

Chapter 1

Introduction to soil ecology

Soil organisms are an integral part of agricultural ecosystems. The presence of a range of soil organisms is essential for the maintenance of healthy productive soils. An excessive reduction in soil biodiversity, especially the loss of species with unique functions, may have catastrophic effects, leading to the long-term degradation of soil and the loss of agricultural productive capacity. As a consequence, more land would be needed for agricultural production to meet demands.

The overlooking and depletion of the beneficial functions performed by soil organisms in agricultural ecosystems as a result of inappropriate soil biological management is contributing to increased rates of land degradation, nutrient depletion, fertility decline, water scarcity, and yield reductions. All these factors have a negative impact on the livelihoods of people who depend directly on agriculture for their subsistence.

One of the main gaps in most agricultural management systems is their failure to consider the option of managing soil biological processes and, in particular, using practices that favour the activity of soil macrofauna as a means to maintain and improve soil fertility. Although not readily visible, relatively more attention has been placed in research and development on the functions of soil micro-organisms – both their positive effects on nutrient cycling and uptake, and the negative effects of soil borne pests, including nematodes (microfauna), and pathogens.

The main aims of this manual are to provide land users and technical people on the ground with: (i) an easy-to-use guide to the main activities of soil macrofauna in agriculture; and (ii) a set of exercises to reveal their activities and importance through a more ecological view of soils. The focus is placed on the visible soil organisms as these can be seen and monitored by farmers. Moreover, they also tend to be representative of soil life as a whole, including the non-visible components which are more difficult for farmers to learn about and understand.

LAND MANAGEMENT: FOOD AND AGRICULTURE

Sufficiency in global food supply is dependent on the intensification of agriculture. As intensification occurs, chemical and mechanical inputs alter, and often substitute, the biological regulation of soil processes.

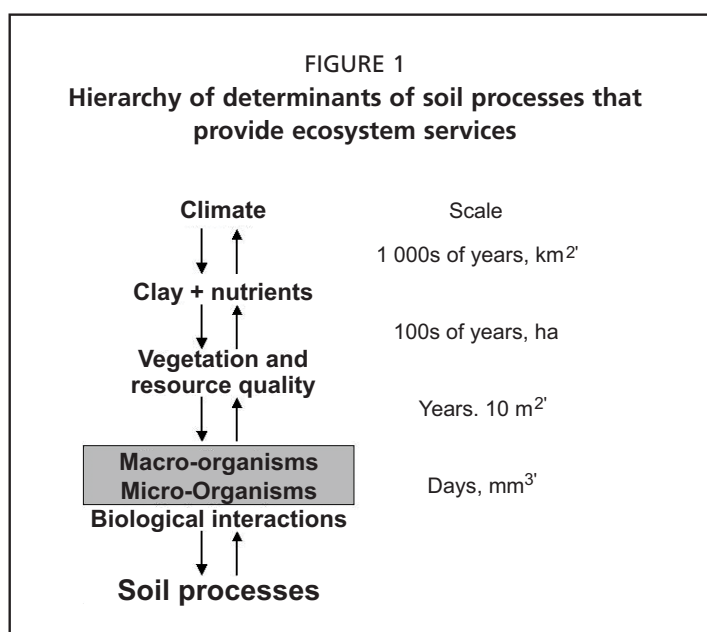
Inadequate soil management is the principal factor behind the worldwide decline in agricultural productivity. Most modern cropping systems require substantial regular inputs of nutrients to replace those removed through harvesting and burning of residues as well as through leaching and erosion. They also

require appropriate tillage and weed management practices to reduce risks of soil compaction and erosion and weed competition; and increasingly no- or reduced-tillage practices are being promoted. In the same way, continued grazing in pastoral environments soon leads to soil degradation through nutrient depletion and compaction unless appropriate legume-grass combinations and grazing rotations are used. In addition, losses and stresses imposed by chemical contamination through use of herbicides and pesticides, as well as chemical imbalances through soil acidification or salinisation may result in impaired soil biological functioning. Faced with such pressures, soils are a threatened resource. The maintenance or amelioration of soil fertility is an essential factor in the development of sustainable and productive agricultural systems in the long-term. This requires the integration of knowledge of biological processes into the design of land-management systems (Lavelle and Spain, 2001).

