

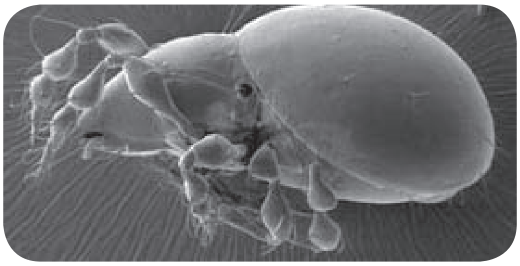


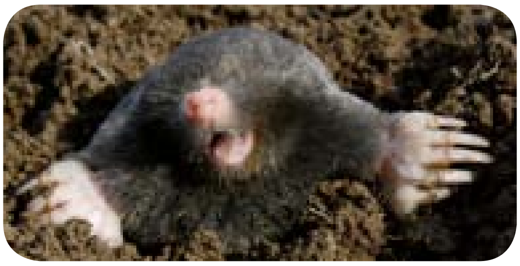


October 2010

Soil Biodiversity and Agriculture

Foreword

Soil biodiversity is an all-too-often neglected element in the larger biodiversity picture. As 2010 is the International Year of Biodiversity we should take the opportunity to celebrate its importance.

Healthy soil depends on the vibrant range of life that lives below the ground, from bacteria and fungi to tiny insects, earthworms and moles. Together, this rich biodiversity brings immeasurable benefits for life on Earth. These include recycling nutrients and enhancing plant health, storing and purifying water, providing antibiotics and preventing erosion, and even mitigating climate change. And although these benefits are largely invisible to us, we benefit from them more than we could ever know. They are of vital importance to our world.

We recognise more and more the role of natural systems in providing sustenance for life and in fighting climate change. Soil biodiversity is a central part of our natural systems. But it is also under ever increasing pressure from human activities. For this reason, the European Commission is treating soil as a priority in its thinking about sustainability.

Healthy soils are essential for sustainable agriculture and forestry. The diversity of our soils is shown by the wonderful range of biodiversity on display above ground. This means that if we do not care for soil, we put even greater strain on our biodiversity, and ultimately on our own sustainability.

Soils are home to over one quarter of all living species, but as yet we do not have a common approach on how to protect this precious resource. As an integral part of its Thematic Strategy on Soil, the European Commission has proposed a Soil Framework Directive. By doing this we hope to prevent further soil degradation across the European Union, to repair the damage that has already been done and to ensure long-term protection. We hope that we will soon be able to agree on the best way to tackle this problem, taking advantage of the momentum of the International Year of Biodiversity.

Most of Europe’s land is maintained by farmers and foresters. They are on the front line in terms of addressing the needs of biodiversity. Farmers, as custodians of much of our land, can play a crucial role in protecting soil biodiversity. The way they use their land and the tools they use to get the most from it have an enormous influence on the cycle of life.

I appreciate very much this initiative by the European Crop Protection Association and the European Landowners Organization. I welcome their commitment to safeguarding our environment by creating awareness of the importance of soil as a resource and in promoting more sustainable forms of land management.

Janez Potočnik
European Commissioner for the Environment

Preface

Fact: soil biodiversity is one of the richest, most complex biological communities on earth - it is home to a larger share of biodiversity and genetic diversity than tropical forests. This publication aims to raise awareness of the critical importance of soil and soil biodiversity. In addition, it highlights some good practice land management techniques that can be adopted to support the generation and regeneration of healthy soil.

During 2010 - the International Year of Biodiversity - the multitude of animals and plants that live in Europe have enjoyed greater public and political interest; this has been reflected in a notable increase in related publications, initiatives and political actions. Colourful images of endangered birds and butterflies call for our attention, but what of the ‘bugs’ and bacteria that inhabit our soil; do earthworms, springtails, soil mites and microbes enjoy the same level of attention?

Their diminutive nature and underground existence keeps them out of sight and out of mind; their other-worldly appearance, their crawling, squirming, gnawing, conspire to render them unattractive; but what they lack in size and beauty, they make up for in numbers and worth. The mites, lice and bacteria that inhabit the world beneath our feet are vital for maintaining balanced ecosystems and agricultural production - quite simply, we could not live without them.

This publication reveals hidden biodiversity, uncovers the animals, plants, fungi and microbes that inhabit the soil and explains the complex and invaluable role that this biodiversity plays in maintaining soil fertility, and in turn, numerous ecosystem services. A fertile soil provides the nutrients for the food we consume; its organisms form the base of the food chain for many carnivorous and herbivorous insects, birds and mammals. Soil acts like a sponge to soak up water and reduce the risk of floods; it acts as a sink for carbon dioxide and other gases and so contributes to the regulation of our climate.

Exploitation of healthy soil has allowed our populations to grow and enjoy improvements in health and wellbeing, but the cultivation of food, feed and fibre can damage soil quality and reduce its capacity to provide agricultural and other ecosystem services. Our reliance on soil and soil organisms affects a use of these natural resources that is potentially unsustainable.

Agriculture has an acknowledged impact on the health of soil and soil organisms; fortunately, research has fostered the development of technologically advanced soil-friendly agricultural practices which can in fact enhance the natural engineering processes that take place within soil. Appropriate land management can allow the sustainable coexistence of agriculture and biodiversity - including soil biodiversity. European soils will benefit from a wider uptake of soil-friendly management practices, and whilst this is something that can be regulated at a national, regional or local level, a broader European soil protection strategy could provide the framework for improving the overall standards of European soil management.

If we understand the value of soil, we have incentive for its protection; if we are aware of good agricultural practices, we have guidance for its sustainable use. This publication aims to deliver both incentive and guidance for the protection of soil whilst inspiring continued research and development of sustainable agricultural practices. All of which are vital, so that farmers and land managers may continue to provide us with the wide variety of nutritious food and the living countryside that we enjoy today.

Dr Friedhelm Schmider
Director General, ECPA

Thierry de l’Escaille
Secretary General, ELO

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Acknowledgements

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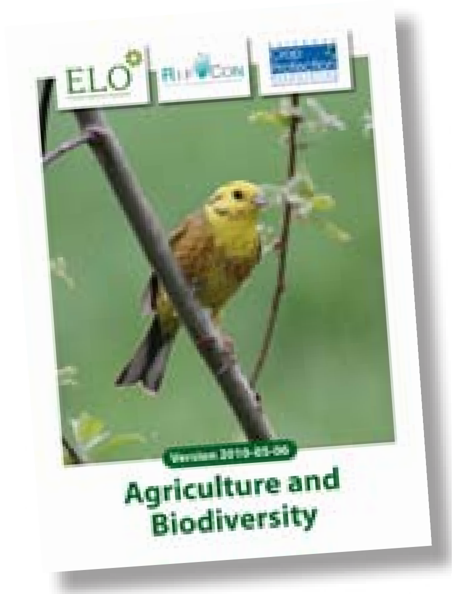


This is the second publication in a series on biodiversity arising from this collaboration. The first publication 'Agriculture and Biodiversity' (June 2010) focuses on farmland birds. You will find all of the publications in this series at www.ecpa.eu from November 2010.

1 The political and social context

We are becoming increasingly aware of the need to put measures into place that will safeguard our future, as we come to better understand the interdependencies of humans, other species and our planet. After the advances of our industrial and technological age we have come to realise that our resources are not unlimited and that it is key to develop approaches that protect them, as well as create holistic, sustainable practices in an energy and resource efficient manner.

As a non-renewable resource, soil and soil protection is key for mankind's future, being called on to continue to deliver agricultural goods - food, feed and fibres, and in some cases biofules - for a growing world population. In view of the increasing pressures it is facing, soil protection becomes more and more an issue of increasing political importance. The unsustainable use of soil, alongside further stresses such as global climate variability and warming, adds increasing pressure on the soil environment. Soil requires political initiatives for it's protection that are considerate of these different threats and pressures.

The European Commission delivered a Communication on the "Soil Thematic Strategy (COM (2006) 231)" and a proposal for a "Soil Framework Directive (COM (2006) 232)" in September 2006. The Communication sets out the Commission's thinking on the need for a common strategy for the protection and sustainable use of European soil and the Directive lays out the kinds of measures which should be taken, proposing a ten-year work program. The Strategy and the Directive proposal were sent to the different European governments and further institutions. The Soil Thematic Strategy is not a legislative proposal and is therefore not subject to a formal process of adoption though it has been already adopted by different institutions. However, the proposal for a Soil Framework Directive is subject to the co-decision procedure in accordance with Article 251 of the EC Treaty and both the European Parliament and the Council have to agree on a common text. So far the Council has been unable to reach a political agreement on the legislative proposal, however it will no doubt be progressed by one of the next presidencies as the issue is expected to gain priority.

Linked to these two pieces of legislation, the Commission more recently issued a contributory report on 'Soil biodiversity: functions, threats and tools for policy makers', completed in February 2010, which reviews the state of knowledge of soil biodiversity, its functions, its contribution to ecosystem services and its relevance for the sustainability of human society.

Soil biodiversity is critical to support a wide range of ecosystem functions and allows for the delivery of public goods, like biodiversity, water filtration and infiltration, soil stability and protection against natural disasters, and thus securing our landscape and natural heritage. Some of these services have a great social importance, exacerbated by the fact that soil is always owned by someone in Europe. Biodiversity in general has been gaining public awareness, with 2010 nominated as the "International Year of Biodiversity" and the agreement to set a new EU target for the protection of biodiversity. The new EU vision is to halt the loss of biodiversity and the degradation of ecosystem services (in the EU) by 2020, restore them in so far as feasible, while stepping up measures to avert biodiversity loss at the global level.

Soil and soil biodiversity health protection are thus key, and impacts on soil - whether at the macro level, such as through increased land sealing due growing urban areas or from mining, or at micro level, such as through increased inputs and outputs both organic or inorganic - need to be looked at as a whole within the broader concepts of securing European agriculture in a sustainable way. A starting point on this, however, is a better understanding of what is soil, what is meant by soil biodiversity, and examples of different influences on soil, and this is what this report sets out to provide.

2 The legal context

To date soil has not been subject to a specific protection policy at the EU level, but it is addressed indirectly through a number of policies, particularly the CAP - either through Cross Compliance or voluntary incentive-based measures, particularly agri-environment schemes. The CAP reflects the importance of soil by promoting good management practices - addressing various threats including erosion, the decline of organic matter, and soil structure damage.

For the EU the 2006 Soil Thematic Strategy also consists of a proposal for a Framework Directive (COM (2006) 232). This proposal sets out common principles for protecting soils across the EU. Within this common framework, the EU Member States are thought to be in a better position to decide how best to protect soil and how to use it in a sustainable way on their territory. Therefore the Member States will be responsible for implementing the principles of the Framework Directive, but defining the detailed protection measures according to their specific conditions and circumstances.

What is the overall legal context? European countries have implemented legislations to protect their soils, some of which are shown in Table 1.

Table 1. List of several National Soil Protection Policies in Europe.[1]

Year	Country	Policy
1987	The Netherlands	Dutch Soil Protection Act
1989	Italy	Italian Soil Protection Act
1992	Czechoslovakia	Czechoslovakian Soil Protection Act
1993	France	French National Soil Redemption and Clean-up Policy
1997	Hungary	Hungarian National Environmental Programme
1998	Germany	Federal German Soil Protection Act
2004	England and Wales	Soil Action Plan for England and Wales

In Germany the "Bundes-Bodenschutzgesetz (BBodSchG)" was implemented in 1998 aiming to ensure and restore the functions of soil. A key message of this national law comprises: "Everybody who is impacting on soil has to act in a manner not to cause detrimental soil modifications". The Bundes-Bodenschutzgesetz was amended by the "Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV)" in 1999.

In Austria protection of soil is regulated by individual legal instruments of the nine Federal States.

England implemented a soil action plan in 2004[2] which was intended to commit the government to improve the protection of the soil. This action plan contains 52 actions towards a more sustainable use of soil and towards a better soil protection.

3 Defining and describing soils

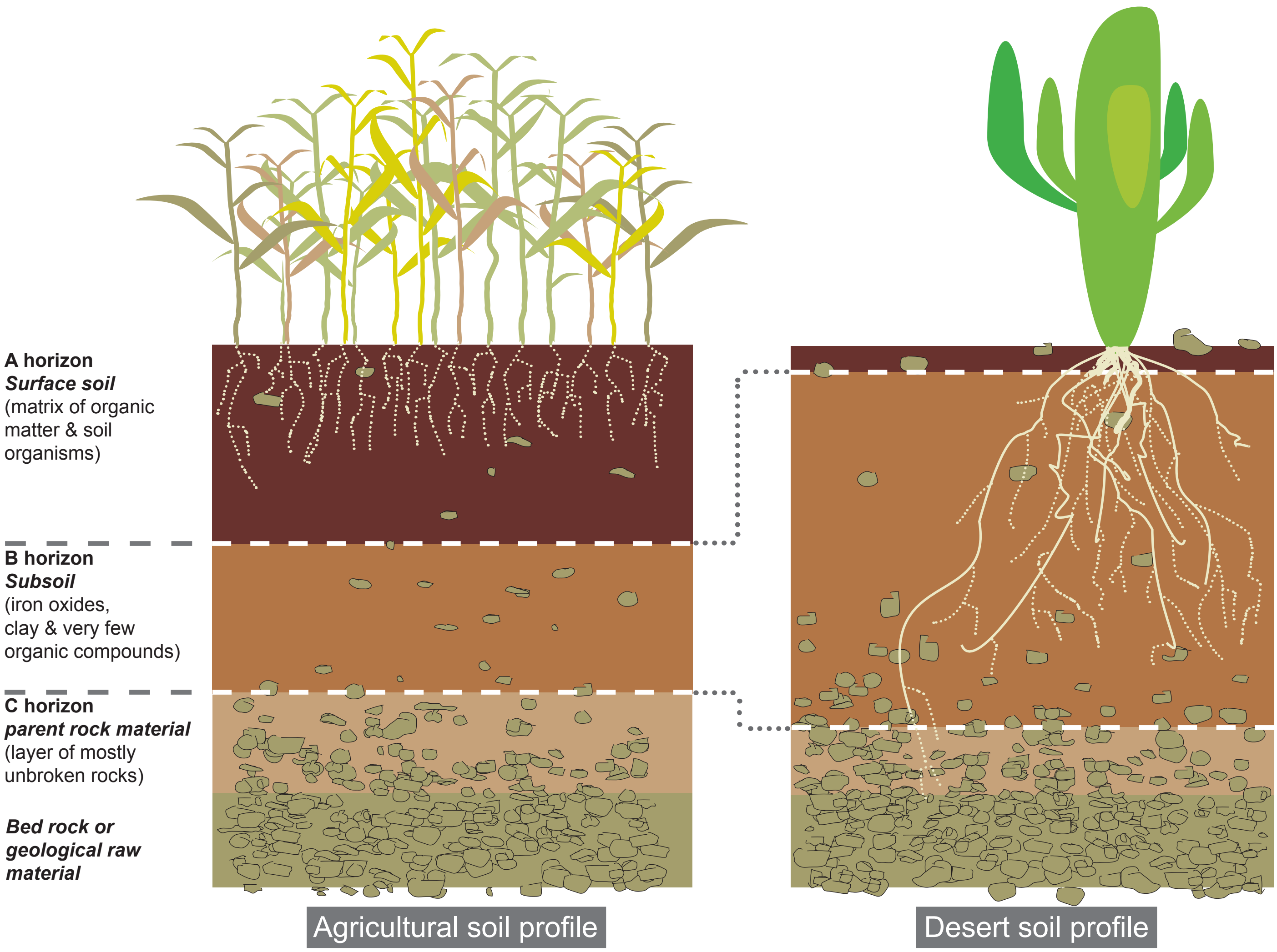
Soil is far more than the shapeless mass it appears to be when we dig our gardens or when we plant flowers in pots; and contrary to popular belief the availability of soil is not infinite. Soil, dirt or mud? Call it what you like, none of these names reveal the complexity or importance of this seemingly mundane, yet vital component of planet 'Earth'.

