GROUND RULES

As the International Year of Soils nears its end, Dr Tudor Dawkins and Dr Farnon Ellwood examine the nature and importance of soil and how farmers can keep it in good shape

The UN's Food and Agriculture Organization (FAO) estimates that around a third of all soils are degraded due to erosion, being overworked or industrialisation. At the same time, the pressure is on farmers to increase food production to feed an ever growing population. As UN secretary general Ban Ki-moon stated on launching the 2015 International Year of Soils, "a healthy life is not possible without healthy soils".

Soil is clearly important: it provides physical support for plants and both the living and non-living components of soil contribute to a variety of significant environmental functions. However, soil has generally been regarded as something of a black box by scientists and farmers.

SOIL'S DIRTY SECRETS

Soil is a dynamic substrate made up of many components. First, there are mineral particles of various sizes (known as fractions), formed from the underlying, or parent, material. There is also water, in which there are dissolved or suspended components – biota from air and soil, including fungi, bacteria, insects and larger life forms, and other organic matter.

This substrate supports innumerable forms of plant, animal and microbial life. Despite an absence of sunlight, life within the soil is incredibly diverse, ranging from microscopic single celled organisms to large, burrowing animals.

As with all ecosystems, soil has its own unique combination of living organisms and abiotic resources that function to maintain a continuous flow of energy and nutrients. As is true of ecological communities above ground, there are well-defined food chains and competition for survival is intense.

A significant proportion of most plants will be in direct contact with soil and dependent on the medium for a supply of simple nutrients, water and anchorage. In some cases, interaction with soil biota is essential for the plant to function – for example, Rhizobium bacteria, which supply the nitrogen building blocks required for protein production.

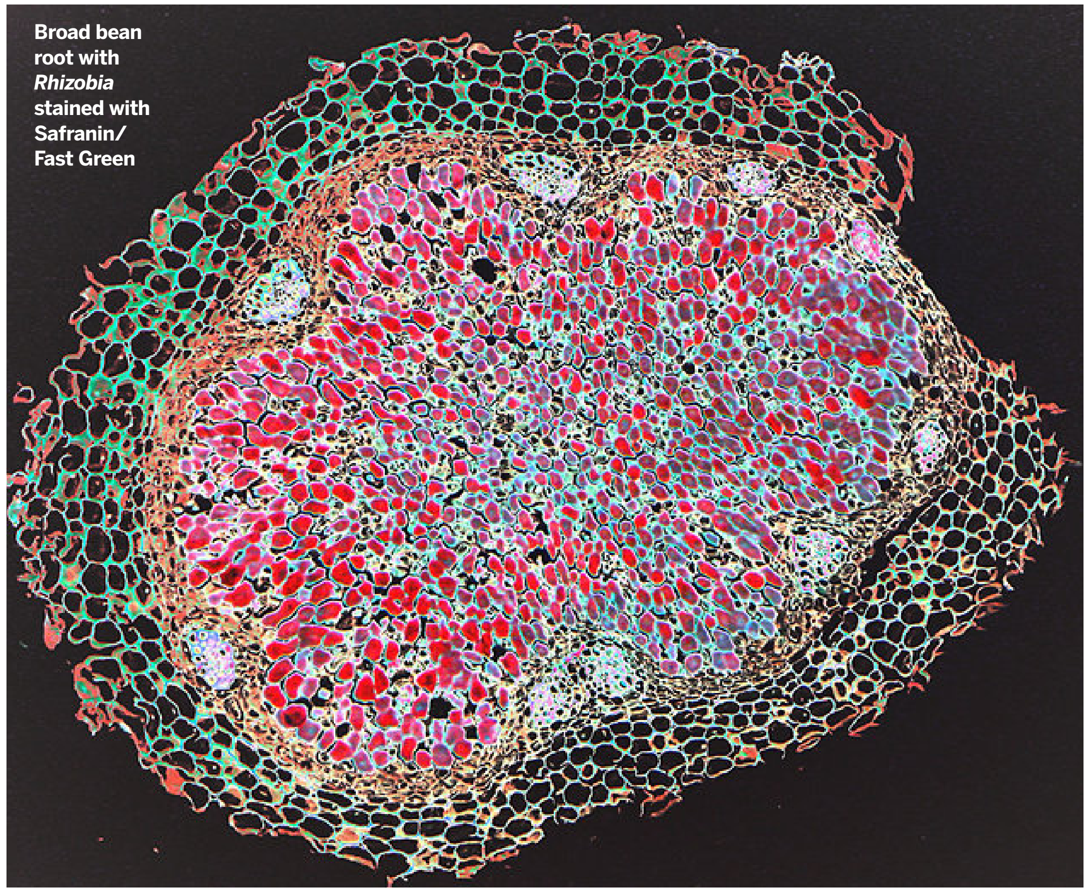
Other soil inhabitants can contribute to the organic matter in soil either directly – as in bacteria, where the mucous secretions they produce help to bind mineral fractions together – or through the production of transformed nutrients (for example, nitrogen and phosphate), which are more available to plants than the elements contained in base materials.