Many systems of agricultural management are not sustainable in the longer term because of the pressures they place on the soil. Production levels may frequently be set on the basis of economic goals rather than the capacity of the soil to withstand particular stresses. Conversely greater attention in agricultural systems to managing the soil biological processes, through providing a beneficial environment for soil macrofauna, can restore soil health and improve soil fertility.

Factors in soil formation and functioning and their effects at different levels

Soil formation depends on five main factors: climate; parent material; topography; and time; as well as living organisms (see Figure 1). With the exception of time, the soil-forming factors are considered as interdependent with multiple feedback effects occurring between them (Chesworth, 1992). Furthermore, a hierarchy exists with climate playing a dominant role over parent materials and topography.



Source: after Lavelle *et al.* (1993).

The soil-forming factors operate wherever soil and soil-forming materials occur, although their relative influences differ between soils and with location on the earth's surface. The soil-forming factors do not influence the soil directly but act through the medium of soil processes. These processes act in potentially different combinations in each environment. Their many combinations and degrees of expression are reflected in the wide diversity of soils found on the surface of the earth (Lavelle and Spain, 2001).

Climate

The regional climate is the dominant factor affecting the formation of all soils (Birkeland, 1984). It interacts with and conditions the effects of the other factors in determining the biota that can survive in particular environments and the seasonality of its activities. Through its control of temperature and moisture regimes, climate determines the phase of the soil water and the intensity of water fluxes. It thereby controls the transport of solid particles and dissolved materials within developing soils, over their surfaces and laterally in the landscape.

Parent material

Parent material is the basic inorganic material from which the soil is formed. Depending on its physical, chemical and mineralogical composition, it will have a strong influence on the composition and texture of the resulting soil. The type of the parent rock affects soil formation (Brewer, 1954; 1964), particularly through:

- the amount of clay that can be potentially formed by in situ weathering – this varies with the nature of the parent rock and intensity of water fluxes (Macias and Chesworth, 1992);
- the amount of alkali, notably sodium (Na) and potassium (K), of alkaline-earth metals, largely calcium (Ca) and magnesium (Mg), and of iron (Fe) that can be released by weathering;
- the ease of release of the above minerals;
- the permeability of the parent rock.

Time

Soils undergo extended and complex series of reactions and processes during formation from their parent materials. The net effect of these eventually leads to the differentiation of fully-developed profiles. This occurs at widely variable rates depending largely on parent materials and environment. In a general way, soils can be divided into those forming over short cycles and long cycles (Duchaufour, 1982). The short-cycle soils develop over periods ranging from less than 10^3 to 10^4 years. The long-cycle soils require periods of from 10^5 to 10^6 years for development. In any case, the long time necessary for soil formation means that it can be considered a non-renewable resource.

