Soil and Biodiversity

What is biodiversity

Biodiversity is the degree of variation of life. This not only includes variation in plant and animal species, but addresses all levels from genetic variation, to diversity of ecosystems. And it spans all habitats, including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part of.

The diversity of organisms on this planet is breath-taking: Somewhere near 1.5 million species have been catalogued to date; and the total number of plants, animals and bacteria is estimated to exceed 11 million.

Beyond numbers, it is of major importance to acknowledge that biodiverse ecosystems are the 'life support' of humankind. The multiple benefits that we derive from ecosystems are known as 'ecosystem services'. An obvious example are the food and genetic resource we depend on.

Why it matters to go underground

Whereas colourful images come to our mind when we think about aboveground biodiversity of animals and plants, aspects of below-ground or soil biodiversity are more vague, or even mysterious. Standing on the land surface, we usually do not see life in the soil; and even here inside of the World Soil Museum the immense role the soil organisms play cannot easily be read from the monoliths on the walls. So why go underground?

The answer is simple: What happens in the soil is important for the aboveground life, and vice versa. Or in other words: Most ecosystem processes and functions that occur within soil are driven by living organisms that, in turn, sustain life above ground. There is ample research in ecology on these aboveground-belowground linkages. An 8-year experiment, e.g., studied a wide range of above- and below-ground organisms and multitrophic interactions in a temperate grassland, and found that plant diversity has strong bottom-up effects on multitrophic interaction networks, with particularly strong effects on lower trophic levels (Scherber et al. 2010).

The diversity of soils - that you see on the walls all around you - could not be understood without the diversity of plants, animals and microbes that contributed to soil formation. Think of the living organisms that break down bare rock through chemical weathering, thus 'kick-starting' soil formation. Or think of the various types of vegetation and the effect of litter quality on soil chemical and physical processes. Another good example is the occurrence of mycorrhizal fungi in soil which can determine the presence or absence of certain plants.

On a larger scale, the correlation of soil and biodiversity can be observed spatially. For example, both natural and agricultural vegetation boundaries correspond closely to soil boundaries, even at continental and global scales (Young & Young, 2001). It is possible to show how typical soil forming invertebrates also follow these boundaries.

Aboveground communities are affected by both direct and indirect consequences of soil food web organisms. (Right) Feeding activities in the detritus food web (slender white arrows) stimulate nutrient turnover (thick red arrow), plant nutrient acquisition (a), and plant performance and thereby indirectly influence aboveground herbivores (red broken arrow) (b1). (Left) Soil biota exert direct effects on plants by feeding on roots and forming antagonistic or mutualistic relationships with their host plants. Such direct interactions with plants influence not just the performance of the host plants themselves, but also that of the herbivores (b2) and potentially their predators. Further, the soil food web can control the successional development of plant communities both directly (c2) and indirectly (c1), and these plant community changes can in turn influence soil biota.

Source: Wardle et al. (2004)

One major ecological driver is the difference in fundamental plant traits between species that dominate (A) fertile systems that support high herbivory and (B) infertile habitats that support low herbivory. Plant traits serve as determinants of the quality and quantity of resources that enter the soil and the key ecological processes in the decomposer subsystem driven by the soil biota. These linkages between belowground and aboveground systems feedback (dotted line) to the plant community positively in fertile conditions (A) and negatively in infertile ecosystems (B).

Source: Wardle et al. (2004).

