SOIL MACROFAUNA FIELD MANUAL

Technical level

Institut de recherche pour le développement

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Technical level

by

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Preface

Soil organisms are an integral part of agricultural ecosystems. The presence of a range of a diverse community of soil organisms is essential for the maintenance of productive soils. Soil organisms are responsible for a range of ecological functions and ecosystem services including: nutrient cycling and nitrogen fixation, control of pest and diseases, organic matter decomposition and carbon sequestration, maintenance of a good soil structure for plant growth and rainwater infiltration, detoxification of contaminants. An excessive reduction in soil biodiversity, especially the loss of species with key functions, may result in severe effects including the long-term degradation of soil and the loss of agricultural productive capacity. Soil health and soil quality are fundamental to the sustained productivity and viability of agricultural systems worldwide.

Substantial efforts are underway to strengthen agricultural biodiversity considerations for sustainable agriculture and natural resources management through improved understanding, capacity building, including methods and tools development as well as partnerships and networking. The Country Parties to the Convention on Biological Diversity (CBD) recognized the importance of Soil Biodiversity as an integral and vital and seriously neglected component of biodiversity for food and agriculture known as agricultural biodiversity, through the establishment of an International Initiative for the Conservation and Sustainable Use of Soil Biodiversity. In its decision VI/5, in 2002, the Conference of the Parties to the CBD invited the Food and Agriculture Organization of the United Nations (FAO), and other relevant organizations, to facilitate and coordinate this initiative.

FAO has been gradually supporting efforts and making available information on the importance of soil biodiversity to sustainable agriculture, including forestry, through a number of activities: a website with background information, case studies and linkages to ongoing programmes and institutions; the organization with EMBRAPA, Brazil, of an international technical workshop which led to the development of a Plan of Action to implement the Soil Biodiversity Initiative (SBI) and through liaison with partners and the CBD Secretariat.

The lack of awareness of the importance of soil organisms and their function among agricultural development actors (research, extension, farmers, etc.) led to the development of this Soil Macrofauna Field Manual with the aim to enhance understanding and capacity for soil biological management. The focus on soil macrofauna (invertebrates larger than 2 mm) rather than the whole range of soil organisms (from microorganisms, protozoa, nematodes and small arthropods to larger soil animals) may seem incomplete. Soil macrofauna (the earthworms, termites, ants, beetles, and millipedes, among others), however, is visible as are their effects, and their study provides a suitable entry point for those involved in agriculture to learn about soil life in the field and the impact of various land uses and management practices.

Especially vital is its role, either directly or indirectly, through the production of biogenic structures, in critical ecological processes, such as nutrient dynamics, carbon accumulation (sequestration), etc. A diverse community of soil macrofauna in any farming system ameliorates soil structure and enhances porosity, thus reducing soil compaction problems. without soil macrofauna and the production of biogenic structures the organic matter in the soil surface will not be incorporated The activities of soil macrofauna and the biogenic structures they produce, help in the incorporation of organic materials in the soil thus restoring levels of soil organic matter and also enhancing nutrient cycling; with a positive impact on plant productivity in crop, pasture and forest lands. Soil organic matter also enhances rainwater infiltration and soil moisture retention thereby reducing risk of erosion and drought. Soil macrofauna also play a role in activating soil microorganisms (bacteria and fungi) and through their activities improve soil health and reduce the incidence of pests and soil-borne pathogens. Finally, some indigenous human populations even use soil macrofauna as a food resource and a source of local medicinal products in combination with plant extracts.

This manual aims to make available information on soil macrofauna and management approaches to help farmers and service providers (extension, research, non governmental organizations, project staff, etc) assess soil health status, and to develop adapted management practices to sustain and improve soil quality under a range of different farming systems.

List of acronyms

C	Carbon
Ca	Calcium
CO_2	Carbon dioxide
Fe	Iron
GHG	Greenhouse gas
K	Potassium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
P	Phosphorous
S	Sulphur
SOM	Soil organic matter

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.

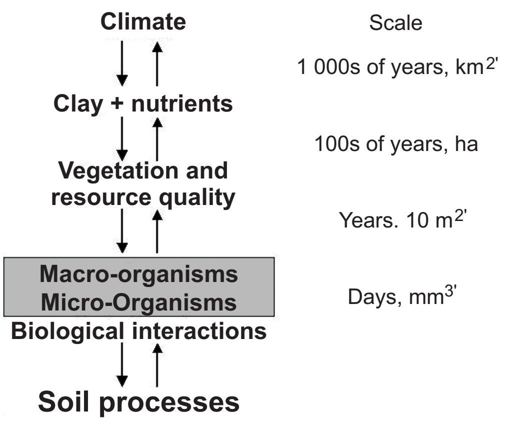
Inadequate soil management is the principal factor behind the worldwide decline in agricultural productivity. Most modern cropping systems require substantial regular inputs of nutrients to replace those removed through harvesting and burning of residues as well as through leaching and erosion. They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

FIGURE 1
Hierarchy of determinants of soil processes that provide ecosystem services



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.

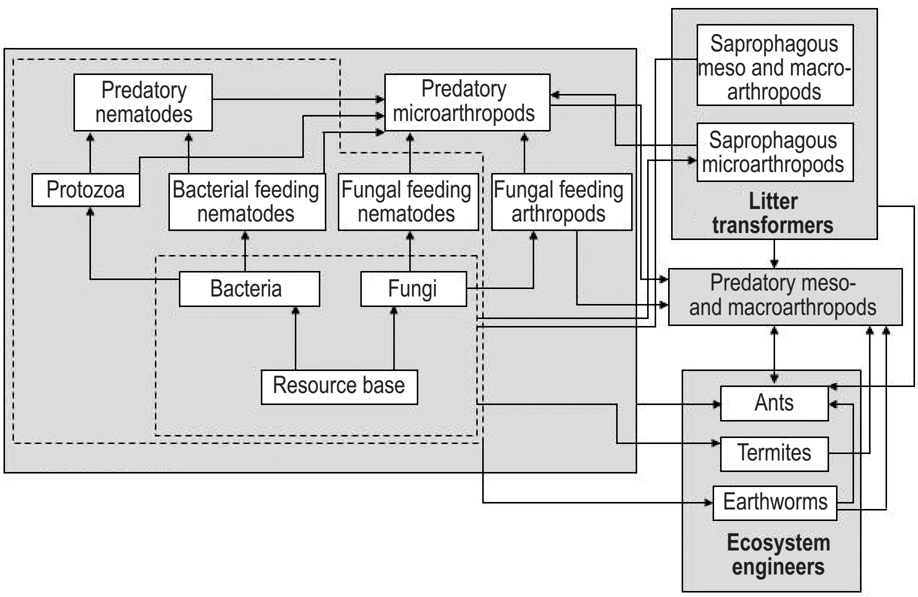
Soil ecosystem

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

FIGURE 2
Diagram of a soil food-web



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

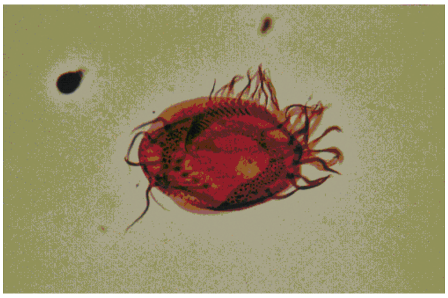


Plate 1
Protozoa.

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.

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

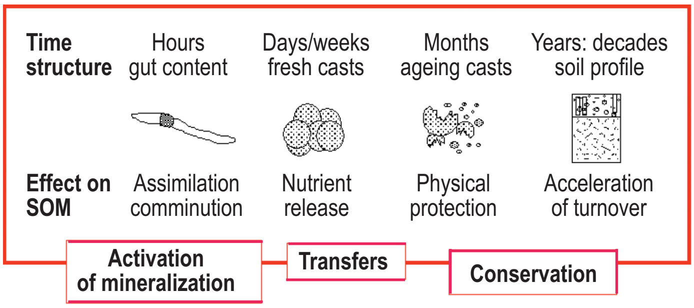
Ants, termites, earthworms and ground beetles can move an important quantity of soil, bringing back to the surface mineral matters from deeper horizons and burying the organic matter from the surface horizons, from litter and from excrements.

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.

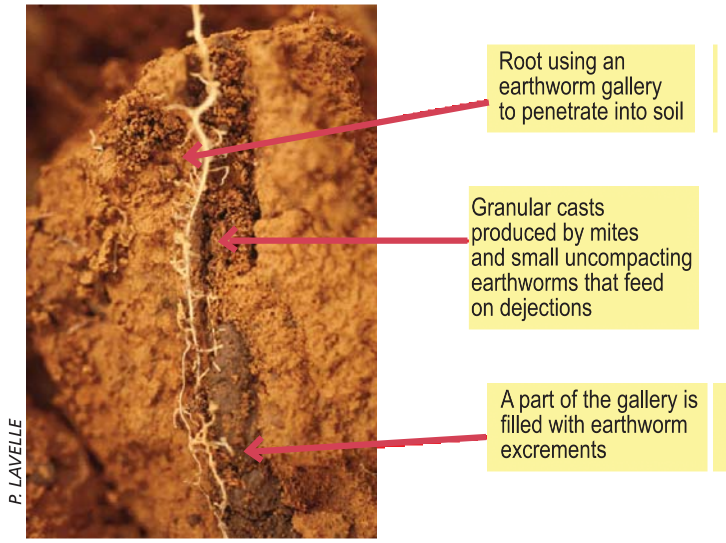


Plate 4
An earthworm gallery filled with casts and a root following the pathway opened by the earthworm. Root hairs are attached to the cast where higher availability of nutrients (C, N and P) exists compared with the surrounding soil. (photo: P. Lavelle)

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

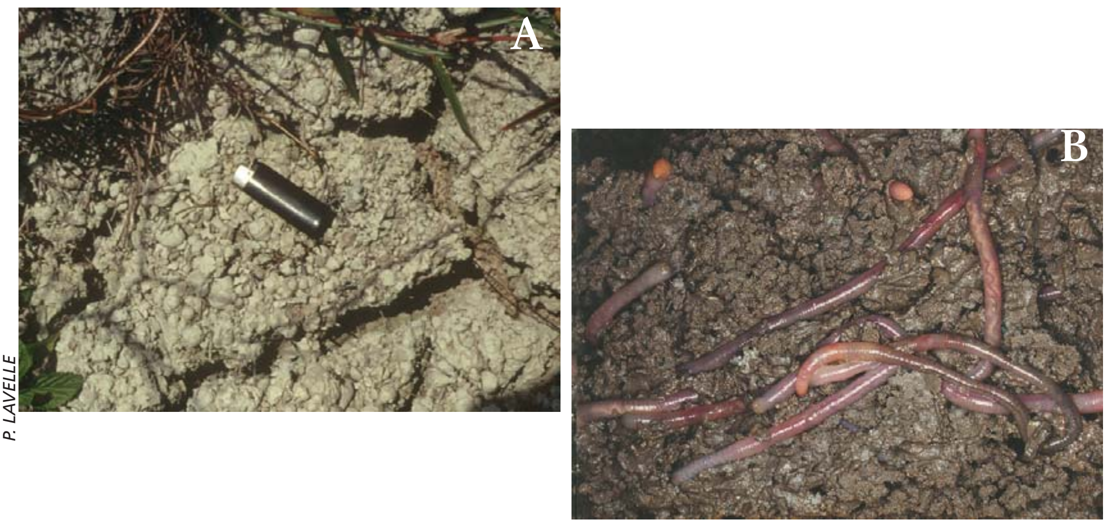
Consequences of soil biodiversity reduction

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.



Chapter 5
Effect of land-use and management practices on soil macrofauna

IMPORTANCE OF MANAGEMENT PRACTICES AND TRENDS IN SOIL MACROFAUNA COMPOSITION

Land-use management has an important impact on soil and its functional role in maintaining ecosystem processes. It generally results in dramatic and rapid changes in vegetation that are likely to affect soil invertebrate communities significantly (Box 2).

BOX 2

Impact of land management on soil macrofauna in the savannahs of Colombia

Burned and grazed savannahs:

- fire (short-term effect):
  - low population density, biomass and diversity,
  - fauna accumulated in deeper soil layers (10–20 and 20–30 cm),
  - earthworms dominant;
- fire (after six months):
  - soil fauna regenerated,
  - no differences compared with the initial savannah;
- grazing:
  - decrease in diversity,
  - decrease in earthworm biomass,
  - increase in the biomass of termites, Coleoptera, Arachnida and Myriapoda.

Improved pastures (with forage grasses and legumes):

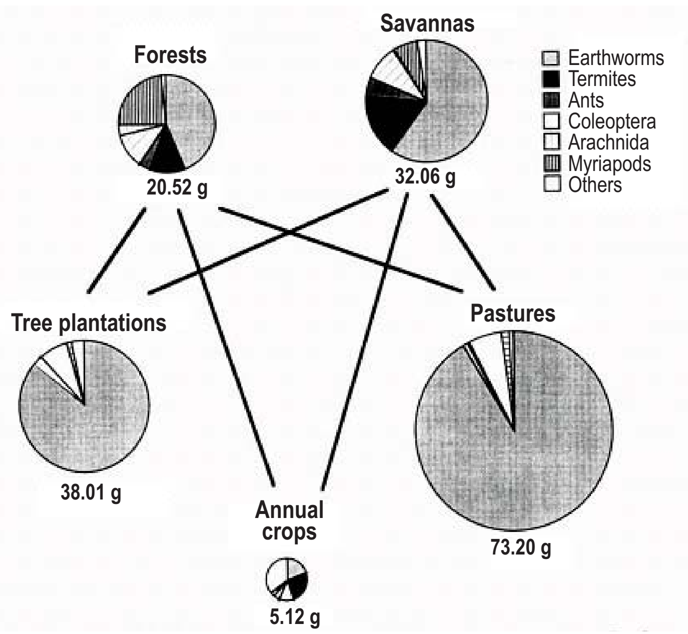
- earthworms predominate,
- high densities of Coleoptera, Arachnida and other invertebrates.

Annual high-input cropping (tillage + fertilizers + pesticides):

- lowest biomass, density and diversity.

Source: Decaëns et al. (1994).

FIGURE 4
Composition of soil macrofauna communities under various conditions



Source: Lavelle *et al.* (1999).

The biodiversity of animals and plants generally declines as an inverse function of the intensity with which crops are cultivated using mechanized methods and agrochemicals, that is agricultural intensification. The intensity with which soils are cultivated also depletes soil-organism communities as a consequence of the toxic effects of agrochemicals, the physical disruption of their habitats, and the reduction in litter availability and hence the SOM resource base. Thus, management practices have important consequences on the composition and abundance of soil macrofauna communities (Figure 4).

Lavelle *et al.* (1994) identified the major trends in tropical soil macrofauna composition as follows. Termites and/or earthworms tend to be dominant in most cases. Termites have adapted to a wide range of semi-arid systems where earthworms are not found. Earthworms are best represented in grasslands in tropical humid areas. They are sensitive to the nutrient status and organic content of soil (Fragoso and Lavelle, 1992). Litter arthropods are predominant where sufficient litter is available. They are represented mainly by millipedes or beetles.Lands with natural vegetation like forests have a highly diversified vegetation. The quality and quantity of leaf litter and the important root production create a particular soil environment that favours the development of a rather diverse and abundant soil macrofauna. When vegetation is cleared and the soil used for cropping, the communities of soil macrofauna are highly depleted as a consequence of an important modification of soil microclimate, the reduction in the quantity and quality of organic matter, the physical perturbation induced by tillage, and the effects of fertilizers and non-targeted pesticides. Earthworms and litter communities soon disappear and are not replaced. Other macrofauna groups such as termites (mainly humivorous) tend to be more persistent. Soils under pasture are more favourable for earthworm development as there is an improvement in leaf-litter quality, a great quantity of manure brought to the soil, and a more limited physical soil perturbation unless seriously overgrazed. Other soil management practices, such as palm tree plantations with herbaceous legume cover or cocoa with a layer at the soil surface and high trees, usually have diverse soil biotic communities (Lavelle *et al.*, 1999).

BOX 3

Management intensification and its effects on macrofauna

- Characteristics of management intensification:
  - reduction in vegetation diversity;
  - decrease in the quantity of leaf litter (organic matter);
  - decrease in the density of the root system;
  - modification of soil microclimate;
  - application of non-targeted pesticides.
- Effects on soil macrofauna communities:
  - decrease in diversity, density and biomass of soil organisms;
  - reduction in or disappearance of epigeic and anecic categories of earthworms and litter epigeic fauna;
  - soil macrofauna is mainly located deep in the soil;
  - dominance of persistent groups such as termites and ants;
  - increase in pest organisms;
  - the activity of beneficial organisms (earthworms and ants) may become detrimental because of the lack of other soil-organism activities (complementarity).

Thus, land management has a dramatic effect on soil macrofauna communities (Box 3). Primary forests have rather diverse and abundant fauna with density and biomass two to three times higher than that in managed systems. Epigeic and litter fauna is well represented and the biological activity is mainly concentrated in the top 20 cm of soil.

