Chapter 3
Soil health

Soil is usually viewed simply as a medium for growing plants. However, in addition to providing a mechanical support for plants, soil enables the storage of water and organic matter, releases elements of biological and pedological importance, and is the place where soil organisms live.

Soil health refers to the capacity of soil to function as a vital living system, a dynamic system. It involves the idea of soil as a living dynamic organism that functions in a holistic way depending upon its condition or state. Soil health depends on the combined effects of three major interacting components. These are the chemical, physical and biological characteristics of the soil. Soil health is enhanced by management and land-use decisions that consider the multiple functions of soil. It is impaired by decisions that focus only on single functions and short-term solutions, such as increasing but not sustaining crop productivity.

Maintaining and improving the capacity of soils to function is essential to human survival, and healthy soil is an essential element within this process (Pankhurst *et al.*, 1997). The ecological attributes of the soil are important since they have implications beyond the quality of the soil or its health, the capacity to produce a particular crop. They are associated with the soil biota, its diversity, its food-web structure, its activity and the range of functions it performs in the system. The soil biota is a vital force that serves to maintain the health of the soils. Soil biodiversity *per se* is not a property of soil that is critical for the production of a given crop, but it may be very important for the continued capacity of the soil to produce that crop.

Soil organisms exert a major control over many soil processes through their effects on: the decomposition of dead organic materials; nutrient cycling; the modification and transport of soil materials; and the formation and maintenance of soil structure. Although sometimes not easily recognized, the biological activity of soils is largely concentrated in the topsoil, from a few centimetres to 30 cm. The living component of the SOM consists of:

- plant roots – 5–15 percent,
- soil organisms – 85–95 percent; and their components:
- macrofauna and mesofauna – 15–30 percent;
- microorganisms – 60–80 percent.

Much of the biological activity is associated with processes that regulate nutrient cycling (mineralization, denitrification, nitrogen fixation, etc.) and the decomposition of organic residues. Soil macrofauna has an important role in these processes as dead organic matter is first consumed by macrofauna that digest it, partially cutting it into small fragments. These small fragments and partially degraded organic residues are then available to mesofauna and microorganisms. Through its burrowing activity, soil macrofauna buries organic matter deep into the soil and stimulates the activity of microorganisms.

Thus, soil organisms participate in a range of processes essential to the functioning of ecosystems. They also constitute an important resource for the sustainable management of agricultural ecosystems and their durability. For example, they play an important role in the dynamics of SOM and nutrient cycling, the purification of water, the detoxification of agrochemicals, and the modification of soil structure. Macroorganisms and microorganisms exert a strong influence on soil properties through the role they play in organic matter decomposition, nutrient redistribution and cycling, and the transformation of such nutrients into forms readily available for plant nutrition. Soil biota and their biological activities are important for soil health and fertility in agricultural soils.

The activities of soil organisms interact in a complex food-web (Figure 2). The soil food-web is a way to relate soil organisms to one another on the basis of what they eat. Some of these organisms feed on living plants (herbivores) and animals (predators), some on dead plant debris (detritivores), some on fungi or bacteria, and others live off, but without consuming, their hosts (parasites). Plants, mosses and some algae are autotrophs. They play the role of primary producers by using solar energy, water and C from atmospheric carbon dioxide (CO2) to make organic compounds and living tissues. Other autotrophs obtain energy from the breakdown of soil minerals – oxidation of nitrogen (N), sulphur (S), iron (Fe) and carbon (C) and from carbonate minerals. Soil fauna and most fungi, bacteria and actinomycetes are heterotrophs, they rely on organic materials directly (primary consumers) and through intermediaries (secondary or tertiary consumers) for C and energy needs. All terrestrial ecosystems, including agricultural production systems, consist of a producer subsystem (the crop), and a decomposer subsystem, and both components depend upon each other.

A biologically healthy soil harbours a multitude of different organisms – microorganisms, such as bacteria, fungi, amoebae and paramecia, as well as larger organisms such as nematodes, springtails, insect larvae, ants, termites, earthworms and ground beetles. Most are helpful to plants, enhancing the availability of nutrients and producing chemicals that stimulate plant growth.