Organisms

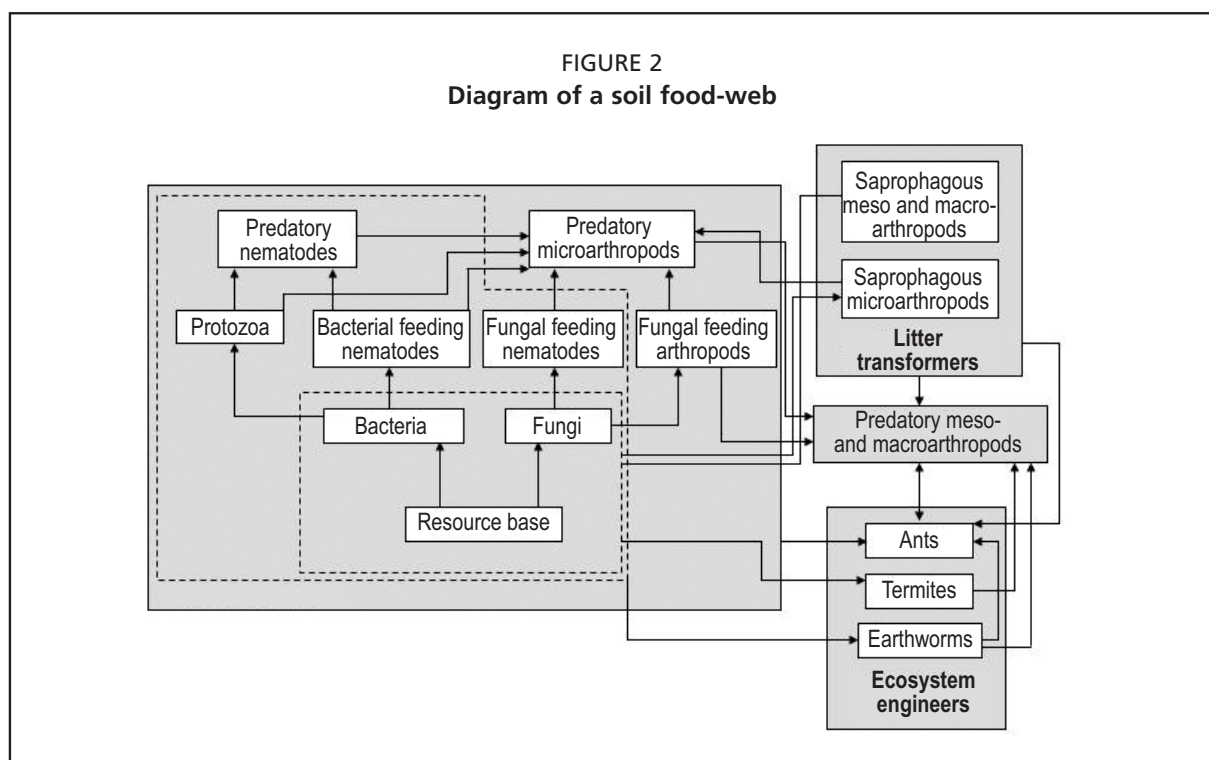
The organisms (or biota) are a major factor in soil formation and their effects determine many differences between soils. The various soil organisms affect certain soil processes in different ways, as described in the section on functional classification in Chapter 2. Soil macrofauna play a particularly important role in soil aggregation and porosity as a consequence of their burrowing and mixing activities. This in turn affects the environment (aeration, soil moisture, etc.) for other soil organisms.

Soil ecosystem

Soils are the part of the earth's surface, which forms a narrow interface between the atmosphere and the lithosphere. Soils are made up of water, gases and mineral matter together with a diverse range of organisms and materials of biological origin. Organic materials in and on the soil are broken down and transformed –mainly by soil organisms– into nutrient elements, which are, in turn taken up by plants and micro-organisms.

Soil organisms are the main mediators of soil functioning at different scales. These functions can be pictured as having a hierarchical relationship. Figure 1 illustrates the hierarchical organization of the determinants of soil processes: climate, soil characteristics – especially the abundance and types of clays and nutrients – and the quality of the organic materials input (Lavelle *et al.*, 1993; Beare *et al.*, 1995). The series of factors affecting soil functioning are determined by both spatial and temporal scales..

Of major importance in ecosystem and soil development and maintenance are the so-called “ecosystem engineers” – as these species control, either directly or indirectly, the availability of resources to other species (Jones *et al.*, 1997). These organisms physically modify, maintain and create new habitats for other organisms. One effect of such organisms is to create higher habitat diversity, which may in turn increase species diversity (Lavelle and Spain, 2001). An example of physical ecological engineers is plant roots that create large voids (spaces) in the soil through root decay (Jones *et al.*, 1997). Other ecosystem engineers are the termites and earthworms that play a major role in moving, mixing and aerating the



Source: Adapted from Wardle (2002).

soil through their burrowing. Other organisms including higher plants and animals also play substantial roles in this respect (see section below on macrofauna).

The functioning of the soil system is also determined by:

- the decomposition rates of dead organic materials, and the balance between mineralization, which releases nutrients available to plants and microorganisms, and humification, which forms reserves of soil organic matter (SOM) and colloidal organic compounds;
- the degree of synchronization of nutrient release with plant demand;
- the soil physical structure, which determines the rates and patterns of gas exchange, soil water movement into and through the soil, and erosion rates.
- The texture of the soil (% of sand, silt and clay) which influences the activity of soil organisms and hence the soil biological functioning.

