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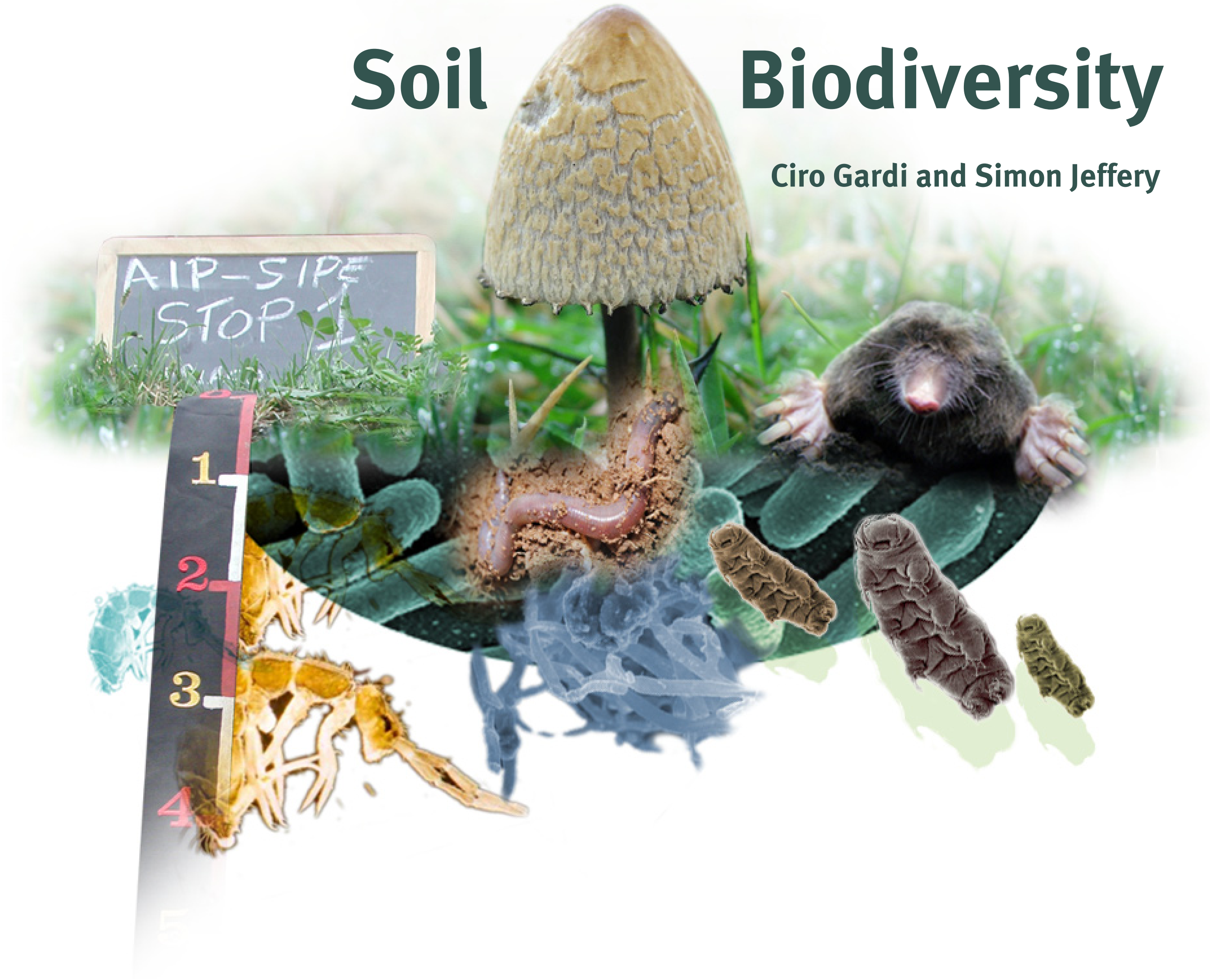
Ciro Gardi and Simon Jeffery