Cropping results in a dramatic decrease in taxonomic richness, density and biomass. Termites are the major component. Earthworms are mainly represented by endogeic species and their distribution in the soil profile is relatively deep (20–30 cm).

Pastures can have very different communities with an overwhelming dominance of populations of the peregrine (wandering) earthworm *Pontoscolex corethrurus*. This is an endogeic earthworm frequently present in disturbed areas and it may build up very large populations in pastures. Other groups of importance are termites and ants. Litter-dwelling populations represent only 4.3–10.5 percent of individuals, most of them concentrated in the upper 10 cm.

Short fallows present low taxonomic richness but increased densities and a slight evolution towards the original forest situation. The association of palm trees with a leguminous cover crop appears to be the most conservative system with both elements of the primary forest and introduced ones. This kind of system can present a large earthworm community with forest and pasture species and high densities of termites and epigeic litter detritivores, which live and feed on the soil surface (Lavelle and Pashanasi, 1989).

MANAGEMENT PRACTICES WITH POSITIVE IMPACTS ON SOIL MACROFAUNA

Examples of positive impacts

Some agricultural management practices have positive impacts on soils, increasing SOM levels and improving soil functioning and plant productivity. For example, conservation agriculture can increase crop production while reducing erosion and reversing soil fertility decline. SOM and biological activity in the rootzone are stimulated by continual additions of fresh organic matter (crop residues, cover crops and manure).

Indirect management practices

Where indirect management practices are used, interventions are a means of managing soil biotic processes by manipulating the factors that control biotic activity (habitat structure, microclimate, nutrients and energy resources) rather than the organisms themselves (Hendrix *et al*., 1990). Examples of indirect interventions include most agricultural practices, such as application of organic materials to soil, tillage, fertilization, irrigation, green manuring and liming as well as cropping system design and management.

In conventional agriculture, soil tillage is considered one of the most important operations for creating favourable soil structure, preparing the seedbed and controlling weeds. However, mechanical implements destroy the soil structure by reducing the aggregate size, and conventional tillage methods are a major cause of soil loss and desertification. A study in France showed that, in fields under reduced or no-tillage and with permanent soil cover, soil organisms can increase by up to four times and the diversity may almost double (Ruiz, 2004). In this kind of management system, the biomass produced is kept on the soil surface and serves as a physical protection of the soil and provides food for the soil fauna.

In general, the vegetal cover on the soil surface creates a more humid environment, which is conducive to the activity of soil organisms. The larger number of earthworms, termites, ants and millipedes combined with a high density of plant roots results in more large pores, which in turn increase water infiltration (Roth, 1985).

Pest management can also benefit from conservation practices that enhance biological activity and diversity, and hence competitors and predators as well as alternative sources of food. For example, most nematode species (especially pathogens) can be reduced significantly by the application of organic matter, which stimulates the action of several species of fungi that attack nematodes and their eggs.

An agricultural technique used in a number of tropical countries in Africa, Asia and South America to ameliorate soil conditions for crops is "ecobuage". This is a complex agricultural system that entails incinerating herbaceous vegetation piled up in mounds and buried under a layer of soil taken from the surroundings. It is a traditional system that is more evolved than the slash-and-burn technique often used in intertropical zones.

A study conducted in the region of Bouenza (Congo) showed that the use of "Maalas" (ecobuage) improved soil macrofauna communities, particularly earthworm communities. The technique supplied the soil with mineral nutrients through slashes, and increased soil pH. The improvement in soil macroinvertebrate communities improved soil structural stability, creating good conditions for plant root development. Thus, this system enabled the cultivation of plants that are demanding in terms of nutrient supply. In addition, the earthworm activity improved soil porosity (macroporosity became more important), allowing plant roots to go deeper into the soil. Improved soil structure enabled the cropping of plants with tubercules that need an aerated soil for their development (Mboukou, 1997).

Experiments at Carimagua (Colombia) suggest that the spatial and temporal array of parcels allocated to different crops may favour the conservation of locally high earthworm-population density and diversity. These spots may serve as reservoirs and refuges for the colonization of depopulated areas (Lavelle *et al.*, 1999).

Direct management practices

These practices involve intervening in the production system in an attempt to alter the abundance or activity of specific groups of organisms (Hendrix *et al.*, 1990). Examples of direct interventions include: (i) inoculation of seeds or roots with rhizobia, mycorrhizae, fungi and rhizobacteria for enhanced soil fertility; and (ii) inoculation of soil or the environment with biocontrol agents (pest or disease), antagonists and beneficial fauna (e.g. earthworms).

Mycorrhizal microorganisms colonize the roots of many plants through a symbiotic relationship. This relationship helps the plants to be more efficient at obtaining available nutrients, such as P and N, and water, both elements vital to plant survival. Mycorrhizae increase the surface area associated with the plant root, which allows the plant to reach nutrients and water that might not be otherwise available. The application of N-fixing rhizobia for the production of common beans in the Parana region in Brazil increased yields by almost 50 percent (FAO report, 2000). This kind of intervention might be a way of reversing the poor yields and nitrogen depletion that plague tropical areas.

In southern India, the long-term exploitation of soil under tea gardens has led to impoverishment of soil fertility and stabilization of yields despite increasing applications of external inputs such as fertilizers and pesticides. The application of high-quality organic matter and earthworms was very effective at increasing tea yields (more than by the application of fertilizers alone) owing to their favourable effects on physical and biological soil properties. Yields increased by 79.5–276 percent (Senapati *et al.*, 1999).

The loss of abundance and diversity of communities under annual crops results invariably in a loss of certain important soil functions (Lavelle, 1996; Giller *et al.*, 1997).

The results obtained in these studies suggest various options for conserving and stimulating the activities of soil macrofauna. For example, the negative effects of annual crops could be reduced by decreasing the intensity and frequency of perturbations such as tillage and the use of pesticides, and by increasing the quantity and quality of the energy resources used by the macroinvertebrates, e.g. the use of legume cover crops and the maintenance of crop residues. Integrated systems of short phases of crops with longer periods of pastures (3–5 years) are also an option for maintaining macroinvertebrate populations as well as bringing other benefits for soil physical and chemical parameters (Thomas *et al*., 1995).

Organic manuring helps to enrich or favour the multiplication of many soil fauna and microorganisms including those antagonistic to soil pests. In recent years, the application of greater quantities of synthetic fertilizers has been very common in contrast to the negligible use of organic manures. The eggs, larvae and pupae of soil insects are liable to be affected either by the soil-inhabiting pathogens or their toxins. However, the absence of organic manures in the soil enables the above pests to thrive owing to the depletion of the natural biotic restricting factors. The increasing use of pesticides has also upset the balance of life in soil when they have been applied directly in the soil and by drip from the foliage. Their subsequent incorporation into soil can also reduce the natural enemies of soil insects.

Certain practices such us improved pasture can result in increased populations of soil macrofauna. The similarity of the original ecosystem and the derived agro-ecosystem tends to be a major determinant of native species' survival, adaptation, resilience and stability within the boundaries of ecosystem management.

The spatial arrangement of pastures alongside cropped plots can accelerate the recovery of macrofauna populations in the cropped plots. Beneficial species, which can be more rapidly established, can also help reverse some of the degrading effects of cropping on soil structure, thereby avoiding the need to solve soil degradation problems with expensive, machinery-intensive strategies. Thus, earthworms become a resource that can be harnessed to improve ecosystem health (Jimenez and Thomas, 2001).

MANAGEMENT PRACTICES WITH NEGATIVE IMPACTS ON SOIL MACROFAUNA

Examples of mismanagement

Example 1

In Corrientes Province (northern Argentina), the use of heavy machinery to prepare soil for rice culture has caused soil compaction (Folgarait *et al*., 1998). This type of soil management has led to important changes in soil macrofauna abundance and diversity. After several years of culture, fields are left fallow. During this period, the soils are recolonized by soil fauna. However, the soil compaction makes this process difficult and the composition of the soil macrofauna is dominated by the ant species *Camponotus punctulatus*. These ants usually build their nests in soil, but soil compaction modifies their behaviour and they construct epigeic mounds. As a consequence, the soil becomes covered by ant mounds 1–2 m high, which can reach densities of more than 2 000 mounds/ha in 2–3 years (Plate 6). This action completely prevents the possibility of further agricultural uses of the land, without extensive and expensive measures to destroy the ant nests and the ant populations.

Example 2

In Manaus (Brazil), the transformation of forest zones into pastures leads to the degradation of the soil as a consequence of mismanagement, phytosanitary problems, poor soil fertility and soil structural modification (linked to fauna activity). Where the forest is converted to pasture, first the machines and then the cattle trampling the soil lead to severe soil compaction, particularly in the top 5–10 cm. However, the most important consequence is that the native soil macrofauna communities are altered radically, with most of the native taxa disappearing. These are replaced by an opportunistic invading species: the earthworm *Pontoscolex corethrurus*, which increases in biomass to represent almost 90 percent of the total soil-fauna biomass.

This species produces more than 100 tonnes/ha of casts, dramatically decreasing soil macroporosity down to a level equivalent to that produced by the action of

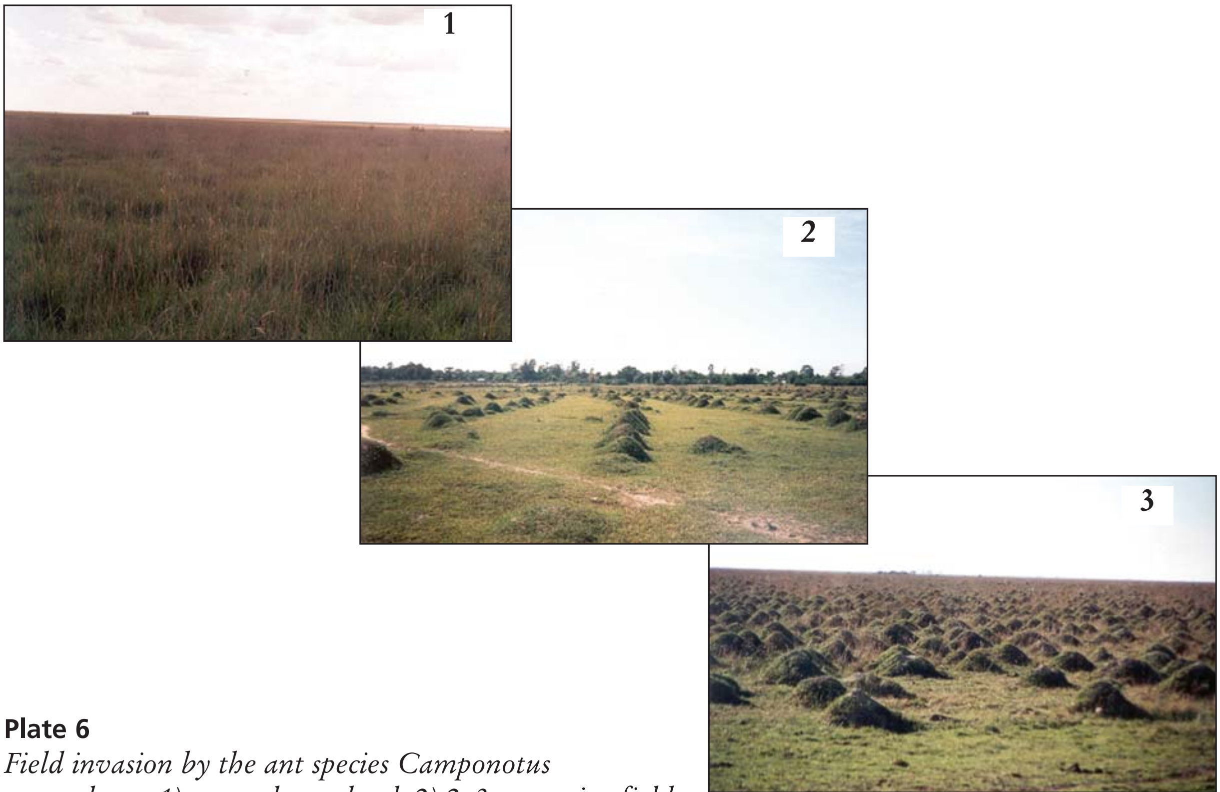


Plate 6
Field invasion by the ant species Camponotus punctulatus. 1) natural grassland; 2) 2–3 years rice-field fallow; and 3) 3–4 years rice field fallow.

heavy machinery on the soil (2.7 cm^3/100 g). During the rainy season, these casts plug the soil surface, saturating the soil and producing a thick muddy layer where anaerobic conditions prevail (increasing methane emission and denitrification). In the dry season, desiccation cracks the surface and the inability of roots to extract water from the soil causes the plants to wilt and die, leaving bare patches in the field (Chauvel *et al*., 1999).

However, this earthworm species can have either a positive or a negative effect in the same soil. For example, Duboisset (1995) verified in a study at Yurimaguas (Peru) that, in the absence of good quality organic additions, *P. corethrurus* causes soil compaction and an increase in dense zones at the surface. However, where crop residues and leguminous mulch are present, the activity of the earthworm translates into a decrease in soil density and a transformation of the pore size distribution with the development of an interaggregate macroporosity.

Example 3

In temperate zones (the Netherlands), some farmers contacted scientists because of an invasion by lumbricid earthworms (*Aporrectodea caliginosa* and *A. rosea*) in the soil. These earthworms species were creating massive structure (similar to that created by *P. corethrurus* in Amazonian pastures) in potato fields (Ester and van Rozen, 2000). Problem areas in the fields with cloddy, compacted structure were identified and these were always associated with high earthworm numbers. When the potatoes growing in these problem areas were harvested, large soil clods (up to 50 cm) were harvested together with the potatoes, rendering the harvesting process impossible and reducing the quantity and quality of the potatoes.

Chapter 6
Structure and ecology of soil macrofauna communities

KEY INDICATOR GROUPS AND THEIR ECOLOGY

The main groups of soil macrofauna in terms of their abundance and the importance of their activities in soil are: earthworms, termites, ants, Myriapoda, Diptera and Coleoptera (Lavelle and Spain, 2001).

Earthworms

Earthworms are terrestrial worms that burrow into and help to aerate soil. They often surface when the ground is cool or wet. They have a segmented body. The body may be divided into two parts: an anterior part with segments containing cephalic ganglions, reproductive organs, gizzards, calciferous glands and hearts; and a posterior part rearward of the hindgut comprising a series of rather similar segments (Figure 5).

Earthworms are invertebrates that may be present in very high densities. They are found in litter and soil in all except the coldest regions of the world. They feed on decaying litter and plant residues in soil. Earthworms are extremely important ecosystem engineers, and play a vital role in soil fertility. They are solitary and they are sampled most effectively by hand-sorting soil samples.

Earthworms have developed a range of adaptive strategies to live in soil. They can be divided into functional groups according to their feeding habits. They are classed into three main ecological types: epigeic, anecic and endogeic (Bouché, 1977; Lavelle, 1981; Lee, 1985). Those that are pigmented (presence of pigment in skin, generally more concentrated in the dorsal part) are divided into epigeic and anecic earthworms.

Epigeic earthworms (Figure 6) live within the litter layers, a changing environment, where they are subject to occasional drought, extreme temperatures and high predator densities. They are generally small (less than 15 cm long on average when adult), homogeneously pigmented (green, blue or reddish) and have rapid movements.

FIGURE 5
General view of an earthworm

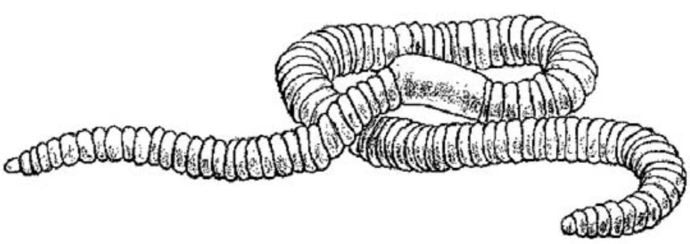


FIGURE 6
Epigeic earthworm

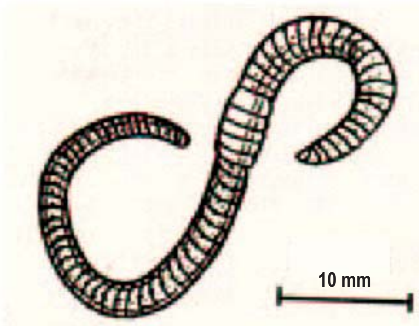


FIGURE 7
Anecic earthworm

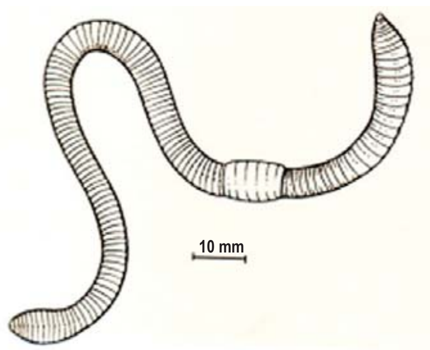
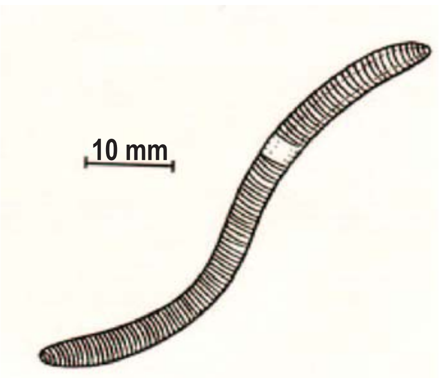


FIGURE 8
Endogeic earthworm



Anecic earthworms (Figure 7) feed on surface litter that they mix with soil. They spend most of their time in the soil. Anecic earthworms are large (more than 15 cm long when adult). They are pigmented dark green, blue, brown or reddish and the pigmentation is concentrated in the antero-dorsal part of the body. They dig subvertical galleries in the soil. The tail may be flat and enlarged in most common species.

