Chapter 1

The Inventory of Soil Biological Diversity: Concepts and General Guidelines

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Soil organisms and soil ecosystem services

Soil is the habitat of an array of organisms in all three taxonomic domains (sensu Woese et al, 1990) and many phyla. The taxonomic classification of living organisms is still controversial (e.g. Margulis and Schwartz, 1998; Cavalier-Smith, 1998, 2004), especially regarding the taxa to be created at higher levels, and the numbers of such higher categories (such as kingdom) to be considered, in addition to domain. However, whatever classification system is used, the diversity of soil biota is high at all levels of analysis (for reviews, see Swift et al, 1979; Lavelle, 1996; Brussaard et al, 1997; Wall, 2004, Bardgett, 2005; Moreira et al, 2006). Table 1.1 lists the main phyla of eukaryotic organisms and prokaryotes that are or can be represented in the soil community, with more than 1.5 million species for the eukaryotes and an estimated species richness far beyond 10,000 for the prokaryotes.

As it is neither practicable nor sensible to address all the organisms present when making an assessment of the biological health of soils (see Lawton et al, 1998), biota have been evaluated (relative to non-biotic agencies and between themselves) for their relative contribution to ecosystem processes (sensu Daily, 1997; Wall, 2004). These processes collectively support the provision of ecosystem services that contribute to the maintenance and productivity of ecosystems by their influence on soil quality and health (Hole, 1981; Lavelle, 1996, Brussaard et al, 1997; Kibblewhite et al, 2008). The processes can be grouped into four main aggregate ecosystem functions:

1 *Decomposition of organic matter* is largely brought about by the enzymatic activity of bacteria and fungi, but greatly facilitated by soil animals such as mites, millipedes, earthworms and termites, which shred the plant or animal residues and disperse microbial propagules. Together, the microorganisms and the animals involved in the

Table 1.1 *Number of described species in the main taxonomic categories of plants and of soil biota, and the main functional groups they represent*

Taxonomic categories[a] [Total number of extant phyla] (examples of soil organisms/common name)	*No of described species in the taxon (all habitats)*	*Functional group[b]*
Domain Eucarya		
Kingdom Plantae [12 phyla]	255,000	
Phylum Bryophyta (mosses)	10,000	1
Phylum Hepatophyta (liverworts)	6000	1
Phylum Filicinophyta (ferns)	12,000	1
Phylum Cycadophyta (gymnosperms)	185	1
Phylum Coniferophyta (gymnosperms)	550	1
Phylum Gnetophyta	70	1
Phylum Anthophyta (angiosperms)	235,000	1
Monocotyledons	65,000	1
Dicotyledons	130,000	1
Kingdom Animalia [37 phyla]	>10 million	
Phylum Tardigrada[d] (water bears)	750	2, 4
Phylum Mollusca[d]	99,000	
Class Gastropoda[d] (includes slugs and snails)	35,000–40,000	2, 4
Phylum Annelida[d] (segmented worms)	>18,000	
Class Polychaeta	9000	Very rare in soil
Class Oligochaeta (earthworms, enchytraeids)	8800	3, 4
Class Hirudinea (leeches)	500	4
Phylum Crustacea[d] [>6 classes]	45,000	
Class Malacostraca[d] (includes Order Decapoda with a hard calcified external skeleton)	25,000	Common only locally
Order Isopoda (wood mites, woodlice)	>11,000	5
Phylum Mandibulata (Arthropoda)		
Sub-Phylum Hexapoda (Insecta)	>900,000	
Order Archaeognata (bristletails)	350	4
Order Thysanura	700	4, 6
Order Blattoptera (cockroaches)	4000	4
Order Dermaptera (earwigs)	1800	2, 4, 6
Order Hemiptera	>80,000	2, 9
Sub-Order Homoptera (planthoppers, cicadas, aphids, shield bugs, true bugs)	55,000	2, 9
Sub-Order Heteroptera	25,000	2, 9
Order Isoptera (termites)	2800	3, 4
Order Orthoptera (grasshoppers, crickets, locusts)	23,000	2, 9
Order Thysanoptera (thrips)	6000	2, 9
Order Coleoptera (beetles)	>350,000	2, 4, 6, 9
Order Diptera (flies, mosquitos, gnats, midges)	>125,000	2, 4, 6, 9
Order Hymenoptera (ants, bees, wasps, sawflies)	115,000	
Family Formicidae (ants)	11,826	2, 3, 6
Order Lepidoptera (butterflies, moths, skippers)	180,000	2, 9
Order Trichoptera	12,000	Riparian only
Order Collembola (springtails)	7500	4, 7
Order Diplura (two-pronged bristletails)	659	2, 6
Order Protura	500	4, 7

