result in compost with more useable nitrogen for the crop.

An added benefit is the reduction of the amount of nitrogen based greenhouse gases escaping from the heap.

Covering the compost pile with geo-fabric, shade net, tall veld/thatching grass or a skin of clay soil helps keep the moisture level stable.

Recent research from the USA has found that covering composts with a deep layer of wood chips stops all emissions of volatile organic compounds (VOCs) including greenhouse gases *(Chafer, personal communication)*.

Worms can be added to composts when the compost heap starts cooling down, although they normally appear at the appropriate time on their own.

Compost teas

Compost teas have been successfully used to inoculate soils with beneficial microorganisms that increase soil carbon, improve soil quality and in many cases, suppress soil and plant diseases.

Compost teas are made by adding small amounts of compost to water and brewing for a while to ensure that the microorganisms are active. There are many ways to make compost teas and some very good websites, such as *www.soilfoodweb.com*, give high quality information on how to do it.

It is best to apply the teas in the late afternoon so that the microorganisms are not killed by ultraviolet light.

Biodynamic preparations

Biodynamic preparations such as Preparation 500 (horn manure) work in a similar manner to compost teas and have been very successful in building soil organic matter, especially humus.

2.3.3. Green manures

Green manures are crops that are grown purely to improve soil health and fertility. They add fresh organic matter and nutrients such as nitrogen when they are incorporated into the soil.

Green manures are generally a part of a crop rotation that is used to break weed and disease cycles. These multifunctional benefits are explained in greater detail in chapters which deal with weed *(chapter 4)* and pest *(chapter 3)* management. Green manures are planted and then incorporated into the soil before the cash crop is planted to provide a release of nutrients for the cash crop. From turning the green manure residue into the soil to planting a new crop requires a rest of about three weeks. This time is needed for the green manure crop to decompose. If crops are planted immediately, without a rest period for decomposition, the crop will show nitrogen withdrawal signs – a yellowing of the plants – due to all soil available nitrogen being withdrawn by microbes to help with the decomposing of the green manure.

Virtually all plants that are grown can be used as green manures; however legumes are preferred because they provide significant amounts of both organic matter and nitrogen.

The use of green manures is one of the oldest and proven methods of improving nitrogen and organic matter levels in the soil.

"The restoration of soil organic matter then, is a problem of increasing the nitrogen level or of using nitrogen as a means of holding the carbon and other materials. This is the basic principle behind the use of legumes as green manures. In building up the organic content of the soil itself, it will often be desirable to use legumes and grasses rather than to add organic matter, such as straw and compost, directly. If legumes and grasses are to be

successfully grown on many of the soils of the humid regions of this country it will be necessary, first, to properly fertilise and lime the soil. Legumes use nitrogen from the air instead of the soil, and thus serve to increase the amount in the soil when their own remains are added to it" (Albrecht, 1938).

2.3.4. Mineral fertilisers

This is the area of the greatest misunderstanding between the organic and non-organic industries. It is also an area where most farming systems seriously mismanage their growing systems.

The standard for most non-organic farming systems has been to apply just three major minerals – nitrogen, phosphorous and potassium (NPK). Consequently, a large proportion of these farming systems use only NPK without testing for other nutrient deficiencies.

The best illustration of this is Von Liebig's Barrel. The amount of water it can hold is limited by the lowest stave. The highest staves do not help to hold more water. It is the same with soil nutrients. High levels of NPK will not increase yields if other minerals are deficient.

Examples:
Plants need high levels of nitrogen to combine with glucose to make amino acids. Amino acids are keys to life because they make DNA, proteins, hormones and other essential components of cells and bodies.

The process of building amino acids from glucose and nitrogen requires a few steps within the plant. One of these steps needs just a few molecules of molybdenum to act as a catalyst for the process. Without it the plant cannot use the nitrogen to make the amino acids. It does not matter how much nitrogen the plant takes up from the soil, it can only use it in the proportion to the amount of molybdenum that it has to produce the amino acids it needs for growth and to produce seeds etc.

Plants need calcium in every cell to transport minerals throughout the plant. Calcium, unlike many other nutrients such as sulphur, potassium and nitrogen is not as mobile within the plant.

As a plant grows, it transfers many nutrients from old leaves before they are shed for use by new leaves. Most plants cannot do this without calcium and need to get new supplies from the soil. This means that it is critical to have good levels of available calcium in the soil.