The unpigmented earthworms (no pigment in skin, same colour on the dorsal and ventral parts, pink or slightly brown owing to the soil ingested) that live and feed in the soil are called **endogeic** earthworms (Figure 8).

The effects of earthworms in the soil differ according to the ecological category of the species involved. However, in many agricultural systems there may be only one type of earthworm.

As a result of their wide range of adaptations, earthworms have diverse functions in the soil (Plate 7). For example, epigeic earthworms are very efficient at making compost but have no impact on soil structure. Anecic earthworms strongly influence soil properties, they build a network of galleries near to the soil surface and deposit casts on the soil surface. Their activity enables the incorporation of large amounts of leaf litter into the soil. Endogeic earthworms are very important in soil structure because of their burrowing activities and their impact on soil aggregation (a concentration of fine soil particles) and SOM stabilization.

Earthworms generally exert beneficial effects on plant growth. However, negative or null effects may be induced in particular situations. The effect on grain yields is also proportional to the earthworm biomass (> 30 g fresh weight) (Brown *et al.*, 1999), although very high biomasses of a single species of earthworms (e.g. *Pontoscolex corethrurus*) may inhibit production under particular situations (see example above). Once the earthworms are established, a dynamic cropping system – involving crop rotations with long-cycle crops or perennials with good organic matter additions – contributes to securing lasting benefits from earthworm activities.

The following exercise, Exercise 5, increases awareness of the effects of earthworms in 'biotillage' – mixing and aerating soil through their burrowing activities.

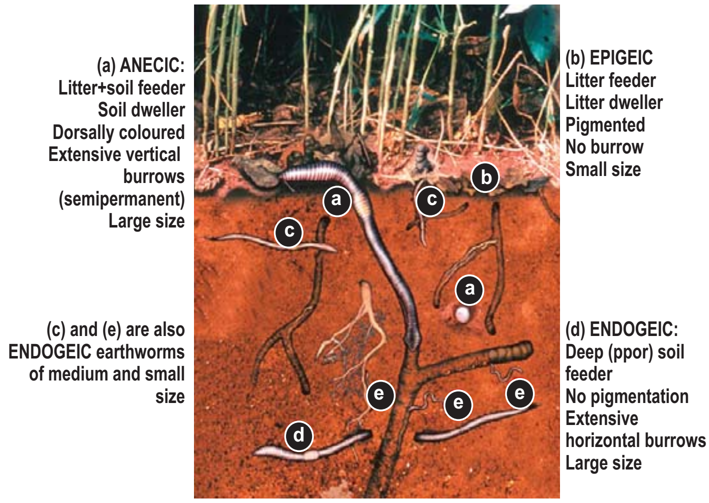


Plate 7
Functional diversity and significance of earthworms (adapted from I. Fabbri, UNESCO).

EXERCISE 5: EARTHWORMS IN ACTION

Background

A terrarium is a closed ecosystem. Animals cycle the nutrients inside the container. The water, oxygen, and carbon dioxide are used, reused, and re-reused. However, energy in the form of sunlight does come from the outside.

As earthworms burrow through the soil, they consume large quantities of soil and fresh or partially decomposed organic matter from the soil surface. Earthworms deposit faecal material (casts) throughout and on top of the soil. As earthworms go upwards and downwards through the soil, they mix soil from the different soil layers with plant and animal debris from the soil surface. This mixing helps make nutrients more available for plant growth and increases water infiltration and air circulation in soil. Earthworm activity also helps roots to go deep into the soil.

Goal

To observe how earthworms dig in the soil and the effects they produce.

Time required

About 45 minutes to create the terrarium (also this can be prepared in advance).

The terrarium should be constructed knowing that results must be observed over several days.

Materials

Paper and pens.

For bottle ecosystem construction:

Two 2-litre clear plastic bottles, a knife, two pieces of mesh not very large (a mosquito net), string, some iron wire, and a lighter.

For the terrarium:

Gravel, fine sand, bedding material, dark potting soil, two pieces of tin foil or dark coloured paper, and two anecic and two endogeic earthworms.

Procedure

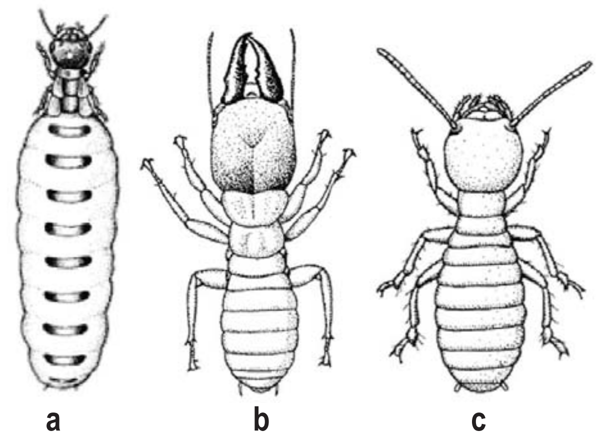
1. Construct two bottle ecosystems for the earthworms. For this:
    a. Rinse the bottles with water only and remove any labels.
    b. Cut the top 15 cm off each bottle.
    c. Make four to six drainage holes in the bottom of each bottle using the iron wire (which you heat with a lighter).
2. Add the following components to the bottom of each ecosystem in this order:
    a. Add some clean, washed gravel to the bottom of the bottle.
    b. Add a layer of moist bedding material.

c. Place a layer of dark potting soil on the moist bedding material.
d. Add a layer of moist sand.
e. Add another layer of dark potting soil (local soils with different colours can be used to realize this exercise).
f. Add a thin layer of organic matter (food). You can pick up some litter in the field or add some fresh vegetable leaves.
g. Add four earthworms on top of the organic matter (two anecic and two endogeic) in one of the bottle ecosystems. Leave the other as a control for your experiment.
h. Put the mesh on the surface of each bottle and fix it using a piece of string.
i. Draw a picture of your ecosystems.
j. Form the tin foil around the bottle ecosystem to limit the amount of light reaching the worms.
k. Place the ecosystems at room temperature or a bit cooler (15–22 °C). Do not place them in direct sunlight.
l. Check your bottle ecosystems every day. Make sure that you:
   i. moisten the soil (about 200 ml of water in each bottle);
   ii. add more moistened food to the top layer if necessary;
   iii. observe your ecosystems and record your observations;
   iv. draw a picture of your ecosystems.

Questions to discuss and points to analyse

1. What happens to the organic matter on the surface of the ecosystem with earthworms?
2. And without earthworms?
3. What do earthworms do with soil layers?
4. Do you see differences between the burrowing activities of the anecic and endogeic earthworms?
5. Why are earthworms considered to be decomposers?
6. Based on your observations, what do you think are the benefits of having earthworms in soils?

FIGURE 9
Main castes of termite colonies: a) queen; b) soldier; c) worker



Termites

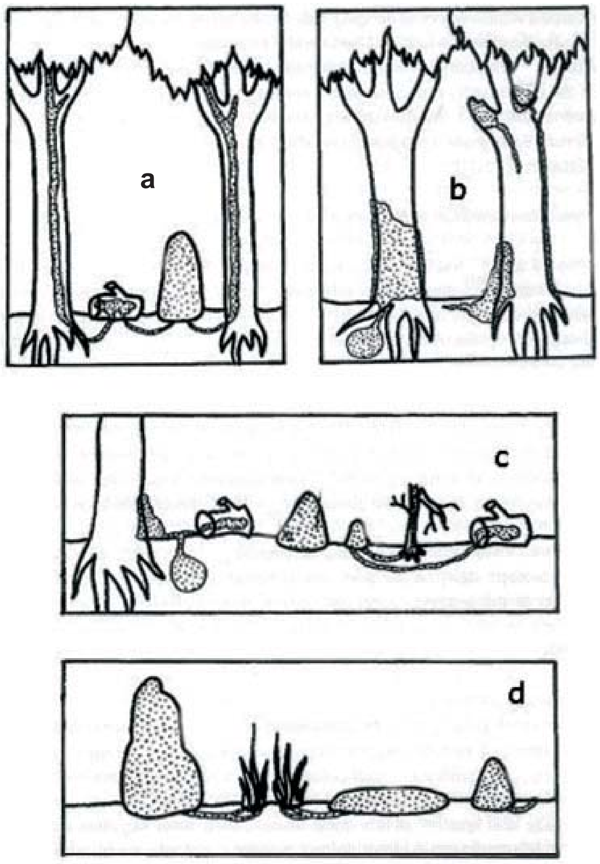
Termites are social insects. This means that they are organized, forming colonies where various castes (different individuals with different roles in the colony) with a set of morphological and physiological specializations coexist. The main castes are: the queen (the termite that forms the colony), the workers and the soldiers (Figure 9). They are abundant and considered a serious pest in dryland areas of Africa. It is important to note that some individuals of the society (reproductive ones) have wings, although they will always be found with the other wingless members of the society. (figure 9)

There are about 3 000 species of termites worldwide. Neither individual termites nor colonies normally travel long distances. This is because they are constrained to live within their territorial border or within their food materials. A number of species feed on living plants and some may become serious pests in agricultural systems where dead residues are scarce, e.g. in forest plantations (Wood, 1996). Most species feed on dead plant materials above or even below the soil surface. These materials include decaying material, e.g. dead foliage of vegetation, woody materials, including roots, seeds and even the faeces of higher animals (Lavelle and Spain, 2001). There are also soil–wood feeders and soil feeders, this means they ingest a high proportion of mineral material. Their nutrition derives mainly from well-decayed wood and partly-humified SOM. Another group of termites grows fungi in its nests (fungus-growing termites).

In general, termites may be separated into five broad groups according to the type of food they ingest (Josens, 1983; Eggleton *et al*., 1996):

- Grass harvesters: these termites harvest the dead leaves of grasses, which may be stored in their nests; they belong to the families Hodotermitidae and Termitidae. A number of species in this category also collect litter: the tropical Australian species Drepanotermes rubriceps stores a wide range of materials in its low epigeal mounds including leaves of grasses, broad-leaved species and a diversity of seeds and small woody litter (Gay and Calaby, 1970).
- Surface litter feeders: termites that forage for leaf litter, live or dry standing grass stems and small woody items, usually cutting the material before consumption or portage to the nest system. They include some subterranean and mound-building Macrotermitinae as well as certain Nasutitermitinae that forage on the surface of the ground, and at least one lower termite, Hodotermes mossambicus, with a similar habit.

FIGURE 10
Selected termite nests in a tropical Australian savannah: (a) and (b) species associated with the exteriors of trees; (c) species attacking wood on the soil surface, dead shrubs and the bark of trees and soil-feeding species living in the mounds of other termites; and (d) nests of epigeal mound-building, grass-harvesting and litter-feeding species nests



Source: Lavelle and Spain (2001).

- Wood feeders: termites feeding on wood and excavating galleries in larger items of woody litter, which may become colony centres. This group also includes termites having arboreal, subterranean or epigeal nests but feeding elsewhere (Figure 10), and many Macrotermitinae cultivating fungus gardens. ("Wood" includes dead branches still attached to living trees and dead standing trees as well as fallen larger items which are fresh, or in any except the terminal stages of decay).
- Soil-wood feeders: termites feeding in highly decayed wood which has become friable and soil-like, or predominantly within soil under logs or soil plastered on the surface of rotting logs or mixed with rotting leaves. This group is synonymous with "intermediate feeders", sensu de Souza and Brown (1994), but not the same as the category "rotten-wood feeders" recognized by Collins (1989).
- Soil feeders (humivores): termites distributed in the soil profile, the organic litter layer and/or epigeal mounds, feeding deliberately on mineral soil, apparently with some degree of selection of silt and clay fractions. Although the ingested material is highly heterogeneous, there are higher proportions of SOM and silica, and lower proportions of recognizable plant tissue than in other groups (Sleaford et al., 1996).

The categories are not mutually exclusive and many species will feed upon at least two sources, especially under unfavourable conditions.

Termites are predominantly tropical in distribution. They may reach extremely high densities. Termites are important ecosystem engineers, and may have a similar role to earthworms in promoting soil fertility in tropical systems. They influence:

(i) soil porosity and texture through tunnelling, soil ingestion and transport and gallery construction; and (ii) nutrient cycling through the transport, shredding and digestion of organic matter.

Ants

Ants may occur in great numbers in soils and on their surfaces. Ants are effective predators, influencing herbivore populations and plant productivity. As with termites, ants modify soil chemical and physical properties by transporting food and soil materials during feeding and mound and gallery construction.

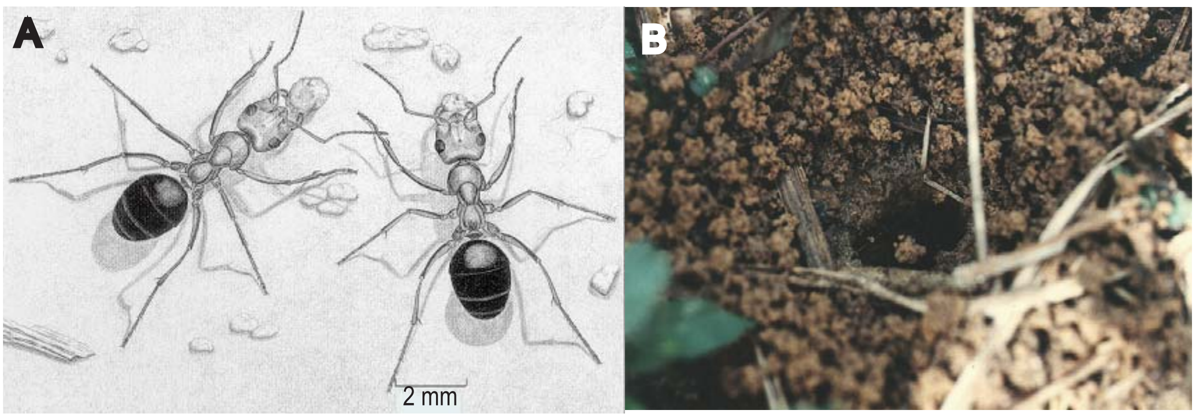
Because of their feeding habits, they are of less importance in regulating processes in the soil than termites or earthworms. In agricultural systems, the leaf-cutting ants of the genera *Atta*, *Acromyrmex* and *Trachymyrmex* are exceptions. They construct very large nests and their harvesting may lead to the incorporation of large amounts of organic matter and nutrients into the soil. In some locations, ants may have an important role in bioturbation (Levieux, 1976; Cowan *et al*., 1985; Lockaby and Adams, 1985) and add their effects to those of other groups of soil macrofauna.

In agriculture, although generally seen as pests, ants may protect crop herbivores such as honeydew-secreting *Homoptera* or act directly as herbivores themselves. Their beneficial role as effective predators should also be noted (Way and Khoo, 1992).

Where they are abundant, ants modify the physical structure of the soil (Figure 11 through the creation of systems of galleries and chambers. This activity influences soil porosity, aeration, infiltration and drainage and creates habitats for smaller organisms.

The activities of ants can also influence the soil chemistry by increasing the amounts of organic matter, P, K and N in the mounds (Petal, 1978; Carlson and Whitford, 1991). The physical changes and the elevated chemical status of many soil materials associated with mounds induce greater mineralization activity by decomposers (McGinley *et al*., 1994) and root and mycorrhizal growth.

FIGURE 11
A) Ants moving soil (from Nardi, 2003); B) a black ant transporting soil out of the nest



Other macrofauna such as woodlice, millipedes and some types of litter larvae, which act as litter transformers with an important shredding action on dead plant tissue, and their predators (centipedes, larger arachnids and some other insects) are also key functional groups that have an important influence on soil fertility.

Plate 8
A millipede from Guadeloupe.

Myriapoda

The group of Myriapoda comprises all soil invertebrates with more than seven pairs of legs. The largest myriapods are divided into two classes: Chilopoda (centipedes) and Diplopoda (millipedes).

Millipedes and centipedes are found on the soil surface, in the litter layers, under tree stumps and decaying logs where they can find food and humidity. Most have a limited ability to penetrate the soil. They move through it by displacing it in all directions.

Plate 9
A scolopendra (centipede).

