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Soil biodiversity: functions, threats and tools for policy makers

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EXECUTIVE SUMMARY

Human societies rely on the vast diversity of benefits provided by nature, such as food, fibres, construction materials, clean water, clean air and climate regulation. All the elements required for these ecosystem services depend on soil, and soil biodiversity is the driving force behind their regulation. With 2010 being the international year of biodiversity and with the growing attention in Europe on the importance of soils to remain healthy and capable of supporting human activities sustainably, now is the perfect time to raise awareness on preserving soil biodiversity. The objective of this report is to review the state of knowledge of soil biodiversity, its functions, its contribution to ecosystem services and its relevance for the sustainability of human society. In line with the definition of biodiversity given in the 1992 Rio de Janeiro Convention¹, soil biodiversity can be defined as the variation in soil life, from genes to communities, and the variation in soil habitats, from micro-aggregates to entire landscapes.

→ THE IMPORTANCE OF SOIL BIODIVERSITY

Soil biodiversity organisation

Soils are home to over one fourth of all living species on earth, and one teaspoon of garden soil may contain thousands of species, millions of individuals, and a hundred metres of fungal networks. Bacterial biomass is particularly impressive and can amount to 1-2 t/ha – which is roughly equivalent to the weight of one or two cows – in a temperate grassland soil.

For the sake of simplicity, this report has divided the organisms and microorganisms that can be found in soil into **three broad functional groups** called chemical engineers, biological regulators and ecosystem engineers.

Most of the species in soil are microorganisms, such as bacteria, fungi and protozoans, which are the **chemical engineers** of the soil, responsible for the decomposition of plant organic matter into nutrients readily available for plants, animals and humans.

Soils also comprise a large variety of small invertebrates, such as nematodes, pot worms, springtails, and mites, which act as predators of plants, other invertebrates or microorganisms, by regulating their dynamics in space and time. Most of these so-called **biological regulators** are relatively unknown to a wider audience, contrary to the larger invertebrates, such as insects, earthworms, ants and termites, ground beetles and small mammals, such as moles and voles, which show fantastic adaptations to living in a dark belowground world. For instance, about 50 000 mite species are known, but it has been estimated that up to 1 million species could be included in this group.

¹ "Biological diversity" means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

Earthworms, ants, termites and some small mammals are **ecosystem engineers**, since they modify or create habitats for smaller soil organisms by building resistant soil aggregates and pores. In this way, they also regulate the availability of resources for other soil organisms since soil structures become hotspots of microbial activities. Moles for instance, are capable of extending their tunnel system by 30 cm per hour and earthworms can produce soil casts at rates of several hundreds of tonnes per ha each year.

Chemical engineers, biological regulators and ecosystem engineers act mainly over distinct spatio-temporal scales, which provide a clear framework for management options. This is because the size of organisms strongly determines their spatial aggregation patterns and dispersal distances, as well as their lifetimes, with smaller organisms acting at smaller spatio-temporal scales than larger ones. Thus, chemical engineers are typically influenced by local scale factors, ranging from micrometres to metres and short-term processes, ranging from seconds to minutes. Biological regulators and soil ecosystem engineers, on the other hand, are influenced essentially by factors acting at intermediate spatio-temporal scales, ranging from a few to several hundreds of metres and from days to years. This provides land managers with two distinct management options for soil biodiversity: direct actions on the functional group concerned, or indirect actions at greater spatio-temporal scales than that of the functional group concerned.