Plants need boron to transport calcium around their structures and into cells. Without adequate boron, plants could have inadequate levels of calcium. It is important to ensure that boron levels in soils are adequate to prevent plants from having multiple mineral deficiencies.

Organic systems use complete fertility
In general, organic farms do not have many soil deficiencies because fertilising systems used come from organic decaying plant and animal materials. These fertilising systems generally contain all the minerals that plants need and in good proportions because this is how they naturally occur in their original state. However, there are instances where organic systems could end up with mineral deficiencies.

Organic as closed systems

Most literature on organic farming refers to organic farming systems as being closed systems that should have minimal reliance on external inputs. However, organic farms are not closed if crops are harvested and sold away at a central marketplace, away from production area. This essentially this exports potential soil nutrients in the produce that leave the farm.

The minerals that are not replenished naturally need to be replaced with inputs brought onto the farm. If more minerals are exported than are naturally replenished by the biology, the system is not sustainable and degrades the soil. Instead, the farming system is being run down which goes against the Principles of Care, Ecology and Health.

The only way a land manager can tell if the soil needs to be replenished is to use regular soil tests to measure the levels of minerals.

It is critical to establish an agreed baseline for a healthy soil. If any minerals have levels that are below the baseline, they need to be applied to the soil to ensure that their available levels are equal or slightly more than the baseline.

Many farms have been depleting their nutrient levels for decades, possibly centuries, and will have multiple mineral deficiencies. It is impractical and too costly to fix this in one go and land managers should consider implementing three to five year programmes to elevate the levels of all nutrients in soils. Once optimal nutrient levels have been achieved, it usually only requires the application of small amounts - normally only kilograms per hectare rather than tonnes per hectare, to maintain the soil.

It is helpful to think of soils as a shop that stores essential nutrients for the crop. If the shelves are full of essential nutrients, plants will select what they need. If the shelves bare, plants will go hungry, stunting the performance of the crop.

Most of the required nutrients in organic farming can easily be obtained from ground minerals. These include lime, dolomite, gypsum, rock phosphate, basalt quarry dust, granite dust and naturally mined potassium sulphate. They can supply virtually every major element, except nitrogen and most trace elements. Trace element deficiencies can be corrected in certified organic systems by using water soluble salts such as zinc sulphate, sodium borate and copper sulphate.

The use of fish emulsions and seaweed are an excellent way to correct trace element deficiencies and build healthy plants.

Legumes, green manures, composts and naturally occurring free bacteria are used to provide nitrogen, as well many other nutrients.

A short term strategy to immediately correcting deficiencies is the foliar application of locked up minerals. Longer term strategies include increasing the levels of humus to help buffer mineral excesses and to increase the levels of other minerals to ensure balanced proportions. It is important not to increase the levels of excess minerals.

2.3.5. Nutrient level recommendations

Soil test nutrient level

The benchmark figures (see opposite page) are an indication only. Albrecht stated that these ratios were guidelines. *"While the above ratios are guide lines…"(Albrecht, 1967).* They are based on a modified Albrecht system but have not been proven for most regions. This means that they can and should be modified in other environments and that there needs to be far more research to establish the best baselines for various regions of the world.

However, until this research has been completed, the recommendation below is a useful guideline.

Please note that the levels in this list are not based on the levels needed by plants as organic agriculture is not based on the model of feeding plants directly with water soluble nutrients. The levels in the list are based on research about the levels needed to build soils that produce good yields of healthy crops.

Suggested minimum baseline recommended nutrient levels	
pH Organic matter	6.0–6.8 3%–6%
Major nutrient: Calcium Phosphorous P1 Phosphorous P2 Nitrogen Magnesium Potassium Sulphur	 1,800 ppm 100 ppm 200 ppm 60 ppm 300 ppm 175 ppm 75 ppm
Trace elements: Zinc Manganese Iron Sodium Copper Boron Chlorine Molybdenum Cobalt	 12 ppm 20 ppm 20 ppm 20 ppm 5 ppm 3 ppm 3 ppm 1 ppm 0.5 ppm
P1 = water soluble; P2 = acid tested	

There is strong evidence that plants need selenium, nickel, silicon, and other elements for good health and high yields, however, there is very little research on the best levels for soils.