Sub-Phylum Myriapoda (millipedes and centipedes)	15,162	
Class Diplopoda (millipedes)	10,000	4, 9
Class Chilopoda (centipedes)	2500	6
Class Symphyla	200	2, 7, 9
Class Pauropoda	700	4, 7
Sub-Phylum Chelicerata[d] [3 classes]	>100,000	
Class Arachnida [11 orders]	93,455	
Order Palpigradi (micro-whipscorpions)	80	6
Order Acari (mites)	45,000	2, 4, 6, 7, 9
Order Pseudoscorpionida (pseudoscorpions)	3235	6
Order Araneae (spiders)	40,000	6
Order Scorpionida (scorpions)	2000	6
Phylum Gastrotricha[d] (gastrotrichs)	400	7
Phylum Acanthocephala[d] (spiny-headed worms)	1000	Arthropod parasite
Phylum Rotifera[d] (wheel animals)	2000	4, 7
Phylum Nemertina[d] (ribbon worms)	900	Very rare in soil
Phylum Nematoda (nematodes, roundworms, pinworms)	15,000	2, 6, 7, 9
Phylum Plathyhelminthes[d] (helminthes, includes turbellarians)	25,000	2, 6
Kingdom Protoctista[c] [30 phyla]	Undetermined number	
Phylum Rhizopoda (amoebae, slime-moulds)	Undetermined number	7
Phylum Dinomastigota[d] (dinoflagellates)	4000	1, 7
Phylum Ciliophora (ciliates)	10,000	7
Phylum Discomitochondria (flagellates and zooflagellates)	800	1, 7
Phylum Diatomacea[d] (diatoms)	10,000	1
Phylum Oomycota (oomycetes)	Hundreds	5, 9
Phylum Rhodophyta (red algae)	4100	1
Phylum Chlorophyta (green algae)	16,000	1
Kingdom Fungi [6 phyla]	>70,000	
Phylum Microsporidia	1500	Parasites only
Phylum Chytridiomycota (chytrids)	1000	5, 9
Phylum Zygomycota (moulds)	1100	5
Phylum Glomeromycota (arbuscular mycorrhizal fungi)	204	5, 8
Phylum Basidiomycota (includes mushrooms and some yeasts)	>22,250	5, 8
Phylum Ascomycota (includes yeasts)	>30,000	5, 8
Domain Archaea[d] [4 phyla]	>344[f]	10
Domain Bacteria[e] [52 phyla]	>8398[f]	1, 5, 8, 9, 10

Notes: a Considering taxonomic categories from the highest to the lowest level: domain, kingdom, phylum, class, order, family, genus, species. Prokaryote (Domains Archaea and Bacteria) classification according to Woese et al (1990). Eucarya kingdoms classified according to Margulis and Schwartz, 1998. Fungi according to James et al (2006).

b Functional groups according to Table 1.2 (this chapter).

c Considered by some authors as Protists or Protozoa and Chromista.

d Includes soil and aquatic organisms.

e Rappé and Giovannoni (2003).

f National Center for Biotechnology Information: (www.ncbi.nlm.nih.gov, accessed 13 May 2007), excluding unclassified, uncultured and unspecified organisms; if these are included the corresponding richness will be 3090 and 79,342, respectively.