Organisms of the soil

It may appear surprising, but there is more life below the soil surface than there is above. In 1 g of soil, there can be more micro-organisms than humans on earth. Now imagine 1 m2 of land. On this tiny area, this is the abundance of the most important soil invertebrate groups in temperate climate regions:

- Flagellates (Protozoans): 100,000,000 - 10,000,000,000
- Roundworms, nematodes (Nematoda): 1,000,000 - 100,000,000
- Mites (Acari): 70 - 400

- Spring tails (Collembola): 50 - 500
- Annelid worms (Enchytraeidae): 30 - 300
- Earthworms (Lumbricidae): 100 - 500
- Snails, slugs (Gastropoda): 50 - 1,000
- Small crustaceans (Isopoda): 30 - 200
- Millipedes (Diplopoda): 100 - 500
- Beetles (Coleoptera), larvae : 100 - 600
- Flies (Diptera), larvae: 100 - 1,000

Many of these soil creatures are not much bigger than the head of a pin and belong to the so-called micro-flora and fauna with body sizes below 100 µm. The mesofauna (100 µm - 2mm) commonly contains organisms such as mites, springtails and nematodes, and the soil macro- and megafauna (>2 mm) is the diverse size class from spiders and beetles through earthworms to moles.

Although many soil organisms have yet to be identified, our understanding of their role and importance is increasing as we discover how they interact with each other and their surroundings in a complex and interdependent system. Soil organisms can be classified into three main groups which describe the principal function they perform in the soil:

- Chemical engineers: This describes all organisms that decompose organic matter. They are able to break down and transform complex compounds containing carbon and nitrogen into carbon dioxide and the nutrients that plants need. Members: Bacteria, fungi, algae, viruses, etc.
- Biological regulators: This is a rather diverse bunch of organisms which control the work of the chemical engineers. Many fragment and displace organic material, exposing it to microbes and creating more surface area, thus boosting the release of nutrients by the chemical engineers. Members: Protists, nematodes, springtails, mites, isopods, millipedes, etc.
- Ecosystem engineers: They spend their lives restructuring their habitat, mixing and moving soil as they graze, thereby creating habitable spaces and conditions for other soil organisms and plant roots. Their indirect contribution to nutrient cycling plays a key role in improving soil fertility and plant production. Members: Earthworms, termites, ants, larvae of many insects, mice, moles, etc.

From the above it becomes clear that soil organisms are not just inhabitants of the soil, they ARE PART OF THE SOIL. And as such they heavily influence soil properties such as hydrology, aeration and gaseous composition, all of which are essential for primary production, the decomposition of organic residues and waste materials, and the greenhouse gas balance of the soil.

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Source: Wardle et al. (2004).

Biodiversity

What exactly is it that make soil biodiversity so important both ecologically and economically?

At the core of this is - in simple terms - the ability of soil organisms to create and refresh soil, thereby producing and maintaining the most essential food source on our planet. When supplied with sufficient 'raw material' in the form of dead organic matter, the soil organisms get to work decomposing the waste to produce humus - complex organic matter with the nutrients necessary to sustain plants. Humus cannot be man-made. It is created by soil biodiversity. In an area the size of a football field, soil organisms produce organic matter equivalent to the weight of 25 cars every year! This work of the soil as 'the great decomposer' may never have been more important than it is today. As the global population heads towards nine billion by mid-century, healthy soils will be critical to our future food supply.

Besides the decomposition of organic matter, there are many ways that the soil food web is an integral part of landscape processes: Soil organisms sequester nitrogen and other nutrients that might otherwise enter groundwater, and they fix nitrogen from the atmosphere, making it available to plants. Many organisms enhance soil aggregation and porosity, thus increasing water infiltration and reducing runoff. Soil organisms prey on crop pests and are food for above-ground animals. They can decompose pesticides, clean contaminated land, and provide life-saving medicines.

Although major gaps of knowledge on biodiversity and ecosystem functioning in soil remain, it is obvious that this rich biodiversity with its complex processes brings immense benefits to life on earth, and last but not least, to our own wellbeing.

The 'decomposer food chain': In most ecosystems the bulk of the energy fixed by primary producers (plants) passes to the decomposer community. This fuels the activity of soil organisms which in turn drives the recycling of nutrients for plant growth.

The value of an earthworm

The Ancient Egyptians valued the earthworm; Cleopatra established laws protecting the earthworm for its useful toil of the Nile Valley.