Millipedes are generally large-bodied arthropods (Plate 8) that feed on plant debris (decomposed wood or leaf materials), leaving behind their numerous droppings that contribute to humus and soil formation. z

Centipedes are generally long, flattened, sometimes large-bodied animals (Plate 9) that actively hunt and eat other invertebrates (and occasionally small vertebrates) in the litter. However, some very small, unpigmented, blind centipede species (mostly *Geophilomorpha*) go down into the soil, following galleries and crevices to about 50 cm. They have large jaw-like structures (forcipules) with poison glands at their base (predators).

Fly larvae

Flies (Diptera) larvae are a very diverse group with an extremely wide range of food sources. They feed on decaying plant material but they tend to be internal feeders on dead plant and animal remains. Sometimes, they can become predominant in soils and may realize an important reduction in litter mass (Healey

FIGURE 12
Different types of Diptera larvae

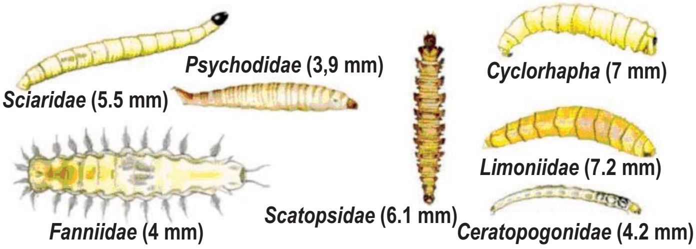
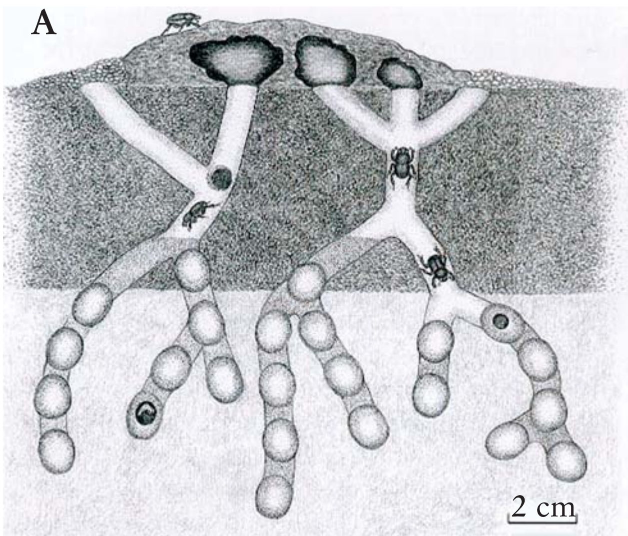


FIGURE 13
Activity of dung-beetles: A) subvertical galleries (from Nardi, 2003); B) white grub

A



B

and Russel-Smith, 1971; Deleporte, 1987). They live mostly in litter. They are probably most important in cold temperate soils, and can be very abundant in pastures (e.g. Tipulidae). Although often easy to confuse with Coleoptera larvae, they tend to be more slender, less grub-like, have smaller mouthparts, and move more actively in the soil (Figure 12).

Beetles

Beetles (Coleoptera) are the most diverse group of organisms in the world (with perhaps 3–5 million species). They differ widely in size (1–100 mm) and in the ecological roles they have in the soil and the litter. They have a similarly high diversity of feeding habits, and soil beetles can feed on fungi, plant roots, other invertebrates, buried wood, dung, corpses and other rotting organic matter. They have a wide range of feeding habits, being saprophagous, phytophagous or predators. Three groups are of great relevance in agricultural soils: (i) larvae from the family Scarabeidae (dung-beetles); and (ii) Curculionidae and (iii) Melolonthinae beetles, whose larvae (white grubs) may be abundant in grasslands and affect crop production by feeding on living roots (Villalobos and Lavelle, 1990).

Dung-beetles play a crucial role by burying dung in natural savannahs and grasslands used for cattle grazing in Africa (Brussaard and Hijdra, 1986). They dig subvertical galleries (like anecic earthworms) 10–15 mm wide down to 50–70 cm with a variable number of chambers that are further filled with large pellets of dung (Figure 13). The adult beetle lays one egg in each of these chambers and then the larva feeds on the pellet to complete its cycle (Lavelle and Spain, 2001). Their presence is generally indicated by small mounds a few centimetres high on the soil surface (Hurpin, 1962).

The following exercises, Exercises 6 and 7, enables participants to classify soil macrofauna, estimate their abundance and observe their effects on the soil, especially on soil structure, porosity and hence water infiltration (Figure 13).

EXERCISE 6: ESTIMATING SOIL MACROFAUNA ABUNDANCE AND ACTIVITIES IN SOIL

(Adapted from Source Anderson and Ingram (1993) and the IBOY report on soil macrofauna (**http://www.bondy.ird.fr/lest/iboy/workshop-report.pd**f) – Lavelle and Spain (2001))

Background

The category of soil macrofauna is defined as consisting of those soil invertebrates that are generally > 2 mm in diameter. Soil invertebrates can be classified according to their feeding habits and distribution in the soil profile as follows:

- ➢ Epigeic species, which live and feed on the soil surface. These invertebrates effect litter comminution and nutrient release. Mainly arthropods, e.g. ants, beetles, cockroaches, centipedes, millipedes, woodlice and orthopterans, together with gastropods and small, entirely pigmented earthworms (dark red, green or brown in colour). They are fast growing and move quickly.
- ➢ Anecic species, which remove litter from the soil surface through their feeding activities. Considerable amounts of soil, mineral elements and organic matter may be redistributed through these activities, accompanied by physical effects on soil structure and hydraulic properties. Earthworms (light or no pigmentation and slow movers) and non-soil-feeding termites are the main groups in this category, but it also includes some arachnids.
- ➢ Endogeic species, which live in the soil and feed on organic matter and dead roots, also ingesting large quantities of mineral material. The two main groups are earthworms (large, antero-dorsal pigmentation and very muscular, with a wedge-shaped tail) and soil-feeding termites.

Goal

By the end of the exercise, participants will know the standard characterization of soil macrofauna in different land-use systems and their relation to soil physical properties, as well as the significance related to the presence of beneficial or harmful groups of soil macrofauna in agricultural soils. The main groups of soil macrofauna are: ants, termites (humus feeders or wood-feeders), earthworms (epigeic, endogeic and anecic), dung-beetles, predator beetles, etc. The structures related to soil organisms and function are: earthworm casts on the surface and in the soil, termite structures, and ant hills (see exercise on biogenic structures).

Time required

Variable. Initial setup: 2 hours.

Materials

Machete (cutlass or parang), spade, plastic weave produce sacks for spreading on the ground, large diameter plastic or metal bowls (cuvettes), trowel, small plastic trays, fine forceps (or entomological forceps), fine paint brushes, sample vials in various sizes with secure alcohol-tight caps, Indian-ink pen (waterproof), stiff card for labels, notebook, large strong plastic bags (sealable), table and plastic chairs (for sorting), alcohol (70 percent), formaline (4 percent) if available for preservation of specimens (4-percent formalin is more suitable for earthworms), and a microscope.

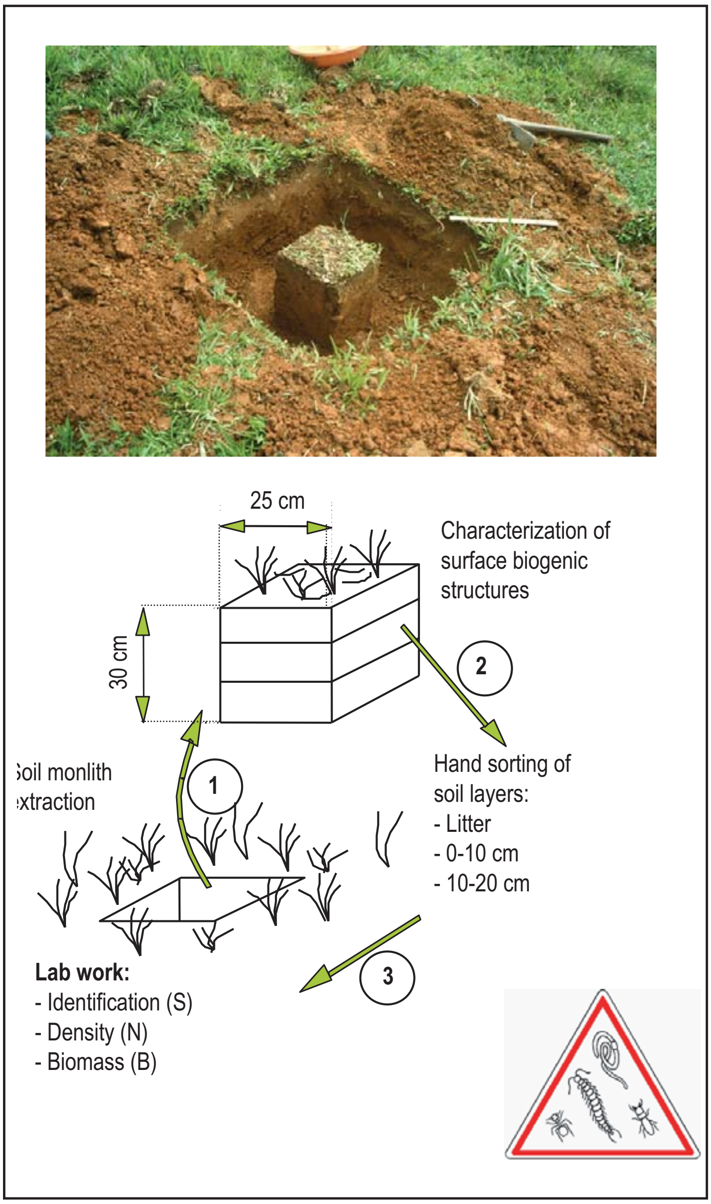
Procedure

The demonstration covers the preparations and material used to sample soil for the presence and abundance of soil macrofauna by performing the sampling methodology of the Tropical Soils Biology and Fertility Institute (TSBF method), which is the digging of soil blocks or monoliths of dimensions 25 cm long, 25 cm wide, and 30 cm deep.

A list of sites to sample showing a gradient in land-use intensification is elaborated by asking participants. Participants can be grouped to assess soil in three different land-use systems.

Steps:

1. Select sample area (land use, plot, etc.) and locate and mark the sampling points for monolith extraction (in the assessment of soil macrofauna communities, the sampling is generally conducted along a transect 40 x 5 m); these are equally spaced along the transect. The target number should be eight, although five will suffice as a minimum number).
2. Where present, remove litter from within a 25-cm square and hand-sort it at the site.
3. Isolate the monolith by cutting down with a spade a few centimetres outside the quadrat and then digging a 20-cm wide and 30-cm deep trench around it. (N.B. In a variant of the method, all invertebrates longer than 10 cm excavated from the trench are collected; these will be mainly large millipedes and earthworms with very low population densities but representing an important biomass. Their abundance and biomass can be calculated on the basis of 0.42-m2 samples, i.e. the width of the block plus two trench widths, squared.)
4. Divide the delimited monolith block into three layers: 0–10 cm, 10–20 cm and 20–30 cm. This can be done conveniently using a machete or parang held horizontally and grasped at both ends. Hand-sort each layer separately. If time is short or the light poor (sorting in closed canopy forest is usually difficult after about 3.30 pm), bag the soil and remove to a laboratory. Ants can be extracted by gently brushing small quantities (handfuls) of soil through a coarse (5 mm) sieve into a tray; the sieve retains the ants.
5. For each layer, the hand-sorted soil macroinvertebrates should be conserved in different containers filled with alcohol and marked using a piece of paper with the sample number and the layer noted on it; the paper is then put into the container.



Description of sampling protocol for the assessment of soil macrofauna in terrestrial ecosystems. Numbers correspond to chronological order and steps taken during sampling (adapted from Anderson and Ingram, 1993).

In the classroom:

1. Use the macrofauna key (see Annexe) to classify the animals from each container into the different main groups.
2. Count the number of individuals of each group present in each sample. Write down the results in a table (Table 3).
3. Recording the data. Make a table incorporating the group found in samples showing the sites where each occurred (e.g. Table 4). (Estimate abundance as number of individuals per square metre from each monolith; multiply the total of individuals of a raw by 16 as $1\ m^2$ is a 4×4 grid with squares of 25×25 cm). Calculate an arithmetical mean. Add up the total of individuals of each container belonging to the same sample.

Questions to discuss and points to emphasize

1. How can we assess soils for biological activity and how can soil macrofauna be estimated and its activities emphasized? Which types of animals are found mainly in litter? And in the soil? What are the main differences between these animals?
2. What forms of invertebrates (millipedes, isopods, molluscs, insects, insect larvae, and worms) live in the soils of agro-ecosystems and how do they relate to a “healthy” agricultural soil? Which land-use system had the highest diversity (greatest number of species)? Why?
3. How would you describe a pest problem related to the presence of macrofauna in the crop analysed? Are there any other symptoms (in the plants) that you could characterize as being associated with an attack by some groups of soil macrofauna, i.e. beetle larvae? How do you think these

results have been influenced by soil management practices in those areas? Consider factors such as amount and type of soil disturbance, organic matter inputs, presence of surface organic layer, etc.

4. Emphasize the main functions related to the activities developed by soil macrofauna: aeration, formation of channels where roots can penetrate, mixing and aggregation, soil compaction, porosity, increasing water infiltration, and burying of organic matter.
5. Emphasize the concepts of: soil quality / soil health; mineralization/ immobilization; autotrophic/heterotrophic food-webs; functional groups of soil biota; rhizosphere ecology; effect of land-use management on soils.
6. How do these findings relate to agricultural productivity and sustainability? Based on this information, would you alter any practices?

TABLE 3
List of macroinvertebrates found in each sample

Site	Ants	Termites	Earthworms	Woodlice	Snails	Spiders	Beetles, others	Number of groups Taxonomical richness
Forest 1 (litter)	325			28				
Forest 1 (0–10)	200			3				
Forest 1 (10–20)	3			0				
Forest 1 (20–30)	0			0				
Total Forest 1	528			31				
Forest 2 (litter)								
Forest 2 (0–10)								
Etc.								

TABLE 4
Woodlice density at four sites distributed across a land-use intensification gradient

Site	Total number of individuals (n = 5)	Total abundance of individuals (n = 5)	Arithmetical mean (ind./m²) (n = 5)
Primary forest	31	496	99.2
Secondary forest			
Grassland			
Crops			
Litter			
0–10			
10–20			
20–30			

EXERCISE 7: EFFECT OF SOIL FAUNA ON SOIL STRUCTURE (SO AFFECTING POROSITY AND WATER INFILTRATION)

Background

Under forest, the great production and cycling of foliage results in much biological activity, humus formation, and hence a dark coloured topsoil. Because of the great number of insects and worms, there are large pores, which allow water infiltration. In contrast, under annual crops, leaf production is much lower, the biomass is largely removed, the soil is tilled several times each year and becomes much drier. Consequently, less food and moisture are available for earthworms and insects, and their habitat is repeatedly disturbed or destroyed.

Goal

To recognize the effect of soil fauna in soil structure by comparing small soil blocks of forest, pastures and crops.

Time required

Two hours.

Materials

Paper, pens and a spade.

Procedure

1. Facilitator/trainer to ask participants to describe the main characteristics (in terms of soil structure, soil colour, type and quantity of vegetation, quantity and size of roots, presence of a litter layer, and presence of soil organisms) of a soil under forest, under pasture and under a cropped system. Make a list containing the characteristics for each situation.
2. A field trip is undertaken to study these systems "in situ", e.g. forest, pasture and intensive or mixed cropping system.
3. At each site, a block of soil is picked up and broken into two parts. There are several points to emphasize to participants:
4. Is the soil easily broken? Is it crumbly?
5. Is there a soil profile from surface to deeper zones? Can you distinguish several layers with different colours?
6. How is the soil to the touch? Can you see soil aggregation? When you pull up a plant and look at its roots, is the soil attached to the roots?
7. Make a drawing of the soil and roots for each situation.
8. At each step (a–d), the trainer explains why soil has these characteristics and the consequences for soil functions. If galleries are found, it could be interesting to follow them and look at the interior. Sometimes roots have colonized earthworm galleries or there are excrements of other animals.
9. Back in the classroom, the list is checked and completed with new information.

BIOGENIC STRUCTURES CREATED BY SOIL MACROINVERTEBRATES

Biogenic structures are those structures created biologically by a living organism. They are mainly earthworm casts, termite mounds and ant heaps. The biogenic structures can be deposited on the soil surface and in the soil, and they generally have different physical and chemical properties from the surrounding soil. The colour, size, shape and general aspect of the structures produced by large soil organisms can be described for each species that produces it. The form of the biogenic structure can be likened to simple geometric forms in order to evaluate more easily the volume of soil moved through each type of structure on the soil surface.

Through these structures, the organisms that produce them can modulate the availability or accessibility of one or more resources used by other organisms. Therefore, their activities, including the building of biogenic structures, are capable of modifying the abundance and/or community structure of populations of other organisms without being involved directly in any trophic relationship (e.g. predation, parasitism, mutualism and competition) (Jones *et al*., 1994, 1997).