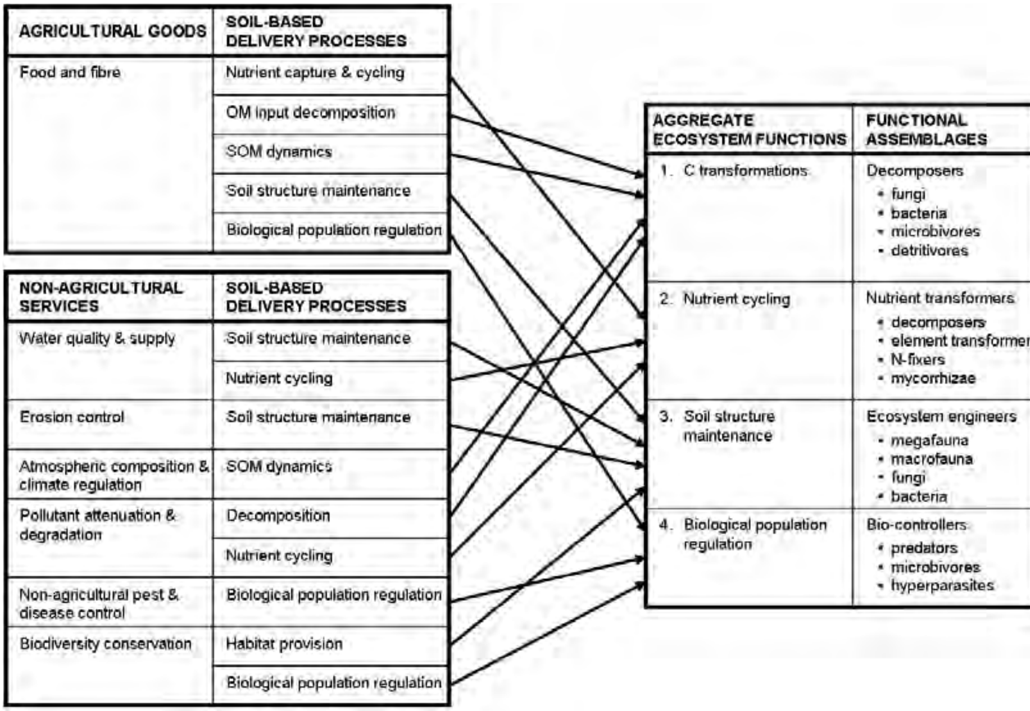
Source: After Moreira et al, 2006

process are called decomposers, but the term litter transformers has now come to be used to describe these animals, where they are not also ecosystem engineers (see below). As a result of decomposition, organic C is released into the atmosphere, predominantly as CO_2 or CH_4, but also incorporated into a number of pools within the soil as soil organic matter (SOM). These SOM fractions vary in their stability and longevity, but within a given soil type and environment a characteristic equilibrium exists between the SOM content and the inflows and outflows of C from the system.

2 *Nutrient cycling*, which is closely associated with organic decomposition. Here again the microorganisms mediate most of the transformations, but the rate at which the process operates is determined by small grazers (micropredators) such as protoctists, nematodes, collembolans and mites. Larger animals may enhance some processes by providing niches for microbial growth within their guts or excrement. Specific soil microorganisms also enhance the amount and efficiency of nutrient acquisition by the vegetation through the formation of symbiotic associations such as those of mycorrhiza and N_2-fixing root nodules. Nutrient cycling by the soil biota is essential for all forms of agriculture and forestry. Some groups of soil bacteria are involved in autotrophic elemental transformations, that is, they do not depend on organic matter directly as a food source, but may nonetheless be affected indirectly by such factors as water content, soil stability, porosity and C content, which the other biota control.

3 *Bioturbation*. Plant roots, earthworms, termites, ants and some other soil macrofauna are physically active in the soil forming channels, pores, aggregates and mounds, and moving particles from one horizon to another. These processes of 'bioturbation' influence and determine soil physical structure and the distribution of organic material. In so doing they also create or modify microhabitats for other, smaller, soil organisms and determine soil properties such as aeration, drainage, aggregate stability and water holding capacity. This set of organisms has therefore been called 'soil ecosystem engineers' (Stork and Eggleton, 1992; Jones et al, 1994; Lawton, 1996; Lavelle et al, 1997). Soil structure and properties are also influenced though the production by the animal engineers of faeces, comprising organo-mineral complexes that are stable over periods of months or more (Lavelle et al, 1997). Bioturbation plays a major role in the regulation of the water balance of the soil (infiltration, water storage capacity and drainage) and strongly influences its susceptibility to erosion.

4 *Disease and pest control*. The soil biota includes a wide range of viruses, bacteria, fungi and invertebrate animals capable of invading plants and animals (including humans) and causing disease and death. In natural ecosystems, intensive outbreaks of soil-borne diseases and pests are relatively rare, whereas such epidemics are common in agriculture. In healthy soils the activities of the potential pests and pathogens are regulated by interactions with other members of the soil biota, which include microbivores and micropredators that feed on microbial and animal pests respectively, as well as a wide variety of microbial antagonistic interactions. In agroecosystems this range of interactions may be reduced because of diminished biological diversity and/or soil environmental changes such as those caused by lowered SOM content.



Source: From Kibblewhite et al, 2008

Figure 1.1 *The relationship between the activities of the soil biological community and a range of ecosystem goods and services that society might expect from agricultural soils*

Figure 1.1 shows the contribution made by the soil biota to ecosystem goods and services as a result of the above processes. In particular it should be noted that the interaction between organic matter decomposition, bioturbation and nutrient cycling will determine the balance between the equilibrium amount of carbon sequestered in the soil (see above) and the emissions of greenhouse gases (principally CO_2, CH_4, NO_x, N_2O). Soil organisms thus play an important role in the regulation of atmospheric composition and hence are major players in climate change.

FUNCTIONAL GROUPS OF SOIL BIOTA

In principle, all the organisms listed as members of the soil community can be allocated to one or more of the four generic functional categories described above, based on the particular function they perform or the specific soil-based process they mediate. In order to link particular soil organisms (collectively soil biodiversity) to the generic functional categories and ultimately the ecosystem services (e.g. Setäla et al, 1998), we resort to the concept of key functional groups, usually defined on trophic criteria (Brussaard, 1998) but qualified by morphological, physiological, behavioural, biochemical or environmental responses, and to some extent by taxonomic character.

