Soil Fertility, Crop Nutrition and Human Health

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SOIL FERTILITY

Fertility is the result of a number of different soil factors and processes working together. These relate to the physical, chemical and biological components that make up the soil.

**Physical**: Soil structure, texture and porosity will influence aeration, drainage, compaction, erosion and root penetration. This will also affect the efficiency of cultivations, crop rotations and irrigation. Physical limits stop plant roots from getting into the soil.

**Chemical**: Acidity, soil nutrient composition and base saturation will influence nutrient availability, deficiencies and antagonistic lock-up. This will affect, and be affected by, the application of fertilisers and lime. Chemical limits stop plant roots from accessing and taking up nutrients.

**Biological**: Microbial activity, crop residue breakdown, humus and earthworms will influence soil formation, root development, the controlled release of soil nutrient reserves, and the activity of pathogenic microbes. Biological limits stop plant roots from making good use of the soil.

These factors do not operate in isolation. A high calcium soil will be very porous, hold little water and suffer from nutrient lock-up, while a soil that compacts easily will not provide a good environment for beneficial microbes.

**Although soil formation is primarily a biological function, microbes can only work with the basic chemistry and structure of the soil they inhabit.** British soils, formed since the last Ice Age over 20 000 years ago, clearly show how fertile soil has been built over bare rock, but this soil still reflects the chemistry and physics of its parent material.

In order to manage and maintain a fertile soil, we need to understand how these factors work together. The final step is to undertake a comprehensive soil analysis that highlights limitations for the growing crop. This should then direct a long-term fertility programme that harnesses the potential of soil reserves and beneficial microbes.

The ideal soil contains 25% air, 25% water, 45% minerals as sand, silt and clay, and 5% organic matter. A soil with this composition would be easy to cultivate, stable, fertile and capable of supporting a diverse range of plant and microbial life.

The diagram shows a soil particle, with the mineral element being held together by organic matter and microbes. Soil nutrient reserves are locked in the organic and mineral fractions of the soil. The plant-available nutrition is held in very fine clay colloids and humus.
Humus plays a central role in soil fertility, having the ability to improve aeration and drainage, soil stability, ease of cultivation, nutrient availability and microbial activity. Humus is made by microbes as they decompose organic matter, and has many soil-improving properties. Humus increases the nutrient holding capacity of the soil, acts as a natural chelating agent for micro-nutrients, and reduces the toxic effect of pollutants. Soils with good levels of humus warm up quicker, encouraging the activity of roots and beneficial micro-organisms.

Nutrients become available to plants as minerals in the soil solution, or once released from soil reserves by root acids and microbial enzymes. Soluble nutrients, such as nitrates, can move to the root zone as plants take in water. However, most of the available nutrition is held on the surfaces of the fine clay and humus particles. These surfaces, called exchange sites, have a negative charge that attract and bind positively charged minerals, called cations.

Cations are formed when compounds dissolve and return to their basic components. The example shows common salt becoming a positive sodium cation and a negative chloride anion. The main cations are calcium, magnesium, potassium, sodium, ammonium and the metallic elements. The main anions are nitrate, sulphate, phosphate and borate. The amount of cations held by a soil is measured as the Cation Exchange Capacity (CEC), which is measured as milli-equivalents (me) per 100 gms of soil. A value of 1 me would mean that the soil can hold 450 kg/ha of calcium, or 270 kg/ha of magnesium, or 880 kg/ha of potassium, of 22 kg/ha of hydrogen. In order to maintain equilibrium, the negative charges in the soil must be balanced by positive charges. This means that exchange sites are always full, safely storing plant nutrients.

In order to release a cation held on an exchange site, some other material must first dislodge or replace it. This is known as Cation Exchange. Plant roots produce organic acids, or exudates, which act as a lubricant for the root, a food source for microbes, and provide hydrogen ions. This hydrogen is used to drive the cation exchange process. Both plants and microbes employ the technique of cation exchange to release nutrients from the soil. It has been estimated that up to 95% of plants’ mineral nutrition goes through the exchange process.

The relative amount of each nutrient on the exchange sites is measured to determine base saturation. This term is used to indicate nutrient balance and the effects of each element on the exchange process.