Scientifically, soil is a natural body consisting of weathered geological materials from the upper lithosphere (Earth´s crust) in which minerals, organic matter from plant and other biotic residues, water, air and billions of living organisms are closely intermingled. Soil is the living upper part of the Earth's crust, a complex natural body and an integral part of the element cycles. It is the link between the atmosphere and the geological formations of the Earth's crust.

Soils are the living upper part of the Earth's crust, and an integral part of the element cycles.

Geological raw material, climate, relief, groundwater, vegetation and the influence of human beings combine and interact to create a variety of different soils, each with a distinct composition of layers. As a result soils have distinctive features and characteristics. Soils generally consist of visually distinct layers. From top to bottom the most common layers include: "A horizon" or surface soil (accumulation of organic matter and soil organisms), "B horizon" or subsoil (accumulation of iron oxides, clay and very few organic compounds) and "C horizon" or parent rock material (layer of mostly unbroken rocks). Depending on location there may be additional or fewer horizons.

Figure 1. A comparison of agricultural and desert soil profiles.



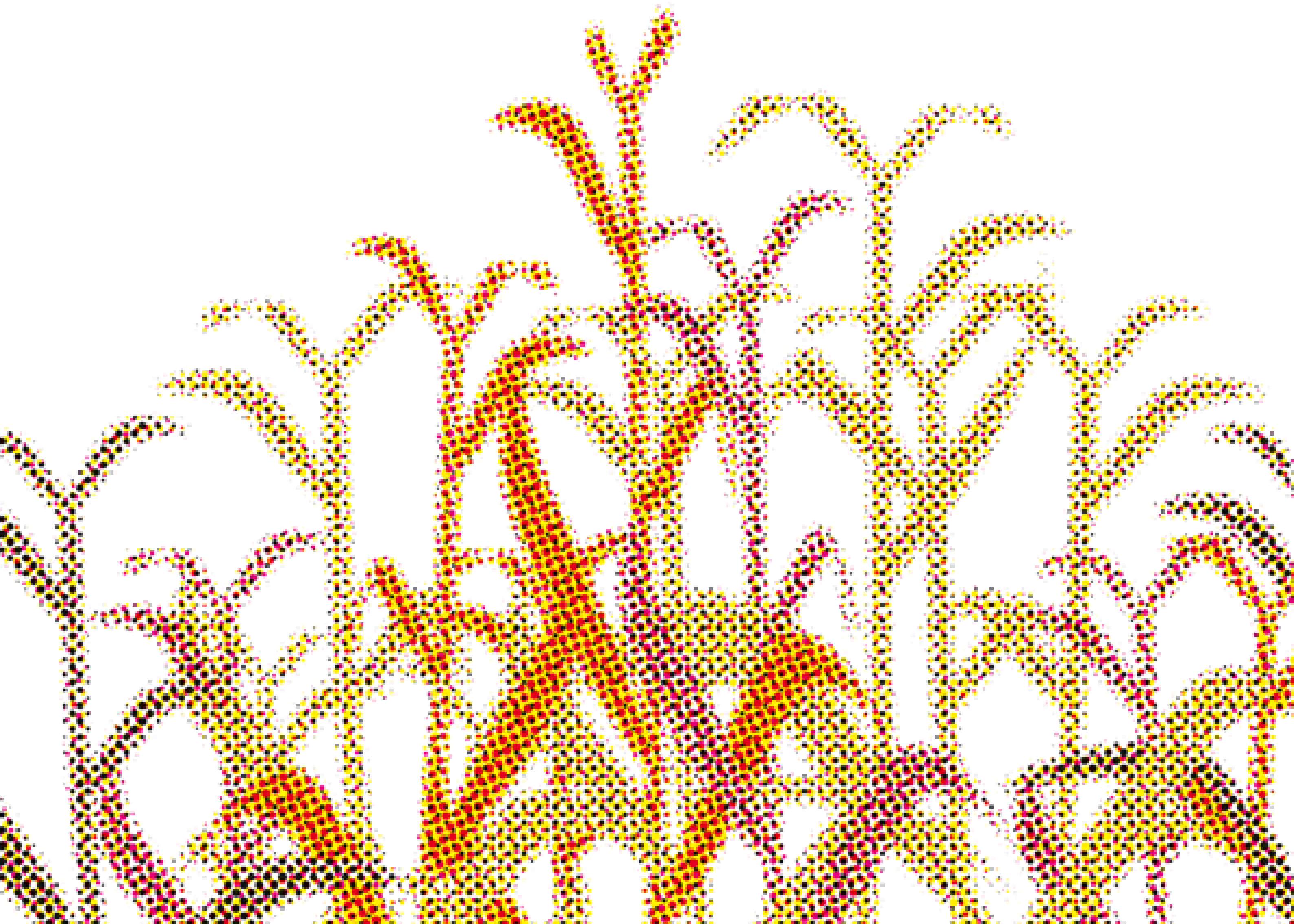
The outstanding importance of the biological factors in soil is described in a recent definition of soil quality:

Soil quality reflects the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation.[3]

This succinct definition reveals the complexity of the matter, and indeed the diverse array of functions performed by soil. Soils are exceedingly diverse and are composed of living and inanimate components. In soils, living organisms and therefore "biodiversity" play a major role, their functions being essential for the delivery of goods and services to humans and the environment because soils as a natural resource perform a number of key environmental functions with key social and economical implications.

Agriculture depends on soil for the supply of water and nutrients, as well as for plant root fixation. Soils, through their structures and their inhabitant species, perform numerous functions including nutrient and water storage, filtering, buffering, as well as breakdown and conversion of matter and gases, thus playing a central role in the protection of water and beneficial exchange of gases with the atmosphere.

Moreover, soil is a biological habitat, gene pool, an element of the landscape, a part of our cultural heritage and in addition, a provider of raw materials[4]. In this context, soils are fundamental for the production of biomass (biological material derived from living, or recently living organisms) in the form of food, feed, fibre and biofuels through agricultural activities.



4 Biodiversity under a footprint

When setting foot on soil, most people are not aware that they are standing on an outstandingly diverse community of plants, animals, and microbes. There are billions and trillions of individuals which are linked together in complex ecological interactions.

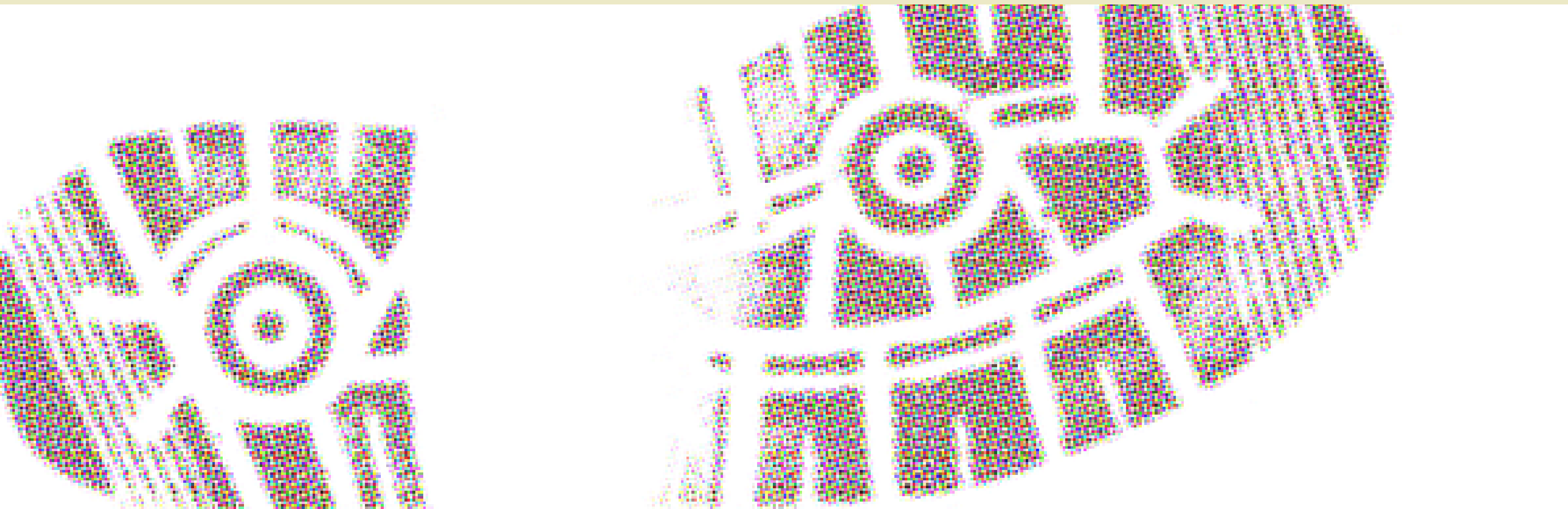
Table 2. Dimensions of biodiversity under a footprint.[5]

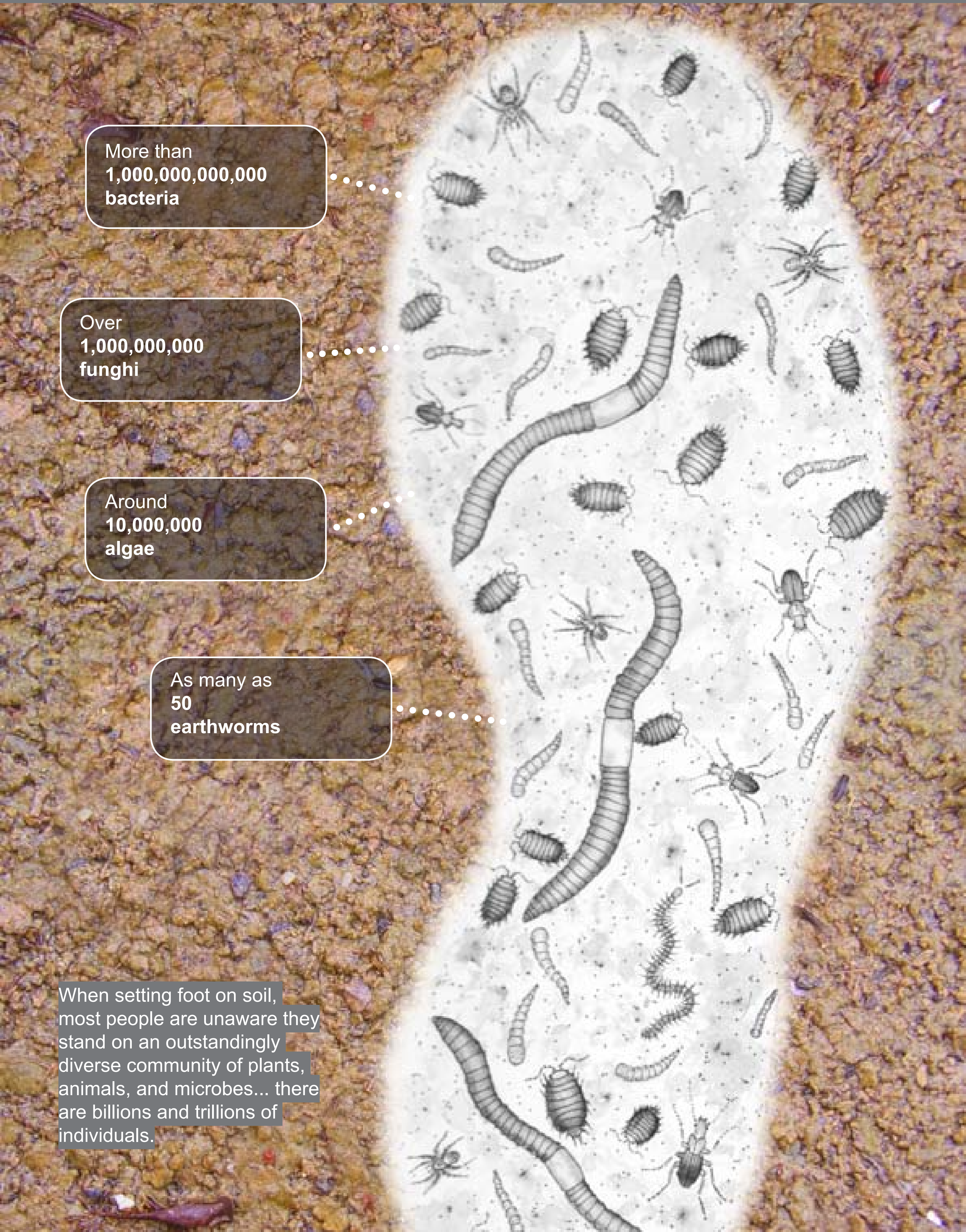
Taxonomic group	Number of individuals	Biomass (g/m²)
Bacteria	10^{12} - 10^{14}	100 - 700
Funghi	10^{9} - 10^{12}	100 - 500
Algae	10^{6} - 10^{9}	20 - 150
Protozoa	10^{7} - 10^{9}	6 - 30
Nematodes	10^{4} - 10^{6}	5 - 50
Mites	2.10^{2} - 4.10^{3}	0.2 - 4
Springtails	2.10^{2} - 4.10^{3}	0.2 - 4
Insect larvae	up to 50	< 4.5
Diplopoda	up to 70	0.5 - 12.5
Earthworms	up to 50	30 - 200

The soil environment is one of the most complex biological communities on earth, home to an even larger share of biodiversity than tropical forests. But, in contrast to birds, flowers or other large and eye-catching organisms, soil organisms are mostly small and inconspicuous, and therefore rarely enjoy public attention. A lot of hobby ornithologists spend time observing birds, and in doing so compile information which is valuable to science - there is nothing similar for earthworms, soil mites or soil inhabiting insect larvae, and while these are less attractive than butterflies or birds they contribute to a wide range of ecosystem services that are essential to the sustainable function of natural and agriculturally managed ecosystems[6].