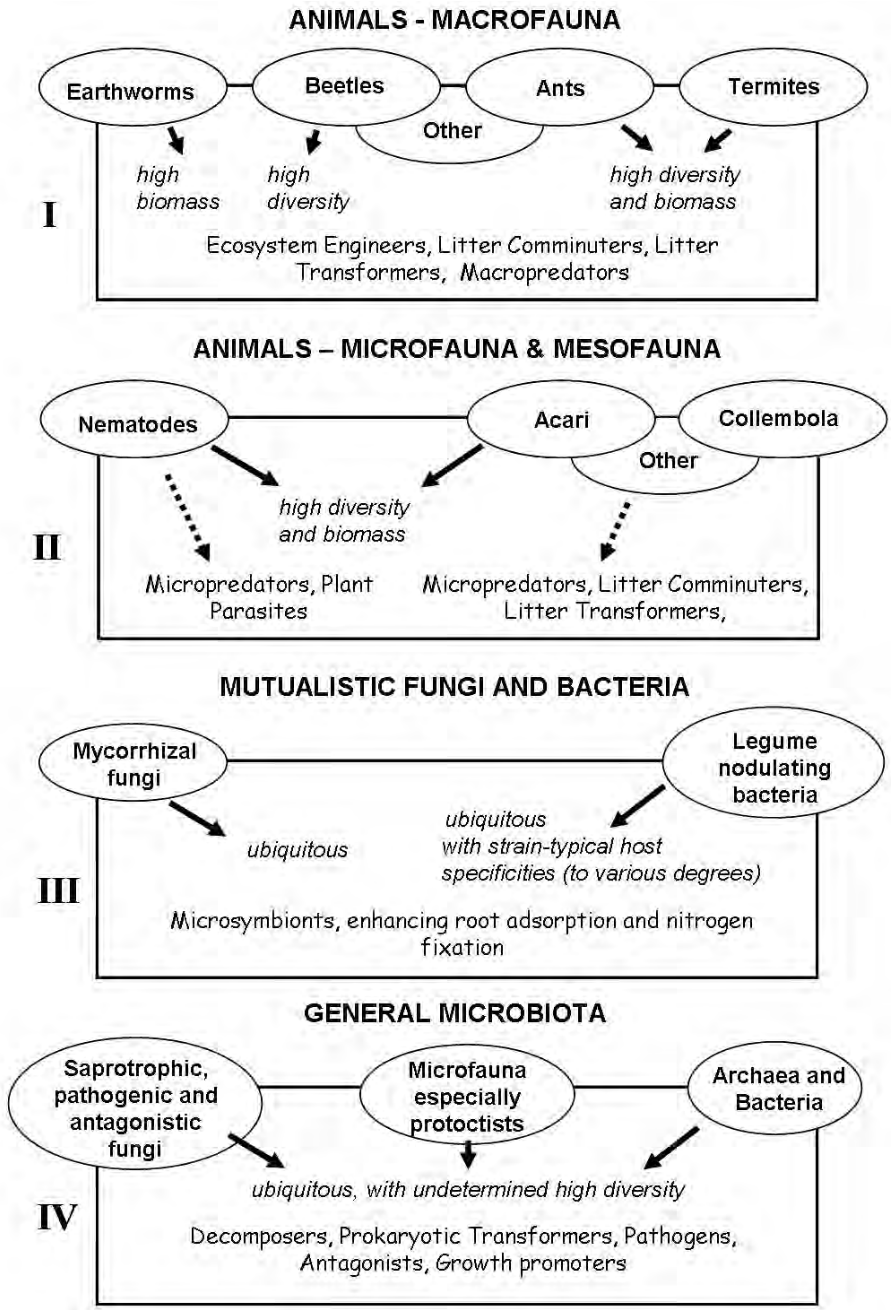
Table 1.2 *Key functional groups of soil biota*

1. **Primary producers** (higher and lower plants): photosynthetic organisms assimilating carbon dioxide from the air, penetrating the soil with rooting systems and translocating organic compounds synthesized above ground.
2. **Herbivores:** animals consuming and partly digesting living plant tissues, including leaf miners and rollers, stem borers and sap suckers.
3. **Ecosystem engineers** (e.g. macrofauna such as termites and earthworms): organisms that have major physical impact on soil through soil transport, building of aggregate structures and formation of pores – as well as influencing nutrient cycling. Can include predators (e.g. many ants).
4. **Litter transformers** (many macrofauna and mesofauna, but some microfauna): invertebrates feeding on microbially conditioned organic detritus and shredding this material (comminution) and making it more accessible to decomposers, or promoting microbial growth in pelletized faeces. This activity can be performed at several spatial scales.
5. **Decomposers** (e.g. cellulose-degrading fungi or bacteria): micro-organisms possessing the polymer-degrading enzymes that are responsible for most of the energy flow in the decomposer food web.
6. **Predators** (many macrofauna and mesofauna): animals which regulate herbivores, ecosystem engineers, litter transformers, decomposers and microregulators through predation.
7. **Microregulators** (e.g. microfauna such as nematodes): animals that regulate nutrient cycles through grazing and other interactions with the decomposer microorganisms.
8. **Microsymbionts** (e.g. mycorrhizal fungi, rhizobia): microorganisms associated with roots that enhance nutrient uptake.
9. **Soil-borne pests and diseases** (e.g. fungal pathogens, invertebrate pests): biological control species (e.g. predators, parasitoids and hyperparasites of pests and diseases) can also be included.
10. **Prokaryotic transformers:** archaea and bacteria performing specific transformations of carbon (e.g.methanotrophy) or nutrient elements such as N, S or P (e.g. nitrification, nitrogen fixation).