Factors influencing soil biodiversity

The activity and diversity of soil organisms are regulated by a hierarchy of abiotic and biotic factors. The main abiotic factors are climate, including temperature and moisture, soil texture and soil structure, salinity and pH. Overall, climate influences the physiology of soil organisms, such that their activity and growth increases at higher temperatures and soil moistures. As climate conditions differ across the globe and also, in the same places, between seasons, the climatic conditions to which soil organisms are exposed vary strongly. Soil organisms vary in their optimal temperature and moisture ranges, and this variation is life-stage specific, e.g. larvae may prefer other optima than adults. For instance, for springtails, the optimum average temperature for survival is just above 20 °C, and the higher limit is around 50 °C, while some bacteria can survive up to 100 °C in resistant forms. Soil texture and structure also strongly influences the activity of soil biota. For example, medium-textured loam and clay soils favour microbial and earthworm activity, whereas fine textured sandy soils, with lower water retention potentials, are less favourable. Soil salinity, which may increase near the soil surface, can also cause severe stress to soil organisms, leading to their rapid desiccation. However, the sensitivity towards salinity differs among species, and increased salinity may sometimes have positive effects, by making more organic matter available. Similarly, changes in soil pH can affect the metabolism of species (by affecting the activity of certain enzymes) and nutrient availability, and are thereby often lethal to soil organisms. The availability of phosphorus (P), for example, is maximised when soil pH is neutral or slightly acidic, between 5.5 and 7.5.

Soil organisms influence plants and organisms that live entirely aboveground, and these influences take place into two directions. Plants can strongly influence the activity and community composition of microorganisms in the vicinity of their roots (called the rhizosphere). In turn, plant growth may be limited, or promoted by these soil microorganisms. Added to this, plants can influence the composition, abundance and activity of regulators and ecosystem engineers, whereas these

species in turn can influence vegetation composition and productivity. Finally, soil organisms can induce plant defence responses to aboveground pests and herbivores and the aboveground interactions can feed back in a variety of ways to the biodiversity, abundance and activities of the soil organisms. In addition, within the soil food webs, each functional group can be controlled by bottom-up or top-down biotic interactions. Top-down effects are mainly driven by predation, grazing, and mutualist relationships. Bottom-up effects depend largely on competitive interactions for access to resources.

Services provided by soil biodiversity

Many of the functions performed by soil organisms can provide essential services to human society. Most of these services are supporting services, or services that are not directly used by humans but which underlie the provisioning of all other services. These include nutrient cycling, soil formation and primary production. In addition, soil biodiversity influences all the main regulatory services, namely the regulation of atmospheric composition and climate, water quantity and quality, pest and disease incidence in agricultural and natural ecosystems, and human diseases. Soil organisms may also control, or reduce environmental pollution. Finally, soil organisms also contribute to provisioning services that directly benefit people, for example the genetic resources of soil microorganisms can be used for developing novel pharmaceuticals. More specifically, the contributions of soil biodiversity can be grouped under the six following categories:

- **Soil structure, soil organic matter and fertility:** soil organisms are affected by but also contribute to modifying soil structure and creating new **habitats**. Soil organic matter is an important ‘building block’ for soil structure, contributing to soil aeration, and enabling soils to absorb water and retain nutrients. All three functional groups are involved in the formation and decomposition of soil organic matter, and thus contribute to structuring the soil. For example, some species of fungi produce a protein which plays an important role in soil aggregation due to its sticky nature. The decomposition of soil organic matter by soil organisms releases nutrients in forms usable by plants and other organisms. The residual soil organic matter forms humus, which serves as the main driver of soil quality and fertility. As a result, soil organisms indirectly support the quality and abundance of plant primary production. It should be underlined that soil organic matter as humus can only be produced by the diversity of life that exists in soils – it cannot be man-made. When the soil organic matter recycling and fertility service is impaired, all life on earth is threatened, as all life is either directly or indirectly reliant on plants and their products, including the supply of food, energy, nutrients (e.g. nitrogen produced by the rhizobium bacteria in synergy with the legumes), construction materials and genetic resources. This service is crucial in all sorts of ecosystems, including agriculture and forestry. Plant biomass production also contributes to the water cycle and local climate regulation, through evapo-transpiration.
- **Regulation of carbon flux and climate control:** soil is estimated to contain about 2,500 billion tonnes of carbon to one metre depth. The soil organic carbon pool is the second largest carbon pool on the planet and is formed directly by soil biota or by the organic matter (e.g. litter, aboveground

residues) that accumulates due to the activity of soil biota. Every year, soil organisms process 25,000 kg of organic matter (the weight of 25 cars) in soil in a surface area equivalent to a soccer field.