Additionally there is a multitude of organisms whose ecological requirements are dependent on soils, such as plants penetrating soil with their roots, birds foraging on soil organisms, moles and voles digging burrow systems in soil.

The number of microorganisms under a footprint is tremendous. Additionally, numerous higher organisms such as arthropods and various worm species inhabit the soil ecosystem. The absolute number of organisms under a footprint will probably range between 10^9 and 10^{14} individuals. From a quantitative perspective, one can postulate that the majority of biodiversity on earth is occurring in soils.





When setting foot on soil, most people are unaware they stand on an outstandingly diverse community of plants, animals, and microbes... there are billions and trillions of individuals.

5 The diversity of soil organisms and their functions

Soil biodiversity is huge - more than 25% of all known animal species on earth are strict soil or litter (organic debris) dwellers[7].

One can consider the ecological functions of soil organisms in two different ways:

- Singly: Distinct groups of soil organisms contributing to individual soil functions.
- Holistically: Soil functions as a result of the complex interactions of all present soil organisms.

This chapter describes the major single systematic groups that inhabit soil, and describes their contribution to soil biodiversity and function.

Figure 2. The diversity of soil organisms and their functions.

5.1 Genetic diversity of soil organisms

Scientists have just started to explore and understand the outstanding diversity of soil microorganisms. In a recent study of the genetic diversity of four major soil microorganism groups (bacteria, archaea, fungi and viruses) minimal overlap in the genetic constitution was found between organisms of different sampling sites, indicating huge genetic diversity both locally and globally.

In an individual sample the actual number of these organisms exceeded the total number of microbial species known to date[8]. This impressive find suggests that a considerable amount - if not the majority - of Earth's soil microbial diversity has not yet been discovered.

Soil organisms exhibit a high degree of genetic diversity - research suggests that the majority of Earth's microbial diversity may have not yet been discovered.

Due to its almost incalculable numbers of microorganisms, soil contains enormous genetic diversity.

5.2 Bacteria

Soil bacteria are soil's unseen majority. The sheer numbers of bacteria in the soil are impressive, one gram of soil contains up to one billion bacterial cells and about 10,000 different bacterial genomes. Bacterial biomass is similarly spectacular, it can amount to 1-2 tonnes per hectare in grassland[9].

Despite the small size of bacteria (usually less than 2 µm) they constitute 3 to 5% of the total soil organic matter content. Only about an estimated 1% of soil microorganisms such as bacteria are known. New species and genera are continuously being discovered[4].

The variety of their metabolic pathways is amazing. Some groups react very quickly to emerging food sources (e.g. litter or organic fertilizer). Others decompose cellulose or persistent organic compounds. These degradation processes may take place in the presence of oxygen (by aerobic bacteria) or in the absence of oxygen (by anaerobic bacteria).

Bacteria are mostly decomposers, they are able to break-down many kinds of natural organic substrates and are thus responsible for more than 90% of the total decomposition of organic matter. The by-products of this decomposition include water, carbon dioxide and other elements - this is the so-called mineralisation process[10].

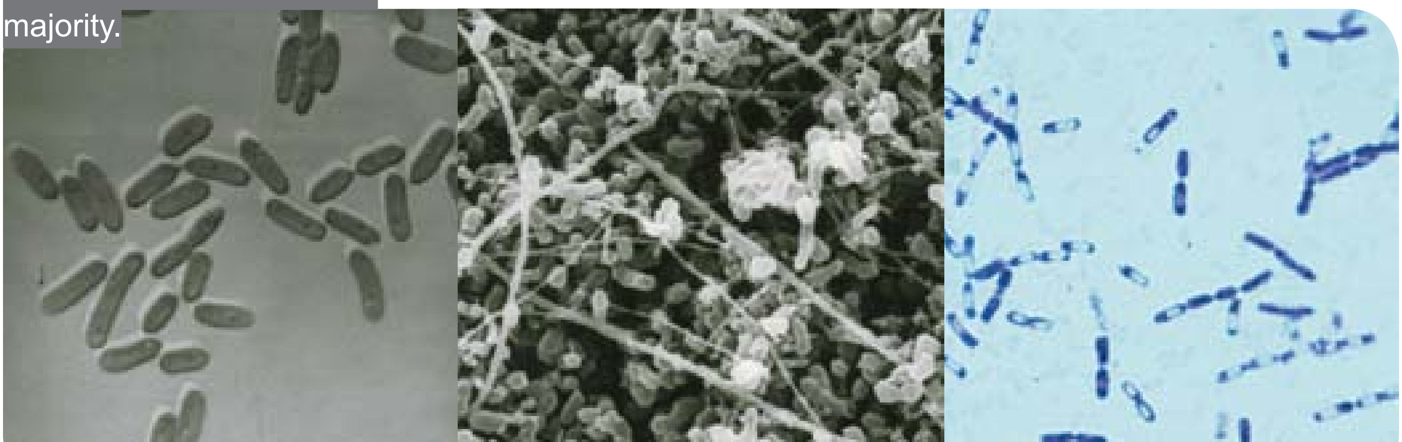
Bacteria are able to use a broad spectrum of biochemical processes to produce energy. For instance, some may fix nitrogen from the atmosphere in a form (the ammonium ion, NH_4+) usable by the host plant - an endosymbiotic association achieved through interaction with the roots of legumes. This process is of particular importance to agriculture as this enables legumes (e.g. clover, lupine and alfalfa) to grow on soils with otherwise low levels of nutrients, especially nitrogen.

Free-living microbes strongly regulate plant productivity through the mineralisation of nutrients that sustain plant productivity - they produce food for plants. Conservative estimates suggest that 20,000 plant species are completely dependent on microbial symbionts for growth and survival - this points to the importance of soil microbes as regulators of plant species richness on earth. Overall, soil microbes can be considered as one of the most important drivers of plant diversity and productivity in terrestrial ecosystems[11].

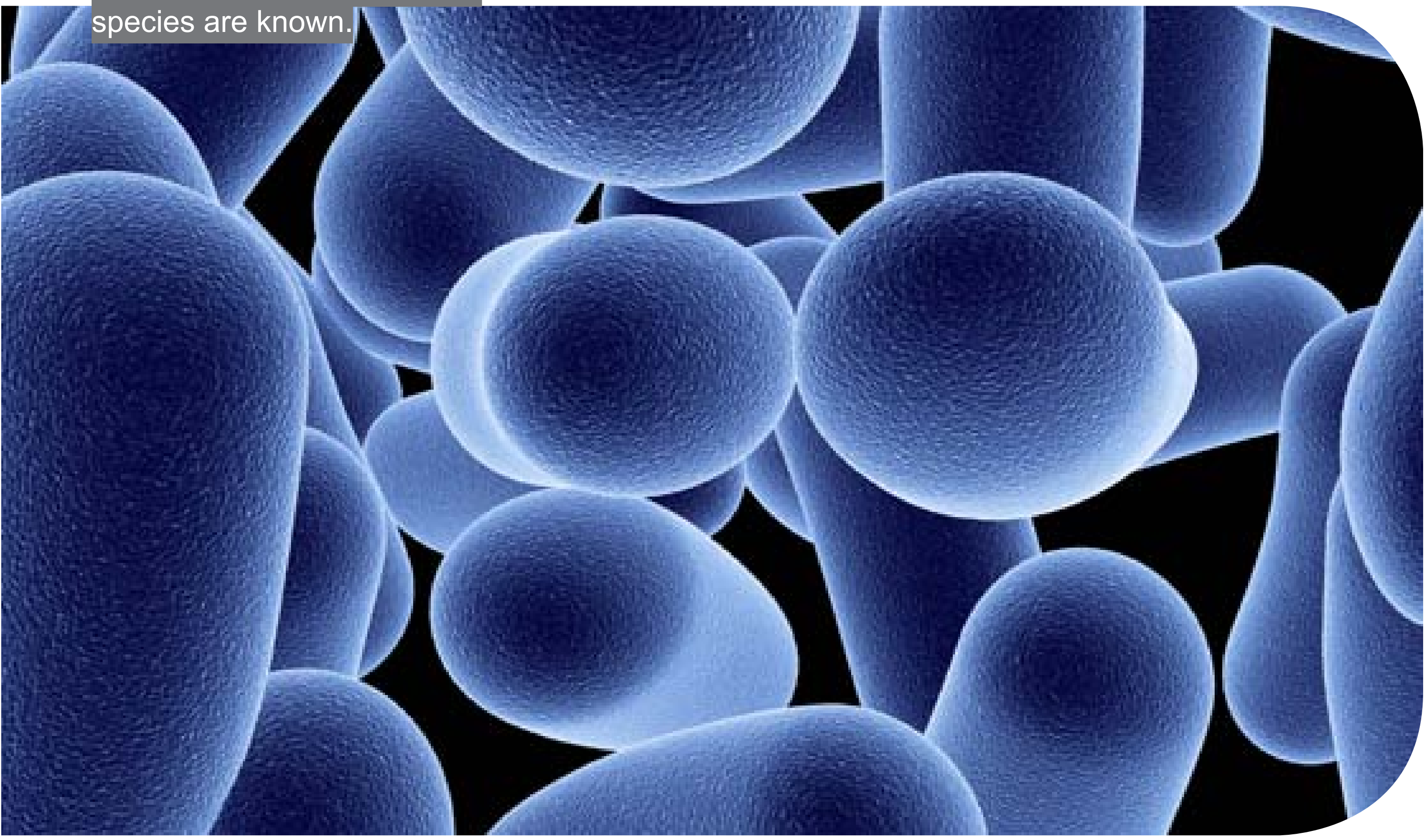
Soil bacteria are also beneficial to humans in a very direct way. Antibiotics, such as actinomycin, erythromycin and streptomycin are produced by actinobacteria, one of the most frequent soil bacteria group. New mechanisms of microbial control are continuously being discovered, such as the recently described new soil bacterial genus *Collimonas* which can in fact inhibit fungal growth[12].

Soil bacteria are not visible to the naked eye. But the number of individuals, genomes, and the ecological and biochemical functions they perform is outstanding. Their known importance for mankind extends from maintaining soil fertility to supporting plant growth as well as providing the basis for antibiotics and other potential medicines of the future.

Bacteria are soil's unseen majority.



An estimated 1% of bacteria species are known.



One gram of soil may contain as many as one billion bacteria cells.

5.3 Fungi

Fungi are classified as organisms separate to plants, animals and bacteria. Most fungi are inconspicuous because of their small size and their hidden life in the soil, on dead matter, and as symbionts of plants, animals, or other fungi.

Fungi are a diverse group of soil organisms. Over 80,000 species living in soil have been described. One gram of soil can contain one million individuals. Fungal biomass may surpass bacterial biomass by a factor of two; in temperate soils it can amount to 2-5 tonnes per hectare[9].

The vegetative part of a fungus is called mycelium, consisting of a mass of branching, thread-like hyphae. Most fungi become noticeable when fruiting, either as mushrooms or moulds. Soil fungi perform an essential role in the decomposition of organic matter and have fundamental roles in nutrient cycling and exchange. Incredibly, some mycelia are exceedingly long and might reach up to 200m per gram soil[13].

While some fungi can be pathogenic, causing diseases in plants, others form mutually beneficial (symbiotic) relationships with them.

An example of a phytopathogen is the detrimental common late potato blight fungi (*Phytophthora infestans*) which can spread, attack and completely damage a crop in less than 48 hours. Another well known fungi group are the mycotoxins that produce highly toxic chemical products and readily colonize crops. Two examples of these are the *Aspergillus* fungi which attack wheat crops and deposit toxic Aflatoxins and the *Fusarium* fungi which infect cereals such as wheat and maize with the highly toxic *Fusarium* poison which can be a challenge to control.

On the opposite, mycorrhizal symbiosis between plants and fungi is one of the most well-known symbiotic interactions and is of significant importance for plant growth in many ecosystems; over 90% of all plant species engage in mycorrhizal relationships with fungi and are dependent upon this relationship for survival[6]. The mycorrhizal symbiotic relationship is particularly interesting as the fungi actually invades and colonises the root cells of a plant; this seemingly intrusive act is in fact essential to the survival of several species of plant including wheat[14].

Other types of fungi exhibit other remarkable adaptations. There are, for instance, specialised fungi that hunt for other soil organisms such as nematodes or protozoans by means of traps such as rings, snares or adhesive structures[9].

Some fungus mycelia might reach up to 200m in length per gram of soil.

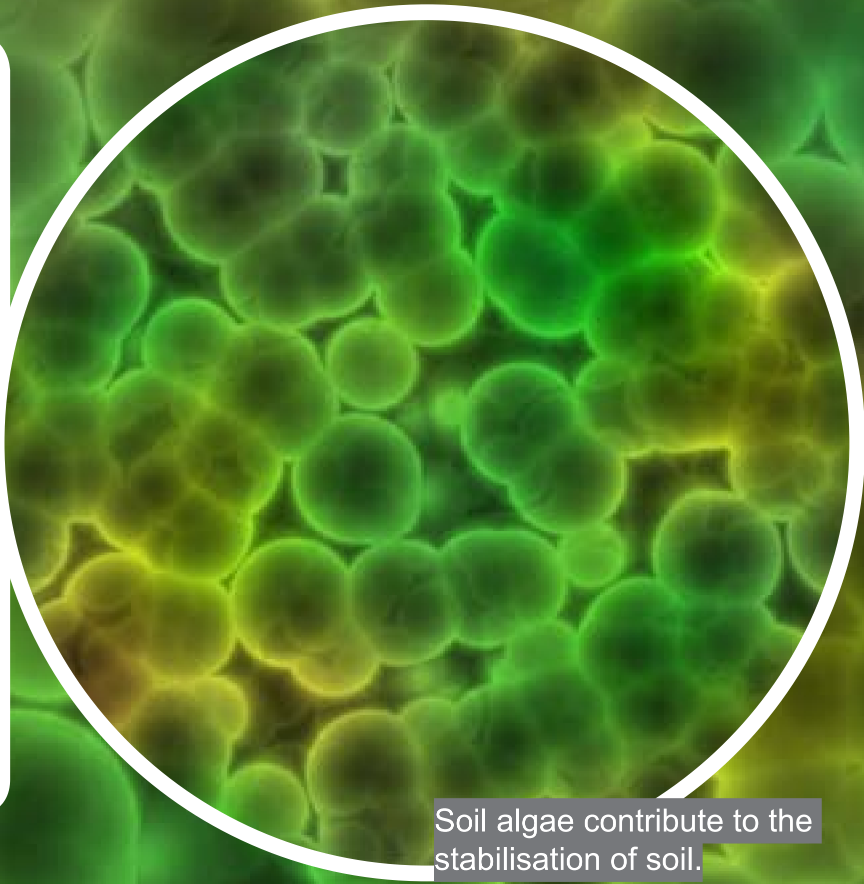
5.4 Algae

Soil algae are similar to plants, so they require light as a source of energy. For this reason algae only inhabit the few millimetres at the top of the soil.