Texture is an important characteristic of soil because it influences many aspects of soil fertility, especially the amount of water held by the soil, its capacity to retain plant nutrients, and the ability of roots to develop and grow through the soil. Soils with a high percentage of clay are said to be “heavy” soils and have a capacity to retain water due to the small pore spaces and high surface tension forces. Soils with a high percentage of sand are considered “light” soils, and tend to hold very little water. Water infiltrates rapidly into sandy soils and is readily drained through the large pores spaces, unless they also contain a lot of organic matter.

This document focuses on the soil macrofauna – the visible soil organisms, in particular the so-called group of ecosystem engineers, as illustrated in the bottom right box in Figure 2. It is intended to be used as a training guide for which a number of practical exercises are provided.

Chapter 2

Soil life and biodiversity

Soil is a still, porous, semi-aquatic medium within which temperature and moisture conditions are highly buffered. Soils were among the first terrestrial environments to be colonized because they possess environmental conditions that are intermediate between aquatic and aerial media (Lavelle and Spain, 2001).

Soil is a large reservoir of biodiversity, often little known. Soil communities are among the most species-rich compartments of terrestrial ecosystems (Anderson, 1975; Usher *et al.*, 1979; Giller, 1996). It is believed that there are twice as many species of organisms living in soil than there are in tropical rainforest canopies. Soil organisms carry out a range of processes that are important for soil health and fertility in soils of both natural ecosystems and agricultural systems. They perform and regulate a major proportion of the organic matter transformations and of the carbon (C) and nutrient fluxes in terrestrial ecosystems (Swift *et al.*, 1979).

The diversity of life in soil, known as soil biodiversity, is an important but poorly understood component of terrestrial ecosystems. Soil biodiversity is comprised of the organisms that spend all or a portion of their life cycles within the soil or on its immediate surface (including surface litter and decaying logs) (Table 1).

The easiest and most widely used system for classifying soil organisms is to group them by size into three main groups: macrobiota, mesobiota and microbiota (Wallwork, 1970; Swift *et al.*, 1979).

Microbiota comprises microorganisms and microfauna. Microorganisms are the smallest of the soil animals ranging from 20 to 200 μm in length (< 0.1 mm in diameter). They are extremely abundant and diverse. They include: algae, bacteria, cyanobacteria, fungi, yeasts, myxomycetes and actinomycetes that are able to decompose almost any existing natural material. Microorganisms transform organic matter into plant nutrients that are assimilated by plants.

Microfauna includes small Collembola and mites, nematodes, and protozoa, among others, that generally live in the soil-water film and feed on microflora, plant roots, other microfauna and sometimes larger organisms (e.g. entomopathogenic

TABLE 1
Soil biodiversity: categories and characteristics

Category	Characteristics	Organisms
Permanent	Entire life cycle in the soil	Mites, springtails (Collembola), earthworms
Temporal	Part of life cycle in the soil	Insect larvae
Periodical	Frequently enter into the soil	Some insects and larvae
Transitory	An inactive phase in the soil (egg, pupa and hibernation) but not an active period	Some insects
Accidental	Animals fall down or are transported by runoff	Insect larvae

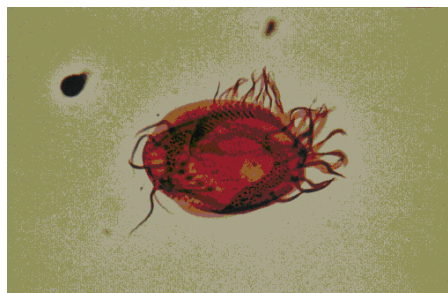


Plate 1
Protozoa.



Plate 2
Microarthropods

nematodes, that feed on insects and other larger invertebrates). Microfauna form the link between the primary decomposers (i.e. microorganisms) and the larger fauna in the detritus food-web in the soil. They are also important to the release of nutrients immobilized by soil microorganisms. The main soil animals in this group are protozoa (Plate 1).

The mesofauna is the next largest group and the animals range in size from 200 μm to 10 mm. in length (0.1–2 mm in diameter). These include mainly microarthropods (Plate 2), such as pseudoscorpions, protura, diplura, springtails, mites, small myriapods (Pauropoda and Symphyla) and the worm-like enchytraeids. Mesofauna organisms have limited burrowing ability and generally live within soil pores, feeding on organic materials, microflora, microfauna and other invertebrates.