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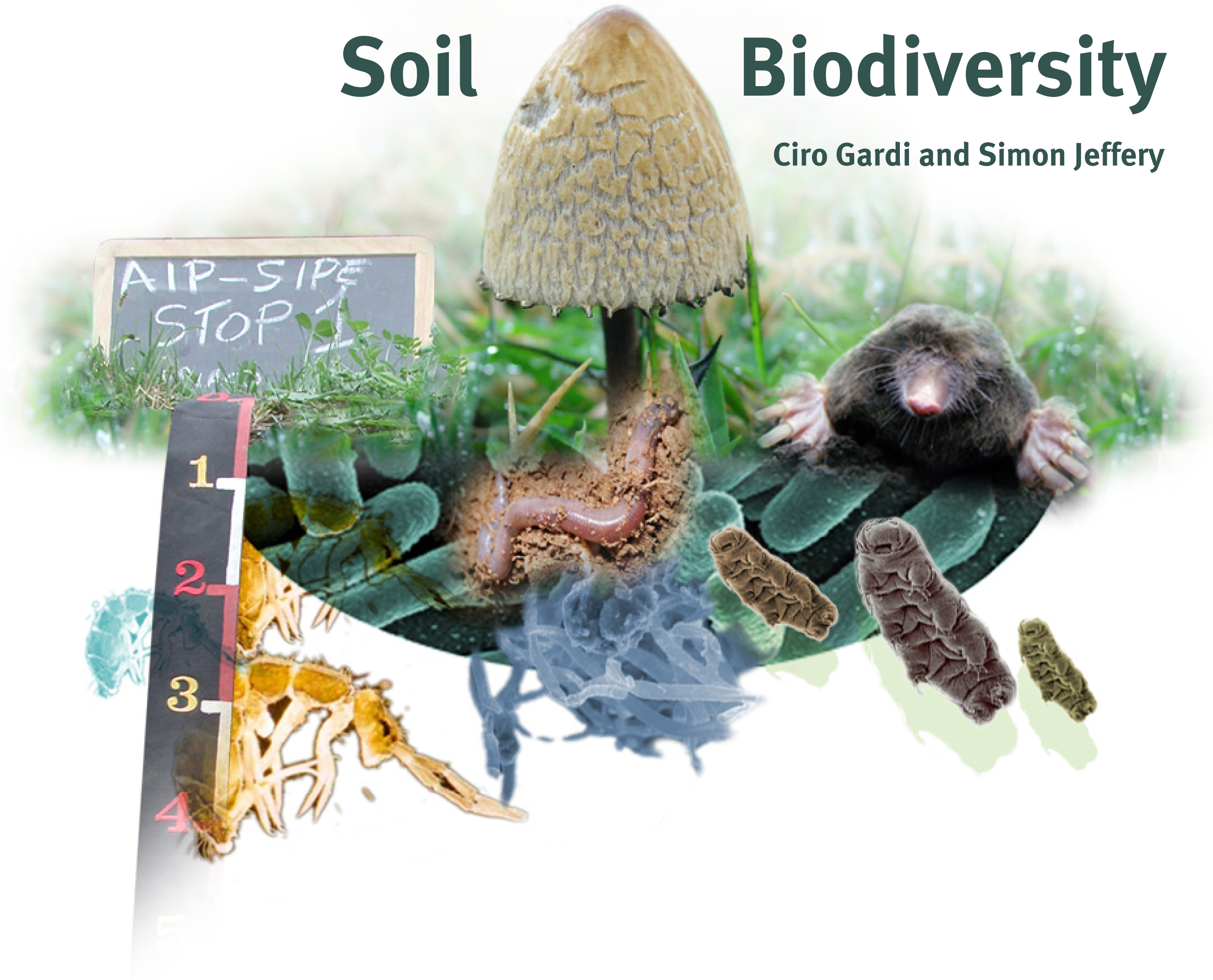

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Soil Biodiversity

What is biodiversity? Biodiversity has different meanings depending on the situation being discussed and the target audience. For example, the *Oxford English Dictionary* defines biodiversity as being "The variety of plant and animal life in the world or in a particular habitat". This is definition is clearly sufficient for non-specialists. However, when looking more specifically at biodiversity, it becomes evident that thought needs to be given to other groups such as fungi, bacteria and archea. As soil is such as diverse system when considered biologically (as well as physically or chemically) it is necessary to include all taxonomic groups. Therefore, throughout this booklet, when referring to "soil biodiversity" it will be in reference to the variety of *all living organisms* found within the soil system.