Plants themselves also create structure by the extraction of water. On certain soils, such as those with a high clay content, extraction causes shrinkage, resulting in soil changes within the profile. As the plant residues decay, they also contribute, passively, to the accumulation of soil organic matter.

To ascertain whether a soil is healthy, plant growth and development is a good place to start. Observations can be made to determine if crops grown on the soil deliver anticipated yields and quality, and if they grow well during their development. Yet there are many reasons why production may fall short of expectations. Here are the areas agronomists can evaluate to provide valuable pointers as to likely limiting factors.

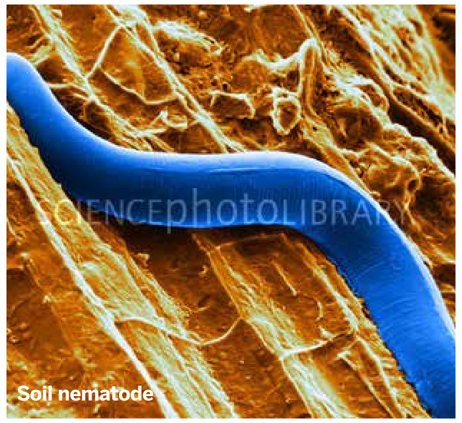
NUTRITION AND PH

Soil pH profoundly affects the capacity of the soil matrix to supply nutrition. Optimum availability of nutrients in UK soils for crop growth occurs at a soil pH of 6–6.5, but an alarming number of soils submitted for analysis are acidic (between pH 5 and 5.5). Levels of phosphate, potassium and magnesium are also often assessed when determining soil pH. Trace elements such as copper and manganese, which are essential for plant metabolic processes, are also often found to be deficient in crop foliage. Macro nutrients



Broad bean root with *Rhizobia* stained with Safranin/Fast Green

Earthworms are important biological agents in soil formation



Soil nematode

Soil microfauna includes protozoa

such as nitrogen and sulphur are key drivers for yield and quality of crops. While these nutrients are abundant in some soils, they are very mobile.

Soil maps can indicate variation within a field, which can be linked to application equipment that applies lime or other nutrients at different rates.

STRUCTURE

There are several techniques for assessing soil strength and the impedance roots may encounter in soils. These mostly involve using penetrometers, or shear vane devices, which can detect impeding layers in the soil profile. Once a layer is identified, digging a hole can confirm where the impedance is and remedial measures can be taken.

Pore space allows gas exchange to occur between soil and roots; a soil that is anaerobic often has a characteristic smell.

The limiting bulk density of root penetration is around 1.5–1.6g/cm^3, depending on the crop species. (An impenetrable medium for roots, such as a stone or rock, has a bulk density of around 2.5g/cm^3.) The durability of the structure, known as aggregate stability, is also an important asset. The passage of machinery over soil with weak stability results in the formation of compacted layers, with few pores and cracks for roots to exploit.

There has been an inexorable decline in the amount of organic matter in soil

Aggregate stability is relatively simple for farmers to assess and can be done with a water bottle by spraying a jet of water over the soil crumbs and observing if the structural units collapse or remain discrete. The advantage of this is that well structured and aggregated soils can withstand heavy rain and the potential for erosion loss.