Soil organisms increase the soil organic carbon pool through the decomposition of dead biomass, while their respiration releases carbon dioxide (CO₂) to the atmosphere. Carbon can also be released to the atmosphere as methane, a much more powerful greenhouse gas than CO₂, when soils are flooded or clogged with water. In addition, part of the carbon may leak from soils to other parts of the landscape or to other pools, such as the aquatic pool. Peatlands and grasslands are among the best carbon storage systems in Europe, while land-use change, through the conversion of grasslands to agricultural lands, is responsible for the largest carbon losses from soils.

Although planting trees is often advocated to control global warming through CO₂ fixation, far more organic carbon is accumulated in the soil. Therefore, besides reducing the use of fossil fuels, managing soil carbon contents is one of the most powerful tools in climate change mitigation policy. The loss of soil biodiversity, therefore, will reduce the ability of soils to regulate the composition of the atmosphere, as well as the role of soils in counteracting global warming.

- Regulation of the water cycle:** soil ecosystem engineers affect the infiltration and distribution of water in the soil, by creating soil aggregates and pore spaces. Soil biodiversity may also indirectly affect water infiltration, by influencing the composition and structure of the vegetation, which can shield-off the soil surface, influence the structure and composition of litter layers and influence soil structure by rooting patterns. It has been observed that the elimination of earthworm populations due to soil contamination can reduce the water infiltration rate significantly, in some cases even by up to 93%. The diversity of microorganisms in the soil contributes to water purification, nutrient removal, and to the biodegradation of contaminants and of pathogenic microbes. Plants also play a key role in the cycling of water between soil and atmosphere through their effects on (evapo-) transpiration. The loss of this service will reduce the quality and quantity of ground and surface waters, nutrients and pollutants (such as pesticides and industrial waste) may no longer be degraded or neutralised. Surface runoff will increase, augmenting the risks of erosion and even landslides in mountain areas, and of flooding and excessive sedimentation in lowland areas. Each of these losses can result in substantial costs to the economy. These costs can be linked to the need for building and operating more water purification plants, remediation costs, and ensuring measures to control erosion and flooding (e.g. the need to increase the height of dikes in lowland areas).
- Decontamination and bioremediation:** chemical engineers play a key role in bioremediation, by accumulating pollutants in their bodies, degrading pollutants into smaller, non-toxic molecules, or modifying those pollutants into useful metabolic molecules (e.g. taking several months in the case of hydrocarbons, but much more for other molecules). Humans often use

these remediation capacities of soil organisms to directly engineer bioremediation, whether *in situ* or *ex situ*, or by promoting microbial activity. Phyto-remediation, which is indirectly mediated by soil organisms, is also useful to remove persistent pollutants and heavy metals.

Soil pollution is a major and acute problem in many areas of the EU, and all alternatives to bioremediation (physical removal, dilution, and treatment of the pollutants) are both technically complex and expensive. Microbial bioremediation is a relatively low-cost option, able to destroy a wide variety of pollutants and yielding non-toxic residues. Moreover, the microbial populations regulate themselves, such that when the concentration of the contaminant declines so does their population. However, to date, microbial bioremediation cannot be applied to all contaminants and remains a long-term solution. Microbial remediation differs from phyto-remediation in a way that it transforms the pollutant instead of accumulating it in a different compartment. The loss of soil biodiversity would reduce the availability of microorganisms to be used for bioremediation.

- **Pest control:** soil biodiversity promotes pest control, either by acting directly on belowground pests, or by acting indirectly on aboveground pests. Pest outbreaks occur when microorganisms or regulatory soil fauna are not performing efficient control. Ecosystems presenting a high diversity of soil organisms typically present a higher natural control potential, since they have a higher probability of hosting a natural enemy of the pest. Interestingly, in natural ecosystems, pests are involved in the regulation of biodiversity. Soil-borne pathogens and herbivores control plant abundance, which enhances plant diversity. Invasive exotic plants that are highly abundant may have become released from their soil-borne controls.