The father of Evolution, Charles Darwin, was fascinated by earthworms. In 1881 he noted: 'It may be doubted whether there are many other animals which have played so important a part in the history of the world, as have these lowly organized creatures.' He calculated that on one acre of land, in one year, earthworms will plough through at least 10 tons of soil.

There are many ways you could try to determine the value of earthworms. A simple way would be to just look at retail values. Assuming that one can get a dozen earthworms for 1 €, and has an earthworm density of 250 per square meter, the total retail value of earthworms on just 1 ha of land would amount to 208.000 €. But this is only part of the story, as earthworms improve the soil chemical and physical characteristics as they burrow beneath the ground. Each year in just 1 hectare, 25-37 tonnes of dry soil passes through earthworms; that is 125-185 full loads of wheelbarrows, or 2,000-3,000 full shovels of soil.

Analyses of earthworm castings reveal that they are richer in nutrients than surrounding soil, often 3 times more calcium, several times more nitrogen, phosphorus, and potassium. Soil samples from a field not fertilized for 5 years but with an active earthworm population was analysed. Based on the reported analyses it was found that 100 tons of earthworm castings will contain 1.8 kg of nitrate nitrogen, 13.5 kg of phosphorus, 32.9 kg of potassium, 40.5 kg of magnesium, and 225 kg of calcium. That is the equivalent to a 4-69-86 (P-N-K) fertilizer and 3/4 ton of limestone worth approximately 60 € per hectare with no fee for spreading or transportation. In addition, one million earthworms will have burrows which will have the equivalent space of 1,200 m of 15 cm drain tile. At an installed price of 3 € per meter for drain tile, those burrows are worth 9,000 € per hectare.

There have been efforts to extrapolate these benefits to all soil organisms and the whole of the terrestrial ecosystem, thus estimating the global economic value of terrestrial biodiversity. According to this work published by Pimentel and colleagues in 1997, entitled Economic and Environmental Benefits of Biodiversity, the annual contribution of biodiversity to the world economy is almost US$ 3 trillion. Out of this amount, approximately $1.5 trillion is attributable to services provided by the variety of soil organisms.

Maybe, an earthworm is not that 'lowly' a creature after all.

How can we measure soil biodiversity?

There is consensus among scientists that we need to learn more about how the soil functions. At present, just 1% of bacterial and fungal species have been identified, compared to over 80% of plants. Fewer than 2% of nematode species are known to us, and just 4% of mites. Without knowing what actually lives down there, how can we possibly understand their role in keeping soil healthy?

Whereas the soil macro- and megafauna is visible to the naked eye, and the mesofauna can conveniently be observed and counted using binoculars, soil microbial diversity is not that easily assessed. With more microbial cells living in in one hand of grassland soil than humans on our planet, how can we possibly measure what is there?

There are currently two types of tests that can be performed: Tests that analyse and classify parts of the microbial material itself ('taxonomic tests'), and tests thatlook at the metabolic products of microbes ('functional tests'). A common taxonomic test is to extract DNA directly from the soil and make a genetic 'fingerprint' of the soil microbial community. To further detect which genes are actively switched on, so-called DNA microarray tests are being used. A DNA microarray is a solid (e.g. glass) surface to which numerous microscopic DNA spots ('probes') are attached. These are linked to fluorescent chemicals, and when fragments of soil DNA connect to these probes the matches can be analysed using UV light in fluorescence spectroscopy.

Functional tests aim at analysing the metabolic activities of soil microbes. An example can be found in the graphs section to the right,

Having standardized field and laboratory methods for assessing key functional groups of soil organisms is however just the beginning. The challenge in the future will be to establish indicators and critical levels of the soil biotic functional assemblages that are needed to maintain the key soil . This could provide the basis for long-term monitoring, just as the quality of water and air is assessed.