Sources of organic nutrients

Allowable organic inputs

All of the nutrients that plants need can be supplied from sources that are allowed in certified organic agriculture. If your farm is certified, please check with the certifier before using any of these. Some certifiers have different requirements from others.

Nitrogen	**Analysis of percentage**
Manure Compost Legumes Green manures Fish emulsion Microorganisms *(azotobacter, yanobacteria, nitrosomas and nitrobacter and other microorganisms)*	4%-8% 1%-4% av. 2% 20–300 kg per ha 0.5%-5% 4%-11% up to 40kg per hectare
Phosphorous	
Manure compost Compost Rock phosphate Bone meal Fish emulsion	up to 2% up to 1% 24%-30% 21%-30% 1%
Potassium	
Naturally mined potassium sulphate Basalt dust Granite dust Kelp Wood ashes Manures Compost Sawdust Fish emulsion	50% up to 1% 4% 3.6%-6% 4%-15% 7% 0.3%-2% 1%-5% 1% 1%
Calcium	
Calcium carbonate (lime) Gypsum Dolomite Rock phosphate	30%-40% 22% 2% 16%-30%
Magnesium	
Dolomite Granite dust	20% 6%
Sulphur	
Elemental sulphur Potassium sulphate Gypsum Manures	100% 18% 17% 0.1%–0.2%

Trace elements

- Rock dusts such as basalt, granite, rock phosphate, gypsum, lime and dolomite contain a wide range of trace elements
- Compost (only if the materials used to make the compost are not deficient in the required trace element)
- Soluble mineral trace element forms are allowed to correct a recognised deficiency, i.e. zinc sulphate, sodium borate, copper sulphate, iron sulphate
- Manures, seaweed, fish emulsion

Soil organic matter has a carbon to nitrogen ratio of between 9:1 to 11:1. Most of this nitrogen is in amino acid form and the current body of science shows that it is biologically available to most plants.

Carbon – Nitrogen Interactions – add carbon to increase nitrogen
Soil organic matter, particularly humus fractions, tends to have a carbon to nitrogen ratio of 9:1 to 11:1. As the carbon levels increase, the amount of soil nitrogen increases in order to maintain the carbon to nitrogen ratios.

This has, in part, led to the belief within non-organic agronomy that it is necessary to add nitrogen to the soil to increase its carbon content. However the reality is the opposite.

Non-organic farming systems that use synthetic nitrogen fertilisers generally have declining soil carbon. There are published studies that show the clear relationship between the addition of synthetic nitrogen and soil carbon loss. The more synthetic nitrogen that is added, the greater the loss of soil carbon in the system (Khan et al.).

The exceptions are some of the non-organic, no-till systems getting small short term increases in the top centimetres of the soil. However, longer term studies show that this small increase is limited to certain soil types, and tends to plateau rather than continuously increase and does not deposit carbon into the deeper levels of the soil. Studies of the best organic systems show continuous increases in soil carbon and soil carbon presence at deeper levels ofthe soil profile.

One of the critical differences between organic systems and non-organic systems is that when organic matter is added to an organic system to increase carbon, nitrogen levels increase in the 11:1 to 9:1 ratio. The reality is that chemical “wisdom” has things backwards and puts the cart before the horse. Farmers should in fact add carbon to increase nitrogen rather than adding nitrogen to increase carbon.

Much of this soil nitrogen is fixed by free living soil microorganisms such as *Azobacters* and cyanobacteria. It has been consistently shown that there is a strong relationship between higher levels of soil organic matter and higher levels of soil biological activity. This biological activity includes free living nitrogen fixers – and they turn the atmospheric nitrogen, the gas that makes up 78% of the air, into the forms that are needed by plants. They do this at no cost and are a major source of plant-available nitrogen that is continuously overlooked in most agronomy texts.

Understanding the ratios

It is important to gain an understanding of how much nitrogen can be stored in soil organic matter for a crop to use. Soil organic matter contains nitrogen expressed in a carbon to nitrogen ratio. This is usually between 9:1 and 11:1 however, there can be variations. The only way to firmly establish the ratio for any soil is to do a soil test and measure the amounts.

Example:
For the sake of explaining the amount of organic nitrogen in soil, we will use a ratio of 10:1 to make the calculations easier.

The amount of carbon in soil organic matter is expressed as Soil Organic Carbon (SOC) and is usually measured as the number of grams of carbon per kilogram of soil. Most texts will express this as a percentage of the soil to a certain depth.