Efficient pest control is essential to the production of healthy crops, and the impairment of this service can have important economic costs, as well as food-safety costs. Ensuring efficient natural pest control avoids having to use engineered control methods, such as pesticides, which have both huge economic and ecological costs. The use of pesticides, for instance, can be at the origin of a loss of more than 8 billion dollars per year due to environmental and societal damages. In natural ecosystems, the loss of pathogenic and root-feeding soil organisms will cause a loss of plant diversity and will enhance the risk of exotic plant invasions. Changes in vegetation also influence aboveground biodiversity. Loss of this ecosystem service, therefore, will cause loss of biodiversity in entire natural ecosystems.

- **Human health:** soil organisms, with their astonishing diversity, are an important source of chemical and genetic resources for the development of new pharmaceuticals. For instance, many antibiotics used today originate from soil organisms, for example penicillin, isolated from the soil fungus *Penicillium notatum* by Alexander Fleming in 1928, and streptomycin, derived in 1944 from a bacteria living in tropical soil. Given that antibiotic resistance develops fast, the demand for new molecules is unending. Soil biodiversity can also have indirect impacts on human health. Land-use change, global warming, or other disturbances to soil

systems can release soil-borne infectious diseases and increase human exposure to those diseases. Finally, disturbed soil ecosystems may lead to more polluted soils or less fertile crops, all of which, if they reach large proportions, can indirectly affect human health, for example through intoxication of contaminated food or massive migrations.

Loss of soil biodiversity, therefore, could reduce our capacity to develop novel antibiotic compounds, it could enhance the risk of infectious diseases, and it could increase the risk for humans to ingest toxic or contaminated food.

The economic value of soil biodiversity

In order to allow for performing cost-benefit analyses for measures to protect soil biodiversity, some economic estimates of the ecosystem services delivered by soil biodiversity need to be provided. Several approaches exist. The valuation can be based on the prices of the provided final products, such as food, fibres or raw materials, or be based on the stated or revealed preference. The stated preference methods rely on survey approaches permitting people to express their willingness-to-pay for (or willingness-to-accept) the services provided by biodiversity and its general contribution to the quality of life (e.g. aesthetical and cultural value, etc.). Alternatively, cost-based methods can be used, in which the value of a service provided by biodiversity is evaluated through a surrogate product. Thus, the 'damage avoided' cost can be estimated, for instance, which is the amount of money that should be spent to repair the adverse impacts arising in the absence of a functioning ecosystem (e.g. in the case of soil biodiversity, the cost of avoided floods). For instance, the consequences of soil biodiversity mismanagement have been estimated to be in excess of 1 trillion dollars per year worldwide.

→ CURRENT THREATS TO SOIL BIODIVERSITY

Soil degradation

The majority of human activities result in soil degradation, which impacts the services provided by soil biodiversity. Soil organic matter depletion and soil erosion are influenced by inappropriate agricultural practices, over-grazing, vegetation clearing and forest fires. It has been observed, for example, that land without vegetation can be eroded more than 120 times faster than land covered by vegetation, which can thus lose less than 0.1 tonne of soil per ha/y. The activity and diversity of soil organisms are directly affected by the reduction of soil organic matter content, and indirectly by the reduction in plant diversity and productivity. Inappropriate soil irrigation practices may also lead to soil salinisation. When salinity increases, organisms either enter an inactive state or die off. An important portion of European soils have high (28%) to very high (9%) risks of compaction. Soil compaction impairs the engineering action of soil ecosystem engineers, resulting in further compaction. This has dramatic effects on soil organisms, by reducing the habitats available for them, as well as their access to water and oxygen. Even more dramatic for soils, sealing caused by urbanisation leads to a slow death of soil communities, by cutting off all water and soil organic matter inputs to belowground communities, and by putting pressure on the remaining open soils for performing all the ecosystem services.

Land use management

Grassland soils are the soils that present the richest biodiversity, before forests and cropped or urban lands. Within rural lands, soil biodiversity tends to decrease with the increasing intensification of farming practices (e.g. use of pesticides, fertilisers, heavy machinery). However, not all soil management practices have a negative impact on soil biodiversity and related services. While in general chemical treatments and tillage aimed at improving soil fertility trade off with soil carbon storage and decontamination services, in contrast mulching, composting and crop rotations all contribute to improve soil structure, water transfer and carbon storage.