Topsoil algae are less dependent on soil nutrients than vascular plants and are thus able to colonize sites lacking a particular layer of the humus.

By excreting extracellular high-molecular weight substances, topsoil algae contribute to the stabilisation of soil particles and therefore to soil structure. This in turn protects soil surface from erosion - literally holding the soil in.

This important service protects the top soil enabling it to grow crops, thus being a bio-indicator for soil quality.



Soil algae contribute to the stabilisation of soil.

5.5 Protozoans

Protozoa are the smallest of soil animals and include a wide variety of different taxa such as amoebae, flagellates and ciliates. Because they require oxygen for respiration, protozoans depend on well aerated soils with a well developed pore system.

In order to endure unfavourable conditions (such as droughts, low oxygen concentrations or high carbon dioxide levels), protozoa have evolved various adaptation strategies forming spores or cysts which can survive unfavourable conditions.

Protozoa feed primarily on bacteria, but also on other protozoa, some are able to utilize soluble organic matter, and sometimes they feed on the myceliae of fungi.

These feeding processes are important elements of soil food chains since they release low-molecular compounds that can be used by plants.

Protozoans like this amoeba mainly feed on bacteria.

5.6 Nematodes

Nematodes are tiny non-segmented worms with rather uniform morphological features. Individual species can often only be identified by small details such as elements of their mouthparts. They can reach densities of 10-50 individuals per gram of soil[9]. Nematodes have evolved a huge variety of modes of living. They are found in nearly every ecological niche on earth. Many feed on bacteria, whereas others live in close connection to plants and have evolved various kinds of interdependencies.

Like all soil organisms, the life of nematodes has direct implications for agriculture. Some are pests - a few species are responsible for plant diseases, such as the root knot nematode or the cyst nematode which affect different crops and have therefore received a lot of attention. Others are beneficial organisms which contribute to the control of agricultural pests, like the soil-dwelling larvae of several beetle species. Nematodes are therefore sometimes used as a biological method to control certain types of soil insects.

A soybean cyst nematode and its egg (magnified 1,000x).

5.7 Potworms

Potworms or enchytraeids are relatives of earthworms with a much smaller size. Potworms are sometimes seen as the most important detritivores (consumers of rotten organic matter) in farmland[15]. Their densities range between 10^2 and 10^6 per m^2 [16]. Potworm activity contributes to soil structure stability through selective burrowing and transport of organic material[17].

5.8 Earthworms

Agricultural soil may contain a living biomass of earthworms in the order of 3000 kg per hectare which is the equivalent of six cows or 60 sheep. Quantitatively, earthworms often form the major part of soil fauna with up to 1000 individuals per m^2 [16].

In agricultural land there are three ecotypes of earthworms:

Anecic earthworms: build long permanent burrows into deep layers of the soil and drag organic matter from the soil surface into their burrows for food.

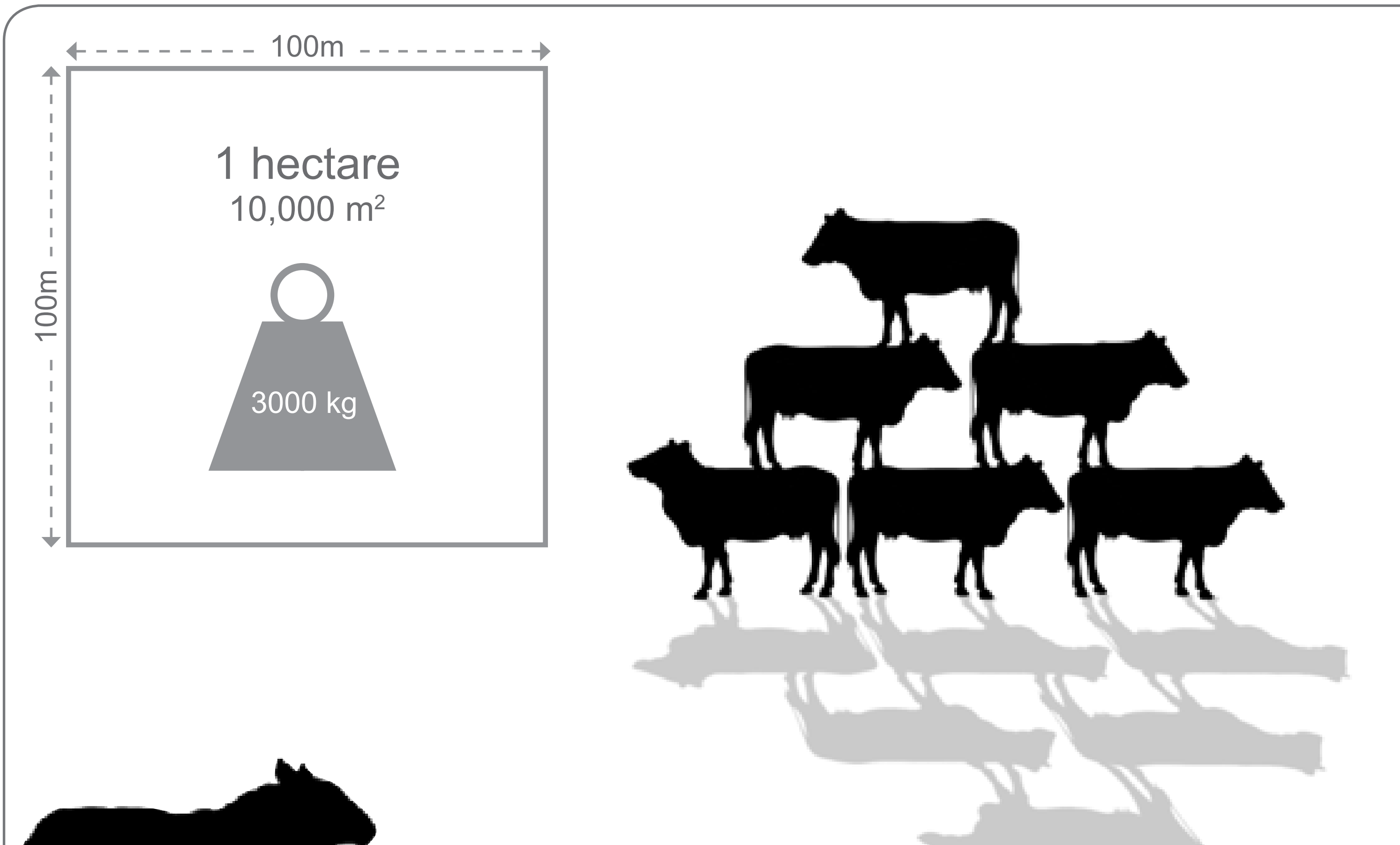
Endogeic earthworms: live exclusively in the soil, only coming to the surface after heavy rain, they feed on organic matter in the soil and build extensive temporary burrows.

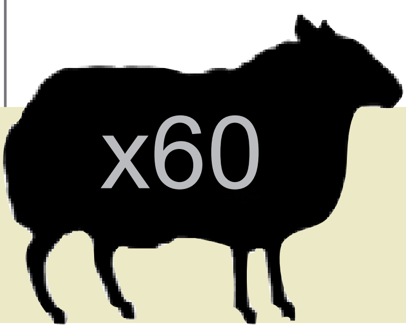
Epigeic earthworms: live primarily on the soil surface and feed on decaying organic matter. They do not build permanent burrows.

Earthworms are well-known animals, but the complexity of their ecology and their importance for soils is often overlooked. Earthworms promote the permeability of soil for oxygen by burrowing and thereby promote aerobic bacteria, they are key contributors to soil bioturbation and they positively influence soil water-holding capacity.

Table 3. The expected impact of the three earthworm ecotypes on key biological processes in agricultural systems.[18]

Biological process	Earthworm ecotype		
	Epigeic	Endogeic	Anecic
Aggregation at the soil surface	high	low	high
Aggregation within the soil profile	low	high	low
Formation of biopores	low	high	high
Decomposition - surface residues	high	low	high
Decomposition - subsurface residues	low	high	low
Carbon sequestration	low	high	low
Nutrient mineralisation	high	high	high
Nutrient loss	low	low	high
Microbial activity	high	high	high
Primary production	low	high	high





Soil may contain a living biomass of earthworms in the order of 3000 kg per hectare - the equivalent of six cows or 60 sheep. It is possible for one square meter of soil to be home to up to 1000 earthworms.

Due to their biomass and their variable ecological functions earthworms play a significant role in the regulation of soil quality:

- Earthworms contribute to the bioturbation of soil. Bioturbation is the physical rearrangement of the soil structure. Earthworms transport dead plant material and litter from the surface into the lower layers of the top soil. For instance, a single earthworm may be able to pull about twenty dead leaves into the soil per night.

- Earthworms deposit faeces on the soils surface which contributes to the biological rearrangement of soil. In temperate climate zones, earthworms produce approximately 25 to 40 tons of faeces per hectare. This means that the first 10cm of the soil layer is stirred within ten years, mitigating compaction and facilitating the distribution of nutrients.

- The burrowing activities of earthworms also positively influence soil water balance through the formation of macropores (air spaces) which allow water to drain into the soil; in addition, earthworm faeces has greater water holding capacity than surrounding soils.

- The burrows excavated by earthworms form a central element of the soil pore system. Pores and channels in the soil allow the infiltration of oxygen which promotes the growth of aerobic bacteria. Furthermore, soil organisms such as springtails, mites and insect larvae benefit from earthworm burrows, using them as their habitat.

- Earthworms are important dietary items for several animals including ground living beetles, millipedes, shrews, moles, hedgehogs and omnivorous bird species. Blackbirds, thrushes, even buzzards, storks and herons will readily eat large earthworms.

- Earthworms are a key indicator organism in acute and chronic laboratory tests for the detection of side-effects of chemicals, including pesticides.

Some earthworm species forage on the soil surface.

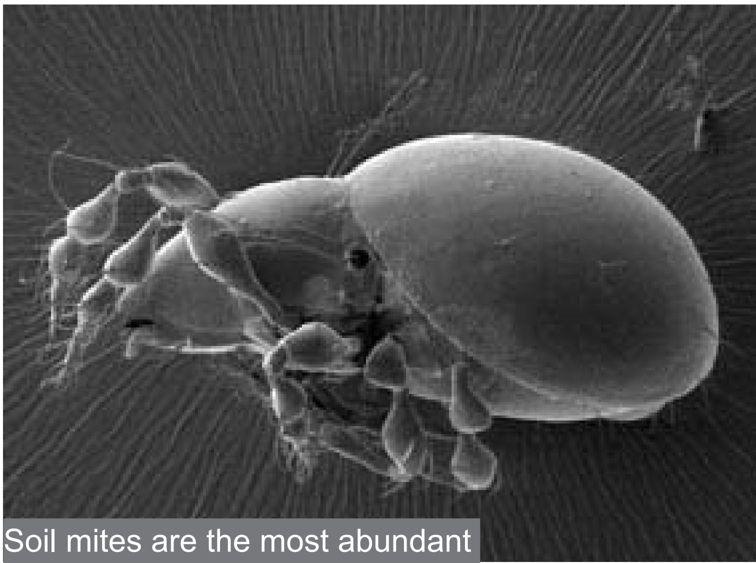
Mating earthworms, which are infact, hermaphrodites.

5.9 Soil mites

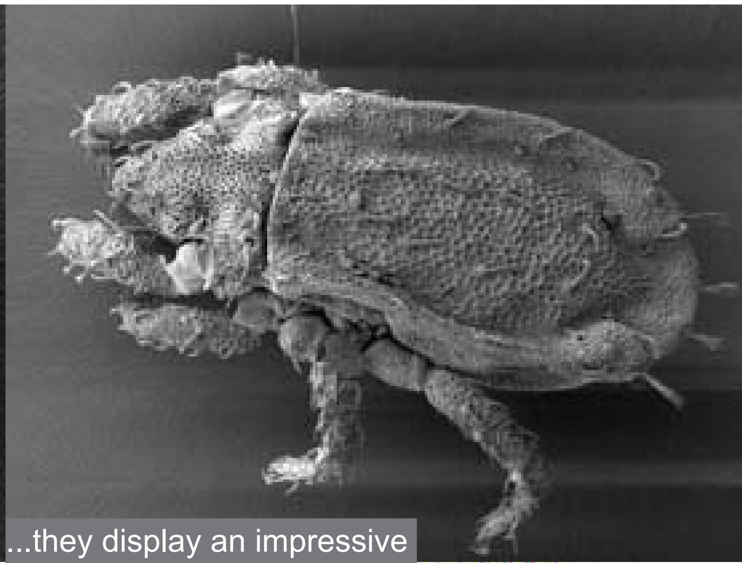
One of the most diverse and successful soil arthropod groups are mites (a taxon which is closely related with the spiders). Soil mites are the most abundant arthropods inhabiting soil[9].

Mites are generally small (0.25 - 1mm for most species) and are characterized by four pairs of legs at maturity. Mites display an impressive variety of different forms and diverse adaptations in order to occupy specific ecological niches. Their modes of living include sucking nutrients from plants and fungi, parasitising insects as well as feeding on microorganisms, dead organic matter or carrion.

Soil mites are particularly abundant in agricultural ecosystems where they are important constituents of soil food webs. Abundances of up to 60,000 animals per m² have been reported.



Soil mites are the most abundant arthropods inhabiting the soil...