ORGANIC MATTER

The surface of the soil is the interface between the lithosphere and the atmosphere. The quantity of living matter at or near this interface is greater than at any region above or below. Yet over the past 50 years, there has been an inexorable decline in the amount of organic matter in soil. As well as improving soil structure, organic matter provides a substrate for consumers and decomposers. Changes in soil management and practice have been blamed for the loss of organic matter and growers are now looking for ways to reverse the trends, normally by adding organic matter to soil. The difficulty is that incorporating 10 tonnes of such material per hectare may only increase organic matter levels by 0.1%. The incorporation of organic matter into the soil does not happen overnight, either – manure and muck need to be broken down by soil biota first.

Soil organic matter is not easy to assess without laboratory techniques, but it is a useful metric. Assessment of soil colour can provide clues: a light-coloured sandy soil with low organic matter content contrasts with a darker loam soil that has been in grassland for a number of years. Generally speaking, values of between 1% and 5% organic matter could be anticipated.

The higher the value, the healthier the soil is likely to be.

WATER

Organic matter also helps with water retention, which can be important later in the life of the crop. A few more days of water supply under dry conditions can make a significant difference to the outcome of the crop in terms of yield and quality. Knowing water availability from soil is important, especially for irrigated crops. When a soil is fully charged with water and no further drainage occurs, the soil is considered to be at field capacity. In contrast, when no more water can be extracted from the soil, the crop is said to be at the permanent wilting point. Addition of water to the soil at this point is not necessarily helpful, as the earth is so dry that the water is not absorbed by the soil. It may take several weeks or months for the water supplied to wet the soil effectively.

When drainage is impeded, water can accumulate on the soil surface. This often happens in winter and can cause oxygen levels in the soil to fall. As the soil becomes increasingly anaerobic, iron is transformed (reduced) from ferric to ferrous iron, which can be toxic to plant roots. The presence of rusty deposits at depth in soils indicates seasonal waterlogging.

BACTERIA

Microorganisms are the ultimate decomposers. They help the release of energy and nutrients by decomposing materials. Animals consume about 5% of primary production green plants, whereas microorganisms decompose about 95%.

Bacteria exceed all other soil organisms in terms of richness and abundance. A gramme of fertile soil can contain 10^7 to 10^{10} bacteria (10 million to 10 billion) and there may be more than two tonnes of bacteria (live weight) per hectare.

The growth rate of bacteria is generally limited by the small amount of readily decomposable substrate. Most organic matter in soils is humus, which is resistant to further enzymatic decomposition.

Augmentation of soils with 'micro flora', such as mycorrhiza, and beneficial bacteria can help establish a good balance in soil that helps plants to grow normally.

The best example of this is the case of the legume lucerne in soils that may not contain the specific bacteria required to infect the plant for nitrogen fixation purposes.

Healthy soils are often associated with diverse bacterial and fungal flora spread across a number of genera. Some soil bacteria are known to produce root and plant growth stimulating substances and fungi such as mycorrhiza can contribute significantly to the phosphate, zinc and water balance of plants.

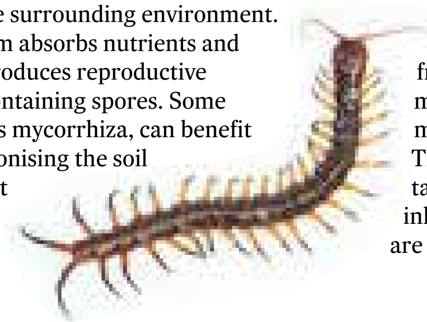
FUNGI

Fungi are heterotrophs that vary greatly in size and structure. Fungi typically germinate from spores and form a threadlike structure called the mycelium. Whereas the activity of bacteria is limited to the surface of soil particles, fungi can grow into the surrounding environment. The mycelium absorbs nutrients and eventually produces reproductive structures containing spores. Some fungi, such as mycorrhiza, can benefit plants by colonising the soil distal to plant roots and re-mobilising phosphate reserves to the benefit of the plant. The plant, meanwhile, provides the mycorrhiza with carbon rich compounds.

It is difficult to determine the amount of fungus per gramme of soil because mycelia are easily broken. In general, the live weight of fungal tissue in soils is thought to be equal to that of bacteria. The science of manipulating soil bacteria and fungi remains relatively unsophisticated, involving bacteria inhibiting substances, and tends to be less than predictable in UK soils. It is, however, possible to measure bacterial (and fungal) activity either directly by measuring soil respiration or by using cellulose rich filter papers and monitoring their decay in soil samples.