A healthy soil produces healthy crops with minimal amounts of external inputs and few to no adverse ecological effects. It has favourable biological, physical and chemical properties.

Among the functions regulated by soil organisms, the most important are:

- decomposition: breaking down litter, creating humus and cycling nutrients;
- converting atmospheric N into organic forms and reconverting organic N into gaseous N;

- synthesizing enzymes, vitamins, hormones and other important substances for plant growth;
- modifying soil structure, thus affecting porosity, water fluxes and organic matter distribution and promoting deeper root growth;
- eating and/or decomposing weed seeds;
- suppressing and/or feeding on soil-borne plant pathogens and plant-parasitic nematodes.

Healthy soils are also essential to plant defences. Unhealthy soils hinder crops' abilities to use their natural defences and leave them vulnerable to potential pests. In contrast, healthy soils arm plants chemically with defence-boosting nutrients and are physically conducive to optimal root development and water use. Healthy soils can also expose weed seeds to more predators and decomposers, and their slower release of N in spring can delay small-seeded weeds (which often need a flush of N to germinate and begin rapid growth), thereby giving larger-seeded crops a head start.

Soil health can be improved by:

- diversifying crop rotations including legumes and perennial forages;
- keeping soils covered year-round with living vegetation and/or crop residue;
- adding plenty of organic matter from animal manures, crop residues and other sources to restore that removed through harvest or lost through burning and breakdown;
- reducing tillage intensity and protecting soils from erosion and compaction;
- using best management techniques to supply balanced nutrients to plants without polluting water.

Consequently, a main objective of every farmer should be to support high levels of potentially beneficial soil organisms and low levels of potentially harmful ones. A soil rich in fresh organic residues –sometimes called particulate or light-fraction organic matter – can feed huge numbers of organisms and foster abundant and diverse biological activity.

The following exercises, Exercises 3 and 4, aim to enhance understanding of soil health and interactions between organisms and the food web.

EXERCISE 3: THE HEALTH OF A SOIL

(Adapted from: Living Soils Manual (Exercise 20) by W. Settle; and Salud de Suelos published by Cornell University)

Background

This exercise can be done together with the quick introductory one. The task here is to establish the comparison between the health of "somebody" and the health of the soil by listing the attributes that characterize a healthy soil, in contrast to unhealthy soils. This also relates ecosystem health to human health.

Goal

To be able to list the principal characteristics that defines "soil health".

Time required

30–45 minutes.

Materials

Newsprint, tape, pens.

Procedure

1. Initiate the discussion by asking "what are the attributes of a healthy soil?"
2. Participants make a list of what they think is a healthy soil; at this point not only biological attributes of soil (presence or absence of organisms) but also physical and chemical properties, e.g. colour, soil depth, if it is easily breakable.
3. Discussion on what characteristics of soils suggest that they are "healthy" or "unhealthy". At this point, the presence of soil organisms can be seen as both a positive and a negative thing, or maybe there is indifference about the presence of organisms in the soil. In general, farmers do not pay special attention to soil organisms unless they are pests.

Questions to discuss and points to emphasize

1. To the group: what are the properties related to healthy and unhealthy soils? While the list may be long, emphasize (and include if not already listed) the following: colour, depth, presence of organisms, and presence of weeds, e.g. *Striga*.

EXERCISE 4: THE SOIL FOOD-WEB

Background

A healthy soil is full of living things. There are thousands of millions of bacteria in one cup of soil alone. Plant roots, insects, fauna other than insects (earthworms, slugs, snails, Isopoda, etc.), bacteria, fungi, nematodes and protozoa are some of the living parts of the soil ecosystem. These organisms help create the environment plants need to grow.