...they display an impressive variety of forms

5.10 Springtails

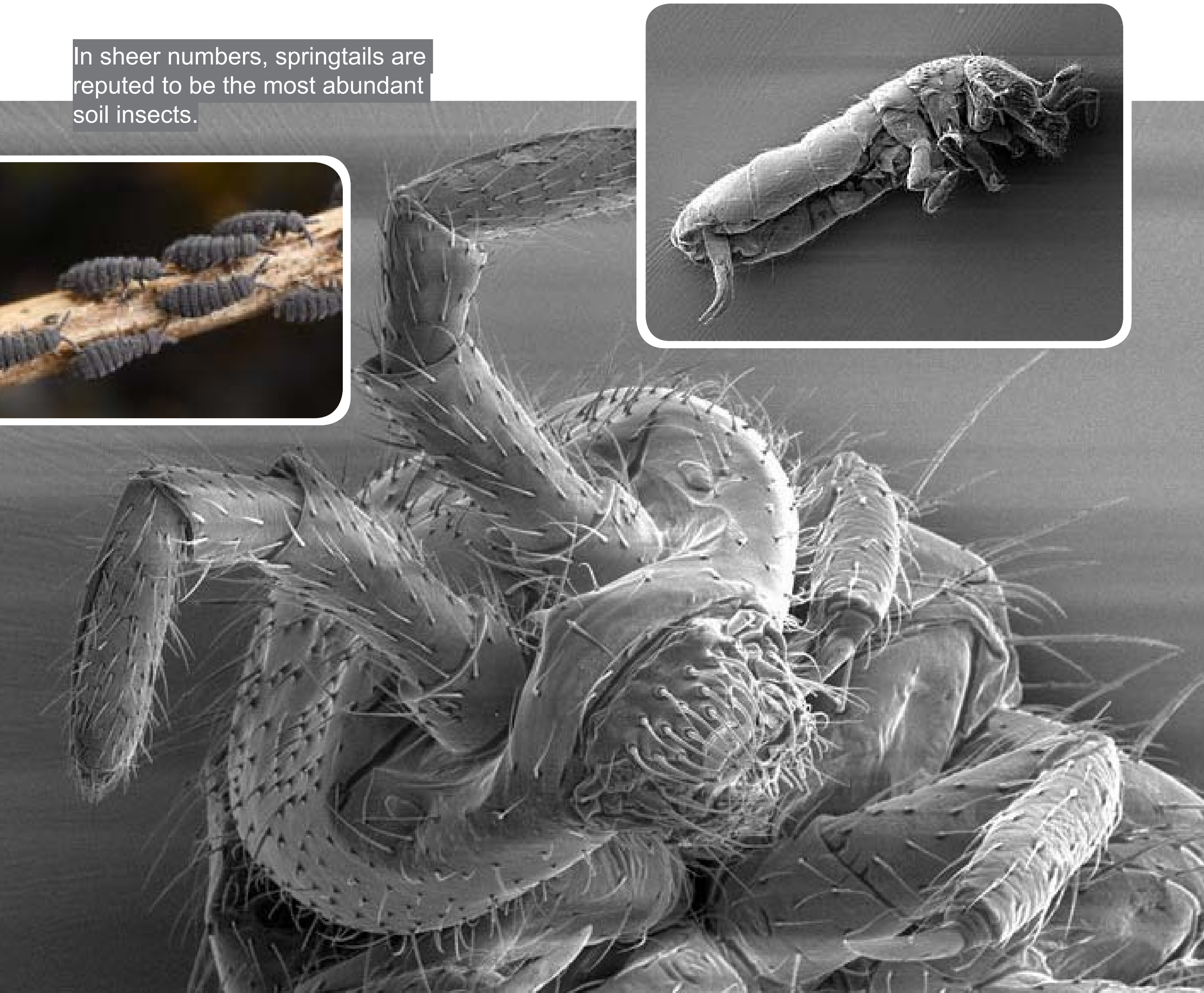
Springtails are arthropods - insects - they are small with an abdominal tail-like appendage that is folded beneath the body and can be used for jumping. Springtails live often on the soil surface or in the soils pore system, but they do not actively dig in the soil.

Numerous species feed on dead organic material and therefore contribute to the production of humus. Through their ability to carry spores of mycorrhizal fungi and mycorrhiza-helper bacteria on their bodies, soil springtails play a positive role in the establishment of plant-fungal symbioses.

Through their active consumption of fungal mycelia and spores of pathogenic fungi springtails may contribute to the control of plant fungal diseases. Others, such as the lucerne flea Sminthurus viridis can be considered as agricultural pests, for example to the legume family, especially alfalfa.

Springtails are another indicator organism in acute and chronic laboratory tests for the assessment of environmental effects of certain chemicals, including pesticides.

In sheer numbers, springtails are reputed to be the most abundant soil insects.



5.11 Insect larvae

The larvae of numerous insect species (e.g. various beetles, moths, flies or midges) live hidden in the soil. Corresponding to their systematic diversity, various modes of living have evolved.

The majority of beetle larvae in the soil are predators, others prefer feeding on fungi or plants. The larvae of flies, midges and butterflies feed predominantly on plant material and also contribute to the break-down of dead plant material.

From an agricultural perspective the occurrence of insect larvae is sometimes considered as a threat and numerous soil-dwellers are serious agricultural pests. Certain insect larvae such as wireworms, corn root worm (*Diabrotica virgifera*) larvae and cutworms cause extensive damage in European crops.

Grubs are plant-feeding beetle larvae.

5.12 Diplopods

Diplopods belong to the order of millipedes and are characterised by a high number of legs (diplopods have two pairs of legs per segment). They inhabit the upper soil layers, most species move around at night to forage for food. Diplopods mostly feed on decaying leaves and other dead plant matter by moisturising their food with secretions and then scraping it into their mouths using their jaws.

Most diplopods feed on decomposing vegetation.

5.13 Centipedes

Centipedes are millipedes that also have a high number of legs, but unlike diplopods, only one pair per body segment. They are mostly carnivores and are characterised by a pair of venomous claws. Centipedes are significant predators in soil ecosystems.

One family of centipedes (the Geophilomorphs) predominantly feed on earthworms - earthworm bodies are easily pierced by their poisonous claws.

Centipedes are predators which are characterised by a pair of venom jaws.

5.14 Woodlice

Woodlice are terrestrial crustaceans, about 3,000 species are known. They primarily inhabit the upper or surface layers of the soil.

Woodlice are omnivores, eating everything from fungi, plant material to animal matter. Their preference is to feed on decaying rather than fresh leaf litter. Terrestrial woodlice may even eat their own faeces due to its dense microbial population.

Because woodlice consume and digest leaf litter, these terrestrial isopods contribute to nutrient recycling through the decomposition of organic matter[19]. Some woodlouse species have been reported to feed on the young leaves of vegetables such as sweet pepper and cucumber[20].

Woodlice are usually nocturnal.

5.15 Ants

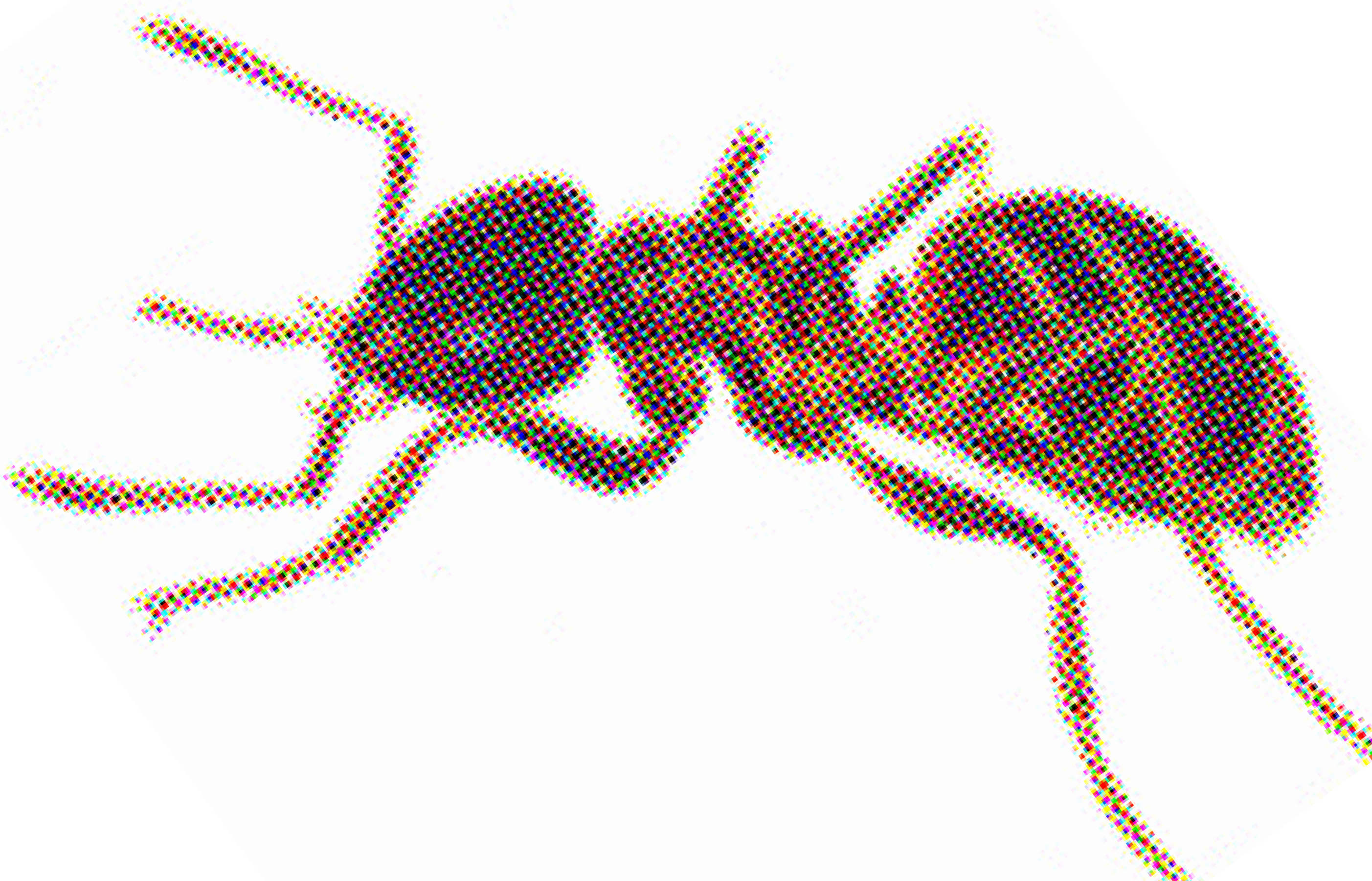
Ants are small social insects related to bees and wasps. More than 12,500 species have been described.

Ants have colonised almost every terrestrial habitat on earth and constitute one of the most successful insect groups. In Europe ants mostly live in subterranean nests, interconnected by small tunnels. In the soil ants act as ecosystem engineers by contributing to the creation of the soil pore system.

Ants also have an important effect on soil ecosystems due to their voracity. Omnivore ant species living in meadows can consume up to 3% of the primary production and 40% of the prey biomass (secondary) available per season.

Many arthropods, so-called myrmecophiles (organisms that live in association with ants), live in ant mounds as specialised inhabitants of ant colonies. Anthills may create patches of mycorrhizal enrichment which can help the growth of plants due to the dispersion of fungal spores. Non-mycorrhizal microbes also seem to favour anthill soils as ants stimulate the abundance of ammonifying bacteria[21].

Ants act as ecosystem engineers by contributing to the creation of the soil pore system.



5.16 Moles and voles

Moles and voles are common fossorial mammals (adapted to digging and a life underground) in agricultural landscapes and thus act as large ecosystem engineers in soil. Several species of both groups live in Europe. While moles are related to shrews and are carnivorous animals, voles are rodents and predominately feed on plant material.

Moles spend almost their entire lives underground. They are excellent tunnel builders and capable of extending their burrows up to 30cm per hour. Moles predominantly feed on earthworms and have been reported to eat up to as much as their body weight each day. Similar to shrews they have venomous saliva that is used to paralyse earthworms. Moles store paralysed earthworms in special chambers of their burrows for later consumption.

Moles are fossorial mammals that rarely emerge onto the soil surface.

Voles are able to build extensive tunnel systems in soil.

Voles are small rodents resembling mice but having a stout body, short ears and tail. Similarly to moles, voles build extensive burrows in the soil. Some species forage for plant material on the soil surface, others rely on plant roots and rarely emerge to the surface. The most common species of agricultural importance, the common vole Microtus arvalis, is considered a serious agricultural pest. Damage to practically all types of agricultural crops has been reported. This species is characterized by an enormous reproduction capacity having up to seven litters per year with five to seven pups each time.

5.17 Plants

Plants are primary producers, their photosynthesis is a basic process supporting human and all kinds of animal life. This 'primary production' is also the basis of microbial and animal life in soil - and herewith the basis of soil fertility. The roots of plants penetrate soil and are thus not only one of the main soil ecosystem engineers[9], but they also transport organic matter into deeper soil layers. Decaying roots also contribute to the formation of the soil pore system.

The major function of roots are to anchor the plant body and to absorb water and inorganic nutrients. The soil region immediately surrounding the roots is called rhizosphere. The rhizosphere is characterized by an enrichment of soil organisms which can be up to 500 times higher compared with other parts of the soil[9].

Animals and humans depend on plant photosynthesis which transforms carbon dioxide and water into high-molecular materials, the plant biomass, using the energy of sunlight. This process also supports the existence of soil animals. In addition, plant roots stabilize soils, support the absorption of water and provide food to soil organisms.

The green parts of plants above the soil's surface die off and become litter. This organic matter is metabolised by animals and microorganisms and is the basis to the production of humus and soil organic carbon content.

The root system of cereal seedlings illustrates the close plant-soil relationship.

6 The holistic perspective - key contributions of soil organisms to agriculture

Soil organisms depend on each other - forming a successful and effective team, where each member performs a special and mutually beneficial task. However, only the co-operation of all the team members can result in a successful outcome, which is, in the case of soils, and described in this chapter, the maintenance of fertility and the diverse ecological goods and services which are provided.

The variety of soil organisms is huge, they belong to very different taxonomic groups and the ecological interactions between them are highly complex. Soil organisms are linked via food chains and food web structures in the soil pore system as well as by numerous metabolic processes. This diversity is the basis for providing the ecological services of soil.