Europe has experienced drastic land-use changes throughout its history, which have shaped the communities of soil organisms found today. Fast and rapid land-use changes are still occurring today, towards increased urbanisation and intensification of agriculture, but also towards forest growth. Soil biodiversity can only respond slowly to land-use changes, so that ecosystem services under the new land uses may remain sub-optimal for a long time (e.g. reduced decomposition of soil organic matter). Land conversion, from grassland or forest to cropped land, results in rapid loss of soil carbon, which indirectly enhances global warming. It may also reduce the water regulation capacity of soils and their ability to withstand pests and contamination. The current urbanisation and enlargement of cities creates cold spots of soil ecosystem services, and one of the challenges is to free soils in urban environments, for example by semi-opening pavement, green roofs and by avoiding excessive soil sealing and a much stronger focus on the re-use of land, e.g. abandoned industrial sites (brownfield development).

Climate change

Global climate change is already a well-known fact and it is expected to result in a further increase of 0.2°C per decade over the next two decades, along with a modification in the rate and intensity of precipitations. As such, climate change is likely to have significant impacts on all services provided by soil biodiversity. It will typically result in higher CO₂ concentrations in the air, modified temperatures and precipitation rates, all of which will modify the availability of soil organic matter. These changes will thus significantly affect the growth and activity of chemical engineers, with implications for carbon storage, nutrient cycling and fertility services. For this reason it is of particular relevance that the 2009 (recently adopted) EU White Paper establishes a framework for action to strengthen the EU's resilience to cope with the impacts of a changing climate. Water storage and transfer may also be affected through a modification of plant diversity and of the engineering activity of soil organisms. Climate change may also favour pest outbreaks and disturb natural pest control by altering the distributions or interactions of pest species and of their natural enemies, and potentially desynchronising these interactions.

Chemical pollution and Genetically Modified Organisms (GMOs)

The pollution of European soils is mostly a result of industrial activities and of the use of fertilisers and pesticides. Toxic pollutants can destabilise the population dynamics of soil organisms, by affecting their reproduction, growth and survival, especially when they are bio-accumulated. In particular, accumulation of stressing factors is devastating for the stability of soil ecosystem services. Pollutants may

also indirectly affect soil services, by contaminating the belowground food supply and modifying the availability of soil organic matter. The impacts of pollutants are not distributed equally among the three functional groups and depend on the species considered, as well as on the dose and exposure time to the pollutant. For instance, microorganisms, which have a very short reproduction time, can develop fast resistance to toxic chemicals and the sensitivity of nematodes to pentachlorophenol after 72 hours of exposure can be 20 to 50 times higher than their sensitivity to cadmium. The exposure of earthworms on the other hand is highly dependent on their feeding preferences, and on their ability to eliminate specific pollutants. Therefore, for each chemical pollutant and species considered, a specific dose-response curve should be determined. Holistic approaches, that investigate the impacts of chemical pollutants on soil ecosystem functioning as a whole are still lacking and only recently started to be covered in ecological risk assessments. However, significant impacts can be expected on nutrient cycling, fertility, water regulation and pest control services.

Genetically modified crops may also be considered as a growing source of pollution for soil organisms. Most effects of GMOs are observed on chemical engineers, by altering the structure of bacterial communities, bacterial genetic transfer, and the efficiency of microbial-mediated processes. GMOs have also been shown to have effects on earthworm physiology, but to date little impacts on biological regulators are known. The available information suggests that GMOs may not necessarily affect soil biodiversity outside the normal operating range, but this issue clearly has been not explored in detail yet.

Invasive species

Exotic species are called invasive when they become disproportionately abundant. Urbanisation, land-use change in general and climate change, open up possibilities for species expansion and suggest that they will become a growing threat to soil biodiversity in the coming years. Invasive species can have major direct and indirect impacts on soil services and native biodiversity. Invasive plants will alter nutrient dynamics and thus the abundance of microbial species in soil, especially of those exhibiting specific dependencies (e.g. mycorrhiza). Biological regulator populations tend to be reduced by invasive species, especially when they have species-specific relationships with plants. In turn, plant invasions may be favoured by the release of their soil pathogen and root-herbivore control in the introduced range. Soil biodiversity can serve as a reservoir of natural enemies against invasive plants. Setting up such biological control programmes could save billions of euros in prevention and management of invasive species.