This module focuses specifically on soil macrofauna communities. The macrofauna contains the largest soil invertebrates. Although the term soil

macrofauna is not well defined, for the purposes of this training material it will be defined at a higher taxonomic level using the broad criterion:

“A soil macrofauna taxon (group) is an invertebrate group found within terrestrial soil samples which has more than 90 percent of its specimens (individuals) in such samples visible to the naked eye”

(IBOY workshop 2000).

Soil macrofauna groups include organisms like earthworms, millipedes, centipedes, ants, Coleoptera (adults and larvae), Isopoda, spiders, slugs, snails, termites, Dermaptera, Lepidoptera larvae and Diptera larvae (see photos in the Annexe - Identification Key on Soil Macrofauna).

In terms of their abundance and their soil forming roles, earthworms, termites and ants are the most important macrofauna components of soils (Plate 3). Indeed, the importance of their activities has caused them to be called “ecosystem engineers” (Stork and Eggleton, 1992; Jones *et al.*, 1997).

They burrow and are important in mixing the soil – known as bioturbation. Macroarthropods and Mollusca are constant inhabitants of litter and, to a lesser extent, of soils, but they have generally more specific ecological roles. Thus, most live in the litter or in the upper few centimetres of soil; saprophagous arthropods play a major role in the breakdown of surface litter.



Plate 3
Earthworm.

Most soil animals occur in the top 30 cm of soil, although some also occur at depth. Soil animals may move to lower soil layers when conditions at the surface are harsh. Most soil animals occur in the surface layer because this layer contains the most food (C and nutrients) in the form of organic matter and other organisms.

In both natural and agricultural systems, soil organisms perform vital functions in the soil. The interactions among organisms enhance many of these functions, which are often controlled by the enormous amount of organisms in soils. These functions range from physical effects, such as the regulation of soil structure and edaphic (in soil) water regimes, to chemical and biological processes such as degradation of pollutants, decomposition, nutrient cycling, greenhouse gas emission, carbon sequestration, plant protection and growth enhancement or suppression (Table 2).

To reduce the huge complexity of organisms that live in the soil, a division of soil organisms into functional groups has been proposed.

TABLE 2
Essential functions performed by soil organisms

Functions	Organisms involved
Maintenance of soil structure	Bioturbating invertebrates and plant roots, mycorrhizae and some other microorganisms
Regulation of soil hydrological processes	Most bioturbating invertebrates and plant roots
Gas exchange and carbon sequestration (accumulation in soil)	Mostly microorganisms and plant roots, some C protected in large compact biogenic invertebrate aggregates
Soil detoxification	Mostly microorganisms
Nutrient cycling	Mostly microorganisms and plant roots, some soil and litter feeding invertebrates
Decomposition of organic matter	Various saprophytic and litter-feeding invertebrates (detritivores), fungi, bacteria, actinomycetes and other microorganisms
Suppression of pests, parasites and diseases	Plants, mycorrhizae and other fungi, nematodes, bacteria and various other microorganisms, Collembola, earthworms, and various predators
Sources of food and medicines	Plant roots, various insects (crickets, beetle larvae, ants, termites), earthworms, vertebrates, microorganisms and their by-products
Symbiotic and asymbiotic relationships with plants and their roots	Rhizobia, mycorrhizae, actinomycetes, diazotrophic bacteria and various other rhizosphere microorganisms, and ants
Plant growth control (positive and negative)	Direct effects: plant roots, rhizobia, mycorrhizae, actinomycetes, pathogens, phytoparasitic nematodes, rhizophagous insects, plant growth promoting rhizosphere microorganisms, biocontrol agents

FUNCTIONAL CLASSIFICATION OF SOIL MACROFAUNA

A functional group consists of a group of organisms that have the same function and similar impact on soil (Gitay and Noble, 1997). There is no single classification system because the criteria used to classify soil organisms and the degree of subdivision applied are a function of the questions being addressed. A simple classification is proposed here to assist users of this manual in better understanding the main types of organisms and subcategories according to their main visual characteristics and functions.