The soil system is dynamic, highly heterogeneous and extremely complex. Soil itself consists of a mineral portion containing mainly silica and a mixture of trace metals, and an organic matter portion containing a large variety of different organic compounds, as well as water and vast array of different organisms. Soil can exist as a variety of textures; with the texture being a product of changes in the relative proportions of sand, silt and clay. It can contain areas of relative dryness, and includes micropores which are almost always water filled apart from in times of extreme drought. The proportion and type of organic matter varies both with depth, and spatially.

This high level of heterogeneity means that soil contains an extremely large number of ecological niches which have given rise to a staggering array of biodiversity. Using a taxonomic approach to measure biodiversity, it is often said that more than half the world's estimated 10 million species of plant, animal and insects live in the tropical rainforests. However, when this approach is applied to the soil, the level of diversity is often quoted as being in the range of hundreds of thousands to possibly millions of species living in just 1 handful of soil!

Measures of soil biodiversity

Measurements of the level of soil biodiversity in a given area are important as a high level of species diversity is thought to indicate a healthy environment. No specific indices exist, or need to be developed for the soil system as biodiversity indices are applicable across the entire range of ecosystems without the need for modification. However, each has its own strengths and weaknesses.

The simplest measures of biodiversity are:

- **Species richness,** normally denoted "S", which is the total number of species found in an ecosystem or sample.
- **Species evenness,** normally denoted "E", which is a measure of how similar the abundances of different species are in a community. Species evenness ranges from zero to one. When evenness is close to zero, it indicates that distribution of organisms within the community is not even, i.e. most of the individuals belong to one, or a few, species or taxa. When evenness is close to one, it indicates that the distribution of organisms within the community is even, i.e. each species or taxa consist of a similar number of individuals.

Clearly, these two measures of biodiversity are much more informative when combined than when used alone.

Other methods which are of the used to quantify biodiversity in an ecosystem are:

Simpson's index (D) gives the probability that two randomly selected individuals belong to two different species/categories. It is often used to quantify the biodiversity of a given habitat and takes into account both the number of species and the relative abundance of each species present.

Simpson's index is calculated as follows:

$$D = \frac{\sum_{i=1}^{S} n_i (n_i - 1)}{N(N-1)}$$

Where S is the number of species,
N is the total percentage cover or total number of organisms,
n is the percentage cover of a species or number of organisms of a species.

It has been noted that the Simpson Index can, in some situations, provide misleading results with some areas which clearly have low levels of biodiversity having a disproportionately higher index. This situation is uncommon, however, and the Simpson Index normally provides a realistic measure of biodiversity with a low index equating to a relatively high level of biodiversity and a high index relating to a relatively lot level of biodiversity.

Shannon-Wiener index (H[1]) (also often referred to as the Shannon Index) is a measure of the order or disorder in a particular system which can be used and applied to ecological systems. When applied in ecology, in order to quantify levels of biodiversity, the Shannon index takes into account both species richness and the proportion of each species within a zone. A higher index is an indication that either there are a relatively high number of unique species or that there is relatively high species evenness.

The Shannon index is calculated as follows:

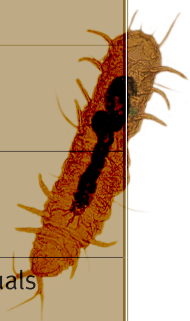
$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

p_i is the relative abundance of each species. This is calculated as the proportion of individuals in a species compared to the total number of individuals in the community: $\frac{n_i}{N}$

n_i is the number of individuals in species i.
N is the total number of all individuals
S is the number of species.