Despite all the research to date, there is no standardised system to allow comparison between different sites and plots, as well as over time. However, some progress is being made: a research programme called ENVASSO (Environmental Assessment of Soil for Monitoring, 2006-2008) has proposed the building blocks for the first comprehensive, harmonised soil information system in Europe. A set of indicators has been suggested that covers all trophic levels, and addresses taxonomic as well as functional aspects.

More recently, the ECOFINDERS project (2011-2014) assesses the 'normal operating range' of a suite of soil organism s and functions and fills knowledge gaps between soil biodiversity, soil functioning and ecosystem services, as well as the valuation of some of these relationships.

Since 1997, soil biodiversity monitoring is a reality in the Netherlands, where 70% of land is agricultural area and concerns about loss of biodiversity are high. As part of the Netherlands Soil Monitoring Network (NSMN), a 'Biological Indicator for Soil Quality' (BISQ) has been developed that contains a wide range of soil biological parameters are being assessed annually in about 300 randomly selected locations.

Homogenised soil and a certain substrate is added to a glass vial. After incubation for a period of time the CO_2 respired as the microbial community utilises the substrates present reacts with a chemical in the gel in the detection plate on top of the vial, leading to a change in colour. Many of these vials can be used simultaneously, with a different substrate in each. By analysing the amount of colour change it is possible to calculate the amount of CO_2 respired by the community in response to different substrates and so differences in the metabolic abilities of microbial communities from different areas or exposed to different stressors can be quantified.

Source: Jeffery et al. (2010).

Threats to soil biodiversity

Biodiversity loss and climate change are two of the most pressing challenges of our time, and soil biodiversity is part of the solution to both. Yet it is under constant threat, largely from human activities that we can control.

To better understand the threats we need to analyse 2 sides of a medal: the pressures placed on soil biodiversity on the one hand, and the vulnerability of the various soil organism communities on the other hand. The latter can be gained from monitoring as described in the section before. But what is the state of knowledge regarding the pressure side?

Probably the main anthropogenic disturbance factor is land use change. Remember how the linkage between above- and belowground diversity has been shown above. As agricultural intensification proceeds, above-ground biodiversity is reduced. As a consequence, the biological regulation of soil processes is altered and often needs to be substituted by the use of mechanical tillage, chemical fertilizers and pesticides. This in turn is assumed to reduce below-ground diversity, which may cause losses of function and reduce the ability of agricultural systems to withstand unexpected periods of stress.

The following is a list of pressures that arise from the driving force of land use change:

- Organic matter depletion: Depleting the level of organic matter in soil means starving the soil organisms that depend on it as source of food and energy. Converting a natural ecosystem such as a forest to farmland, for example, cuts the soil carbon pool by 50-75%. In nearly half of Europe's soils organic matter levels are below 2%, seen by some as critically low.
- Chemicals can affect soil organisms directly, with toxic effects on their reproductive ability and survival, or indirectly, by contaminating their food supply or habitat. The most common chemicals involved are pesticides, fertilisers, petroleum-derived hydrocarbons, solvents, and heavy metals. Some contaminants, such as pharmaceuticals, steroids, hormones or

nanoparticles, may have detrimental effects on soil organisms, but research into these potential hazards is just at the beginning.
- Compaction is caused by both natural and human activities, particularly the use of heavy machinery in farming on wet soils. It causes air to be squeezed out of the soil, preventing water infiltration and destroying networks of tunnels and pores created and used by 'soil architects' such as earthworms. Especially in connection with organic matter depletion it leads to both a reduction in soil biodiversity and a modification of community composition.
- Sealing describes any impermeable layer between the above-ground and below-ground environment as the result of urbanisation and the widespread use of asphalt and concrete. It instantly affects the diversity and abundance of soil organisms, but can also cause 'off-site' damage, as displaced water runs off to other areas where it may cause erosion and flooding.

Other relevant drivers besides land use/land use change are the use and release of Genetically Modified Organisms (GMO), that may impact on soil biodiversity and promote genetic resistance in the pest species they are designed to target. And finally climate change which is expected to impact on soil organisms directly, by altering their habitat and food web, or indirectly, through increased erosion, droughts, wildfires and so on.