When any one element dominates the exchange sites, nutrient imbalances, antagonistic lock-up and genuine deficiencies can occur. The ratio of one element to another is far more important than levels of available or total nutrients.

For example, a calcium-dominated soil will have problems with phosphate and trace element availability, which will be reflected by the plants and animals feeding from the soil. Cation exchange and base saturation also determine the pH of the soil, and should always be measured before any form of fertiliser or lime is applied.

Cation exchange provides a convenient means of storing nutrients as they are released from soil reserves, before they are needed by the plant. Without this facility, available nutrients would be washed away. The exchange process also gives plants as means of controlling nutrient uptake, via root exudates and beneficial microbes, creating a supply and demand situation.

The importance of cation exchange is being illustrated by GPS mapping, which is showing large variations in crop growth that are neither explained by standard soil tests, nor corrected by additional NPK fertilisers.

Almost 95% of all plant material is made up of carbon, hydrogen and oxygen. The remaining 5% or so constitutes mineral elements, which we call nutrients. While nitrogen, phosphate and potash are considered major nutrients, no less important are the trace or micro-nutrients. These elements are used to convert the basic sugars that are produced by photosynthesis, into the amino-acid building blocks of life. These vital acids are shaped into proteins, enzymes, hormones and DNA.

Photosynthesis is the process that plants use to pull carbon from the air and turn it into carbohydrate. Driven by sunlight this process is the basis for all life on Earth.
Trace elements are needed to maintain the activity of this essential process. In the form of enzymes, they act as the plant’s bio-chemical tool kit and allow metabolism to function properly.

Enzymes are not consumed by the processes they regulate, and as such, only small amounts of each element are required. However, any limit to availability can place a large stress on the plant, reducing health and growth.

Some of the nutrients required by plants are:

- **Carbon (C):** A major constituent of all organic molecules, accounting for around 40% of plant dry matter.
- **Hydrogen (H):** Used as an energy carrier and links with carbon to form sugars and carbohydrates.
- **Oxygen (O):** A vital part of most organic compounds, carbohydrates and redox reactions.
- **Nitrogen (N):** The key to protein formation, amino-acids and enzyme systems.
- **Phosphorus (P):** Essential to all living cells for sugar formation and the storage and transfer of energy.
- **Potassium (K):** Regulates water movement, plant structure and the transfer of carbohydrates.
- **Sulphur (S):** Links with nitrogen to form protein, and is a major part of amino-acids and enzymes.
- **Calcium (Ca):** An essential part of cell walls and membranes, protein synthesis and plant defence.
- **Magnesium (Mg):** Essential to photosynthesis, chlorophyll, cell repair and metabolism.
- **Boron (B):** Links to calcium and nitrogen uptake, protein synthesis and the formation of hormones, sugars and carbohydrates.
- **Copper (Cu):** Involved in protein synthesis, seed formation, plant defence (in the form of lignins and phenols) and chloroplast.
- **Iron (Fe):** Essential to enzymes involved in respiration, photosynthesis and disease-resistance mechanisms.
- **Manganese (Mn):** Vital to photosynthesis, enzymes, cell repair and disease resistance mechanisms.
- **Molybdenum (Mo):** Vital to enzymes needed to regulate and control nitrogen metabolism (N-fixing bacteria).
- **Zinc (Zn):** Required for starch formation, enzyme systems, phenols and disease resistance mechanisms.
- **Silica (Si):** Considered non-essential, but involved in cell membrane formation and disease resistance.

Simply having these minerals in the soil is not enough to ensure healthy, productive plant growth. The elements must be available, and in the correct ratios and forms. Two basic rules govern the availability and metabolism of nutrients: The first is the Law of the Relative Minimum, which states that “the yield of a crop is limited by the deficiency, of insufficient supply, of any one element, even though all other necessary elements are present in adequate amounts”.

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This means that if a plant needs 20 kg of nitrogen and 20 g of boron, if the boron is limited to 10 g, growth will be reduced and the nitrogen will not be used effectively.

The second law is that of Relative Maximum, which states that ‘mineral availability and plant uptake will be limited by the element most dominant in the soil, either in solution as an applied fertiliser, or in the cation exchange sites of the soil complex’. This means that nutrient lock-up and antagonisms will cause minerals to remain unavailable to the plant when calcium ties up phosphates and trace elements.