6.1 Formation of humus – mineral organic complexes and soil aggregates

Humus is the name given to the stable end product of the microbial break-down of plant and animal residues in the soil. It occurs in different types, depending on humidity and temperature, in various degradation stages, in forms of mixtures with mineral components and a variability of living soil organisms. Humus can hold 3-5 times its own weight in moisture, it therefore increases a soil's capacity to withstand drought conditions.

Humus can hold around 80-90% of its own weight in moisture.

Figure 3. The process of humus formation: an overview of the contribution of several groups of organisms.

Primary sources of organic matter	Plants, animals, microorganisms die, dead organic matter accumulates. Range: 1 to 10t per hectare per year in central European climate zones.
Prephase of decomposition	Impact of precipitation, wetting, drying, and leaching.
Primary decomposition by soil organisms	Macrofauna (earthworms, arthropods etc.) shred the structures, enlarge the surfaces, dissolve the tissue structures, and degrade cells of the primary organic matter by ingestion.
Secondary decomposition by soil organisms	Secondary decomposition (decay) is basically performed by bacteria and fungi which split high molecular molecules (e.g. proteins, lignin, cellulose) to smaller, water-soluble molecules (like amino acids, sugars) for later total decomposition or the formation of high molecular complexes.
Mineralisation and formation of humus	Total decomposition of some water soluble molecules to carbon dioxide, water and elements by bacteria is a process called mineralisation. The remaining molecules are used by these organisms to construct humic substances as water insoluble stable organic complexes of high molecular weight.

Humus formation occurs very slowly in temperate climates, e.g. Central Europe. About 100-300 years are needed for the formation of 1cm of humus in the top soil. Humus normally does not occur as a distinct humus layer, but is mixed with mineral components. The humus content in top soils varies considerably - fertile arable soils in central Europe have mostly a humus-rich top soil of around 20-30cm soil depth.

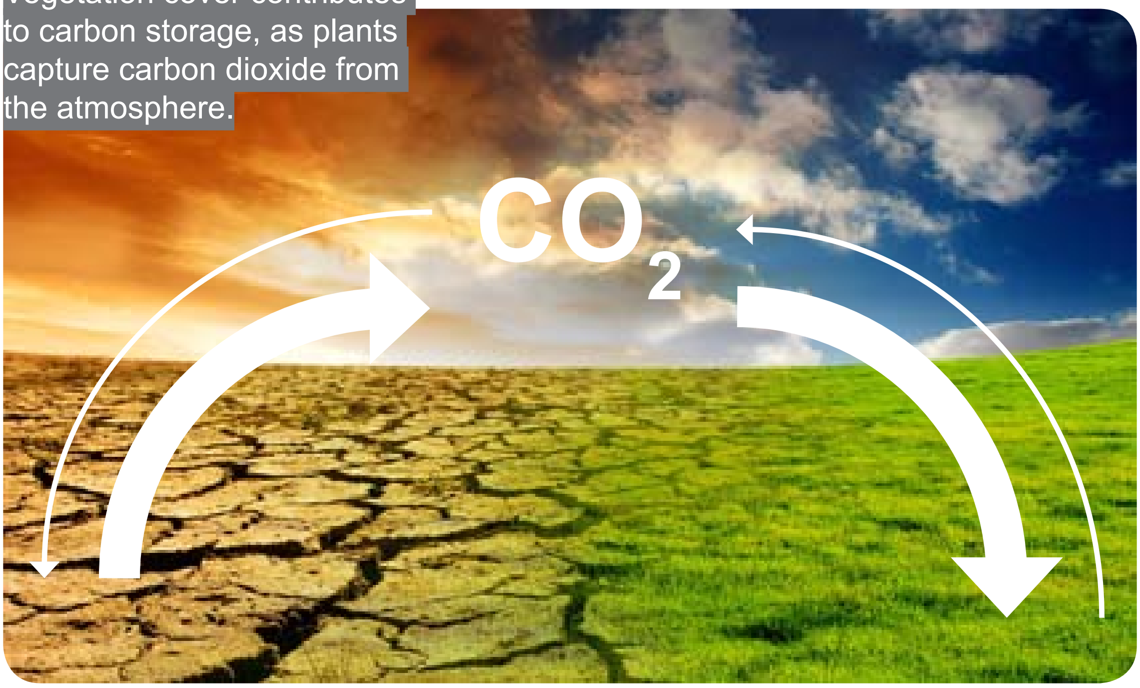
It takes somewhere between 100 and 300 years for 1cm of humus to develop in top soil.

6.2 Total decomposition (mineralisation) of organic matter and carbon cycling

A second step in the decomposition of organic substances is the total decomposition (mineralisation), which means the conversion of organic compounds into water, carbon dioxide and individual elements - normally the nutrients which were contained in the original organic matter.

Soil biodiversity is the most important factor in the global carbon cycle and therefore impacts upon agricultural production and global climate change. Soils store carbon predominantly in the form of soil organic matter (humus), but they also release it in the form of carbon dioxide (CO_2), thus acting as both a carbon sink and source. Soil is the second largest carbon pool on earth, with an estimated quantity of 1,550 gigatons. Soils therefore can act as a buffer, influencing global warming through carbon sequestration. Different types of soils and different land uses can contribute to either the sink or the source of CO_2. The varying potential of soil - depending on land use - to capture or release carbon, makes land use changes one of the biggest contributors to the global carbon cycle.

Vegetation cover contributes to carbon storage, as plants capture carbon dioxide from the atmosphere.

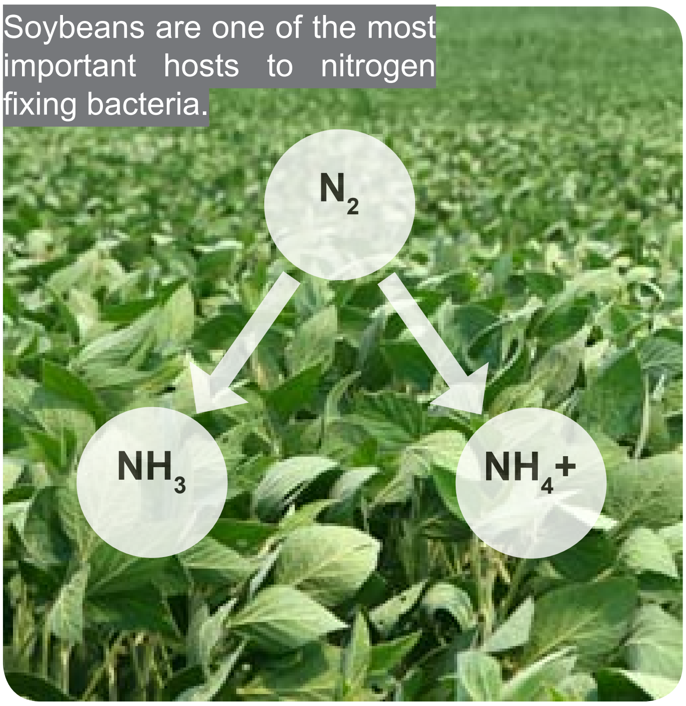


The carbon fixed by rooted plants, algae and cyanobacteria is returned to soil as organic matter or when soil organisms excrete or die[22]. This is the largest fraction of soil carbon. It consists of soil organic carbon, which is formed by accumulated organic matter and living soil biota. Soil organic carbon is released into the atmosphere again mainly during the respiration of soil animals constituting one of the most important sources of atmospheric CO_2 [9].

6.3 Fixation of atmospheric nitrogen (N_2) and nitrogen cycling

Elemental nitrogen (N_2) is the largest constituent of air (about 78% by volume), but nitrogen can be assimilated and converted to biomass by plants and soil microorganisms only in a mineral form. Atmospheric nitrogen therefore needs to be converted or 'fixed' into a form that is readily available for uptake by plants and microorganisms. Such inorganic nitrogen sources can reach the soil by various ways.

The most important natural process is the nitrogen fixation in soils by nitrogen fixing bacteria. These either live freely in soil or symbiotically in certain plant families, which contain symbiotic bacteria within nodules of their root system. These nitrogen-fixing root nodule bacteria have developed a highly efficient way to reduce elemental nitrogen (N_2) from the atmosphere to ammonia (NH_3) or ammonium ions (NH_4+). Because this reaction depends on anaerobic conditions, the bacteria need a specific habitat which they find in nodules produced by the roots of symbiotic plants.



Soybeans are one of the most important hosts to nitrogen fixing bacteria.


Mineral nitrogen fertiliser.

Legumes are a family of plants which produce root nodules and benefit from the fixation of nitrogen by the bacteria. Important leguminous crop plants include soybeans, peas and beans. Members of the legume family are also used as green manure. Green manure plants are grown for a specific period and afterwards ploughed under. Clover, lupine and vetch are important green manure crops.

Biological N fixation comprises an important economic service provided by the soil biota, particularly in agricultural ecosystems. Here leguminous plants may fix more than 100kg N / ha / year. The total annual contribution of N-fixation by soil microorganisms in both agricultural and natural ecosystems has been estimated at ca. 140 to 170 million tons of N, valued at about US$ 90 billion per year[23].

Besides biological nitrogen fixation in soils, soils also receive nitrogen in the form of nitrogen oxide, which is produced through the enormous energy of lightning which splits gaseous nitrogen molecules (N_2) present in the atmosphere to form nitrogen oxides. The same happens during the combustion of air and fuel in motor engines. The nitrogen oxides produced by both lightning and the internal combustion engine is deposited on the surface of the soil in rainfall in a process called atmospheric nitrogen deposition.

In agriculture nitrogen is also added to the soil via organic materials and mineral nitrogen fertilizer. There are three types of organic materials used in soil management and fertilization: animal manure, plant residues and compost. Mineral nitrogen fertilizers are produced by the Haber-Bosch process invented in 1910 which extracts atmospheric nitrogen. At the moment, the Haber-Bosch process produces nitrogen fertilizer, mostly in the form of anhydrous ammonia, ammonium nitrate, and urea[24].

There are fundamental interactions between soil biodiversity and the gaseous elements of air - oxygen, nitrogen and carbon dioxide - these interactions are vital for soil organisms, and, vice versa.

6.4 Influences of soil organisms on soil structure

Soil organisms affect the physical properties of soil in many ways, and soil structure influences soil quality, and in turn, agricultural production.

6.4.1 Formation of soil pore systems and the formation of aggregates

Under natural circumstances soil does not form a compact mass, it is permeated by a complex network of tunnels, gaps and capillary holes. This network of 'soil pores' allows gas and water exchange with the soil surface and the atmosphere[25]. Soil organisms are involved in the formation and the stabilisation of this pore system in two different ways:

- The digging and excavation activities of earthworms, moles and voles contribute to the formation of the soil pore system. Springtails and mites also stabilise these pore systems with faecal excretions. The surfaces of these pores are colonised by bacteria and algae which secrete and metabolise as an active biofilm.

- Soil organisms ingest organic matter together with mineral material creating faeces which form distinctive soil aggregates. Other organisms fix different mineral and organic soil particles thereby forming biofilms (a collection of microorganisms that have joined together) this has the effect of fixing different mineral and organic soil particles thereby forming a variety of soil aggregates, which are mostly stable, especially in the uppermost soil horizon -the so called A-horizon. The stability of these aggregates depends very much on the amount of organic matter used for fixing soil minerals, such as clays and oxides into soil aggregates.

Soil pore system with:
macropores >10µm Ø,
medium pores 0.2-10 µm Ø
and small pores <0.2 µm Ø.

6.4.2 Bioturbation, the mixing of soil materials

Bioturbation is the mixing of soil particles by soil organisms and plants. This process is mostly important for the creation of the A-horizon, the upper-most part of soil. Organic matter comes from above ground photosynthesis and biomass production, and it is the process of bioturbation of certain soil organisms that ensures organic matter is mixed with the mineral soils developed by the weathering of rock material. Therefore, plant litter from the soil surface (e.g. leaves) is taken down into deeper soil layers.

Earthworms play a particularly important role, with many species leaving their burrows during the night and collecting plant material which is then pulled into their burrows. The formation of an A-horizon - which contains a mixture of mineral and organic matter is the result of bioturbation.

Earthworms are the major engineers of the soil pore system.

6.4.3 Regulation of water and air in soils

The availability of water and air in soil is a basic requirement for plant growth and therefore agriculture. Soils capacity to hold water is closely related to its pore system and specifically the number of pores and the distribution of pores of varying size. Optimal conditions for plant growth occur when 60% of the soil pore volume is filled with water. Due to its specific structure and high content of clay-humus-aggregates, earthworm faeces retain significantly more water than surrounding soil. Indeed, the majority of soil organisms have a very positive impact on soil water capacity, they facilitate both water infiltration and water retention.

Soils are a naturally structured body, which consists not only of solid elements but also of water and an array of pores, capillaries, tunnels and gaps. These structures are of key importance for soil functioning - they are created and stabilised by soil organisms.

A soil with a high water retention capacity requires less irrigation.

6.5 Contribution to soil protection and remediation

Soil biota, especially microbes like bacteria and fungi play an important role in the metabolisation and total decomposition of synthetic compounds such as those contained in plant protection products (pesticides) and chemicals in general.

These microorganisms ingest compounds as food and a source of energy, and in varying time frames are able to decompose them into simpler compounds of water, carbon dioxide and individual elements. This important transformation activity ensures that these compounds break down in the soil and do not accumulate.