Based on consultations of 20 international experts, a series of Europe-wide maps of potential threats to soil biodiversity has been published in 2013. It shows high scores (high potential threats) in several parts of the UK and central Europe which are determined by the combined effect of a high intensity agriculture with a high number of invasive species and by the risk of soil organic matter depletion.

On the positive side, scientists all over the world have begun to quantify the causal relationships between

- the composition, diversity and abundance of soil organisms
- sustained soil fertility, and
- environmental effects such as greenhouse gas emission and soil carbon sequestration.

In the field of applied sciences, a major EU research project called RECARE is looking into developing effective prevention, remediation and restoration measures for a large range of soil threats. One of the outcomes of RECARE will be policy messages to stimulate renewed care for soils in Europe, and the wider world.

Driver-Pressure-State-Impact-Responses (DPSIR) framework applied to soil biodiversity. 'Driving forces' are the socio-economic and socio-cultural forces driving human activities, which can either increase or mitigate pressures on the environment.

'Pressures' are the stresses that human activities place on the environment. 'State' refers to the state or condition of the environment. 'Impacts' are the effects of environmental degradation, and 'Responses' refers to the responses by society to the environmental situation.

Source: Jeffery et al. (2010).

Managing soils to protect biodiversity

Soil organisms are widely neglected in conservation efforts. All too often, they are 'out of sight and out of mind'. However, understanding the aboveground-belowground linkages, and given the multiple threats to soils as outlined in the previous sections, it is our responsibility, to preserve the quality of soil before it is too late, and before its resident species and their fragile habitats are lost.

It is not surprising that soil management has a direct impact on biodiversity - including practices that influence soil volume and structure, or biological and chemical characteristics, One can even say that managing soil biodiversity is (at) the root of sustainable agriculture! Farmers, as custodians of much of the land, can play a crucial role in protecting soil biodiversity, since their choice of tools and techniques has an enormous influence on belowground biodiversity.

Farming for soil biodiversity may include, but is not restricted to:

- Mulching, or covering soil, for example with crop residues or compost; this helps retain heat, preserve moisture and prevent erosion. Organic mulches can be broken down by soil organisms and help to improve soil structure, as well as sustain micro-organisms.
- Applying organic residues (crop residues, manure, compost) to the soil; this provides food for soil organisms. In combination with reduced tillage intensity, this promotes ecosystem engineers that restore water infiltration and prevent erosion.
- Crop choice is also significant; legumes (peas and beans) act as natural fertilisers as they help fix nitrogen in soil. Rotating the type of crops planted can help prevent the build-up of pathogens and pests, and preserve nutrients in the soil.

The beauty of the above measures is that they also help to combat another major driver, climate change. By fixing or 'sequestering' organic carbon in soils, they contribute to fight increasing atmospheric CO_2 levels. Many more technologies and approaches exist. If you are interested in this topic, have a look at the WOCAT database. It comprises 'best practice' examples in the field of sustainable land management (SLM) from over 50 countries in all climatic regions of the world.

Awareness about the vital importance of soil biodiversity is also increasingly recognised by policy makers. A Soil Thematic Strategy has been formulated by the European Commission in 2007. It lead to a State of Soil in Europe report (2012) that also covers soil biodiversity; and it is hoped that a European Soil Framework Directive will be in place soon. At an even higher level, the Global Soil Biodiversity Initiative (GSBI) was launched in September 2011. This is a scientific effort to develop a comprehensive course of action and bring global awareness of ecosystem services provided by soil biodiversity.

Taking steps to protect soil species may be doubly useful: while measures to protect above-ground species do not necessarily help below-ground biodiversity, efforts to protect soil communities are very likely to help conserve endangered plants and animals that are better-known. Policies that target soil biodiversity directly or indirectly by protecting their environment could therefore have a much greater impact than anticipated.

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