**Conventional agriculture thinks of nutrition in chemical terms: NPK. But plant nutrition relies on the biological activity of microbes, something which has been seriously overlooked.**

Microbes play a central role in the decomposition and recycling of energy and nutrients held within organic matter. Microbes convert complex biological materials into simple units, which are then used to fuel the metabolism of plants and animals.

Soil microbes are responsible for the controlled release of inorganic minerals. By producing acids and enzymes, bacteria can dissolve rock phosphate and make potassium, magnesium, calcium and trace elements available to plants. Nutrients such as nitrogen, carbon and sulphur can be pulled from the air and fixed into a biological form. Animals also rely on microbes. The digestive system is host to many different types of microbe that are used to break down plant material such as cellulose and proteins. The microbes feed on these materials and can convert them into forms which the animal can digest, metabolise and make use of.

As a plant has no digestive system, it must rely on the micro-biology of the soil to maintain a supply of nutrients. The relationship between plants and microbes has evolved over millions of years, to good effect. But in agriculture, this relationship is upset by NPK fertilisers and toxic rescue chemicals. Biological farming systems harness microbes, and find that nutrient availability increases over time, despite the fact that little NPK fertiliser is being applied.

The rhizosphere, or root zone, is where the physical, chemical and biological properties of the soil combine to feed the plant. The ease with which a root can penetrate the soil and obtain nutrients will determine how well the plant grows. Root hairs extend the surface area of the root system and begin to extract nutrients from the surrounding soil. If the soil structure is poor and compaction is a problem, root hairs will not be produced and nutrient uptake will be reduced. As roots develop and extend into the soil, they release energy-rich organic acids, which make it easier for roots to move through the soil and break down soil particles. These exudates attract bacteria, fungi and actinomycetes, which feed and multiply. As microbes do this, they release and convert soil nutrients, which the plant can then consume.

Plants can spend anything from 10% to 90% of their energy income on supporting soil microbes. In return for this, microbes decompose organic matter, fix nitrogen from the air, and promote the availability of water, carbon and plant nutrients.

Microbes also improve soil structure by producing materials called polysaccharides. These long chain-like glues bind soil particles together, maintain porosity and give the soil more resistance to compaction.

By building nutritional defences within the root and actively competing with pathogens for food and space, beneficial microbes can make a major contribution to plant health. Anti-pathogen materials such as the antibiotic streptomycin, and direct attacks on pathogenic cells by other microbes, can generate a high level of biological control for soil-acting plant diseases such as Rhizoctonia, Take-all en Sclerotinia.

The diagram shows a close-up of a plant root hair, with two types of beneficial microbe. The first is a bacteria known as Rhizobia, which infect root cells and form nodules. These nodules contain the enzyme ferredoxin which traps nitrogen from the air. This nitrogen, which can reach levels of 250 kg/ha/year, is released into the soil as the nodules begin to decompose.
The second group of microbes are Mycorrhizae, which live within root cells and send thread-like hyphae out into the soil. These hyphae create a myco-rhizosphere that is active in releasing minerals from the soil and transporting them to the root.

Mycorrhizae can increase root surface area by up to 100 000 times and actively transport nutrients to the plant from up to 40 mm away.

The end result is that plants receive a much higher level of nutrition from the soil reserves. The benefit of this decreases as levels of soluble phosphate increase, and will effectively stop when high applications of nitrogen fertiliser are used. The effect of micorrhizal association on the growth rate and mineral content of shoots, in winter beans, is shown below:

The level of nutrition that a plant can access not only places limits on growth, but also affects health and disease resistance. Foliar pathogens use exo-enzymes to break down leaf tissue, enter cells and feed on the plant. To combat this, the plant has a number of defences. Physical defences include a layer of wax on the leaf surface, and the strong binding material, lignin. Silica and calcium are used to maintain cell structure, keep layers of cells bound together and prevent pathogen invasion.