The functions that soil organisms in the macrofauna category carry out depend largely on the efficiency of their digestive systems (which themselves depend on their interactions with soil microorganisms, e.g. bacteria) and on the occurrence and abundance of the biological structures that they produce in the soil. Using these two criteria, three large functional groups of invertebrates can be distinguished: micropredators, litter transformers, and ecosystem engineers (Lavelle, 1997).

The micropredator group contains the smallest invertebrates, protozoa and nematodes. They do not produce organo-mineral structures (Lavelle, 1996, 1997), and their principal effect is to stimulate the mineralization of soil organic matter (SOM) (Coûteaux *et al.*, 1991; Ingham *et al.*, 1985).

In the litter-transformer group, mesofauna and some macrofauna organisms are involved in litter decomposition (Lavelle, 1996). When these invertebrates re-ingest their excretions, which serve as incubators for bacteria (Swift *et al.*, 1979), they assimilate metabolites liberated by microbial actions.

The “ecological engineers” or “ecosystem engineers” (Jones *et al.*, 1994) are those organisms that produce physical structures through which they can modify the availability or accessibility of a resource for other organisms. Among the innumerable life forms that inhabit soils, only a small number of macroinvertebrates (earthworms, termites and ants) are distinguished by their capacity to excavate soil and produce a wide variety of organo-mineral structures, such as excretions, nests, mounds, macropores, galleries and caverns. Their structures have been described as “biogenic structures” (Anderson, 1995). Their activities and biogenic structures can modify the abundance or structure of their communities (Jones *et al.*, 1994, 1997). The functional role of these structures is thought to be important because they represent sites where certain pedological processes occur: stimulation of microbial activity; formation of soil structure; SOM dynamics; and exchange of water and gases (Lavelle, 1997).

Table 2 summarizes these functional groups in relation to the ecosystem services they provide. Soil organisms contribute to the regulation of several critical functions in soil:

- Decomposition and nutrient cycles, hence organic matter dynamics.
- Soil structure: The activities of certain organisms affect soil structure, porosity and aggregation – especially the “soil engineers” such as worms and termites – through mixing soil horizons and organic matter and increasing porosity.

- Carbon sequestration and gas exchange: The activities of certain organisms determine the carbon cycle – the rates of carbon sequestration and greenhouse gases (GHGs).
- Soil hydrological processes, in relation to effects on soil structure and porosity (see above).
- Control of pests and diseases: Certain soil organisms can be detrimental to plant growth, e.g. the buildup of nematodes under certain cropping practices. However, they can also protect crops from pest and disease outbreaks through biological control and reduced susceptibility.
- Soil detoxification: Soil organisms can also be used to reduce or eliminate environmental hazards resulting from accumulations of toxic chemicals or other hazardous wastes. This action is known as bioremediation.
- Plant production: Plant roots, through their interactions with other soil components and symbiotic relationships, especially Rhizobium bacteria and Mycorrhiza, play a key role in the uptake of nutrients and water, and contribute to the maintenance of soil porosity and organic matter content, through their growth and biomass.

The loss of biodiversity is a dramatic manifestation of the poor management of natural resources (Solbrig, 1992). The biological impoverishment caused by inappropriate management could affect the continuous dynamic functioning of ecosystems (Lubchenco *et al.*, 1991). It is important to preserve biodiversity in order to maintain the integrity of the processes that sustain the ecosystem services, such as primary productivity, nutrient cycling and consumption of oxygen (Baskin, 1994). Biodiversity is also important to maintaining resilience (Spratt, 1997), i.e. the soil capacity to recuperate its initial situation after a natural or human-induced perturbation. Thus, a system that is functioning properly is one that will persist despite natural environmental fluctuations (Palmer *et al.*, 1997). There are plausible arguments for an increase in stability increase in diversity such as greater numbers of functionally interchangeable species or species groups, each susceptible to slightly different perturbations, or greater segregation of species into compartments that interact little if at all. In this regard, the removal of any species may increase the susceptibility of the system to the perturbation which may be due to a natural event, such as climatic variability, or human induced, for example toxicity of an agrochemical or effects of severe compaction due to repetitive tillage.