Many soil organisms drive the decomposition process and nutrient cycle. Millipedes, earthworms, Isopoda, other macrofauna and mesofauna organisms, bacteria and fungi all feed on dead organic material and convert nutrients to a form plants can use. Earthworm castings, lumps of worm droppings, are rich in nitrogen, potassium and phosphorus. Earthworms, termites and ants are natural "tillers" that also mix and aerate the soil. One mature oak tree can drop over 100,000 leaves each year. Imagine what would happen without these amazing natural recyclers. The soil ecosystem also contains predators that hunt the pests that feed on plant parts. Spiders, centipedes and predatory beetles search for prey in the soil and leaf litter. All of these organisms make up the soil food-web.

A farmer's goal is to provide an environment that supports soil organisms. These organisms will continually decompose organic material to a form that will keep a crop growing.

Goal

To understand the concept of interactions and cycles in soil.

Time required

3–4 hours.

Materials

Character identification tags (names).

Pictures of each character – plant, earthworm, nematode, arthropods, insects, fungi, bacteria and protozoa.

Equipment for each character as described:

- plants – string, 2 cards marked energy, and 2 cards marked carbon;
- earthworms – 2 water bottles, 2 vitamin bottles, 2 whisks, 2 trowels, and 2 bottles of glue;
- nematodes – 1 vitamin bottle;
- arthropods and insects – 1 each plastic millipede, spider and beetle, and 1 "Good Guy" sign;

- ➢fungi – 1 water bottle, and 1 vitamin bottle;
- ➢bacteria – 1 vitamin bottle per bacteria;
- ➢protozoa – 3 nitrogen signs.

One hand lens per trainee (farmer/extension...).
One trowel and plastic tray per sub-group.
Identification guide for soil insects and arthropods (see Annex).
Note books.

Procedure

In the classroom:

1. Inform the study group that, in addition to its non-living components, soil contains a whole world of living organisms. Ask trainees to name some organisms that live in the soil.
2. Explain that these organisms make up the soil food-web and have important roles in the soil ecosystem. Ask what happens to leaves that fall to the ground in autumn. The group discusses the importance of soil organisms in decomposition, nutrient cycling and soil improvement.
3. Before doing the simulation, show pictures of the range of soil organisms and discuss which organisms are plant eaters, decomposers, tillers, predators, etc., and review their roles in the soil ecosystem. (See Chapters 4 and 6.)
4. The trainees are invited to act out the parts of different organisms in a soil ecosystem. The trainer assigns roles (e.g. earthworm, plant,...), hands out props and reviews each participant's action before starting the simulation. The participants do the simulation for about 30 seconds and are then asked to stop, look around and process.
5. What happened here? How did the plants and animals help each other? What would happen if someone sprayed a pesticide that killed one group of animals? The simulation is repeated, but this time without all of the insects and arthropods. How would this affect the soil foodchain? Is there a better alternative?

Move to the field:

1. Inform trainees of the purpose of the study to examine some animals that live in the soil.
2. Split the participants into small groups, and give each participant a hand lens, and each sub-group a trowel and a plastic tray to collect soil.
3. Sub-groups find and examine the animals in the soil with the hand lens; they should try to identify some of them and to draw pictures of some of the organisms in their journals.
4. Return the animals and soil to the field.

Questions to discuss and points to emphasize

1. Did you find many animals?
2. Do you think there is a healthy population of soil organisms?
3. What did some of the animals look like?
4. Did you see any of the animals we talked about in the classroom?
5. Can you describe one of the animals you found and explain its role is in the ecosystem or how it helps the soil?
6. What does the soil provide for the animal?
7. If trainees found enough animals, they can try to make a foodchain from their lists.

Chapter 4
Introduction to soil macrofauna

Soil macrofauna consists of a large number of different organisms that live on the soil surface, in the soil spaces (pores) and in the soil area near roots. Their way of living, their feedings habits, their movements into the soil, their excretions and their death have direct and indirect impacts on their habitat. The biological activities of soil macrofauna regulate soil processes and soil fertility to a significant extent.

The effects of soil macrofauna on soil can be divided into three classes: physical, chemical and biological effects. These effects are determined by the functional group involved in the process.