The next defences are chemical. Copper and zinc are used to make phenols and phyto-alexins, which have anti-fungal properties. Manganese is used to build enzyme inhibitors, blocking the pathogen’s own chemical attack capability. If nutrient levels are low, manganese will be taken away from other plant functions, such as photosynthesis, causing further stress on the plant. An additional defence comes from beneficial microbes in the root zone, which stimulate phenol production and transfer products such as streptomycin to the plant.

The disease will interrupt normal plant functioning and cause amino-acids and sugars to move from cells to the pathogen. Pathogens target plants which can provide them with suitable nutrition, notably nitrogen in the form of aminyl-nitrate. Feeding the plant with different types of nitrogen fertiliser can influence pathogen activity. Plants with a high sugar content (brix) have more energy and soluble minerals that can be mobilised for defence.
Over fifty years ago Weston Price and Sir Robert McHarrison published detailed studies on the impact of diet on human health. Since then, agriculture has adopted increasingly artificial methods of production and food quality in terms of mineral and vitamin content has declined.

The foundation of this decline lies in soil management. By ignoring the fact that soil fertility is a biological rather than a chemical function, plants and animals suffer nutritional imbalances that limit their health, growth and performance. Comparing organic and conventional methods, below, shows the difference in yield and mineral content of wheat. The organic crop takes up far more nutrition than the conventional crop, which will be passed on to those who eat the grain, provided it is processed carefully.

As soil management influences crop quality, agriculture can be linked directly to human health. Nutrition provides plants and animals with resources for growth, health and development. The food we eat does the same for us.

The first step towards managing a living soil is to undertake a comprehensive soil analysis. It is important to evaluate the level of availability of major and micro-nutrients, cation exchange capacity and base saturation, before making any decisions relating to the soil or the crop. The aim must be to identify any deficiencies, excesses or antagonisms within the soil complex. Taking a soil sample provides the opportunity to take a close look at the structure of the soil, find soil pans, check on the decomposition of crop residues and see how far roots have to go to find moisture.

Cultivation is a primary tool for soil management. Compaction layers should be broken up and materials such as humates added to the soil to stop the layers re-forming. Ploughing can be a useful means of controlling weeds and producing a clean seedbed, but care should be taken not to plough deeper than 18 to 24 cm. If a soil balancing program is to be used, it is important not to bring sub-soils up into the top 80 cm of soil. On thin soils over chalk, and heavy clays the depth of top soil can be increased by managing organic matter. Setaside, straw incorporation, cover crops and fertility building leys can all be used to achieve this.
Choice of fertiliser will influence the biology and chemistry of the soil. Applications of soluble nitrogen and phosphate can seriously restrict the activity of beneficial microbes. Once the microbes have switched off, increasing amounts of NPK will be needed to maintain crop growth, as the contribution from the soil declines. Products like muriate of potash can have detrimental effects on soil pH, nutrient availability and the activity of soil microbes. Lime applications should never be made unless base saturation and cation exchange have been measured, as excess calcium can greatly reduce nutrient availability.

In most soils there is sufficient phosphate, magnesium and potassium to last for hundreds of years. This soil reserve is locked away and only becomes available in response to roots and microbes. Sometimes, there simply is not enough available material to support the crop, and fertiliser applications have to be made. In these situations simple fertiliser forms, combined with humic acids and bio-stimulants will support soil fertility and crop growth. Trials with arable crops and pastures have shown that good yields can be obtained from soils over a thirty year period, without using NPK fertilisers. Levels of available nutrients have actually increased over this time, despite extractive cropping, and soil tests show very little change in nutrient reserves.

When poor decomposition of crop residues or slow release of nutrient reserves is a problem, applications of live microbes may be required. Microbial populations change with each season and crop, and may not have the right food source or conditions for growth. Managing the soil to provide a habitat for beneficial microbes will result in better, healthier plant growth. The following steps can be used to build a fertile, living soil:

- Use a comprehensive soil analysis to identify the limiting factors (and potentials) within each field.
- Make soil improvements as necessary, to correct any deficiencies, excesses or structural problems.
- Stimulate soil organisms to build fertility, i.e. get microbes to feed and protect the plant.
- Reduce or omit conventional phosphate and potash fertilisers; let the soil provide this.
- Select the most appropriate nitrogen source to meet the needs of the soil-crop combination.
- Reduce or omit crop protection chemicals; use nutrition and ecology to maintain health.