The following two exercises, Exercises 1 and 2, are proposed for assisting farmers, farmer field schools, extension staff and researchers – to recognise and list the properties of living organisms, to identify functional groups and compare soils in terms of soil life and soil biological activity. It can be conducted to diagnose the soil life and health on a specific farm or as a training exercise.

EXERCISE 1: IS THE SOIL A LIVING THING?

(Adapted from: Living Soils Manual (Exercise 20) by W. Settle)

Background

This is a quick introductory exercise. The task is simply to list the basic characteristics that define living organisms, in contrast to non-living things, and to determine if soil can be considered a living thing. The second task is to introduce the concept of a functional group.

Goal

To recognize and list the properties of living organisms.

Time required

15–20 minutes.

Materials

Newsprint, tape and pens.

Procedure

1. Facilitator/trainer to initiate the discussion by asking: “Is the soil a living or a dead thing?”
2. Participants contribute to making a list of characteristics that uniquely define living organisms.
3. Discussion on what characteristics of soils suggest that they are “alive”.

Questions to discuss and points to emphasize

1. While the list may be long, it should be emphasized (and included, if not already listed), the following: (i) feeding; (ii) growth; (iii) breathing (respiration); (iv) reproduction; (v) elimination of wastes; and (vi) death.
2. Which of these characteristics can be said to be true for soils? While the soil itself is a composite of both living and non-living things, it nevertheless shares several characteristics of a living entity. Principally, (i) it breathes, (ii) it needs to be fed, (iii) it creates waste products, and (iv) in many respects, it can “die” (ask the group if they know of any examples in which soils have been damaged and degraded to the point of being “dead”?)
3. How many living organisms are there in the soil? Encourage the group to list how many organisms they distinguish in the soil.

The amount of living organisms in 1 ha of soil down to 20 cm in depth will depend on where it is sampled, when and under which land-use practice. Pose the question: how many kilograms of insects, worms, bacteria and fungi they believe are in a typical hectare of soil. To date, most participants have seriously underestimated how much living material exists in the soil (especially bacteria and fungi). Values will be different for the tropical and temperate zones (and depend greatly on the amount of organic matter in the soil).

EXERCISE 2: SOIL LIFE AND BIODIVERSITY

Background

The text in the section on soil life and biodiversity should serve trainers as a basic text for organizing this exercise. This exercise will also be used as the basis of the section about soil health.

Goals

To put together a list with the name of organisms living in soils in order to quantify the important soil biodiversity.

To associate them to their functions (beneficial, neutral and harmful). This should be useful to introducing the concept of functional group and to identifying key functional groups.

Time required

30 minutes.

Materials

Paper, pens and blackboard.

Procedure

1. Facilitator/trainer to ask trainees to give the names of all the organisms that they know that live in soil and to make a list putting together all the responses.
2. When the list has been completed, ask if they are they beneficial, harmful or neutral.
3. Note down the responses beside each name on the list. This should enable the trainer to divide the original list in three parts: beneficial, harmful and neutral animals, to include those organisms that can be beneficial and harmful at the same time or animals difficult to class.
4. Ask: What do the organisms do in the soil? Why they are beneficial, detrimental or neutral? Participants justify their answers by providing an explanation of what they do, i.e. the function they perform.
5. Note the responses for every organism in the list in order to reorganize the last groupings to establish assemblages of functional groups. At this stage, the concept of functional groups should be introduced.

Questions to discuss and points to emphasize

1. Do you think soil is a rich diverse environment or is it poorer than other environments? The trainer can give some information about the species richness in soil compared with other environments and explain how the diversity of organisms is related to the diversity of soil habitats and resources.

2. Do you think diversity is important to soil? Why? Develop the idea that a soil with a higher diversity is more likely to function than a poorer soil because: (i) it is a guarantee that all the activities necessary to soil function will be realized; and (ii) soil should be able to better resist to external aggressions (natural or human induced). The trainer could also introduce the idea that diversity is also related to the existence of a balance between animals through predation and competition that can protect soil from harmful effects of pests.
3. How do you relate the presence of beneficial or harmful organisms to the health of the crop or the plants? Examples: nematodes and root damage; earthworms and aggregates of different size.