Organisms of the soil

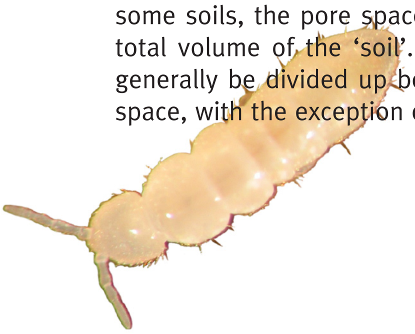
As previously stated, the soil environment is home to an incredible diversity of organisms. Added to that, the organisms which are found there are also often exist at astonishingly high levels of abundance. The level of abundance and diversity varies from soil to soil, depending on factors such as organic matter content, soil texture, pH and soil management practices. Below is the approximate abundance and diversity of organisms divided into groupings according to size, typically found in a handful of temperate grassland soil.



Microfauna Size range: 1-100 µm	**Mesofauna** Size range: 100 µm-2 mm	**Megafauna** Size range: ‹ 2 mm
Bacteria 100 billion cells from 10.000 species	**Tardigrades**	**Earthworms**
Fungi 50 km of hyphae from 500's of species	**Collemobla**	**Ants**
Protozoa 100.000 cells from 100's of species	**Mites**	**Woodlice**
Nematodes 10.000 individuals from 100's of species	Combined 1.000's individuals from 100's of species	Combined 100's individuals from 10's of species

Smaller size ⇢ larger size

The reason that such as large abundance of organisms can be found in just one handful of soil is due to the pore space found within soil which is where the organisms live. While it may appear to be solid, soil normally contains a large amount of pore space and in fact, in some soils, the pore space can make up 50% of the total volume of the 'soil'. The pore space itself can generally be divided up between air and water filled space, with the exception of in times of water logging or extreme drought. The surface area of this pore space can exceed 24,000 m^2 in 1 g of clay soils, with the total surface area decreasing with increasing silt and sand content. This demonstrates that, at the scale of micro-organisms, there is huge amount of space to function as a habitat for organisms in soil, and this is the reason that a relatively small amount of soil can be home to such a vast array and abundance of life.



The functions of Soil Biodiversity

Problems arise when we try to use the taxonomic approach to quantify soil biodiversity, especially when we move into the microscopic world of bacteria. Firstly, only a small percentage of soil bacteria, probably <10%, are currently culturable in the laboratory and this limits the amount of research that can be undertaken on them in a laboratory. Added to this, as bacteria can swap large amounts of DNA between themselves, the very definition of what makes a 'species' is unclear for bacteria. Indeed, there is no widely accepted consensus for defining 'species' in bacterial systematics.

More importantly, we would be *dramatically* underestimating the value of soil biodiversity if we were to use only the taxonomic approach. It is the diversity of the processes, the "functional diversity", carried out by the soil biota which gives soil biodiversity such high value.

Soil organisms perform many important functions such as playing a large role in the cycling of nutrients. For example, this includes the moving carbon from the soil to the atmosphere through microbial decomposition of soil organic matter and a complete understanding of this function is highly pertinent in this age of growing concern over atmospheric carbon dioxide levels. Other functions include the aiding of soil fertility through input of nitrogen and carbon into the soil, as well as affecting and maintaining soil structure. The soil biota also aids the cleaning of water supplies as water filters down through the soil, as well as the removal of pollutants from the soil through degradation.

It is clear that the soil biota performs many vital roles covering a vast range of processes and functioning at a range of different scales from the micro, sub-aggregate scale up to the global scale. Soil biodiversity is therefore known to play a very important role within the global system, and ongoing research continues to highlight this point.

Nutrient cycling

All global nutrient cycles contain an edaphic phase to a greater or lesser extent. Many of the cycles are highly complex, involving a range of enzymes and biochemical process which are not going to be discussed here in depth. However, an overview of the processes which occur and are reliant on the soil biota are presented below.