There is no precise agreement on the definition of the functional groups and how many of these groups should be discerned within in a typical soil environment, so the concept is heuristic and can be modified for whatever analytical purpose is in hand, but a good case can be made for at least ten categories. These are presented formally in Table 1.2 and used to annotate the taxonomic categories listed in Table 1.1. Note that some functional groups include a wide range of related and sometimes unrelated taxa, while others have high taxonomic specificity. For this reason, and because many components of soil biota are taxonomically intractable, there have been few studies of agricultural soil health in which the whole taxonomic spectrum has been sampled representatively in the same place and at the same time (Bignell et al, 2005).

Target groups of soil biota

In designing fieldwork the challenge is to select a subset of the soil biota that adequately reflects the anticipated taxonomic spectrum, and which at the same time includes all the functional groups considered important. The functional importance of any species or group of species is likely to be related to their relative abundance and biomass, so assess-



Note: Fauna are classified according to body width: macrofauna >2.0mm; mesofauna 0.1–2.0mm; microfauna <0.1mm. Alternatively, nematodes and protoctists can be considered as components of the general microbiota, a group which includes many organisms with specialist roles, as well as a diversity of generic decomposers.

Figure 1.2 *Main functional groups studied in the CSM-BGBD project classified according to domains and kingdoms, size and related ecosystem processes* ing presence/absence alone is insufficient to the above purposes. Nonetheless it is also important to also look within functional groups to discover those taxa that meet the criteria to be considered ecosystem engineers (sensu Jones et al, 1994), and keystone species (sensu Davic, 2003).

The taxonomic groups nominated below are thus selected on the basis of their diverse functional significances to soil fertility and soil quality (hence the term 'target taxa'); and their relative ease of sampling, isolation and identification (Figure 1.2). These are the taxonomic groups that were addressed in the Conservation and Sustainable Management of Below-ground Biodiversity project (CSM-BGBD) and for which methods of inventory and characterization are provided in the subsequent chapters. Furthermore, a number of these taxonomic groups are very important in their own right as contributors to overall biotic diversity, for example beetles, ants, enchytraeid worms, spiders, mites, nematodes and (probably) protoctists (protists), all of which comprise large numbers of species in comparison with other higher taxonomic groups (Table 1.1). In this context, the geographical distribution, the introduction of exotic and invasive species and loss of endemic species then also become a concern.

The target groups included are:

1. *Macrofauna – earthworms*, which influence both soil porosity and nutrient relations through tunnelling, and ingestion of mineral and organic matter, and which act as regulators of soil biotic populations at smaller spatial scales, for example mesofauna, microfauna and microsymbionts.
2. *Macrofauna – termites*, *ants* and *beetles*, which influence or mediate a) soil porosity and texture through tunnelling, soil ingestion and transport, and gallery construction, b) nutrient cycles through transport, shredding and digestion of organic matter, and c) biological control as predators.
3. *Other macrofauna* such as woodlice (Isopoda), millipedes (Diplopoda) and some types of insect larvae, which act as litter transformers, with an important shredding action on dead plant tissue, and their predators (centipedes, larger arachnids, some other types of insect). Some species can also have detrimental effects by becoming pests.
4. *Mesofauna*, such as collembolans and mites, which act as litter transformers and micropredators (grazers of fungi and bacteria, and predators of other soil animals), thus contributing to smaller-scale organic comminution processes and exerting a strong regulatory role within the soil biota. Some species of mites and the larval forms of many soil arthropods are small enough to be classified as microfauna.
5. *Microfauna* – such as nematodes and protoctists, which a) influence turnover in their roles as root grazers (plant parasites), fungivores, bacterivores, omnivores and predators, b) occupy existing small pore spaces in which they are dependent on water films, c) usually have very high generic and species richness, d) have a strong role in the regulation of microbial abundance and activity, and e) as insect pathogens are important as a source of biological control.
6. *Arbuscular mycorrhizal fungi*, which associate with plant roots, improving nutrient availability, and reducing attacks by plant pathogens as well as improving tolerance to environmental stresses.
7. *Legume-nodulating bacteria* and, when relevant, other N-fixing microsymbionts, which transform atmospheric N_2 into NH_3, which is a form available for plant growth.

8 *Phytopathogenic, saprotrophic* and *antagonistic fungi*, which determine or mediate (in different cases) crop viability, the turnover of organic carbon during decomposition, and plant diseases, and contribute to the potential biological control of pests and diseases.