There are several main groups of biogenic structures that are commonly found in agricultural systems, with different importance and consequences in agro-ecosystems.

Earthworm casts

Depending on the size of the earthworms that produce them, casts may range from some millimetres to several centimetres in diameter, weighing only a few grams or more than 400 g:

- Granular: These casts are very small and are formed by isolated faecal pellets (Lee, 1985). These casts can be found on the soil surface or in the soil, and are generally produced by epigeic earthworms (Plate 10).
- Globular: These casts are larger and formed of large aggregates (Plate 11). These are normally produced by endogeic and anecic earthworms. The casts produced by anecic earthworms comprise an accumulation of somewhat isolated, round or oval-shaped pellets (of one to several millimetres in diameter) that may coalesce into "paste-like slurries" that form large structures (Lee, 1985). Hence, casts are large in size and tower-like, and made of superposed layers of different ages, the older (i.e. dry and hard) located at the base and the more recent (i.e. fresh and soft) on the top. Casts produced by anecic earthworms have a higher proportion of organic matter, especially large particles of plant material and a larger proportion of small mineral components than in the surrounding soil.

Both granular and globular casts are normally found in agro-ecosystems in sub-Saharan Africa. (Plate 10 Plate 11)

P. LAVELLE

Plate 10
Granular casts on the surface of an African soil.

P. LAVELLE

Plate 11
Globular casts deposited by an African earthworm.

Earthworm burrows

Earthworms construct burrows or galleries through their movement in the soil matrix. The type and size of the galleries depends on the ecological category of earthworm that is producing it. Anecic earthworms create semi-permanent subvertical galleries, whereas endogeic worms dig rather horizontal burrows. These galleries may be filled with casts that can be split into smaller aggregates by other smaller earthworms or soil organisms. The galleries are cylindrical and their walls coated with cutaneous mucus each time the worm passes through.

Soil microorganisms (bacteria) concentrate on the surface of the gallery walls and within the adjacent 2 mm of surrounding soil. This micro-environment comprises less than 3 percent of the total soil volume but contains 5–25 percent of all the soil microflora; it is where some functional groups of bacteria predominate (Lavelle and Spain, 2001).

Termite mounds

Termite mounds (termitaria) are among the most conspicuous features in sub-Saharan Africa, especially in savannah landscapes. Termite mounds (Plate 12) are of diverse types and they are the epigeal part of a termite nest that originates belowground. Therefore, the termite mounds have at least some part of their structure below the ground surface. In Africa, termites build up half of the biomass of the plains. Their nests may occur in different locations, e.g. within the wood of living or dead trees, in subterranean locations, in other nests formed by other termite species, and by forming epigeal and arboreal nests.

Termites process large quantities of material in their building activities, thereby affecting the soil properties as compared with surrounding soils (Lee and Wood, 1971). Soil texture and structure are strongly modified in the termite mounds. In general, the soil of termite mounds exhibits a higher proportion of fine particles (clay), which termites transport from the deeper to upper soil horizons. Termites that build epigeic domes normally cement soil particles with variable quantities of salivary secretions and excrements rich in organic matter (Lee and Wood, 1971; Wood and Sands, 1978; Kooyman and Onck, 1987; Lee and Foster, 1991). The enrichment of faecal organic matter explains the differences in concentrations of both C and mineral elements observed between termite mounds and the soil (Lobry de Bruyn and Conacher, 1990; Black and Okwakol, 1997; Lopez-Hernandez *et al*., 1993).

C. ROULAND

Plate 12
Two different kinds of termite mounds.

Ant heaps

Because of their feeding habits, ants may be of less importance than termites and earthworms in regulating soil function. The exception to this is the tropical American genus *Atta*, the leaf-cutting ant. These ants make subterranean nests and their leaf harvesting may lead to enormous incorporations of organic matter and hence nutrients into the soil (Lavelle and Spain, 2001).

Many other ants nest in the soil. In some locations, ants may be important agents of bioturbation (Levieux, 1976; Cowan *et al*., 1985; Lockaby and Adams, 1985). A number of species also concentrate plant nutrients in their nests and the surrounding soils (Wagner, 1997). Ground-dwelling ants, particularly the mound-building ants, can be considered ecosystem engineers (Folgarait, 1998) in that they modulate the availability of resources and alter the soil and surface environments in ways that affect other organisms (Jones *et al*., 1994).

As with termites, ants also modify soil chemical and physical properties by transporting food and soil materials during feeding and mound and gallery construction. These activities affect soil developmental processes and fertility and may modify the nature and distribution of the vegetation.

Where abundant, ants modify the physical structure of the soil through the creation of systems of galleries and chambers. This activity influences soil porosity, aeration, infiltration and drainage, and it also creates habitats for smaller soil organisms.

Ant activities can also influence the chemistry of the soil, notably by increasing the amounts of organic matter, P, K and N in the mounds (Petal, 1978; Carlson and Whitford, 1991). Many soil materials associated with ant mounds induce greater mineralization activities by decomposers (McGinley *et al.*, 1994) and heightened root and mycorrhizal growth.

Roots

Although not generally considered soil organisms, they grow mostly within the soil and have wide-ranging, lasting effects on both plant and animal populations aboveground and belowground. Therefore, they are included in soil biota.

The rhizosphere is the region of soil that is immediately adjacent to and affected by plant roots. It is a very dynamic environment where plants, soil, microorganisms, nutrients and water meet and interact. The rhizosphere differs from the bulk soil because of the activities of plant roots and their effect on soil organisms.

Roots produce exudates that can help to increase the availability of nutrients in the rhizosphere and they also provide a food source for microorganisms (bacteria). This results in a larger number of microorganisms in the rhizosphere than in the bulk soil. Their presence attracts larger soil organisms that feed upon these microorganisms. The concentration of organisms in the rhizosphere can be up to 500 times higher than in the bulk soil.

An important feature of the rhizosphere concerns the uptake of water and nutrients by plants. Plants take up water and nutrients into their roots. The soil organisms near the rhizosphere influence plant roots because:

- they alter the movement of C compounds from roots to shoots (translocation);
- earthworm galleries (burrows) provide an easy pathway for roots to take as they grow through the soil (Plate 10);
- mycorrhizal associations can increase nutrient uptake by plants;
- some of them are pathogenic and can attack plant roots, e.g. nematodes.

Growing roots also produce important soil aggregation through the production of exudates mixed with clay and other mineral particles (Plate 13). Aggregation in the rhizosphere may also result indirectly through the accumulation of faecal pellets of earthworms and other invertebrates that feed in the rhizosphere. This function is very important for preventing soil erosion.

Plate 13
Aggregation effect of roots.

Numerous soil macrofauna groups create biogenic structures (endogeic and epigeic structures) that influence soil processes and structure (Figure 14. Earthworms, termites and ants form the main groups of soil macrofauna recognized as "soil engineers" and the structures that they produce may serve to evaluate their impact on both the soil and other organisms living in it (Anderson and Ingram, 1993; Lavelle, 1997).

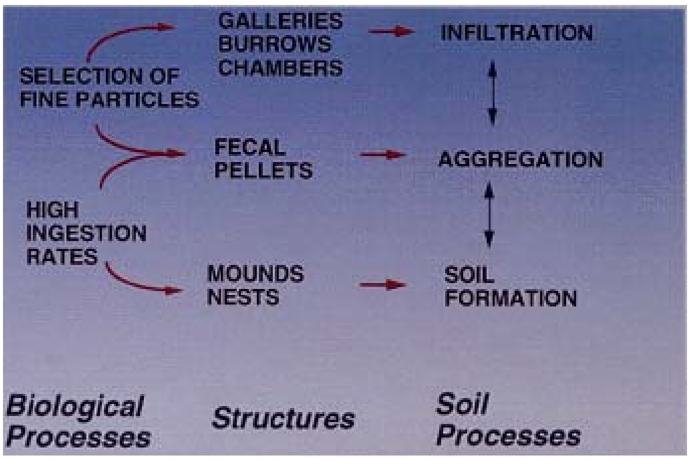
Depending on the type of structure considered the impact on soil will be different. The physical structures produced on the soil surface by ecological engineers can be classified into three main categories (Decaëns *et al*., 2001) (Box 4):

1. Earthworm casts: very compacted structures, large aggregates, high organic C content and assimilable nutrients.
2. Termite mounds: low compacted structures, large aggregates, high organic C content and assimilable nutrients.
3. Termite surface channels and ant nests: slightly compact and granular aggregates, low organic C content and assimilable nutrients.

Species producing structures typical of groups 1 and 2 (termites and earthworms) accumulate organic C on the soil surface and probably influence organic matter dynamics and the rate of release of mineral elements assimilable by plants (Black and Okwakol, 1997; Lavelle *et al*., 1998; Lobry-de-Bruyn and Conacher, 1990). These structures are characterized by their large size. In contrast, structures in group 3 (termite channels and ant nests) are much smaller.

The production of aggregates with diverse physical-chemical characteristics may result in the efficient regulation of soil structure. For example, in Côte d'Ivoire, the smaller earthworm species break up the casts produced by larger species, thus preventing excessive

FIGURE 14
Effects of fauna on soil structure



Source: Lavelle (1997).

accumulation on the soil surface (Blanchart *et al*., 1997; Rossi, 1998). In Carimagua (Colombia), a similar regulation is carried out by termites, it visibly accelerates the degradation of the large casts produces by earthworms (Decaëns, 2000).

In Amazonian pastures (Manaus, Brazil) the presence of abundant populations of the earthworm species *Pontoscolex corethrurus* leads to considerable soil compaction because these populations are not associated with species able to break their casts down into much smaller aggregates (Chauvel *et al*., 1999).

The following exercises, Exercises 8 and 9, facilitate the observation of biogenic structures created by soil macrofauna and the estimation of quantities of soil moved and relate soil macrofauna to their ecological roles in the soil.

BOX 4

Biogenic structures on soil surface

Structure	*Properties*	*Aspect*
Earthworm casts	Very compacted structures Large aggregates High organic matter content High assimilable nutrient content	
Temite mounds	Low compacted structures Large aggregates High organic matter content High assimilable nutrients	 
Termite channels Ant nests	Slightly compacted structures Granular aggregates Low organic matter content Low assimilable nutrients	 

EXERCISE 8: IDENTIFICATION OF BIOGENIC STRUCTURES AND CALCULATION OF SOIL MOVED BY SOIL MACROFAUNA

Background

This exercise can be done during a transect or a field trip for the observation of soil structure, and also during the agro-ecosystem analysis (AESA) that is conducted during the Farmer Field School process. Selected types of land-use management will be studied.

Goal

The goals of this exercise are: (i) to identify the main types of biogenic structures and be able to relate them to the soil organisms that produce them; (ii) to highlight the importance of biogenic structures when they are present in the soil and their effects on soil surface topography; and physical characteristics of casts depending on the type, i.e. granular or globular, etc.; and (iii) to relate some important concepts (e.g. aggregation, compaction, nutrient dynamics, and organic matter) to the presence of biogenic structures.

Time required

Two or three hours.

Materials

Pen, pencil, notepad and a ruler.

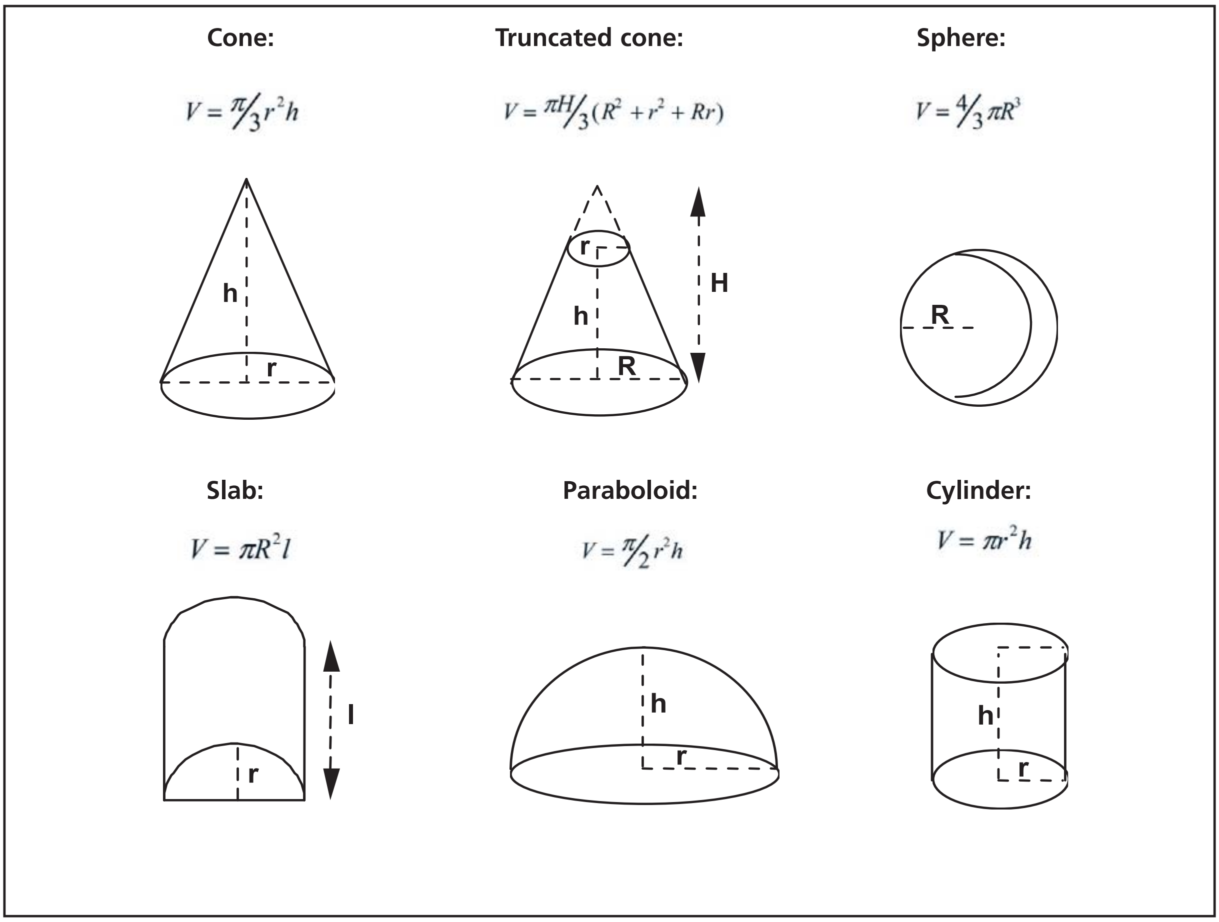
Procedure

1. Facilitator trainer to walk with participants through the field plot and identify those structures on the soil surface that are likely to have been produced by soil organisms.
2. Measure the size of the structures according to simple geometrical forms: cone, sphere, etc. (see below).
3. Examine their construction. Are they formed by a single structure or by the superposition of layers and/or small soil particles that are different from the rest of the soil?

Questions to discuss and points to emphasize

1. Are there obvious differences between plots under different land-management practices in terms of the presence of biogenic structure types? Which land-use practice shows the highest amount and diversity of structures? Which structures were compact and which not? Why?
2. How would you relate what is happening in terms of soil health? Are the presence of these structures a problem for the productivity of the crop or do you think that they are beneficial?

(If the trainees are not used to doing calculations by applying equations, then lead the discussion through the implications about the presence of these structures in the farming system). Geometrical forms to calculate the total volume of different surface biogenic structures produced by earthworms, termites and ants:



V = volume; *R* = radius (major); *r* = radius (minor); *h* = height; π = *pi* number (3.1415)
Source: Decaëns *et al.* (2001).