There is an accepted approximation ratio for the amount of soil organic carbon in soil organic matter. This is SOC ×1.72 = SOM.

The issue of working out the amount of SOC as a percentage of the soil by weight is quite complex as the specific density of the soil has to be factored in. This is because some types of soils are denser and therefore heavier than other soils. This will change the weight of carbon as a percentage of the soil.

To make these concepts readily understandable, we will use an average estimation developed by Dr Christine Jones, one of Australia's leading soil scientists and soil carbon specialists. According to Dr Jones: "…a 1% increase in organic carbon in the top 20cm of soil represents a 24 t/ha [24 000 kilograms] increase in soil OC…" (Jones, 2006).

This means that soil with 1% SOC could contain 24 000 kilograms of carbon per hectare. With a 10 to 1 carbon to nitrogen ratio, this soil would contain 2 400 kilograms of organic nitrogen per hectare in the top 20cm.

Table of the amount of organic nitrogen held in the soil

1% SOC	2 400 kg of organic N per hectare	1.72% SOM
2% SOC	4 800 kg of organic N per hectare	3.44% SOM
3% SOC	7 200 kg of organic N per hectare	5.16% SOM
4% SOC	9 600 kg of organic N per hectare	6.88% SOM
5% SOC	12 000 kg of organic N per hectare	8.50% SOM

Good management of soil organic matter means that the soil around the root layer of the crop will contain enormous amounts of organic nitrogen. It contains tonnes and tonnes of nitrogen rather than the hundreds of kilograms that are recommended to be added in most agronomy texts. This shows that there is no need for farmers to pay the huge costs to purchase synthetic nitrogen. Good farm management means that the farms could get considerably more crop available nitrogen for free.

Nitrogen drawdown

Some organic matter sources with carbon to nitrogen ratios of more than 100 to 1 such as sawdust, branches, peanut shells, dried leaves and bark can cause a temporary soil nitrogen deficiency if the organic matter is still fresh when added to soils with limited biological activity. This is because most microorganisms that break down organic matter need carbon to nitrogen ratios of between 20:1 and 30:1. These microorganisms will draw nitrogen from the soil to make up the ideal ratio, creating a temporary deficiency until the decaying process returns nitrogen into the soil.

The best way to avoid this temporary nitrogen deficiency is to either compost or to age the organic materials before they are added to the soil. Either way, the organic matter will be partially or completely decomposed and will have their appropriate decomposing microorganisms when added to the soil. This will negate or reduce the need for the microorganisms to use the soil nitrogen as they have already started the decaying process using other sources.

Experience has shown that good organic soils tend to have enough microorganisms and soil nitrogen to breakdown organic materials with significantly higher carbon to nitrogen ratios without causing a temporary nitrogen deficiency.

Developing a nutrition programme for crops

It is important to get a complete soil test that will give the levels of all the nutrients in the soil.

With this in mind, the following calculations will support the development and implementation of an adequate nutrition programme for your soil.

The amount of nutrients needed

It is only necessary to add the nutrients where soil test levels are lower than the minimum level in the list above.

([recommended level in the list]–[soil test level]) x 2 = [the amount of nutrient that you need apply] in kilograms per hectare (kg/ha). [2 is a conversion factor based on 150mm of soil depth. A soil depth of 300mm soil depth would require a conversion factor of 4].

Amount of organic fertiliser to apply

Units of the nutrient x % concentration of nutrient in fertiliser = amount of fertiliser to be applied to the field per ha.

Cost effectiveness

Very often farmers cannot afford all the nutrients needed for the recovery of severely depleted soils over a period of one year. Instead, it should be planned over several years to build up the soil minerals to optimum levels. Once optimum levels are achieved, it is relatively easy to work on a nutrient budget based on estimates of nutrients lost through crop exports, runoff using soil tests every three years.

Exercise for soil analysis:

Nutrient: (N) . . . .
Recommendation: (R) . . . .
Soil test results: (S) . . . .