METHODS FOR INVENTORY OF BELOW-GROUND BIODIVERSITY: GENERAL PRINCIPLES

Current methodology does not allow for the identification of all species in the soil environment. In many phyla the majority of species are still unknown. The species concept is also highly variable across the soil biota – for instance between the bacteria, the fungi and the invertebrate animals. In the cases of the Archaea and Bacteria, molecular and biochemical characterization now replaces traditional identification approaches. The methods employed for extracting the different groups of organisms from the soil are also very different from one group to another. These factors, plus the sheer scale of the diversity found in the soil, necessitate a selective approach to below-ground biodiversity inventory, using the concept of key functional groups as described above.

It is as yet an unresolved question what relationship exists between species diversity, functional diversity (the number of functional groups), functional composition (the nature of the functional groups) and the occurrence and intensity of ecological processes. One would expect ecosystem services that rely on functional groups that are composed of relatively few species and/or are highly specialized to be most vulnerable to stress and disturbances that affect these functional groups. To the best of our knowledge this holds for shredders of organic matter (see litter transformers in Table 1.2), nitrifying and denitrifying bacteria (as part of the prokaryotic transformers), bacteria involved with C1 compound and hydrogen transformations (e.g. methanogenic, methylothrophic), iron, copper and sulphur chemolithotrophs, mycorrhizal fungi (among the microsymbionts) and bioturbators (i.e. ecosystem engineers) – in contrast with the high diversity and functional redundancy of the majority of decomposers. This invokes questions like 'what is the minimum number of species within functional groups to ensure soil ecosystem resilience against natural and anthropogenic stress', and in relation to that 'what are the key species (if any) within functional groups'. This invites evaluation of the effectiveness of an individual species in performing a particular function. Therefore, when adopting the concept of key functional groups, questions like those above should be considered in defining the purpose for the investigation of below-ground biodiversity, and will reflect upon the methods to be used.

Standard methods are needed to describe ecosystems in a consistent manner. This manual addresses the methods for the inventory and characterization of below-ground biodiversity, focusing on functional groups and allowing for assessment of diversity, abundance and species composition. Assessments of biotic community compositions are dependent on the positive identification of the collected specimens; this requires a high level of available taxonomic expertise, which for some groups and in some countries is a major challenge. Taxonomic issues are not addressed in this handbook, though references are provided for keys to the identification of species in the various functional groups.

More specifically, the methods have been developed or chosen and modified for use in landscapes of varying land use in order to provide means of assessing the impact of (for instance) agricultural intensification, habitat fragmentation and cropping management on soil biological diversity, but should serve to answer a range of questions in similar contexts. A brief description of the project for which the methods were developed and tested is given in the Preface.

Inventory of below-ground biodiversity across space and timescales

Land use change as the primary driver of changes in soil biological diversity

An inventory may demonstrate whether soil biota are responsive to human-induced disturbances such as agricultural practices, deforestation, pollution and climate change. If so, there may then be many negative consequences in terms of diminished delivery of ecosystem services, including loss of primary productivity through changes in soil fertility and/or increases in soil-borne disease, loss of cleansing potential for wastes and pollutants, disruption of global elemental cycles, and feedbacks on greenhouse gas fluxes and erosion. Global food supply depends on intensive agriculture; as intensification proceeds above-ground biodiversity is reduced, with consequences for the below-ground biodiversity and thence the biological regulation of soil-based ecosystem services. These regulatory functions are often described as being 'substituted' by inputs such as the use of mechanical tillage, chemical fertilizers and pesticides (Kibblewhite et al, 2008). This is also assumed to reduce below-ground diversity, which if accompanied by the extinction of individual species may cause losses of function and reduce the ability of agricultural systems to withstand unexpected periods of stress, bringing about undesirable effects. Large numbers of farmers in the tropics have limited access to inputs but in an attempt to intensify production the complexity of their agroecosystems has become drastically reduced nonetheless. An alternative solution is to intensify while at the same time retaining a greater degree of above-ground diversity. The maintenance of diversity of crops and other plants in cropping systems is widely accepted as a management practice that buffers farmers against short-term risk. Enhanced biodiversity and complexity above ground contributes to the re-establishment or protection of the multiplicity of below-ground organisms able to carry out essential biological functions. This can be considered at both the field and the landscape level to enhance structural complexity and functional diversity, especially in degraded lands.

What to sample for, where and when

Although this is a manual of practical instruction, such practice must as far as possible reflect the consensus of ecological theory, and in particular current thinking about community structures at different spatial and temporal scales that determine the provision of ecosystem services. However, the processes of disturbance (and recovery) that affect below-ground biodiversity also manifest themselves at different spatial and temporal scales (i.e. various frequencies) that are often linked. The central tenet is that the functional significance of biological diversity changes across scales in space and time (Swift et al, 2002, Lavelle et al, 2004). Broadly, this means that what is measured, and where and when it is measured, has to take account of the features of biodiversity that are likely to affect overall ecosystem services in different types of comparison.