PHYSICAL ROLE OF SOIL MACROFAUNA

Five main physical effects of soil macrofauna can be highlighted:

- ➢ macromixing,
- ➢ micromixing,
- ➢ gallery construction,
- ➢ fragmentation,
- ➢ aggregate formation.

Macromixing

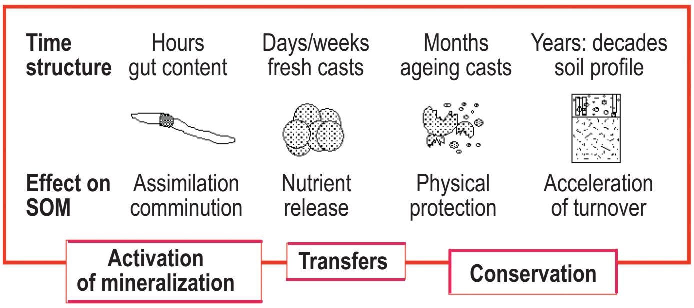
Ants, termites, earthworms and ground beetles can move an important quantity of soil, bringing back to the surface mineral matters from deeper horizons and burying the organic matter from the surface horizons, from litter and from excrements.

For example, a large nest of *Atta* ants comprises several million individuals. It forms a cavity in soil with numerous chambers. The excavated earth is deposited on the soil surface surrounding the nest. The removal of fine material in depth sometimes creates porous zones under the nest where water can be accumulated temporarily.

The macromixing activity of earthworms is of major importance to soils. It can be measured by the quantity of casts found on the soil surface. Earthworms can produce 40–250 tonnes of casts per hectare per year (Figure 3). Some can produce up to 2 500 tonnes of casts per hectare per year.

Some beetles (especially those of the subfamily Scarabeidae) are **coprophagous** – they are very efficient at incorporating and removing excrements that are on the soil surface. For example, just a couple of *Heliocopris dilloni*, a large African species, can bury a piece of dung in one night (Waterhouse, 1974).

FIGURE 3
Organic matter decomposition process regulated by earthworms



Source: from Lavelle (1997).

Micromixing

Other groups of soil macrofauna influence soil structure in a less spectacular way, but the micromixing that they realize is as important as macromixing. These organisms, mainly represented by Diptera larvae, have a more limited capacity to dig the soil. They stay on the soil surface where they realize a fundamental task for the incorporation of organic matter to soil. However, they can be carried into soil by leaching to a depth of up to 60 cm.

Gallery construction

Gallery (burrow) formation is very important for soil aeration and water flux. For example, earthworms and termites develop networks of galleries that improve large spaces in the soil macro-porosity by 20–100 percent (Edwards and Bohlen, 1996).

Earthworms can burrow an estimated 400–500 m of galleries per square metre in grasslands. These galleries are denser in the top 40 cm and can represent up to 3 percent of the total soil volume. In these conditions, the waterholding capacity of soil can increase by 80 percent and water flux can be from four to ten times faster.

Earthworm activity is very important in agricultural soils with a high degree of compaction and a ploughing pan that prevents water flux. This situation decreases water infiltration and increases surface runoff and erosion. Earthworms pierce the ploughing pan, so improving water infiltration and offering new paths for root penetration. Termite excavation activity has a similar effect on soils (Gullan and Cranston, 1994), and in some cases can reduce the compaction of surface layers. Where organic matter is present in the soil, the bioturbating and decomposing activities of termites can reduce soil compaction, increase its porosity and improve its water infiltration and retention capabilities. Such conditions encourage root penetration, vegetative diversity and the restoration of primary productivity (Mando, 1997).

Thus, galleries make up a draining system that collects rainwater and facilitates its flow. Water drags small material into these tunnels, which become the preferential paths for soil penetration for roots and leached clays. Galleries are also the soil penetration paths for other surface invertebrates with more limited burrowing capacities, e.g. very small earthworms, slugs, insect larvae, and mesofauna.

Litter fragmentation

The fragmentation of dead wood (lignin material), carcass and litter is one of the most important activities of soil fauna. It has a major effect on organic matter evolution in soil, conditioning the activity of bacteria, fungi and microfauna populations. Fragmentation is performed by phytosaprophagous animals (i.e. animals feeding on decayed plant material and dead animals).