{ [recommendation]-[soil test level] } x 2 = [amount of nutrient you need apply] kg/ha

{(R) . . . . - (S) . . . . } x2 = (U) . . . . . units of (N) . . . . . needs to be applied kg/ha
Fertiliser:. . . . . . .(F) contains (F%) . . . . .%(N)
(U) . . . . . x (F%). . . . . = ...kg/ha
= . . . . t/ha (F) . . . . . to be applied to the field

Example: Calcium (Ca)

Soil test indicates 1 000 ppm
The list recommendation is 1 800ppm
(1 800 – 1 000) x 2 = 1 600 units of Ca needs to be applied

Gypsum contains 22% Ca
1 600 Ca x 0.22 = 7 270 kg/ha = 7.3 t/ha Gypsum to be applied to the field or Lime containing 33% Ca

1 600 Ca x 0.33 = 4 850 kg/ha = 4.85 t/ha Lime to be applied to the field

2.4. Avoiding farming techniques which destroy soil organic matter

The continuous application of organic matter such as composts, manures, mulches and via plant growth will not increase soil organic matter levels if farming practices destroy soil organic matter. The following are some of the practices that result in a decline in soil organic matter and the alternatives that prevent this loss.

2.4.1. Only use organic nitrogen forms

The use of synthetic nitrogen fertilisers is one of the major causes of the decline of soil organic matter (SOM). This is because it stimulates the growth of a range of bacteria that feed on nitrogen and carbon to form amino acids for their own growth and reproduction. These bacteria have carbon to nitrogen ratios of between 20:1 and 30:1. In other words every tonne of nitrogen applied results in the bacteria consuming between 20 to 30 tonnes of soil carbon (SOC). Using the standard ratio of SOC ×1.72 = SOM this mean that around 35 tonnes of organic matter is being lost from the soil!

Freshly deposited carbon compounds tend to readily oxidise into CO_2 unless they are converted into more stable forms. Stable forms of carbon take time to form. In many cases it requires years to rebuild the bank of stable carbon back to the previous levels.

Ensuring that a carbon source is included with nitrogen fertilisers protects the soil carbon bank, as the microbes will use the added carbon, rather than degrading the stable soil carbon. Composts, animal manures, green manures and legumes are good examples of carbon based nitrogen sources.

Where possible, nitrogen should be obtained through rhizobium bacteria in legumes and free living nitrogen fixing microorganisms. These microorganisms work at a stable rate fixing the nitrogen in the soil air into plant-available forms. They can utilise the steady stream of newly deposited carbon from plant roots to create amino acids, rather than destroying humus and other stable carbon polymers.

Research shows a direct link between the application of synthetic nitrogenous fertilisers and the decline in soil carbon.

"The application of soluble nitrogen fertilisers in the petroleum-based system stimulates more rapid and complete decay of organic matter, sending carbon into the atmosphere instead of retaining it in the soil as the organic systems do" *(La Salle and Hepperly, 2008).*

Scientists from the University of Illinois analysed the results of a 50 year agricultural trial and found that synthetic nitrogen fertiliser resulted in all the carbon residues from the crop disappearing as well as an average loss of around 10 000kg of soil carbon per hectare. This is around 33 000kg of CO_2 per hectare on top of the many thousands of kilograms of crop residue that is converted into CO_2 every year.

The researchers found that the higher the application of synthetic nitrogen fertiliser, the greater the amount of soil carbon lost as CO_2. This is one of the major reasons why non-organic agricultural systems have a decline in soil carbon while organic systems increase soil carbon. (*Khan et al., 2007; Mulvaney et al., 2009).*

2.4.2. Carbon builders rather than carbon eaters

The use of synthetic nitrogen fertilisers changes the soil biota to favour microorganisms that consume carbon, rather than the species that build humus and other stable forms of carbon. By stimulating high levels of species that consume soil carbon, the carbon never gets to increase and usually continues to slowly decline.

Legumes, free living microorganisms and compost are carbon based nitrogen suppliers. They provide a carbon source as well as a nitrogen source so they do not consume existing soil carbon and convert it into CO_2.

The use of composts with microorganisms that build stable carbons will see soil carbon levels increase, if the farm avoids practices that destroy soil carbon.

The aim is to change the balance of the soil biology away from the species that consume carbon and turn it into CO_2 so that there are more species that build stable carbon forms such as humus and glomalin.