The aim should be to reduce intra-group variability and maximize variability between groups. The major challenge then is how to define these 'groups' in relation to spatial and temporal scale levels such that this is achievable. For example, we may expect a large variation in numbers and diversity of earthworms, moving from one plot to the other or from the field to the hedge at field boundary, while for the land use zone, that combines these elements within the land use system, the numbers or diversity may remain stable. That is to say that inventory of the earthworm species of any particular plot may fall well short of the purpose of assessment of the diversity of the whole area, as might be needed if the objective of the inventory is for conservation of below-ground biodiversity. Likewise, the difference in decomposition rate or symbiotic nitrogen fixation between two spadefuls of soil from the same field is probably a question of which microorganisms are present in each, but between two adjacent fields in the same landscape it could be a matter of drainage or site management history or equally well whether termites or some other ecosystem engineer were more active in one site than the other.

Between two landscapes or two regions we would expect climate and parent material to be the main determining factors in soil forming processes. Soil formation at the regional scale is one of the ecosystem services that integrate processes over all scales. The climate, parent materials and soils will be the major determinants of all ecosystem services at the landscape level, but there might be a significant biotic influence if one or more important functional group were missing or depleted in a particular one location, or if the parent forest ecosystem had been reduced to a relict in one place but maintained in a mixed landscape at the other.

Temporal scales are important for degradation processes (for example the progressive loss of macropores, the erosion of finer soil particles and the depletion of complex organic matter may ultimately destroy productive capacity beyond recovery) and also for rehabilitation (the life cycles of different biotic taxa vary from hours to years, and may incorporate obligate dormancies, while fecundities also vary and therefore the time required for a growing population to reach a minimum critical size where it can become self-sustaining will also be different from one organism to another). The main theoretical concepts that correspond to these concerns are openness and connectivity, and are discussed in detail for soil and sediment ecosystems by Wall (2004). Their impacts on the design of our own sampling and measurement protocols are strongly reflected in Chapter 2 of this manual.

The four levels of spatial scale for sampling given below are those used in the CSM-BGBD project (see Preface) and are given as an example. Every project will need to determine the scales appropriate to its own objectives. Table 1.3 provides a summary of the hierarchy levels (modified from those proposed by Lavelle et al, 2006), the related processes of change that will effect below-ground biodiversity (and associated ecosystem services) and the component of below-ground biodiversity of particular relevance at that level.

1 *Landscape.* At the highest level the spatial distribution of below-ground biodiversity will be strongly influenced by gradients in altitude (and temperature), gradients or transitions in moisture and gradients in soil properties derived from mineral base and vegetation. The land use pattern superimposed on these effects of climate,

geology, vegetation and soil will be a further major determinant at this level. The spatial characteristics of the land use distribution (e.g. patchiness of the land use components like forest) will also have an important influence on the biodiversity. The inventory of below-ground biodiversity at a landscape scale must therefore capture the distribution, sizes and shapes of these gradients and patches in order to explain possible variation in below-ground biodiversity.

At the landscape level it is difficult to evaluate the effect of below-ground biodiversity on the provision of some ecosystem services like 'water quality and supply' or 'erosion control' and it is unlikely to be important compared with effects of the vegetation. Below-ground biodiversity, including the discovery of exotic invading species, is in this case thus more useful as an indicator of soil response to management. Protection and conservation of key (agro) ecosystems and habitats are the main option for intervention. Timescales for these processes (e.g. change in land use composition and landscape configuration) to take effect may vary between years (exceptionally) and hundreds of years.

2 *Land use zone*. Land use zones are defined as areas with a particular land use and management regime (Huising, 1993), for example a zone with commercial tea plantations or an area characterized by smallholder subsistence agriculture. These zones are typically characterized by a particular combination of land-cover types. The above-ground biodiversity is determined by the variety of crops grown in the area and vegetative elements associated with fallows, windbreaks, hedgerows, woodlots and other managed landscape features. Lateral interactions are an important component for below-ground biodiversity and the way the system functions, most notably when the agriculture is agroforestry. Gradients in soil properties do occur at this level, but are associated with management; for example Vanlauwe et al (2006) and Tittonell et al (2007) describe soil fertility gradients as the result of variable resource allocation within farm. It is, therefore, at this level that below-ground biodiversity should be studied in the greatest detail with respect to land use change. Land use intensification is typically associated with the removal of vegetative elements such as on-farm trees, with loss of their inputs and impacts, for instance the niches for particular soil organisms which the trees provide. Thus the relation between the spatial distribution patterns of the above-ground biota and those of below-ground species are of particular interest. At this level the timescales in which changes related to land use and land cover characteristics occur are shorter, ranging from a few years to several decades.