6.6 Pests originating from soil biodiversity

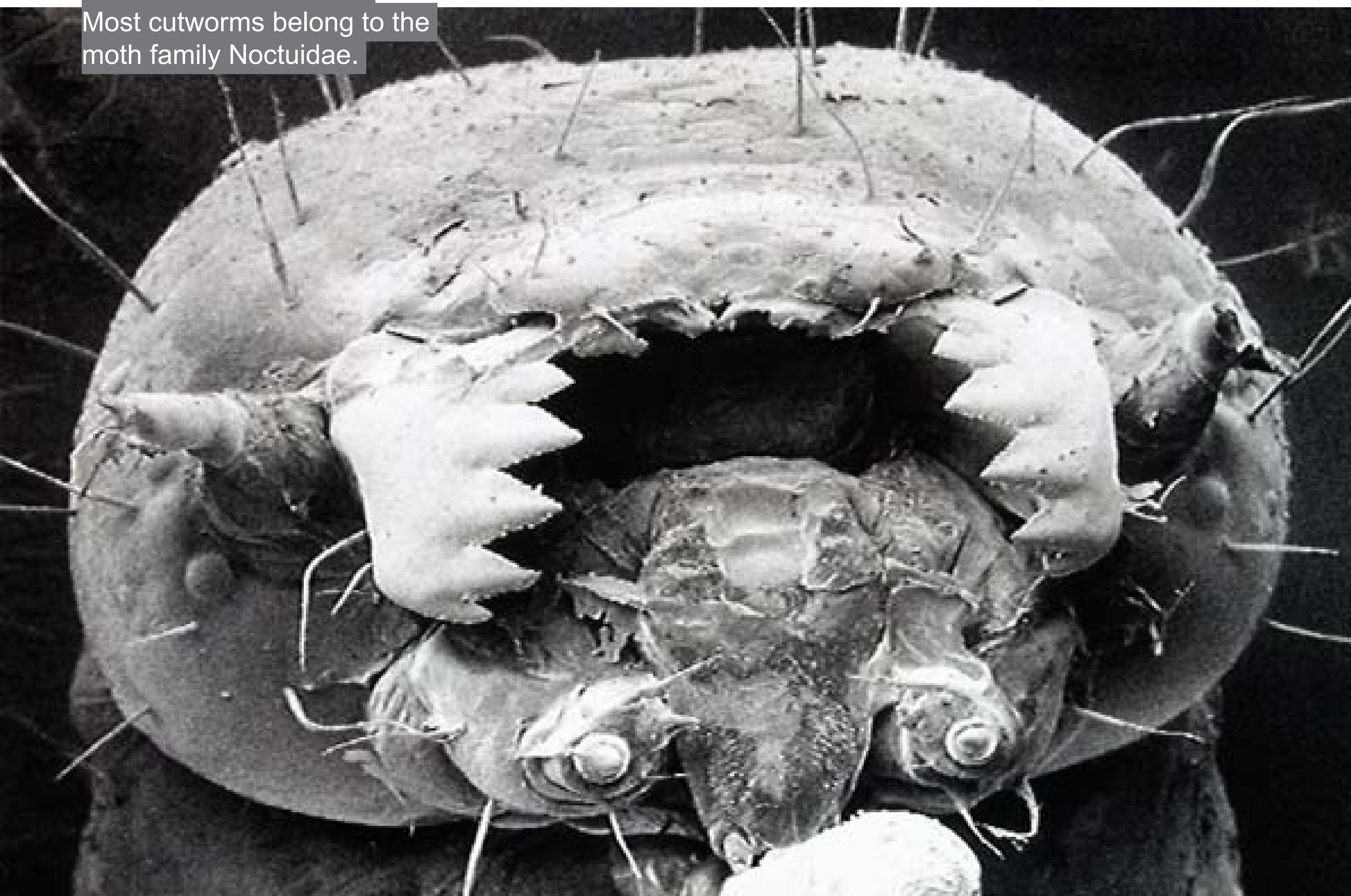
Soil biodiversity is not only beneficial to agriculture. Soil is home to a number of major pest species for agricultural crops. In particular several beetle and moth larvae are agricultural pests. Wireworms - larvae of some click beetles (*Elateridae*) - feed on the roots of various crops (such as potatoes) and have the potential to cause significant agricultural and economic damage.

The so-called 'corn root worm' (genus *Diabrotica*) is one of the most destructive beetle species. It affects the cultivation of maize on a global scale. Inadvertently introduced to Europe in the early 1990s the corn root worm is quickly spreading over the continent. In 2002, the corn root worm was detected in Paris, by 2007 it had reached Germany. Since its introduction the beetle has spread to 15 European countries[26]. As a consequence the European Commission has issued emergency measures (Commission Decision 2003/766/EC of the 24th of October 2003 on emergency measures to prevent the spread within the Community of *Diabrotica virgifera* LeConte). In the US, current estimates indicate that corn root worms cause $1billion in lost revenue each year, which includes $800million yield loss and $200million treatment costs[27].

Soil dwelling larvae of some members of the moth family *Noctuidae* are considered a pest for vegetable growing. The larvae are called 'cutworms' because of the manner in which they cut down young plants as they feed. Most noctuid larvae feed at night, resting in the soil or in their food plant during the day.

Soil organisms are not only beneficial to agriculture. Soil is also home to major crop pests.

The head of a cutworm.
Most cutworms belong to the moth family Noctuidae.



7 The economic value of soil biodiversity

Soil biodiversity takes care of the management of soil health, structure and composition. This in turn provides the needed base for successful plant life and therefore the food source for most human and animal life. One can conclude that it is therefore economically ‘priceless’. However, various studies have been made to estimate the economic value of the different services soil biodiversity provides.

Recycling of organic wastes is considered to be one of the most important uses of soil biodiversity. Mankind produces more than 38 billion metric tons of organic waste on a global scale annually. Were it not for the decomposing/recycling activity of soil organisms, much of the globes land surface would be literally covered with organic debris. The economic value of this service represents approximately 50% of the total benefits of soil biotic activity worldwide (>US$ 760 billion)[23].

Table 4 World economic benefits of soil biodiversity (modified).[22]

Activity	Involvement of soil biodiversity	Estimated world economic benefits (x 10^9 US$ / year)
Waste recycling	Fungi, bacteria, protozoans	760
Soil formation	Earthworms, ants, termites, fungi facilitate soil formation	25
Nitrogen fixation	Biological nitrogen fixation by bacteria	90
Degradation of chemicals	Soil micro-organisms play a key role in degrading or modifying pollutants	121
Pest control	Soil provides microhabitats for natural enemies of certain animal pest species	160
Pollination	Many pollinators (for instance bumblebees and solitary bees) have a soil-dwelling phase in their life-history	200

8 The influence of agriculture on soil organisms

Agriculture requires fertile soils and is therefore dependent on a high level of soil biodiversity. However agriculture itself has a major influence on biodiversity in agricultral landscapes including the diversity of soil organisms. An example of this is ploughing which highly oxygenates soil, and crop selection which influences the species types that may inhabit the underlying soil.

A simple assessment of the effects of farming activities on soil is not possible for a variety of reasons, including:

- The multitude of soil organisms and their numerous ecological interactions - whilst certain farming practices may be beneficial for one group, they may have negative consequences for another.
- Rock parent materials and climatic conditions vary considerably accross Europe, these result in a large variety of soil types - as a consequence, land management activities which are designed to positively impact one area, may impact negatively if applied elsewhere.

Mechanical soil treatment is one of the most important agricultural influences on soil.

8.1 Mechanical soil treatment

Annual ploughing can have far-reaching effects on biodiversity.

Mechanical soil treatments, such as ploughing (turning over the upper layer of soil), are common agricultural practices which aim to increase the productivity of the soil, creating a seedbed for future planting.

What are the benefits and drawbacks of ploughing from the point of view of a three millimetre long springtail, a thin-skinned earthworm or the biofilm on a particle of soil? An overview is given in Table 5.

Table 5 **Some benefits and drawbacks of mechanical soil treatments, such as ploughing, from the perspective of soil organisms.**

Consequences of treatment	Benefit	Drawback
Turnover of soil clods	The formation of new soil structures - the basis for renewed natural succession	Disturbance of the established pore system and stress for soil organisms
Intermixing of litter and root material	Biomass becomes available for degradation by soil organisms	Fewer food sources for surface litter feeding animals
Exposure to light	New habitat for phytosynthetically active soil biota, e.g. algae	Most soil organisms are not adapted to direct solar radiation and will try to escape
Exposure to precipitation	Formation of small ponds which promote the growth of protozoans and algae	Increased risk of leaching and changes in pore water conditions
Physical change	Soil compaction may be reduced	Bigger animals can be affected (e.g. earthworms)
Exposure to air	Facilitation of aerobic soil organisms	Disturbance of soil micro climate and anaerobic conditions
Formation of clods	Creation of new microhabitats with different soil humidity	Drying up of soil surfaces

8.2 Application of chemicals

8.2.1 Use of fertilisers

The nutrient content of soil has been, and continues to be influenced by agricultural activities. In Europe, human impact on soil fertility can be described through two key stages in history:

- In many regions agricultural practice from the middle ages to the 19th century resulted in soil nutrient deprivation. This was because nutrients removed from soil systems during hervesting were not replaced in sufficient quantities, thus reducing soil biodiversity.
- Since the start of the last century, the widespread use of mineral fertilisers and the intensification of livestock farming have led to an increase in the nutrient content of many agricultural soils. In turn, this has led to the formation of nutrient rich soils and a corresponding growth of the soil organism community.

The effect of fertilisation on soil organisms can be either direct (e.g. facilitation through increased food resources or inhibition through direct damage) or indirect (e.g. more food resources through an increase in plant productivity). The diversity of soil organisms translates to an equally diverse response of soil life to the application of fertilisers. Examples include:

- The abundance of different groups of soil mites and certain species of nematodes can be reduced by the application of mineral fertilisers.
- The abundance of root-sucking and bacterial-feeding nematodes can be increased by mineral fertilisers.
- Certain groups of earthworms respond more positively to compost fertilisers than to mineral fertilisers[28].
- In general, the addition of nutrients is positive for soil biota. However, there are constraints, soil biota are sensitive to changes in soil pH and the concentration of salts present in soil pore water solutions[29 & 30].

The typical application of fertiliser.

8.2.2 Use of plant protection products

Plant protection products (pesticides) are essential tools for agriculture - keeping problematic pests under control is essential to provide a sustainable supply of safe, affordable and nutritious food. In order to fulfil these functions and to protect crops effectively, they need to be biologically active. Because soil organisms can be exposed to the compounds following an application in the field, a comprehensive body of legislation has been established to evaluate the safety of plant protection products. These regulations ensure that, when applied properly, plant protection products (pesticides) do not cause unacceptable effects on soil organisms.

Plant protection products are important tools for sustainable food production.

Tests and risk assessments on soil organisms follow scientific principles in ecotoxicology and are the basis of any registration. Table 6 outlines several tests which are required for the registration of plant protection products in Europe - according to Directive 91/414/EEC, and replaced by Regulation (EC) No 1107/2009 as of the 14th of June 2011. These tests comprise important soil functions as well as relevant groups of soil organisms. They are either conducted in the laboratory (under highly standardised conditions) or in the greenhouse or in the field reflecting realistic conditions for soil organisms and farming practices.

Table 6 **Testing of soil organisms and soil functions in the context of current plant protection product registrations in Europe.**

Test subject	Laboratory	Field / Greenhouse
Earthworms	●	●
Springtails	●	●
Soil mites	●	●
Soil nitrification	●	
Carbon mineralisation	●	
Degradation of organic matter		●
Soil fauna in general		●

Most tests with soil organisms are conducted according to internationally accepted guidelines such as OECD or ISO. These tests allow the quantification of different relevant parameters. For example, in the case of earthworms, acute, reproduction and sublethal effects are measured and quantified in the laboratory. Field tests may be conducted on a diverse range of soil organisms including earthworms from different taxonomic and ecological groups. In order to ensure that long-term effects do not go unnoticed, field tests can last up to one year or longer. Importantly, tests and risk assessments are carried out with individual active ingredients, with products (which may contain more than one active ingredient) and with metabolites (which may be formed when active ingredients degrade in the soil). Degradation rates in different soil types, the occurrence of metabolites and their relevance for soil organisms are considered too.

Risk assessments are based on the comparison of effect concentrations of the compounds (ecotoxicity, which is measured by the above mentioned ecotoxicological tests) and exposure. Exposure (which reflects the concentrations to which organisms are exposed) can either be quantified by the recommended application rates using mathematical modeling techniques or may be determined directly from the analysis of field soil samples after the application of a product.

In a risk assessment, exposure and toxicity are both considered. To achieve safety which ensures that exposure dosages are in a range which is safe to the soil organisms, assessment (safety) factors are added. If needed, the risk which is quantified in the risk assessment process can be further mitigated through risk management measures. These include:

- Reduction of the application rate.
- Reduction of the number of applications.
- Use of special formulations such as seed treatments or granules which cause only a localized exposure in the soil.
- Timing of the application may be adjusted so that less product reaches the soil layer.

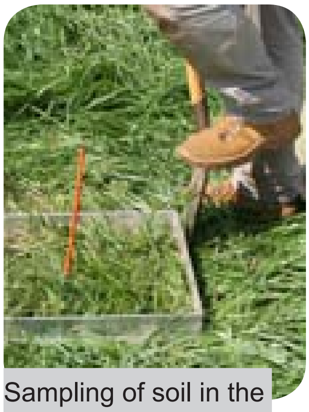
The registration of plant protection products ensures that they can be part of sustainable agriculture practices that safeguard soil biodiversity.

Some tests to assess potential effects on soil organisms and soil functions.

Testing earthworms in standard soil in the laboratory.

Determining the body weight of earthworms in the laboratory.

A ‘litterbag’ is burried in soil to assess litter degradation.



Sampling of soil in the field to analyse soil organisms.

8.3 Erosion

Erosion and soil compaction can result in a decline in soil biodiversity. Erosion is a gravity-driven natural process which affects many parts of the earth's surface. Mountains are lowered by weathering and erosion and some coasts are eroded by the force of waves and sea currents. Soils can also become exposed to the erosive influences of ice, water and wind, which remove and dislocate particles, but this can be mitigated through good land management practices.

Erosion destroys the home of soil organisms - removing fertile top-soil at a rate which exceeds that at which it can be replaced. Soil erosion is a global problem, and one of the major threats to European agriculture.

Around 40% of all arable and permanent crop land soils worldwide are considered as being seriously degraded as a result of erosive processes[31]. Globally, each year an area of fertile soil equivalent to the size of the Ukraine is being lost (600,000km²). The extent of soil erosion varies highly between different countries and regions. For instance in the German federal state of Brandenburg, 18% of soils are considered to have been degraded by wind erosion and additional 8% have been degraded by water erosion. Currently erosion affects almost 50% of European soils with erosion rates up to 17 tonnes per hectare and year. This figure surpasses a soil formation rate of about one tonne per hectare per year[9].

There are many parameters influential to the extent and rate of soil erosion, these include:

- Large field areas often devoid of any morphological structures, such as hedges, that could potentially mitigate the erosive effects of wind or water.

Erosion is one of the major problems for soils in European agriculture.

- Cultivation of row crops (such as sugar beet, maize, potato and vegetables) which only provide partial soil cover and protection. Cultivation of crops that provide minimal soil coverage through certain seasons, such as wheat and oil seed rape during the winter.
- Intensity of mechanical soil treatments which disturb the soil pore systems and induce the loss of organic matter in the top soil. This has the effect of drying the soil and removing protective plant covering – both increase soil vulnerability to erosion.
- Heavy agricultural machinery compresses the soil crumb structure which can break down and become compacted.