SOIL ANIMALS

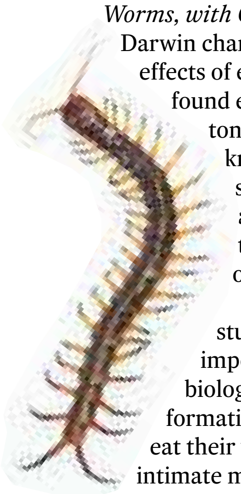
Soil animals can be considered both consumers and decomposers because they consume organic matter and some decomposition occurs in the digestive tract. Fauna is generally classified into size classes: microfauna, mesofauna and macrofauna. This classification system encompasses the range from smallest (1–2µm for the microflagellates) to largest (over 2 metres for giant earthworms).



The microfauna (protozoa, rotifers, tardigrades, small nematodes) inhabit water films. The mesofauna are largely restricted to existing airfilled spaces, while the macrofauna are able to create spaces by burrowing, which has a large influence on soil structure.

Nematodes are microscopic worms and are the most abundant animals in soils. Most are free-living and inhabit the water films surrounding soil particles. Water is easily lost through their skin, and when soils dry out or other unfavourable conditions occur, nematodes encyst or form a resting stage. Nematodes live on dead and decaying organic matter or living roots, or prey on living organisms.

Earthworms are perhaps the best known of the soil animals. Modern ecology first took notice of them in 1881 when Charles Darwin published his book *The Formation of Vegetable Mould Through the Actions of Worms, with Observations of their Habits.* Darwin championed the beneficial effects of earthworms, after his studies found earthworms may deposit 4–6 tonnes of excreted material, known as castings, on the surface of a hectare of soil annually. This could result in the buildup of a 2.5cm layer of soil every 12 years.



Since then, numerous studies have shown the importance of earthworms as biological agents in soil formation. Essentially, earthworms eat their way through the soil. The intimate mixing of soil materials in the digestive tract of earthworms, the creation of channels and production of castings modify the soil structure, leaving the soil more porous. Channels open to the air at the soil surface greatly increase water infiltration.

Earthworms prefer a moist environment with an abundance of organic matter and a plentiful supply of available calcium. They also avoid water saturated soils. Earthworm numbers vary greatly from location to location, with estimates of abundance ranging from a few hundred to more than a million per hectare. Attempts to increase earthworm activities in soils have been largely unsuccessful, as numbers likely represent an equilibrium population for the existing conditions.

Arthropods make up a large proportion of the remaining soil fauna. The most abundant are mites and springtails – primitive insects less than a millimetre long. Springtails live in the macropores between litter layers, feeding largely on dead plant and animal tissue, and fungal mycelia. Other important soil arthropods are spiders, insects (including larvae), millipedes, centipedes and woodlice. Millipedes feed mostly on dead organic matter, whereas centipedes are carnivorous. The numbers of millipedes and centipedes in the soil is small compared with springtails and mites, but their size, and therefore their biomass, may be greater.

Microorganisms and soil animals work as a decomposing team

Microorganisms and soil animals work together as a decomposing team, simultaneously dismantling organic matter as soon as it reaches the soil. Holes made in vegetation by animals such as mites and springtails allow microorganisms to enter. Soil animals also break up organic debris and increase the surface area for the subsequent activities of bacteria and fungi. Soil animals ingest bacteria and fungi, which continue to function within the digestive tracts of the animals before being excreted elsewhere. Material is thus subjected to decomposition in several stages and in different environments. Organic matter, and in fact the entire soil, is ingested by earthworms, producing a mixing of organic and mineral matter.

A good barometer of soil health and an easy measurement to conduct is to count how many earthworms there are in the soil. A healthy soil may contain as much as five tonnes of life per hectare. The table above details some of the estimated soil flora and fauna that inhabit a healthy soil.

In a similar vein, observing and mapping crop responses in different areas of the field can provide a practical and useful measure of soil condition. From an agricultural perspective, a healthy soil is difficult to define, but the simple observation of the factors described above can help the agronomist and grower make a subjective assessment of the health and sustainability of the soil they manage.

Dr Tudor Dawkins is technical director of Pro Cam UK, an agronomy services company.
Dr Farnon Ellwood is senior lecturer in environmental biology, University of the West of England, Bristol.