Aggregate formation

After litter has been fragmented, it is easier for organic matter to be broken down into the stable form known as "humus", and then to form soil aggregates – the clumping together of soil particles forming a crumbly healthy structure. Earthworms, termites, millipedes, centipedes and woodlice ingest soil particles with their food and contribute to aggregate formation by mixing organic and mineral matter in their gut.

DIRECT AND INDIRECT CHEMICAL EFFECTS OF SOIL MACROFAUNA

The most important chemical effect of macrofauna on soil is the modification of food quality through its passage in the gut and particularly the mineralization of organic matter and the release of nutrients. Soil macrofauna also influences soil chemical composition through the deposition of excrement.

The main indirect chemical effect is the mineralization of N, P and S through the activation of microflora. Soil microorganisms represent an important proportion of the soil living component (60–80 percent). However, in order to be active, they need to be in contact with SOM (which they feed on). Because of their inability to move in soil to search for food, microorganisms are only active during short periods of time (the time necessary to consume the organic matter around them) and in a limited number of microsites (where temperature and moisture conditions are suitable for their activity). The rest of the time, soil microorganisms are "in dormancy" and they are able to survive "hard times" in this way (Jenkinson and Ladd, 1981). The contrast between the potential of soil microorganisms for an extremely fast turnover of organic matter and the field reality has been called the "Sleeping Beauty Paradox" (Lavelle *et al.*, 1994a). Macrofauna that has the ability to move the soil and change environmental conditions at the scale of microorganisms can interrupt this dormancy (acting as "Prince Charming"), providing assimilable substrates (root exudates, earthworm mucus and other materials) that initiate the metabolic capabilities of microorganisms. Hence, they appear to be major regulators of microbial activities.

Interactions between microorganisms (with a high capacity to digest almost all organic substrates) and macrofauna (with the potential for mechanical activities) are the basis of the biological systems of regulation that determine soil function (Lavelle and Spain, 2001).

BIOLOGICAL EFFECTS OF SOIL MACROFAUNA

In a natural soil, a complex and dynamic balance exists between the different groups of organisms with different feeding habits. Predation and competition are the main factors controlling this equilibrium. Predation has an important role because it establishes a balance between the number of individuals and the quantity of available resources. Competition is another way to maintain soil fauna populations in balance with soil resources.

Another biological effect of soil macrofauna is the disappearance of dead animal material. This work is realized by **necrophagou**s (which feed on dead and/or decaying animals) and **coprophagous** organisms (feeding on dung or excrement) such as Diptera larvae, Coleoptera and Lepidoptera larvae and adults. They clean the soil surface and incorporate organic matter into soil. In addition, soil macrofauna disseminates bacteria and spores through excrement dispersion in soils or by on-body transport. Earthworms determine the vertical repartition depth in soil. .

Thus, through their different activities and effects on soil, soil organisms create and accumulate structures that give soils specific architectures (Lavelle, 2002). Networks of galleries, the accumulation and spatial array of biogenic aggregates and surface deposits are among the conspicuous features that can be observed in the field. The nature and array of these structures depend on the organisms that have produced them. The physical and chemical parameters of the soil that was used to make the biostructures are also important as they determine the resistance and persistence of these structures (Chauvel *et al.*, 1999).

The sum of structures deposited over time by these organisms have specific textural, structural and architectural properties that influence the physical-chemical properties of soil and the smaller fauna and microflora that live in this environment.

These sets of structures (pores, aggregates, etc.) that have been accumulated by soil organisms can be colonized by rather specific communities of microorganisms, other invertebrates and possibly roots. The environment in these structures can be very different from that of soil. For example, the availability of C, mineral N and P that can be assimilated may be enhanced significantly in fresh earthworm casts or fresh termite pellets when compared with the ingested soil (Lavelle and Spain, 2001). As a consequence, other groups of organisms such as litter transformers, micropredators, microorganisms and fine roots may become established in these domains (Plate 4).