EXERCISE 9: THE CARD GAME

Goal

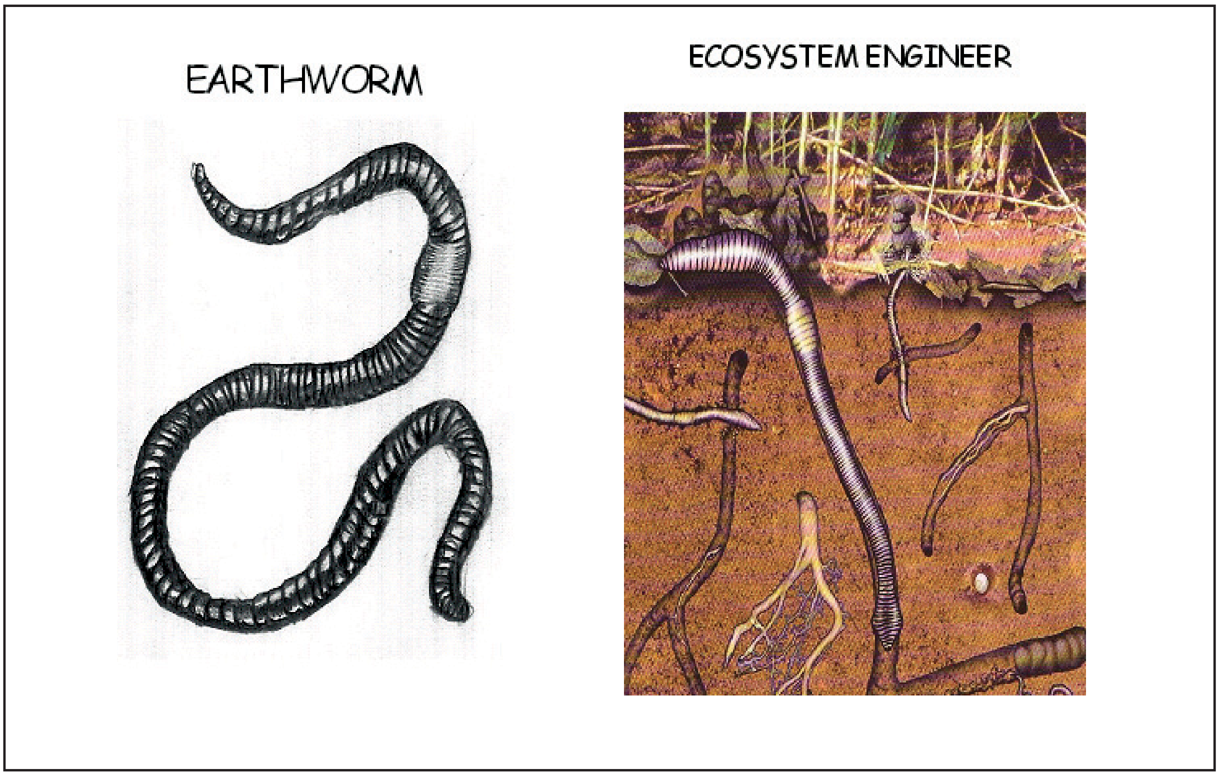
To relate the presence of soil macroinvertebrates to their ecological role in soil.

Materials

Cards (a pair of cards for each group of soil macroinvertebrates).

Procedure

There are two types of cards: one with the image or drawing of a soil macroinvertebrate, and another with the image of the effect of this group in soil, e.g. earthworms and a soil with galleries and casts on the surface. On cards showing a soil macroinvertebrate, the name of the organism will be written. Cards, each showing an image of their functional role in soil, will have the name of their ecological role (see figure below).



All the cards are distributed to the participants. Each of them should pass one card to the person on their right until someone forms a correct pair. The first person to form a pair is the winner.

RELATIONSHIPS BETWEEN KEY INDICATOR GROUPS AND OTHER SOIL ORGANISMS

Most soil organisms live in a variety of symbiotic relationships. Symbiotic relationships include: mutualism (both organisms benefit); commensalism (one organism benefits, the other does not but is not harmed); competition; parasitism (one organism benefits, the other is harmed); and predation (one organism benefits from the other by killing it). These relationships allow many diverse organisms to live in conditions that they could not live in on their own. Together they create substances and recycle materials that create the conditions necessary for life in the soil.

Thus, some key indicator groups present these kinds of relationships with other soil organisms. For example, termites are associated closely with specific microbial communities related with termite digestion. Termites also interact with other soil organisms by mutualism, symbiosis, commensalism and predation or parasitism. There is a symbiotic relationship between termites and ants, some termite species profit from the presence in their nests of ants to feed on the residues of dead individual ants (Jaffe *et al*., 1995).

In some cases, red wood ants have been found in association with earthworms (Laakso and Setäla, 1997). It is a mutualistic relationship; the surface of the ant nest mound provides a better environment than that of the surrounding soil for earthworms (favourable temperature, moisture and pH, and an abundant food supply) and earthworms prevent the nest mounds from becoming overgrown by moulds and fungi.

Another example of the association of a key indicator group with microorganisms are the fungus-growing ants (which include the leaf-cutting ants). These ants collect various materials and feed them to a symbiotic fungus that lives in their nests. The ants then feed on special nutritional bodies produced by the fungus. This is an example of mutualism. The ants obtain food from the fungus, and the fungus has a place to live protected by the ants from predators and parasites.

Large-blue butterfly larvae spend most of their larval stage inside ant nests, either eating ant larvae or being fed by the ants as if they were the ants' own brood (like cuckoos). This is an example of parasitism. The butterflies are dependent on the ants for survival, and have evolved special mechanisms to trick the ants into looking after them.

However, there is another type of relationship between soil organisms that does not rely on trophic interactions but on the biogenic structures produced by the ecosystem engineers. Through their activities, earthworms, termites and ants produce a large variety of macropores (e.g. galleries and chambers) and organo-mineral structures (e.g. earthworm casts, termite mounds, and ant nests) that influence hydraulic properties, macroaggregation and organic matter dynamics in soil (Anderson, 1995; Lavelle, 1996; 1997).

Through their mechanical and feeding activities, ecosystem engineers modify living conditions (the physical environment and the availability of food resources) for other smaller and less mobile soil organisms, and hence influence their abundance and diversity (Lavelle, 1996).

One of the main constraints on the activity of soil organisms is the difficulty of moving in the soil. The mineral soil environment is compact and movement for most species is only possible through the network of pores, galleries and fissures created by the activity of ecosystem engineers.

Biogenic structures, particularly earthworm casts, increase macrofauna density. Some organisms prefer to live inside casts or in the underlying soil because casts have high organic matter content (Guggenberger *et al*., 1996; Rangel *et al*., 1999) and may represent a valuable food for smaller earthworms and humivorous termites. The biomass of roots is increased locally below casts (Decaëns *et al*., 1999) and this may be beneficial to larvae or rhizophagous Coleoptera.

When litter is consumed by earthworms, some changes occur in its composition. These changes attract some litter-dwelling species, such as Isopoda and Diplopoda (Szlavecz, 1985), that prefer to consume this litter. Small predatory species (Chilopoda and Arachnida) can find high prey densities of microfauna and mesofauna species taking advantage of earthworm-enhanced living conditions (Brown, 1995; Loranger *et al*., 1998).

Other species may respond to changes in soil structure and to the creation of new specific microhabitats. Macropores that result from earthworm activity can be considered as habitats for some microfauna and mesofauna species (Haukka, 1991; Loranger *et al*., 1998). Large numbers of corn-root worm eggs have been found in earthworm burrows (Kirk, 1981). Ants and termites have been observed using galleries as communication ways (Decaëns *et al*., 1999). Where soil is totally lacking in protection for surface living organisms (i.e. without litter and herbaceous layer), earthworm structures may be used as specific refuges by litter-dwelling arthropods and could help their maintenance and/or rapid recolonization of the soil surface after perturbations.

Earthworm activities tend to depress nematode populations, especially phytoparasitic species (Boyer, 1998; Roessner, 1986). This effect is the result of changes in the soil environment (Yeates, 1981) and the activation of nematophagous fungi (Edwards and Fletcher, 1988).

Relationships between biogenic structures produced by ecosystem engineers and other organisms may be critical for the conservation and dynamics of SOM and the regulation of soil physical properties. For example, when small organisms feed on large and compact earthworm casts, they prevent their excessive accumulation on the soil surface, which otherwise may lead to a superficial soil compaction and affect plant growth negatively (Rose and Wood, 1980; Chauvel *et al*., 1999). Moreover, they may re-activate organic matter decomposition by making organic resources available to microorganisms that were sequestered in dry casts (Lavelle, 1996).

Chapter 7

Monitoring impacts of land management: a problem-solving perspective

Land-management systems have an impact on soil environment. Soil physical, chemical and biological properties are modified considerably by agricultural practices. They may affect soil organisms either positively or negatively, so modifying the size and composition of soil biological communities, with important consequences on soil fertility and plant productivity (Table 5).

TABLE 5
Effects of different management practices on soil organisms and soil function

Management practice	Effect on soil organisms and function
Tillage	More rapid decomposition of organic matter; higher ratio of bacteria/fungi; lower populations of macrofauna and mesofauna; short-term increase in nutrient availability but increase in long-term losses; better root growth in tilled layer; higher erosion risks.
No-tillage	Higher populations of macrofauna, mesofauna and microfauna; greater ratio of fungi/bacteria; organic matter accumulation on soil surface; nutrient conservation; lower runoff and erosion; increase in presence and incidence of pests and diseases.
Organic matter input	Changes in decomposition rates and organism populations (some increase, others decrease, depending on the type of material); increased nutrient availability, storage and exchanges; improved soil physical structure and water relations; reduction in acidity and aluminium toxicity; greater microbial and fauna activity, especially detritivores.
Fertilization	Usually, reduction in mycorrhization and N_2 fixation (with P and N, respectively); mineralization-immobilization balance changes; increased plant production and organic matter inputs; increases in populations of some organisms through greater food supply.
Pesticides	Reduced incidence of diseases and pest, parasites and pathogenic organisms, but negative effects on non-target biota such as beneficial insects and earthworms; improved plant production but often creation of dependence; destabilization of nutrient cycles; loss of soil structure; long-term increased resistance of target biota.
Crop rotations	The "rotation effect"; improved pest and disease management; more efficient soil nutrient utilization; greater diversity aboveground and belowground; higher populations, biomass and activity of most organisms (especially with legumes); improved soil aggregation and infiltration; reduced bulk density; higher organic matter.
Inoculation of selected soil biota (e.g. rhizobia, mycorrhizae, earthworms,rhizo-bacteria, antagonists, biocontrol agents)	Increased N fixation, nutrient availability in soil, water uptake and efficiency of nutrient acquisition by plants; higher yields; increased heavy metal tolerance; better resistance to plant diseases, pests and parasites; increased soil porosity, aeration, aggregate stability, water infiltration and holding capacity; faster decomposition rates and nutrient cycling.

Source: expanded from Swift (1997).

Clearing forests or grasslands for cultivation modifies the soil environment drastically and, hence, also modifies the numbers and kinds of soil organisms. The quantity and quality of plant residues and the number of plant species are, in general, greatly reduced, as a result the range of habitats and foods for soil organisms is reduced significantly. The use of large quantities of agrochemicals (pesticides, herbicides and inorganic fertilizers) and tillage practices has a negative influence on soil communities by reducing their numbers and hence the beneficial ecological functions in which they participate.

The beneficial effects of soil organisms on agricultural productivity that may be affected include:

- organic matter decomposition and soil aggregation;
- breakdown of toxic compounds, both metabolic by-products of organisms and agrochemicals;
- inorganic transformations that make available nitrates, sulphates and phosphates as well as essential elements such as iron (Fe) and manganese (Mn);
- N-fixation into forms usable by higher plants.

Decomposition is the central process in soil. The breakdown of organic residues by soil microflora to release plant nutrients is often accelerated in the presence of soil fauna (Swift *et al*., 1979; Seastedt, 1984; Tian *et al*., 1992). The breakdown of plant residues by soil fauna increases the exposure of substrates to the microflora, leading to enhanced nutrient release (Scheu and Wolters, 1991).

In the humid tropics (e.g. Nigeria), the rate of breakdown of plant residues where earthworms and millipedes are present may be twice as high as where they are not present (Tian *et al*., 1997).

Farmers need to create favourable conditions for soil life. They should manage organic matter so as to create a fertile soil in which healthy plants can grow. In tropical agriculture, where poor farmers generally suffer from decreasing soil fertility and declining soil water dynamics, the restoration of SOM is essential for the stabilization of production. Declining soil water dynamics is partly a result of drought conditions but also significantly affected by loss of vegetation cover, soil crusting and compaction and loss of soil organic matter. These result in reduced surface infiltration, water retention and permeability through the soil as well as increased runoff and hence erosion.

However, this situation cannot be achieved by merely incorporating organic matter into the soil as the degradation process under tropical conditions is too fast to allow any medium- or long-term improvement in soil properties. In addition, the incorporation into soil of organic matter implies tilling the soil, which accelerates its breakdown and destroys soil structure and organisms.

The primary need is to feed soil organisms and to regulate their living conditions, while protecting them from harmful chemical and mechanical impacts. For example, shallow tillage, ridge-tillage, or no-tillage and surface management of crop residues has often led to increases in earthworm activity compared with areas where deep tillage is practised. Earthworms are a resource that may be used in agriculture because their effects on nutrient dynamics and the physical structure of soil may significantly enhance plant growth and conserve soil quality (Jiménez and Thomas, 2001). Management options that stimulate the activities of these organisms could promote sustainable production in tropical agro-ecosystems (Swift, 1987; Myers *et al.*, 1994).

For example, the success of earthworm-management techniques may depend on: the choice of suitable species; the provision of adequate organic supplies to feed the worms; and the maintenance of a minimum diversity in all invertebrate communities. Therefore, all these biological resources need to be managed at the same time (Senapati *et al.*, 1999).

In the humid tropics, "in-soil" technologies that incorporate organic residues into the soil to stimulate the activities of local or inoculated populations of soil-dwelling earthworms should be preferred in most cases to "off-soil" techniques (vermicomposting) that simply use earthworms to prepare compost. The vermicomposting of residues allows the rapid transformation of fresh residues into compost that can be used readily in the field. However, a large amount of C is lost that might have been used to sustain mechanical activities of earthworms and other invertebrates in the soil. Endogeic earthworms participate in the humification of organic matter, but they also contribute to: the macroaggregation of soil particles; the maintenance of macroporosity; and the intimate mixing of organic compounds, with effects on the long-term sustainability of soil fertility (Blanchart *et al.*, 1997). Vermicomposting should only be recommended when the quality, the amount or the location of organic residues makes them unsuitable for local use in agriculture. "In-soil" technologies are based on the use of endogeic and anecic earthworms that influence soil physical properties significantly. These technologies manipulate earthworm communities either directly, through the massive inoculation of suitable populations, or indirectly, by promoting suitable conditions for the activity of the already existing population through the manipulation of plant communities and/or organic inputs.

The loss of SOM and nutrient deficiency is one of the most important problems facing farmers. SOM is of key importance to optimizing crop production, minimizing environmental impacts and, thus, improving soil quality and the long-term sustainability of agriculture. SOM benefits crops by providing nutrients, especially N, as it is decomposed by microorganisms. Furthermore, it: (i) binds soil particles together so that they prevent erosion; (ii) improves soil structure and tilth, which allows water, air and nutrients to move readily to living organisms; (iii) is a strong absorber of pesticides, organic wastes and heavy metals; and (iv) is a part of the cation exchange complex, which holds many nutrients and resists losses to leaching.

In a natural grassland or forest ecosystem, SOM accumulates with soil development and eventually reaches an equilibrium, which is determined mainly by the environment, natural vegetation and soil organisms. A decrease in SOM leads to a decline in soil aggregate stability (Castro Filho *et al.*, 1998) and in crop yield (Burle *et al.*, 1997). Where soil is tilled and cropped, massive changes occur within the soil system.

Tillage mixes oxygen into the soil and breaks up its structure, giving microbes all they need in order to burn up organic matter and release CO_2 into the atmosphere more quickly than when this process is realized naturally by soil organisms. In the natural state, much of the SOM is protected. The soil system can be thought of as a structure with millions of tiny pores of all sizes and shapes. Much of the SOM is trapped in areas inaccessible to microbes. Other organic particles are clumped (aggregated) together, so allowing microbes access to the outside while the centre remains protected. Soil organisms such as earthworms mix SOM and mineral particles, thereby facilitating its access by microorganisms. Tillage speeds up this process; stirring, churning and mixing everything together. Microbes suddenly find a feast of nutrient rich material and proceed to multiply, liberating excess nutrients that, if not taken up by the crop, vulnerable to be leached out of the soil with rain or irrigation water.

The rate and degree of organic matter depletion is influenced by: (i) type of crop residues; (ii) tillage practices; and (iii) type and severity of wind and water erosion.

In conventional agro-ecosystems, crop residues are removed or burned after harvesting. Unless other organic materials are added to the soil, this will lower the amount of SOM, and so inorganic nutrient inputs are needed to sustain plant growth. The loss of SOM has a negative effect on soil macroinvertebrates, whose abundance decreases as a consequence of the reduced amount of food available. In addition, conventional systems are characterized by repetitive tillage, which physically disturbs the soil and reduces greatly the abundance of soil macrofauna. Most SOM is contained in the surface horizons of soils. Soils become more sensitive to erosion under such management practices, and the physical removal of topsoil by wind and water erosion can result in a further significant loss of organic matter.

Organic matter losses can be minimized through the application of conservation farming practices, which include:

- using permanent crop covers to prevent erosion and add organic matter;
- employing crop rotations that include forages and legumes;
- adding manures and organic wastes to supplement crop residues;
- realizing mulching on the soil surface;
- using an adequate and balanced fertilizer programme that creates healthy crops and good residues;
- using no-tillage where possible or minimum tillage;
- In no-tillage, seed is drilled directly into the stubble or the surface residues which have been flattened with a knife roller or killed with a herbicide without first ploughing the soil.