The consequences of erosion are numerous. One of the most obvious is the loss of humus and nutrients from the upper soil, leading to reduced fertility, reduced water holding capacity, and reduced water permeability, i.e. the reduction in potential for water flow from the surface to ground water reserves. Deposition of eroded soil material, pesticides and fertilizers into water bodies can be a secondary phenomenon.

8.4 Salinisation

Salinisation is defined as the natural or human-induced accumulation of water-soluble salts in the soil. The increased salt concentration can result from inappropriate irrigation, overexploitation of ground water or naturally from marine storms in coastal areas. Increased salt concentration can seriously negatively impact soil biodiversity as the change of pH value and salt concentration in the pore systems can poison soil organisms. In Europe between 1 and 3 million hectares are affected by increased salinisation. This is particularly relevant for parts of the Mediterranean area[9].

Salinisation affects agricultural land in Europe too.

8.5 Soil compaction

Soil suffers compaction when it is unable to withstand external physical pressures applied to it. Compaction causes a loss of soil structure, decrease in soil volume, an increase in density, a decrease in porosity and reduced hydraulic conductivity[32].

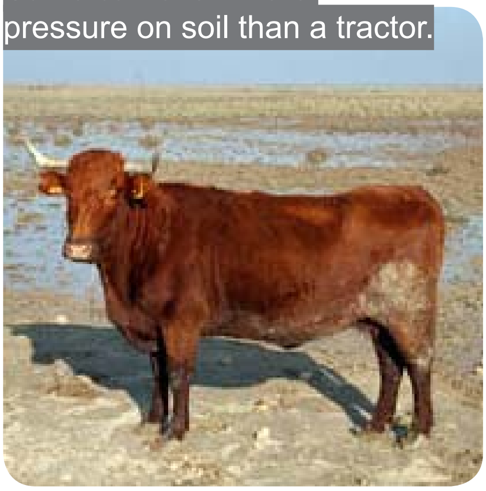
Compaction limits the suitability of a soil as a habitat, this in turn reduces the speed at which organisms repopulate the soil and recreate an optimal soil pore system, which leaves a soil vulnerable to erosion.

Soil compaction can result from the use of heavy machines, particularly if they are used on wet soils. Machinery load, type and dimension of pneumatic tyres, vehicle speed, wheel slip and number of passes all contribute to compaction rates[32 & 33]. With increasing agricultural intensification the weight of older generation vehicles steadily increased.

Livestock can also significantly compact agricultural soils - particularly on pastoral systems. Grazing animals such as cattle, horses and sheep can exert high compressive forces onto the soil, they may also cover even a greater area of a paddock than wheeled vehicles do in cropping systems. Pressures exerted by animal hooves may be more than two-fold the pressure exerted by an unloaded tractor[32].

Soil compaction results mainly from heavy machinery.

Cattle can exert more pressure on soil than a tractor.



Agricultural practices and natural processes can have tremendous influences on soils and on soil biodiversity.

9 How can agriculture contribute to the conservation of soil biodiversity?

9.1 General principles

The existence of rich soil diversity and its ability to provide 'ecological services' should not be taken for granted - these ecosystem services are vulnerable.

Soil is of fundamental importance to agriculture and therefore also human health and the economy. Therefore conservation of soils is a driving factor for the economic success of any agriculture business.

In order to remain economically viable, farmers need to respond rapidly to changes in markets. The reduction of set-aside land or the adoption of more efficient cultivation methods, e.g. on maize for the production of biofuel, are examples of quickly changing economic scenarios, which directly impact land use and soil biodiversity.

The high diversity of different soil types and the many possible ways of managing soils to favour the conservation of biodiversity will need case-by-case analyses and responses.

While many agricultural practices can have an influence on soil biodiversity there are in fact a variety of farming practices that have been developed to protect soil organisms. Large field areas with an array of morphological structures, such as hedges, mitigate the erosive effects of wind and water.

It is necessary to adapt agricultural management practices to local soil conditions. Production techniques that foster and maintain soil biodiversity include abandonment of traditional tillage and implementation of reduced or non-tillage practices; adjusting the application regimes for mineral fertilizer and pesticides can also benefit soil biodiversity - as can a modified irrigation strategy. Maintaining a suitable level of organic matter in top soil is essential for conserving soil biodiversity, this can be achieved by leaving enough organic residues on the soil after harvest in order to rebuild humus.

Conservation of soil biodiversity is essential for agriculture.

In view of the growing food need on available, or even shrinking, agricultural land, conservation of soil and soil biodiversity is a key driving factor. It will need to be carefully managed through sustainable agricultural techniques in order to ensure soil health and availability for future generations.

9.2 What tools are available?

In general, soil conservation measures must be location-specific, tailored to soil type, slope, climate, available machinery, and crop rotation practices - there is no 'one size fits all' solution for conserving soil biodiversity. However, some options can be presented as examples of the different measures available (Figure 4).

9.2.1 Plant cover supports soil protection and biodiversity

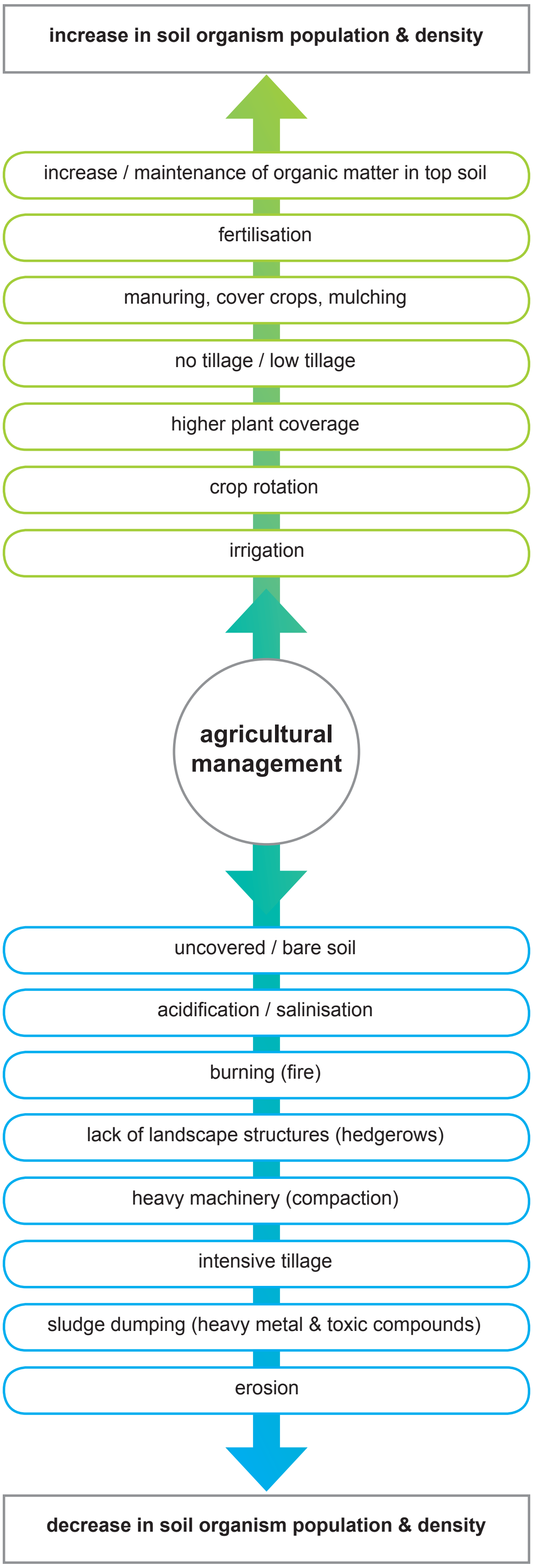
Plant roots contribute to the formation of soil structure, provide stability, maintain an availability of oxygen and organic food sources for soil organisms and protect soil against desiccation. Vegetation also limits the erosive effects of rain by reducing the force at which raindrops hit the soil. Following pasture phases or perennial crop harvest, agricultural soils are often found in their most structured and biologically active state; they most likely have a relatively high organic matter content and will be turning over nitrogen more quickly. Therefore, mixed and intercropping systems increase soil biodiversity[34].

Various techniques have been developed to maintain soil biodiversity, each is recognised as good practice and can have favourable impact on soil biodiversity, regardless of the soil type, which can vary considerably between regions.

- The use of intertillage can protect the soil surface, covering the soil between major crops.
- Additional undersown seeds can protect the crop and have beneficial effects on soil, such as the planting of legumes.
- Treatments such as mulch sowing have been developed to conserve the soil by preventing it drying out and maintaining or increasing its pore system.

Green cover on crops promotes soil biodiversity.

Figure 4. Trends of agricultural practices influencing soil biodiversity (modified from [8])



9.2.2 Mulching

The protective cover of plant material that is placed on agricultural soils is called mulch. The mulch layer can consist of a wide variety of organic matter such as plant material, compost, and sewage sludge. The main purpose of mulching includes reduction of weed pressure, conservation of soil moisture, moderation of soil temperature and protection against erosion.

Mulching with organic matter such as compost, plant material or animal manure leads to an increase of soil fauna, including earthworms. Earthworm biomass under mulching has been recorded as 12 times higher than that found in other farming systems.

Low tillage farming may have less detrimental consequences for soil biodiversity.

9.2.3 Conservation tillage / no-tillage

Reduced tillage and in particular no-tillage management systems can reduce soil disturbance, increase soil organic matter content, improve soil structure and increase soil water holding capacity. This results in a higher level of biological activity and a complimentary increase in soil biodiversity[34].

No-tillage farming is a way of growing crops that avoids disturbing the soil structure through tillage. It is a well known agricultural technique which can increase the amount of soil organic matter, improve the water storage capacity of soil, and decrease erosion. It also increases the amount and variety of soil organisms.

Reduced and managed tillage can minimise effects on soil organisms.

9.2.4 Location specific tillage

Limited and targeted mechanical soil treatment can minimize the negative impact of tillage on soil organisms, it is therefore recognised as a key management tool for the prevention of soil erosion. Location specific tillage practices include:

- Not ploughing in the direction of the slope. The effect of this tremendously reduces water runoff and soil erosion in the direction of the slope.
- Reduction of soil compaction. Soil compaction can be minimised for instance by reducing the number of vehicle passes or by driving on special tracks.
- Changes in ploughing practice.
- A sufficiently high proportion of unploughed areas within arable landscapes can have beneficial effects on soil biodiveristy.

9.2.5 Adequate crop rotation

As a general rule, monocultures are less beneficial to soil biodiversity than a system of crop rotation. Further beneficial influences are a reduction in the use of heavy machinery, a diverse vegetation cover and the availability of a variety of organic materials.

Rotating cereal and oilseed crops with annual or biannual nitrogen fixing legumes increases the amount of nitrogen available to crop plants and also to the soil ecosystem - this leads to an increase in soil organism density[34].

In addition, crop rotation can be used to control plant pathogens. An example is the corn rootworm which thrives during continuous cultivation of maize. The spatial distribution and abundance of this insect pest can be reduced with targeted crop rotation systems.

9.2.6 Appropriate use of fertilizers and pesticides

An appropriate external supply of nutrients is indirectly beneficial to soil organisms because it stimulates the primary production of plant phyto-biomass; it is directly beneficial because it increases the availability of nutrients in the water of the pore system in which the organisms live.

The risk posed by pesticides to soil organisms are reduced by the appropriate use of the products. When applied according to instructions provided on the label of products, potential unacceptable side-effects on non-target soil organisms are prevented.

9.2.7 Protection of landscape elements

Landscape structures such as boundary ridges or hedgerows around arable fields, and marginal borders around water bodies provide relatively undisturbed habitats for soil organisms. Therefore, ‘buffer strips’ alongside cropping fields, surface waters, field margins or ‘beetle banks’ increase the number and diversity of species, including insects, earthworms and plants.

Farming practices can include a range of management techniques that manage soils sustainably and promote soil biodiversity.

Landscape structures such as hedges are beneficial for soil biodiversity.

10 Conclusions

Soil biodiversity, which is the multitude of organisms living under our feet, has many important characteristics and functions. Soil organisms show a fascinating diversity of body shapes, ways of living, and ecological interactions. Soil biodiversity is a key parameter for maintaining the fertility and productivity of the soils - thereby safeguarding food production.

The need for increased agricultural production, or the requirements to manage climate change, present challenges to mankind. Soil is a limited and increasingly finite resource, which is likely to come under increasing pressure from human activities, including agriculture.

The complex ecological interactions between soil organisms and agriculture are not yet fully understood - there is a need for continued research. However, there are many tools and management techniques already available for the sustainable management of soil, although uptake of these tools and techniques could be improved.

As is so often the case with issues of this complexity, solutions can be elusive, and stakeholder agreement hard to come by. However, all can agree that soil is of paramount importance and therefore strategies for it's protection should be found. Soil requires protection and careful management by farmers, the public and policy-makers - this is essential if we are to conserve the medium that supports our life, and helps us grow our future.

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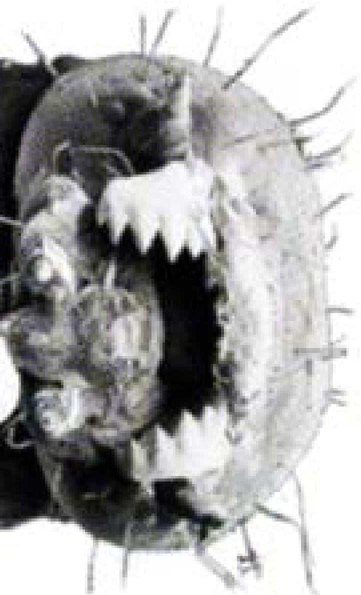

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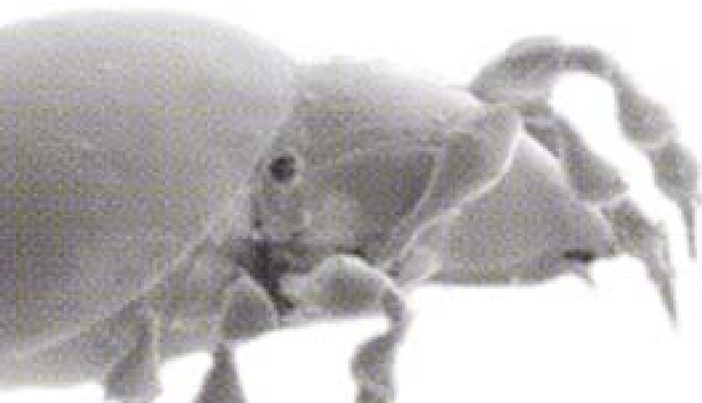

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