→ POTENTIAL SOLUTIONS

Indicators and monitoring schemes to track soil biodiversity

Establishing the state of soil biodiversity and assessing the risks of soil biodiversity loss, requires the development of reliable indicators, so that long-term monitoring programmes can be set up. Such indicators need to be meaningful, standardised, and easily measurable. To date, no comprehensive indicator of soil biodiversity exists, that would combine all the different aspects of soil complexity in a single formula and allow accurate comparisons. However, there exist a host of simple indicators that target a specific function or species group, and many of which are based on ISO (International Organization for Standardization) standards. Although widely accepted reference sets of indicators, reference ecosystems and

standardised sampling protocols are missing, much is to be expected from the use of novel molecular tools in assessing and monitoring soil biodiversity.

The lack of awareness of the importance of soil biodiversity in society further enhances the problem of the loss of ecosystem services due to loss of soil biodiversity. So far, budgets spent on schemes for monitoring soil biodiversity remain insufficient. The cost of the monitoring scheme is often estimated as extremely expensive, but when we consider the cost per hectare it is often less than one euro. While several regional monitoring programmes have been developed in the recent years, no consensus exists on their scope, duration, or on the parts of the soil system that they represent, which makes their results difficult to compare. The Environmental Assessment of Soil for Monitoring (ENVASSO project)² is the first attempt to develop a comprehensive and harmonised soil information system in Europe. It offers a set of minimum reference indicators for soil biodiversity that can constitute a standard against which future monitoring schemes should be developed. Such activities need to be integrated with programmes that study the relationship between soil biodiversity and the resulting ecosystem services.

Existing policies related to soil biodiversity

To date, no legislation or regulation exists that is specifically targeted at soil biodiversity, whether at international, EU, national or regional level. This reflects the lack of awareness for soil biodiversity and its value, as well as the complexity of the subject. Several areas of policy directly affect and could address soil biodiversity, including soil, water, climate, agricultural and nature policies. However, currently, soil biodiversity is only indirectly addressed in a few Member States through specific legislation on soil protection or regulations promoting environmentally-friendly farming practices.

Given the differences among belowground and aboveground biodiversity, policies aimed at aboveground biodiversity may not do much for the protection of soil biodiversity. In contrast, the management of soil communities could form the basis for the conservation of many endangered plants and animals, as soil biota steer plant diversity and many of the regulating ecosystem services. This aspect could be taken into account or highlighted in future biodiversity policies and initiatives, such as the new strategy for biodiversity protection post-2010.

To promote soil biodiversity protection, an EU dimension would offer several benefits. It should focus on the main drivers of soil biodiversity loss, namely land use and climate change, in order to provide long-term sustainable solutions. In addition, attention should be paid to clarifying the linkages between soil biodiversity, its functions, and the impacts of human activities, by estimating the economic value of its services. To this end, the development of monitoring schemes would allow quantifying and communicating on the changes in soil biodiversity and their impacts. This is crucial in order to improve awareness on the central role of soil biodiversity and for developing capacity-building among farmers to promote biological management. The introduction of mandatory monitoring requirements could contribute, as has happened in other fields (e.g. the requirements for the monitoring of surface water status under the Water Framework Directive), to triggering the development of adequate indicators and

² ENVASSO website: www.envasso.com/content/envasso_home.html; last retrieval 23/12/2009.

monitoring methodologies. In this regard, the EU proposal for a Soil Framework Directive³ presented by the European Commission in 2006 provides the legislative framework for introducing specific monitoring requirements.

For the future, more attention should be given to developing and refining existing soil biodiversity and ecosystem management opportunities under different land uses and socio-economic conditions, and to integrating those strategies within the existing bodies of legislations (e.g. cross compliance, Habitats Directive, etc.).