The use of no-tillage in different kinds of crops in the Parana region (southern Brazil) has improved soil environmental conditions for plants and soil animals compared with soils under conventional tillage management systems. Results include: reduced erosion; enhanced nutrient-use and water-use efficiency by crops; and improved crop yields and profitability, especially after a transition period of a few years. No-tillage practices have also increased soil macrofauna diversity and accelerated population recovery after the cessation of conventional tillage practices. Soil organisms that have benefited especially from no-tillage are: natural predators (important for the biological control of pests); bioturbators (important for improving soil physical structure); and decomposers (important for recycling plant residues). Finally, the lack of soil disturbance at no-tillage sites has led to: increased SOM in the top-most soil layers; increased protection of the soil surface with plant residues; and increased populations of beneficial soil invertebrates (FAO report, 2000).

In contrast to ploughed systems, no-tillage management leads to accumulation of plant residues on the soil surface. This decreases the rate of decay of crop material and, therefore, helps to maintain good SOM levels. The adoption of soil conservation practices that reduce soil erosion will assist in reducing losses and maintaining SOM.

Increasing the amount of crop residue will also assist in maintaining and/ or increasing SOM levels. This can be accomplished by selecting crops that produce more residue, by adequate fertilization and by rotations of cereals with legumes and forage crops, especially those with deep extensive rooting, as well as minimising the removal or burning of crop residues. In sandy soils or soils low in organic matter, the addition of manure and the inclusion of legumes in the rotation, or as a green manure crop, will be needed to enhance SOM and minimise fertiliser losses (if used) through leaching.

Conventional tillage practices, based on the use of hand hoes, ploughs – animal drawn and powered – and harrows are likely to destroy soil structure and make the soil vulnerable to compaction and erosion. Wheel traffic or pressure (weight per unit area) exerted on the soil surface by large animals, vehicles and people can cause soil compaction. Compaction occurs where moist or wet soil aggregates are pressed together and the pore space between them is reduced. Compaction changes soil structure, reduces the size and continuity of pores, and increases soil density (bulk density). Compaction reduces the capacity of the soil to hold water, the rate of water movement through the soil, and the storage capacity of the soil. Compaction and crusting of the soil surface also limits water infiltration resulting in increased runoff and vulnerability to erosion and hence further loss of potential productivity. When the amount of water that enters the soil is reduced, less water is available for plant growth and percolation to deep root zones.

Soil compaction can also be caused indirectly by a decrease in soil organisms and hence loss of biological tillage.

Deep tillage is harmful to soil organisms. It can kill them outright, disrupt their burrows, lower soil moisture, and reduce the amount and availability of their food. Other inappropriate land-management practices, such as the use of certain pesticides and some inorganic fertilizers, can also be harmful to soil life. All these practices result in declining soil life and SOM, which are important for oxygen, water and nutrient cycles, including moisture retention, water infiltration and plant nutrition. In general, soil tillage reduces the abundance of soil organisms. Termites, earthworms, beetles and spiders are among the main groups of soil macrofauna usually much reduced by tillage practices (Wardle, 1995). As they are reduced, their functions in soils (burrowing, decomposition and cycling of nutrients, soil aggregation and predation) are altered, leading to soil degradation and increases in pests and plant diseases.

Compaction reduces the capacity of the soil to hold water, the rate of water movement through the soil, and the storage capacity of the soil. Compaction and crusting of the soil surface also limits water infiltration resulting in increased runoff and vulnerability to erosion and hence further loss of potential productivity. When the amount of water that enters the soil is reduced, less water is available for plant growth and percolation to deep root zones.

The alteration of soil macrofauna abundance and diversity as consequence of soil-management practices may lead to serious problems of soil compaction. The functions previously performed by depleted organisms are no longer performed and the activity of surviving organisms may become excessive and produce a negative effect on soil. In the Brazilian Amazon (Manaus) the transformation of the forest zones into pastures, the use of agricultural machinery and trampling by cattle has led to severe soil compaction, particularly in the surface layer (5–10 cm). However, the most important consequence was that the native soil macrofauna communities were radically altered, most of the native taxa disappearing. The activity of the compacting earthworm species *Pontoscolex corethrurus* produces more than 100 tonnes/ha of castings. The excessive accumulation of these compacted structures is wholly prevented by small invertebrates that feed on them and break them down into smaller structures. However, where these organisms are not present because of soil compaction by cattle or machinery, this function is not performed and the accumulation of compacted casts affects plant growth negatively (Chauvel *et al*., 1999).

Where soil density increases significantly, it limits plant growth by physically restricting root growth. Severe compaction can limit roots to the upper soil layers, effectively cutting off access to the water and nutrients stored deeper in the soil. Anaerobic conditions (lack of oxygen) can develop in and above the compacted layer during wet periods, further limiting root growth.

Compaction alters soil moisture and temperature, which control microbial activity in the soil and the release of nutrients to plants. Anaerobic conditions increase the loss of soil N through microbial activity. Compaction also changes the depth and pattern of root growth. These changes affect the contribution of root biomass to SOM and nutrients. By reducing the number of large pores, compaction can restrict the habitat for the larger soil organisms that play a role in nutrient cycling and can thus reduce their numbers.

Biological activity may be used to reduce soil compaction. In Burkina Faso, organic mulch (cow manure or straw) was applied to soil surfaces in a three-year study in order to trigger termite activity (Mando, 1997). The termites restored crusted soils through their burrowing and decomposing activities, properly managed by careful additions of organic matter. The increase in soil porosity and the improvement in water infiltration and retention capabilities of the soil encouraged root penetration and hence crop productivity. Termites can become a major crop pest in drylands when there is inadequate alternative dead and dried up organic matter – their preferred food source. Best practices and deterrents need to be researched and adapted with farmers for specific farming systems. For example, making use of termite predators, such as ants and birds, through diversified farming systems, reducing plant water stress and vulnerability to termite attack, and use of plants with repellent properties.

Soils with a well-developed structure and high aggregate stability are more resistant to compression than other soils. Near-surface roots, plant litter, and aboveground plant parts reduce the susceptibility to compaction by helping to cushion impacts. Vegetation also adds SOM, which strengthens the soil, making it more resistant to compaction. Conventional tillage, especially in tropical latitudes, causes rapid oxidation and mineralization of organic matter and, as a result, declining SOM levels.

Conservation tillage is linked with increased earthworm activity (Mele and Carter, 1999); mulched stubble in particular favouring large increases in earthworm numbers. The retention of maximum levels of crop residues on the soil surface and a lack of soil disturbance create a more favourable habitat for soil animals. Earthworm channels and termite galleries increase the volume of soil pores, which should increase soil aeration and water entry into the soil (Ehlers, 1975; Holt *et al.*, 1996). The number of large soil pores under no-tillage practices can be up to sevenfold greater than under conventional tillage systems.

Another practice to improve a compacted soil is the growing of plants with large taproots that are more effective at penetrating and loosening deep compacted layers, and the use of shallow, fibrous root system to break up compacted layers near the surface. Roots also reduce compaction by providing food that increases the activity of soil organisms.

Conventional tillage methods are a major cause of severe soil loss and desertification through soil compaction and accelerated erosion by wind and water. Worldwide, it is responsible for about 40 percent of land degradation. Agricultural lands could be protected or saved from degradation and erosion by applying an environmentally friendly tillage approach and the use of cover crops and mulching practices.

The intensity of tillage is a recognized factor affecting the amount of runoff and soil erosion that occur in croplands. In turn, the amount of runoff and soil loss directly affects soluble and absorbed chemical transport, particularly plant nutrients from fertilizer application. Soils with no-tillage management practices present a much lower sediment loss than soils under conventional practices. No-tillage keeps crop residues on the soil surface, which is highly effective in controlling the loss of sediment from water-runoff events. The loss of soil nutrients such as soluble N and P is reduced by up to 50 percent where no-tillage is adopted.

Conventional tillage, especially in tropical latitudes, causes rapid oxidation and mineralization of organic matter and, as a result, declining SOM levels. Thus, no tillage practices are highly preferable as they leave a protective blanket of leaves, stems and stalks from the previous crop on the surface, to protect the soil from erosion, minimise compaction and maintain soil structure, enhance infiltration and provide organic matter for soil biological activity. These also lead to enhanced fertiliser efficiency.

There are several ways of modifying tillage systems to improve soil resistance to erosion and enhance soil macrofauna populations:

- leave a rough surface or adequate residue cover for erosion control;
- bury crop residues for pest control, depending on the system;
- leave as mulch cover when possible;
- do as little physical disruption (tillage) as possible;
- use crop rotations with specialized cover crops – essential for breaking the cycles of weeds and pests and for compensating for higher-value crops with inadequate quantity and quality of residues, such as edible beans and soybeans, with high C:N ratios in their straw.

The adoption of conservation tillage is sometimes restricted by concerns about potential increases in certain pests, particularly plant pathogens and insect pests. The complex interactions within a more diverse soil community in no-tillage may provide protection against the pest organisms, but the time required for this shift in communities may be too long for farmers' economic requirements. The use of synthetic chemical pesticides, particularly herbicides, may be unavoidable in the early years, but they have to be used with care in order to reduce the negative impacts on soil life. To the extent that a new balance between the organisms of the farm-ecosystem, pests and beneficial organisms, crops and weeds, becomes established and the farmer learns to manage the cropping system, the use of synthetic pesticides and mineral fertilizer tends to decline to a level below the original "conventional" farming level.

Where soil insects become a pest, they contribute to a poor yield. The damage caused by pests can be responsible for 40–50 percent of crop loss. Groundnut plants are particularly susceptible to attacks by soil insects because the pods develop underground. Groundnut culture is an important crop and component of the diets of many smallholders in sub-Sahelian Africa. They have access only to 1–2 ha, from which they derive the food to support their family and sometimes all their income.

Soil organisms like white grubs, e.g. *Diabrotica* larvae, some species of termites, millipedes, wireworms (Elateridae), false wireworms (Tenebrionidae) and ants can became serious groundnut pests in Africa, Asia, and Central and South America. All these organisms are podborers and attack roots, causing important crop loss.

There are four basic approaches for managing soil insects in groundnut crops:

- apply insecticides, alone or in various combinations;

- manipulate natural control processes;
- rely on host plant resistance;
- employ management practices that prevent the insects from multiplying unduly

The application of insecticides is not recommended because they are usually not sufficiently effective and they are expensive. Aside from the well-known hazards that these chemicals present to the environment and humans, they can be accumulated by plants. These chemicals are not pest specific and kill other beneficial organisms present in soils. This can led to the proliferation of other organisms that become more harmful. For example, in a Malawi field, there was a proliferation of termites following an insecticide application because of the disappearance of their natural enemies, the ants.

It is most important that the natural control processes should not be disturbed. Thus, the unavailability of insecticides in many African countries is not necessarily a bad thing. The abundance of natural enemies indicates that there is little reason for considering the release of exotic or any other natural enemies. However, any management procedure that encourages the proliferation of suitable predators and parasites should be considered the best solution.

In Cuba, the banana weevil *Cosmopolites sordidus* is an important pest that may be responsible for up to 40 percent of crop loss. Some ant species, beetles and earwigs are natural predators of this beetle and they may reduce banana weevil populations significantly. The creation in banana plantations of environmental conditions suitable for the development of these predators appears to be the best way to realize a biological control. Integrated pest management is imperative as it is an effective and cost-efficient system (Gold and Messiaen, 2000; FAO report, 2000).

In Nigeria, a way of controlling termite invasions is to cultivate plants that have repellent or antibiotic properties, or at least not to remove them from the fields. The plants include: basil, termite grass *Vetiveria nigritana*, *Digitaria sp.*, lemon grass *Cymbopogon shoenanthus*, and elephant grass *Pennisetum purpureum*. Some farmers also introduce soldier ants into termite mounds.

Spacing can also have a significant effect on the damage caused by pests (Jayaraj *et al*., 1986). A study in India showed that in plots with 15-cm spacing between cotton plants in rows spaced 75 cm apart, the average percentage of attacks by the ash weevil grubs was 17 compared with 22 percent in 20-cm spacing and 31 percent in 30-cm row spacing.

Crop rotation and intercropping using plants that are not hosts for a certain pest are very important to preventing the survival and the continuous reproduction of the pest throughout the year.

The best solution to problems caused by pests could be a whole-farm ecological approach to pest management that considers beneficial organisms as mini-livestock that can be managed (Dufour, 2000). These organisms could develop more readily and be more effective biocontrols when provided with a habitat with adequate and easily available resources. This way to increase the habitat for beneficial organisms should be understood and practised within the context of overall farm management goals.

Some key questions that could help in the implementation of a such system are:

- concerning pest and beneficial organisms:
  - What is the most important pest (in economic terms) that requires management?
  - What are the most important predators and parasites of the pest?
  - What are the primary food sources, habitat and other ecological requirements of both the pest and of beneficial organisms? (Where does the pest infest the field from, how is it attracted to the crop, and how does it develop in the crop? Where do the beneficial organisms come from, how are they attracted to the crop and how do they develop in the crop?)
- concerning timing:
  - When do pest populations generally first appear and when do these populations become economically damaging?
  - When do the most important predators and parasites of the pest appear?
  - When do food sources (dead organic matter, nectar, pollen, alternate hosts and prey) for beneficials first appear? How long do they last?
  - What native annuals and perennials can provide habitat?

Thus, the identification of strategies to improve field conditions for pest management should consider: reduction of pest habitat (i.e. reduce/alter locations from which pest invades or reduce/alter overwintering pest sites in temperate regions); augmentation of beneficial habitats (insectary establishment; considering both perennial and permanent plantings such as hedgerows and annual options), and trap crops planted specifically to be more attractive to the pest that is the crop to be harvested. Table 6 provides a description of planting systems that can be used in this approach.

The idea of undisturbed beneficial habitat distributed at intervals in or around crop fields is a good solution for these purposes. Depending on the plant species, these “perennial islands” provide food resources for beneficial organisms as well as refuge (or over-wintering sites in temperate regions) from which crops can be colonized.

TABLE 6
Practices for an ecological approach to pest management

Practice	Description
Companion planting	A mix of species of plants within a row or bed – this could be difficult to manage for farmers owing to varying cultural needs such as planting time, irrigation needs and harvesting.
Strip planting, strip cropping	The practice of growing two or more crops across a field wide enough for independent cultivation (e.g. alternating six-row blocks of soybeans and corn or alternating strips of alfalfa with cotton) could be easily adapted to vegetable production systems. Like intercropping, strip cropping increases the diversity of a cropping area, which in turns may help “disguise” the crops from pests. Another advantage is that one of the crops may act as a reservoir and/or food source for beneficial organisms.
Multiple cropping	The production of more of one crop in the same land in one year. Depending on the type of cropping sequence used, multiple cropping can be useful as a weed control measure, particularly where the second crop is interplanted into the first.
Interplanting	The seeding or planting of a crop into a growing stand, such as overseeding a cover crop into a grain stand.
Intercropping	The practice of growing two or more crops in the same, alternate or paired rows in the same area. This technique is particularly appropriate in vegetable production. The advantage of intercropping is that the increased diversity helps to “disguise” crops from insect pests and, where done well, may allow for more efficient utilization of limited soil and water resources.
Cover crops	Cover crops and green manures can be integrated into both perennial and annual cropping systems. Cover crops, often a legume or grass species, prevent soil erosion and suppress weeds. A cover crop can also be used as a green manure.
Green manures	Generally incorporated into the soil to provide N and organic matter for subsequent crops. When incorporated, some cover crops in the Brassica family (e.g. rapeseed, broccoli and radish) have the ability to suppress nematode pests. Left in the field as residues, some grasses will provide more than 90% weed suppression.
Windbreaks, shelterbelts and hedgerows	These are linear barriers of trees, shrubs, perennial forbs and grasses that are planted along field edges or other unused areas. Where done correctly, they reduce windspeed and, as a result, modify the microclimate in the protected area. Aside from providing a microclimate favourable to beneficial organisms, shelterbelts also protect against wind erosion of soil, decrease the dessicating effect of wind on crops, and provide wildlife habitat.
Permanent border	A strip of permanent vegetation bordering a field. A border such as this can be modified to attract beneficial insects through the cropping season if the proper plants are used and sufficient water is made available.