2.4.3. Use organic forms of weed, pest and disease control

Research shows that the use of biocides (herbicides, pesticides and fungicides) causes a decline in beneficial microorganisms. As early as 1962, Rachel Carson quoted research about the detrimental effect of biocides on soil microorganisms in her ground breaking book *"Silent Spring"(Carson, 1962)*. Since then there have been regular studies confirming the damage agricultural chemicals are causing to our soil biota *(Cox, 2001 and 2002).*

Research by of one of the world's leading microbiologists, Dr Elaine Ingham, has shown that these chemicals cause a significant decline in the beneficial microorganisms that build humus, suppress diseases and make nutrients available to plants. Many of the herbicides and fungicides have been shown to kill off beneficial soil fungi *(Ingham, 2003)*. These types of fungi have been shown to suppress diseases, increase nutrient uptake (particularly phosphorous) and form glomalin.

Avoiding the use of toxic chemicals is an important part of the process of developing healthy soils that are teeming with the beneficial species that will build the stable forms of carbon.

2.4.4. Use correct tillage methods

Tillage is one of the oldest and most effective methods of preparing planting beds and controlling weeds. Unfortunately it is also one of the most abused methods, resulting in soil loss, damage to the soil structure and carbon loss through oxidation of organic matter when used incorrectly.

As a result, opinions have shifted with many farming industries pushing no-till, using herbicides and GMOs as sustainable agriculture. The pendulum of opinion is beginning to swing back to tillage now that various problems of non-organic no-till systems are emerging.

Tillage will always have a role in weed management, soil aeration and building soil health. Appropriate tillage does increase soil organic matter and ensures minimal erosion. *(Reganold et al., 1987; Zimmer, 2000).*

It is important that tillage does not destroy soil structure by pulverising or smearing the soil peds. Farmers should be aware of the concept of good soil "tilth". This is soil that is friable with a crumbly structure not a fine powder or large clumps. Both of these are indicators of poor structure and soil health. These conditions will increase the oxidation of organic matter, turning it into CO_2.

Tillage should be done only when the soil has the correct moisture. Too wet and it smears and compresses. Too dry and it turns to dust and powder. Both of these effects result in long term soil damage that will reduce yields, increase susceptibility to pests and diseases, increase water and wind erosion and increase production costs. Tillage should be done at the correct speeds so that the soil cracks and separates around the peds leaving them intact, rather than smashing or smearing the peds by travelling too fast. Good ped structure ensures that the soil is less prone to erosion.

The Rodale Farm Systems Trial and the Long term FiBL trials show that it is possible to increase soil carbon with correct tillage. *(Mader et al., 2002; Pimentel, 2005).*

Deep tillage using rippers or chisel ploughs that result in minimal surface disturbance while opening up the subsoil to allow better aeration and water infiltration, are the preferred options. This will allow roots to grow deeper into the soil, ensuring better nutrient and water uptake and greater carbon deposition. Minimal surface disturbance ensures that the soil is less prone to erosion and oxidation thereby reducing or preventing organic matter loss.

Research by Ohio State University compared carbon levels between no-till and non-organic tillage fields and found that, in some cases, carbon storage was greater in non-organic tillage fields. The key is soil depth.
They compared the carbon storage between no-till and ploughed fields with variable plough depth – in the first 20cm of the soil the carbon storage was generally much greater in no-till fields than in ploughed fields. When they examined 30cm and deeper, they found more carbon stored in ploughed fields than in no-till.

The researchers found that farmers should not measure soil carbon, based just on surface depth. They recommended going to as much as 1m below the soil surface to get a more accurate assessment of soil carbon *(Christopher, Lal and Mishra, 2009).*

2.4.5. Control weeds without damaging the soil

A large range of tillage methods can be used to control weeds in crops without damaging the soil and losing carbon. Various spring tynes, some types of harrows, star weeders, knives and brushes can be used to pull out young weeds with only minimal soil disturbance.

Example:
Rotary hoes are very effective. However, this should be kept shallow at around 25mm to avoid destroying the soil structure. The fine one inch layer of soil on the top acts as a mulch to suppress weed seeds when they germinate and conserves the deeper soil moisture and carbon. This ensures that carbon is not lost through oxidation in the bulk of the topsoil.

There are several cultivators that ensure accuracy for controlling weeds. These can be set up with a wide range of implements and can be purchased in sizes suitable for small horticultural to large broad-acre farms.

2.4.6. Avoid soil erosion

Erosion is a significant way in which soil carbon is lost. The top few inches of soil is the area richest in soil organic matter. When this thin layer of soil is lost due to rain or wind, the organic matter is lost as well.