The importance of the functions performed in soils by macrofauna and the physical, chemical and biological changes induced in a soil environment as a consequence of its activity make it a vital part of all ecosystems, including agro-ecosystems.

Soil macrofauna is involved in:

- degrading organic matter and mineralizing nutrients;
- controlling pathogen populations;

- improving and maintaining soil structure;
- mixing organic matter through the soil.

The reduction of aboveground biodiversity is normally associated with the alteration of several environmental parameters including the carbon supply to the soil, which provides the basis for a more or less diversified soil population (Barros *et al*., 2002).

The reduction in diversity of soil organisms causes a dysfunctioning of the ecosystem. This dysfunctioning may result in disequilibrium between beneficial and harmful organisms, which can lead to harmful organisms to become dominant.

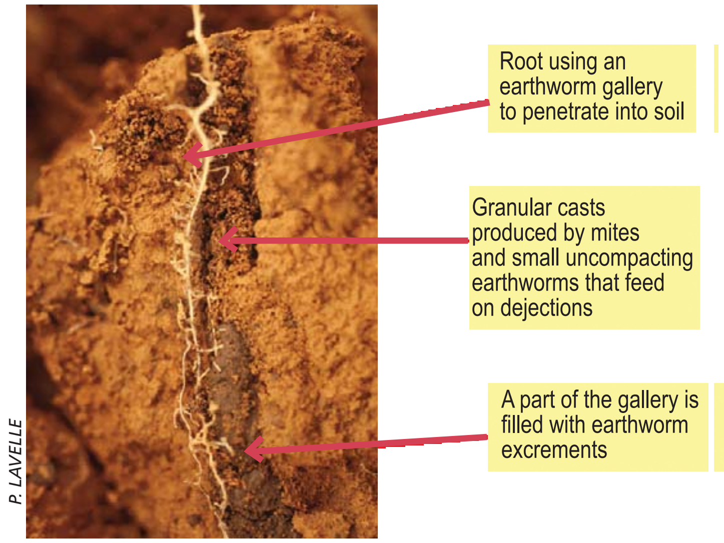


Plate 4

An earthworm gallery filled with casts and a root following the pathway opened by the earthworm. Root hairs are attached to the cast where higher availability of nutrients (C, N and P) exists compared with the surrounding soil. (photo: P. Lavelle)

In other cases, as result of a reduction in macrofauna, the activities of a beneficial organism can become detrimental (Box 1). Barros *et al*. (1996) and Blanchart *et al*. (1997) showed the results of dysfunctioning caused by the disequilibrium between compacting and uncompacting macroinvertebrates

The activity of the earthworms in the pastures of central Amazonia can be positive where the other groups of the macrofauna remain present. However, as soon as the compacting earthworm *P. corethrurus* becomes largely dominant and the decompacting fauna groups disappear, a compacting activity begins, resulting in the formation of a massive surface layer (Plate 5).

Improvements in soil management to avoid a reduction in soil macrofauna diversity and to guarantee suitable soil conditions for these organisms to develop are the only way to ensure long-term soil functioning and to protect cultures from pests.

BOX 1

Consequences of soil biodiversity reduction

The consequences of soil biodiversity reduction:

- It provokes a disequilibrium between beneficial and harmful organisms, which can became dominant.
- It leads to an increase in organisms harmful to plant production because of the lack of predators:
  - aphids, phytophagous nematodes, some microorganisms, bacteria and fungi;
  - white grubs (melolonthid and rutelinid larvae) in groundnut yields in Africa that cause root damage, make plants less able to resist drought and more susceptible to invasion by termites and soil fungi;
  - wireworms (Elateridae) and false wireworms (Tenebrionidae) are podborers;
  - millipedes and ants can act as podborers and be a serious pest.
- The activity of beneficial organisms can increase immoderately and become a serious problem:
  - huge number of epigeic ant mounds in Argentina;
  - high soil compaction caused by compacting earthworms in Brazil.

Plate 5

A) Aspect of the surface of a soil compacted by Pontoscolex corethrurus; B) Pontoscolex corethrurus.

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