→ WHAT WE DON'T KNOW

Several knowledge gaps exist on components of soil biodiversity, and **new groups of soil organisms** having potentially high ecological significance (e.g. Archaea) have only recently been considered as having specific functions in soil ecosystems.

In addition, no consistent relationships between soil species diversity and soil functions have been found to date, implying that more species do not necessarily provide more services. This is because several species can perform the same function. Indeed, the services provided by soil and soil biodiversity should not be considered in isolation, but rather as different facets of a set of highly associated functions performed by soil biota. Such a holistic knowledge of soil is currently lacking and we do not yet have an exact understanding of the potential interlinkages among services.

Another factor of uncertainty is that sometimes even the mechanisms underlying one specific service are not perfectly understood. For instance, it is not yet known exactly how biodiversity can control pest spread or how to quantify the final impacts of soil biodiversity disturbance to human health, even if it is observed that a qualitative relationship exists. Finally, an economic evaluation of these services would be useful, but a homogeneous approach to perform this evaluation is not yet available.

Regarding the factors influencing soil biodiversity, a number of experimental difficulties still need to be solved (e.g. how to reproduce natural conditions in laboratory models appropriately) and more information needs to be collected, especially for some classes of organisms (e.g. the effect of pH on nematodes).

Finally, regarding threats, more research is needed to estimate the impacts on soil organisms and functions. Individual studies focused on local soil ecosystems will be indispensable to develop a global view and to measure the effects on soil biodiversity appropriately. In addition, there is now a clear need for further studies on potential interactions among threats (e.g. how climate change influences the impacts of chemical pollution).

³ www.ec.europa.eu/environment/soil/index_en.htm.

DID YOU KNOW THAT...?

- One hectare of soil contains the equivalent in weight of one cow of bacteria, two sheep of protozoa, and four rabbits of soil fauna (p. 47, 55, 58).
- There are typically one billion bacterial cells and about 10,000 different bacterial genomes in one gram of soil (p. 49).
- Every year, soil organisms process an amount of organic matter equivalent in weight to 25 cars on a surface area as big as a soccer field (p. 35).
- Only 1% of soil microorganism species are known (p. 31).
- Some nematodes hunt for small animals by building various types of traps, such as rings, or produce adhesive substances to entrap and to colonise their prey (p. 50).
- Some fungi are extremely big and can reach a length of several hundred metres (p. 49).
- Some species of soil organisms can produce red blood to survive low oxygen conditions (p. 55).
- Some crustaceans have invaded land (p. 66).
- Termites have air conditioning in their nests (p. 64).
- Bacterial population can double in 20 minutes (p. 112).
- The fact to be ingested by earthworms or small insects can increase the activity of bacteria (p. 91).
- Soil bacteria can produce antibiotics (p. 113).
- Bacteria can exchange genetic material (p. 37).
- Soil microorganisms can be dispersed over kilometres (p. 73).
- Some soil organisms can enter a dormant state and survive for several years while unfavourable environmental conditions persist (p. 48).
- Fungal diversity has been conservatively estimated at 1.5 million species (p. 49).
- Earthworms often form the major part of soil fauna biomass, representing up to 60% in some ecosystems (p. 62).

- Several soil organisms can help plants to fight against aboveground pests and herbivores (p. 108).
- Ninety per cent of the energy flow in the soil system is mediated by microbes (p. 46).
- The elimination of earthworm populations can reduce the water infiltration rate in soil by up to 93% (p. 100).
- Moles are very common, and can be found everywhere in Europe, except in Ireland (p. 67).
- Moles need to eat approximately 70% to 100% of their weight each day (p. 68).
- Moles can paralyse earthworms thanks to a toxin in their saliva. They then store some of their prey in special 'larders' for later consumption – up to 1,000 earthworms have been found in such larders (p. 68).
- The improper management of soil biodiversity worldwide has been estimated to cause a loss of 1 trillion dollars per year (p. 114).
- The use of pesticides causes a loss of more than 8 billion dollars per year (p. 110).
- Soils can help fight climate change (p. 99).