2.4.7. Encourage vegetation cover

Vegetation cover is the best way to prevent soil and organic matter loss.
It is not always necessary to eradicate weeds. Effective management tools such as grazing or mowing can achieve better long term results.

Maintenance of soil organic matter requires a continuous supply of plant residue to the soil.

2.4.8. Avoid burning stubble

Practices such as burning stubble should be avoided. Burning creates greenhouse gases and exposes soil to damage from erosion and oxidation. It wastes valuable organic matter that can add more carbon to the soil.

2.4.9. Bare soils should be avoided as much as possible

Research shows that bare soils lose organic matter through oxidation, wind and rain erosion, and kills microorganisms. Cultivated soils should be planted with a cover crop as quickly as possible. The cover crop will protect the soil from damage and add carbon and other nutrients as it grows. The correct choice of species can increase soil nitrogen, conserve soil moisture through mulching and suppress weeds by out-competing them.

There are various forms of organic no-till systems that sow directly into rolled, grazed or cut cover crops and pastures with very effective yields. As the soil carbon builds up, the yields increase with many outperforming the non-organic crops in the district.

2.5. Organic soil management benefits for climate change adaptation

In October 2014, the Rodale Institute published a paper containing long term research findings on the impact of organic soil management on climate change reversal. The paper combines findings from the Rodale Institute and other research institutions and is called *"Regenerative Organic Agriculture and Climate Change – A Down-to-Earth Solution to Global Warming."*

Robert Rodale, son of American organic pioneer J.I. Rodale, coined the term 'regenerative organic agriculture' to distinguish a kind of farming that goes beyond simply 'sustainable.' Regenerative organic agriculture *"takes advantage of the natural tendencies of ecosystems to regenerate when disturbed. In that primary sense it is distinguished from other types of agriculture that either oppose or ignore the value of those natural tendencies."*

Regenerative organic agriculture is marked by tendencies towards closed nutrient loops, greater diversity in the biological community, fewer annuals and more perennials, and greater reliance on internal rather than external resources. Regenerative organic agriculture is aligned with forms of agro-ecology practiced by farmers concerned with food sovereignty the world over.

We are at a critical moment in our history because we have exceeded total annual global greenhouse gas emissions of 52 GtCO2e. We need to drop those emissions to below 41 GtCO2e if we are to have a chance of limiting warming by 1.5°C.

Amongst all the complicated debates and denial happening in government and scientific institutions around the globe, Rodale Institute's research has shown that there is an immediate, simple and effective solution - put the carbon back to work in the terrestrial carbon "sinks" that are literally right beneath our feet. Excess carbon in the atmosphere is toxic, but we are, after all, carbon-based life forms, and returning stable carbon to the soil can support ecological abundance.

"Simply put, recent data from farming systems and pasture trials around the globe show that we could sequester more than 100% of current annual CO_2 emissions with a switch to widely available and inexpensive organic management practices, which we term 'regenerative organic agriculture'."

"These practices work to maximise carbon fixation while minimising the loss of that carbon once returned to the soil, reversing the greenhouse effect."

Regenerative organic agriculture for soil-carbon sequestration is tried and true. Humans have long farmed in that fashion, and there is nothing experimental about it. What is new is the scientific verification of regenerative agricultural practices. Farming trials across the world have contrasted various forms of regenerative and conventional practices and studied crop yield, drought impact, and carbon sequestration. Some of these studies are in their third decade of data collection, such as this Institute's Farming Systems Trial, and there are important fresh looks such as in the new Tropical Farming Systems Trial ("TFST") on the Caribbean slope of Costa Rica. Taken together, the wealth of scientific support for regenerative organic agriculture has demonstrated that these practices can comfortably feed the growing human population while repairing our damaged ecosystem. This scientific support has also led the United Nations Commission on Trade and Development ("UNCTAD") to issue, its report in September 2013, *"Wake up Before It's Too Late"*, a powerful call for the return to these sustainable practices.

Today there are farmers and agricultural scientists in every corner of the world committed to and excited about the results of regenerative organic agriculture's role in reversing both climate issues and food insecurity, and the specific research needs have been well documented. Now is the time to harness cutting-edge technological understanding, human ingenuity and the rich history of farmers working in tandem with the wisdom of natural ecosystems. Now is the time to arrive at a stable climate by way of healing our land and ourselves – through regenerative organic agriculture.