3 *Plot or patch*. At the plot level the functional composition and activities of the biota are of particular interest and, as far as the inventory of below-ground biodiversity is concerned, so are the relative abundances of species belonging to the various trophic levels and functional groups that govern the stability of foodwebs and provision of support functions. At this level, community structure and interactions are regulated by the local (plot-specific) architecture of the soil (Lavelle et al, 2006). The plot or patch (if not too big) is within the functional domains of ecosystem engineers, including plant roots. Changes in the soil architecture, whether brought about by changes in the functional composition and activity of the ecosystem engineers or tillage of the soil, will have an effect on the trophic interactions and thereby on the (structure of the) foodweb. Organic matter input management and the use of agrochemicals will further impact the foodweb structure.

Inoculation of any kind directly impacts below-ground biodiversity and can therefore be aimed to correct for imbalances in the functional compositions (or even to enhance particular functions) and the foodweb (e.g. introduction of predators to control a particular disease). Such intervention should therefore be informed by the inventory and relative abundances of species belonging to defined functional groups or levels in the food chain. At the plot level the underlying delivery processes mediated by soil organisms for the provision of support services, such as soil structure maintenance and organic matter input decomposition, have relatively short timescales and will show seasonal variation. Structural changes within the biotic community (foodweb connections, functional composition) may take place within years.

4 *Sub-plot niche or microhabitat*. This level refers to the microhabitats that accommodate the microbes and the microfaunal components of the soil system which regulate them. These exist at the scale of the soil horizon, the individual aggregate and the individual particle, and are segregated into functional domains (e.g. rhizosphere, drilosphere, termitosphere, etc.), reflecting the dependence of the smallest organisms on the ecosystem engineers for the provision of their substrates (for detailed concepts and terminology see Lavelle and Spain, 2001). Functional redundancy (different species or strains performing the same function) amongst the primary transformers, competition and efficiency are of particular relevance here, and in relation to this the degree of genetic diversity within the microorganisms is also of interest. Options for management interventions at the sub-plot scale are currently limited, mainly inoculation with microbial species, but an understanding of the processes and interactions is ultimately vital, as this is the most fundamental unit of soil function.

The 'interventions' listed in Table 1.3 are partly derived from the concept of 'hierarchical management of soil biota' as described by Swift (1998). The list of interventions and measurements related to below-ground biodiversity does not aim to be exhaustive, but rather illustrative, and there is a certain overlap between scale levels in the parameters to be measured.

Data requirement

The methods in this manual provide for the assessment of a large number of parameters of below-ground biodiversity. Irrespective of the specific objectives and experimental design of any study, data will still have to be gathered per sampling point, for which the best available methods consistent with a sensible use of time and resources are given in Chapters 3 to 10. Overall, the inventory of below-ground biodiversity using the methods in this manual may provide the following data and information, depending on the type of analyses performed:

Concerning biodiversity:

- taxonomic richness at species or higher, or lower (e.g. strain for microsymbiont) level;
- abundance (all) and biomass (for animals) of taxa;
- abundance and biomass of functional groups (FGs);

Table 1.3 *Hierarchical levels in inventory and management of below-ground biodiversity, reference units, associated process of change and relevant biodiversity components*

Layer or aggregation level	*Type of unit*	*Number of classes or units*	*Process/intervention*	*Measurement/ biodiversity parameter*
Landscape	Area characterized by mosaic of land uses and of ecosystems like larger watershed	Unspecified; maybe several per biome or region within a country	Land use conversion; protection of land uses and landscape elements of particular relevance to biodiversity and to maintain provision of ecosystem services (e.g. forest patches, biological corridors)	Soil biological diversity; exotic and invasive species
Land use zone	Area with characteristic land use and land cover pattern and management regime	3–20 types of land use zones within a particular landscape (depending on the level of detail of the classification)	Land use intensification, land degradation; maintaining biological refuge areas and above-ground biodiversity, Integrated Natural Resources Management and land conservation practices	Functional diversity, species diversity and composition esp. with respect to ecosystem engineers; spatial distribution pattern
Plot, Patch	Area with a particular use and management, e.g. agricultural field, vegetation plots, woodlot, etc.	10s to 100s per land use zone	Intensification of land and crop management, erosion; improved cropping systems and organic matter management, minimum tillage etc., inoculation	Relative abundance of species within and between functional groups and trophic levels; functional composition
Niche, Microhabitat	e.g. soil horizons, rhizosphere, drilosphere		Management of keystone biota; introduction of biological control agents, inoculation with microsymbionts	(Microbial) biomass and activity; genetic diversity

- relative proportions of FGs;
- overall quantitative indices of richness and evenness.

Concerning soil, land use, land use intensity, and land cover:

- apparent cropping or fallow usage;
- current land and crop management practices;
- basic physical and chemical soil properties; slope and aspect;

- above-ground vegetation character;
- climatic averages and actual rainfall to sampling date;
- precise history of use since undisturbed forest or other pre-cultural vegetation.

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