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KEY ON SOIL MACROFAUNA

NO LEGS

1. NON-SEGMENTED, CLEAR HEAD WITH TENTACLES: *MOLLUSCA*
   a) With shell (Fig. 1)
   b) Without shell (Fig. 2)

Fig.1: *Mollusca with shell: Snails*

Fig.2: *Mollusca* without shell: Slugs

2. SEGMENTED
   a) Worm-like, more than >15 body segments, pigmented:
   - Earthworms (most > 20 mm long) (Fig. 3)
   - Suckers at both ends of flattened body – Hirudinea (leeches) (Fig. 4)

Fig.3: *Earthworm*

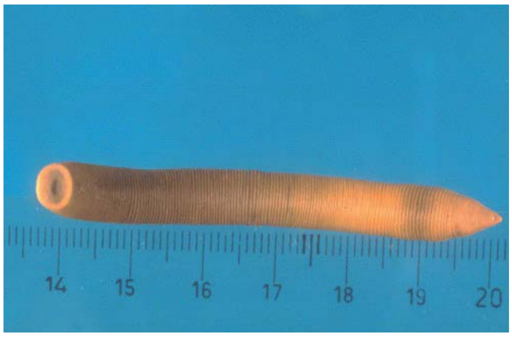


Fig.4: *Hirudinea* (leeches)

   b) Not worm like, less than < 15 segments
   - ***Beetle larvae***, generally with strongly developed head capsule (well-developed coronal structure). Often U-shaped and more or less swollen. (Fig. 5)

➢ ***Diptera larvae***, often without strongly developed head capsule. Long and thin, not U-shaped (Fig. 6)

Fig.5: *Beetle larvae*

Fig.6: *Diptera larvae* (larvae of certain flies)

LEGS

1. NO WINGS
   ➢ **3 pairs of legs: insect**
   - Caterpillar-like - soft and fleshy body
     - Pseudo-legs (4 pairs or fewer): *Lepidoptera larvae* (butterfly larvae) (Fig. 7)
     - No pseudo-legs: Beetle larvae (often U-shaped "grubs") (Fig. 8)

Fig.7: *Lepidoptera larvae*

Fig.8: *Beetle larvae*

- Abdomen > 6 segments, > 4 segmented antennae
  - Conspicuous pronotum (the upper dorsal plate of the first segment of thorax):
    i. Pronotum saddle-shaped, not projecting forward: *Orthoptera* (grasshoppers) (Fig. 9)
    ii. Pronotum not saddle-shaped, projecting forward over head: *Blattaria* (cockroaches) (Fig. 10)

Fig.9: *Orthoptera*

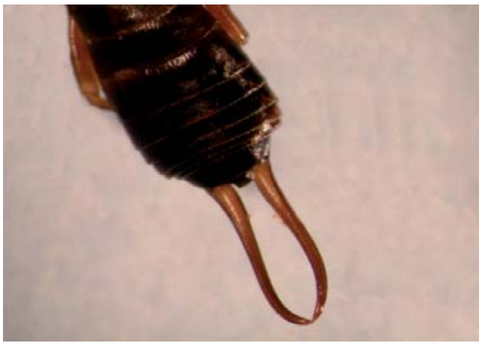
Fig.10: *Blattaria*

  - Pronotum not conspicuous:
    i. Mouthparts formed into sucking tube held under body, no palps: *Hemiptera* (such as lace bugs, aphids and woodlice) (Fig. 11)

Fig.11: *Hemiptera*

    ii. No tube, palps: Abdomen ends in a certain number of cerci (paired appendages on the rear-most segments of many arthropods) either:

a) 2 cerci
   * Curved into pincers: *Dermaptera* (earwigs) (Fig.12)
   * Long and thin, at least 1/3 length of abdomen, projecting from tip, Antenna short - < 2 x head width: *Coleoptera larvae* (Fig. 13)



Dermaptera (earwigs) (Fig.12)

* Short – maybe located forward of tip of abdomen:
  » Antenna long, 8 segments: *Isoptera* (blind poorly pigmented, sometimes with large mandibles [soldiers], legs fully developed, tropics and subtropics) (Fig. 14)

Fig.13: *Coleoptera larvae*

Fig.14: *Isoptera*

  » Antennae short, < 6 segments: *Beetle larvae*, flat, short antennae (< 8 segments) (Fig. 15)

Fig.15: *Beetle larvae*

b) No cerci; with a certain number of antennal segments:

* <6 antennal segments, with 3 clear thoracic segments: *Beetle larvae* (Fig. 16)

Fig.16: *Beetle Torax*

* >10 antennal segments, with wasp waist,
  » with1-2 petioles: *Ants* (Fig. 17)

Fig.17: *Ants*

  » no petiole: other *Hymenoptera* (bees and wasps)
* >10 antennal segments, with wasp waist,
  » Long and thin: *Phasmida* (stick and leaf insects) Fig. 18)
  » Long antennae, small: *Psocoptera* (bark lice) (Fig. 19)

Fig.18: *Phasmida*

Fig.19: *Psocoptera*

» Short antennae: *Beetle larvae* or *wingless adults* (Fig.20)

Fig.20: *Beetle larvae* or wingless adults

➢ **4 pairs of legs: Arachnida (sometimes pedipalps –the second pair of appendages of the head and thorax section– look like an extra pair)**

- Thorax and abdomen separated by a constricted waist, pedipalps without claws: *Spiders* (Fig. 21)
- Thorax and abdomen fused into one, without pedipalps
  - Body clearly segmented, with ocularium (eye-area tubercle): *Opilions* (very spider-like) (Fig. 22)

Fig.21: *Spiders*

Fig.22: *Opilions*

  - Body not segmented, without ocularium: *Acarina* (mites and ticks) (Fig. 23)

Fig.23: *Acarina* (mites)

- Pedipalps with claws
  - Large claws, telson (sting): *Scorpions* (Fig. 24)
  - Small claws, without telson: *Pseudoscorpions* (Fig. 25)

Fig.24: *Scorpions*

Fig.25: *Pseudoscorpions*

➢ 6/7pairs of legs: *Isopoda* (Fig. 26)

Fig.26: *Isopoda*

➢ more than >15 pairs of legs:
- One per segment: *Chilopoda* (centipedes, generally flattened) (Fig. 27)

Fig.27: *Chilopoda*

- Two per segment: *Diplopoda* (millipedes) generally more rounded, usually > 30 pairs of legs): (Fig. 28)

Fig.28: *Diplopoda*

2. WITH WINGS
   a) 2 wings; no appendage: *Diptera* adults
   (with halteres –small knobbed paired structures–) Fig. 29. *Diptera*

Fig.29: *Diptera*

b) 4 wings
- Mouthparts modified into sucking tube, no palps: *Hemiptera* (Fig.30)
- Biting mouthparts, palps

Fig.30: *Hemiptera*

- Forewings hardened to form a wing case
  - Hind legs long
    - i. Hind legs modified for jumping, head not partially covered by pronotum: *Orthoptera* (Fig. 31)
    - ii. Hind legs not modified for jumping, head partially covering pronotum: *Blattaria* (Fig. 32)

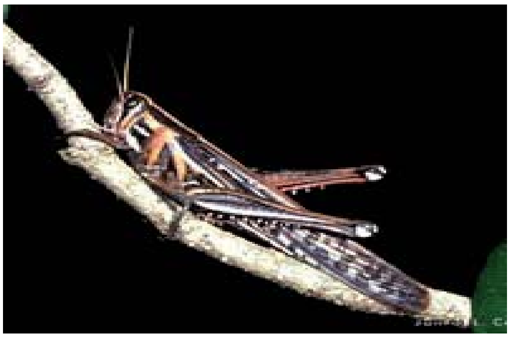


Fig.31 *Orthoptera*

Fig.32: *Blattaria*

  - Hind legs short
    - i. Abdomen with terminal pincers: *Dermaptera* (Fig. 33)

Fig.33: *Dermaptera*

    - ii. No pincers: *Coleoptera* (Fig. 34)

Fig.34: *Coleoptera*

- Forewings not hardened - hind legs modified for jumping, pronotum saddle shaped: Orthoptera (Fig. 31)

c) Other winged groups are rarely found in hand-sorted soil samples, but examples are shown: *Lepidoptera, Hymenoptera*,etc. (Fig. 35)

Fig.35: *Hymenoptera*

Glossary

Anecic
Anecic invertebrate species remove litter from the soil surface through their feeding activities. Considerable amounts of soil, mineral elements and organic matter may be redistributed through these activities, accompanied by physical effects on soil structure and hydraulic properties. Earthworms (large, dark antero-dorsal pigmentation and very muscular, with a wedge-shaped tail) and non soil-feeding termites are the main groups in this category, but also some arachnids.

Arthropods
Invertebrate animals (such as insects, arachnids, or crustaceans) having an exoskeleton, a segmented body and jointed limbs.

Autotroph (from the Greek *autos* = self and trophe = nutrition)
An organism that produces organic compounds from carbon dioxide as a carbon source, using either light or reactions of inorganic chemical compounds, as a source of energy. An autotroph is known as a producer in a food chain. Plants and other organisms that carry out photosynthesis are phototrophs (or photoautotrophs). Bacteria that use the oxidation of inorganic compounds such as hydrogen sulphide or ferrous iron as an energy source are chemoautotrophs.

Biogenic
A physical structure that is produced by living organisms or biological activity with important consequences in soil and ecosystem processes.

Bioremediation
The process by which living organisms act to degrade hazardous organic contaminants or transform hazardous inorganic contaminants to environmentally safe levels in soils, subsurface materials, water, sludges, and residues.

Bioturbation
The translocation of soil material within the soil profile mixing of above-ground litter with the mineral soil by animals or plants (roots).

Coprophagous
Feeding on dung or excrement (from the Greek *copros* = faeces and *phagein* = eat).

Decomposition
The biochemical breakdown of organic matter into organic compounds and nutrients, and ultimately into its original components.

Detritivore
Also known as saprophage, detrivore or detritus feeder (from the Latin, *detritus* = rubbed or worn away; *vorare* = to devour). It refers to an organism which feeds upon organic detritus of plant or animal origin, such as epigeic earthworms or dung beetles.

Diazotrophic
Organism that can use dinitrogen as its sole nitrogen source, i.e. capable of N_2 fixation.

Endogeic
Endogeic invertebrate species live in the soil and feed on organic matter and dead roots, also ingesting large quantities of mineral material. The two main groups are earthworms (light or no pigmentation and slow movers) and soil-feeding termites.

Entomopathogenic (from the Greek *entomon* = insect, and pathogenic = causing disease)
Insect-attacking organism.

Epigeic
Epigeic invertebrate species live and feed on the soil surface. These invertebrates affect litter breakdown and nutrient release. Mainly arthropods, for example: ants, beetles, cockroaches, centipedes, millipedes, woodlice, grasshoppers, together with gastropods (snails/slugs) and small or medium-sized entirely pigmented earthworms (dark red, green or brown colour, fast movers).

Exudates
Soluble sugars, amino acids and other compounds secreted by roots.

Heterotroph
An organism able to derive carbon and energy for growth and cell synthesis by utilizing synthesized organic compounds.

Humivorous
Organism feeding on the organic soil component.

Humus
It is the well-decomposed, relatively stable part of the organic matter, usually dark coloured. The term may refer to decaying plant material in advanced stages of decomposition; or the last stage of decomposition process, the humic compounds, i.e. where the more recalcitrant carbon components are found.

Invertebrate
Animal without a backbone (dorsal spine).

Litter
Upper layer of organic debris on the soil surface, essentially the freshly fallen or only slightly decomposed material (leaves, branches, bark fragments, twigs, etc).

Macro-invertebrates
Animals lacking a backbone and internal skeleton and that are visible to the naked eye, i.e. > 2 mm long, such as snails, earthworms, and insects.

Micro-arthropods
Micro-arthropods are small invertebrates (< 2 mm) with an exoskeleton. The most well known members of the micro-arthropod group are mites (Acari) and springtails (Collembola).

Micro-organism (microbe)
Living organism too small to be seen with the naked eye (< 0.1 mm); includes bacteria, fungi, protozoans, microscopic algae, and viruses.

Mineralization
The conversion of organic compounds into inorganic, plant-available compounds such as nitrates. This is accomplished by soil organisms as they consume organic matter and excrete wastes.

Mulch
The organic residues that are kept in the soil surface, not only to protect the soil from raindrops, but also to enhance infiltration, avoid weed development and provide nutrients to the soil.

Mycorrhiza (pl. mycorrhizae) – (from the Greek, *mycos* = fungus and *rhiza* = root)
The symbiotic association of certain fungi with roots. The fungi receive energy and nutrients from the plant. The plant receives improved access to water and some nutrients. Except for Brassicas (mustard, broccoli, canola) and Chenopods (beet, chard, spinach), most plants form mycorrhizal associations.

Necrophagous – (from the Greek, *nekros* = dead and *phagein* = to devour)
Pertaining to those organisms that feed on dead and/or decaying animals.

Organic matter
Any material that is part of, or originated from, living organisms. It includes plant residue, mulch, compost, and other materials.

Parasite
Organisms that live temporarily or permanently on or within other living organisms (plant or animal hosts) for the purpose of obtaining food.

Parasitism
A two species association in which one species, the parasite, lives on or in a second species, the host, for a significant period of its life and obtains nourishment from it. The parasite may or may not cause death to the host.

Pedogenic
Related to soil forming processes.

Pedology
The scientific study of soils, including their origins, characteristics, and uses form a physical point of view.

Phytoparasitic
Parasite on plants.

Phytophagous
Feeder on plants or materials of plant origin.

Phytosaprophagous
Feeding on decaying vegetable matter.

Predator
An animal that feeds on other animals.

Pronotum
The upper (dorsal), often shield-like, hardened body-wall plate of the prothorax, located just behind the head of an insect.

Rhizobacteria
Bacteria that colonize roots.

Rhizobia
Bacteria able to live symbiotically in roots of leguminous plants, from which they receive energy and often utilize molecular nitrogen. Collective common name for the genus *Rhizobium.*

Rhizophagous
Feeding on roots.

Rhizosphere
The area that is immediately (1-2 mm) around plant roots, including the roots itself. This is an area of intense microbial activity, where plants, microorganisms, other soil organisms, and chemistry, interact in complex ways.

Root nodule
A knoblike growth occurring on the roots, especially of leguminous plants, in which bacteria fix the atmospheric nitrogen and make it available in inorganic form for the plant.

Saprophagous (from the Greek, *sapros = rotten and phagein* = to eat)
Pertaining to organisms which feed on dead or decaying animal or vegetable matter.

Soil aggregation
The process whereby primary soil particles (sand, silt, clay) are bound together into large particles (soil aggregates), with secondary soil materials such as iron oxides, silica or organic matter, by physical and chemical forces and/or substances derived from root exudates and microbial activity. Soil aggregates are the building blocks of soil structure.

Soil macrofauna
Soil organisms visible to the naked eye (>2 mm diameter) that include those invertebrates that live in, feed in or upon the soil, the surface litter and their components (snails, earthworms and soil arthropods like ants, termites, millipedes, centipedes, pillbugs and other crustaceans, caterpillars, cicadas, ant-lions, beetle larvae and adults, fly and wasp larvae, earwigs, silverfishes, spiders, scorpions, crickets and cockroaches). A soil macrofauna group is an invertebrate group found within terrestrial soil samples which has more than 90 percent of its individuals visible to the naked eye.

Soil mesofauna
Soil organisms generally ranging in size from 0.1 to 2 mm in diameter. These include mainly micro-arthropods, such as pseudo-scorpions, protura, diplura, springtails, mites, small myriapods and the worm-like enchytraeids. Mesofauna have limited burrowing ability and generally live within soil pores, feeding on organic materials, microflora, microfauna and other invertebrates.

Soil microfauna
Soil-dwelling micro-organisms that cannot be seen with the naked eye (<0.1 mm diameter) extremely abundant, ubiquitous and diverse. The microfauna includes nematodes, protozoa, turbellarians, tardigrades and rotifers that generally live in the soil water films and feed on microflora, plant roots, other microfauna and sometimes larger organisms (e.g., entomopathogenic nematodes feed on insects and other larger invertebrates).

Soil microflora
The microflora includes algae, bacteria, archaea, cyanobacteria, fungi, yeasts, myxomycetes and actinomycetes that are able to decompose almost any existing natural material.

Soil organic matter (SOM)
The total organic matter in the soil. It can be divided into three general pools: living biomass of microorganisms, fresh and partially decomposed residues (the active fraction), and the well-decomposed and highly stable organic material (passive fraction). Surface litter is generally not included as part of soil organic matter.

Soil resilience
The capacity of a soil to recover its functional capacity after a disturbance.

Thorax
The insect body region behind the head which bears the legs and wings.

Vermicomposting *(Lombricompostage)*
Composting system based on intensive management of worms, usually in specialized containers. The soil-like by-product resulting from worms digesting organic matter can in turn be applied to plants.

Soil organisms are an integral part of agricultural ecosystems. The presence of a range of a diverse community of soil organisms is essential for the maintenance of fertile soils and productive lands for agriculture and forestry. However, one of the main gaps in agricultural management systems is the lack of awareness and understanding and hence inadequate management of soil biological processes to maintain and improve soil productivity. Soil organisms are responsible for a range of ecological functions and ecosystem services including: nutrient cycling and nitrogen fixation, control of pest and diseases, organic matter decomposition and carbon sequestration, maintenance of a good soil structure for plant growth and rainwater infiltration, detoxification of contaminants. An excessive reduction in soil biodiversity, especially the loss of species with key functions, may result in long-term degradation of soil and the loss of agricultural productive capacity. This manual provides information to help technical level staff, researchers and educators to assess soil health status, and provides some methods, tools and advice on how to sustain and improve soil quality under different farming systems. A major focus is placed on soil macrofauna, the visible part of the surprisingly rich soil life, and its activities in agricultural soils, as this is, firstly, reasonably representative of soil biodiversity as a whole (including micro- and meso-organisms and populations) and, secondly, is the part of soil life that can be readily observed and monitored in terms of effects of various management practices.