One of the most widely discussed nutrient cycles in recent times is the carbon cycle because of its pertinence to the theory of climate change. The carbon cycle occurs when carbon dioxide (CO_2) is fixed into organic form through the process of photosynthesis. Plants are most famous for performing this process, but a range of microbial organisms including algae, cyanobacteria and some other forms of bacteria are also capable of photosynthesis. In the carbon cycle, this fixed carbon can move up through trophic levels as photosynthetic organisms, or "primary producers", are grazed upon by "primary consumers" such as herbivores, and these in turn can be predated by "secondary consumers" and so on.

The carbon that was initially fixed by photoautotrophs is returned to the soil organic matter when the organisms die, or through excreta. This carbon, which forms part of the organic matter of the soil, can then follow one of two pathways. It can be subject to microbial decomposition whereby microbes use the organic substance as an energy source and the carbon is returned back to the atmosphere in the form on respired CO_2. However, there are several factors or mechanisms which can increase, sometimes dramatically, the residence time of carbon in soils. One factor is the level of recalcitrance of the carbon form. For example, short-chain carbohydrates are highly labile and do not generally remain in soils for long. However, more complex molecules, especially lignings and tannins are much more recalcitrant and can remain in soils for many years.

Other mechanisms exist by which carbon can remain in the soil for extended periods of time, possibly centuries. One example of this is peat bogs which, due to their waterlogged nature, have highly restricted gaseous exchange between the atmosphere and bog itself. This means that subsurface areas of peat bogs become anaerobic and acidic and this severely restricts the microbial decomposition of the organic matter.

In mineral soils, however, it is less common for water logging to occur and so prevent microbial decay. In these soils, it is more common for it to be inaccessibility of organic matter to microbial attack which prevents its decay. This can occur because the organic matter is stuck between soil aggregates meaning it is protected from access by microbes, because it is in micro-pores which are too small for microbes to enter, or just because, on the micro-scale, there are no microorganisms in the vicinity which are capable of decomposing the substance. This means that the organic matter content of a mineral soil can be relatively stable until a disturbance process such as tillage occurs. This then exposes previously protected organic matter to attack and so causes a flush of microbial biomass as this newly released energy source is utilized by the soil microbiota, and also leads to a reduction in the soil organic matter content of soils.

The nitrogen cycle relies heavily on the soil biota. The largest pool of nitrogen is the atmosphere with is almost 80% nitrogen. Gaseous nitrogen is not able to be utilised by the majority of the organisms on Earth, including plants. It first requires 'fixing' by microorganisms, through the actions of free living microbes such as cyanobacteria and various genera of bacteria and actinomycetes, or by symbiotic microbes such as *Rhizobium* which form root nodules in legumes. This nitrogen fixation process converts gaseous nitrogen into ammonia which can be utilized by plants or a large fraction of this ammonia is also converted into other plant available forms first into nitrite (NO_{2}) and then into nitrate (NO_3).

Conversion of nitrogen products such as nitrates and nitrites back to nitrogen gas occurs through a process known as denitrification. This process occurs in anaerobic conditions where bacteria use nitrogen, due to the absence of oxygen, for anaerobic respiration.

The nitrogen cycle has very important agricultural and environmental implications as it affects both soil fertility, due to the fact that nitrogen is often the limiting nutrient for crop growth, and it can also be a source of the green house gas N_2O. For these reasons, among others, the nitrogen cycle has become a major research topic in recent years. This has shed new light on the processes and organisms involved in the cycle. For example, over the past few years, research has uncovered the various roles played by archea in the nitrogen cycle and demonstrated that they are able to perform both assimilatory processes, such as nitrogen fixation and nitrate assimilation, as well as dissimilatory roles such as nitrate respiration and denitrification (Cabello *et al.,* 2004).

There are many other nutrients which are vital for life on this planet which have important edaphic phases reliant on the soil biota, generally for the decompositional stages of the cycle. For example, phosphorous is an important element for life on Earth and is used for several different biological processes, as well as being a vital part of both DNA and RNA. While plants are the most important organisms regarding the uptake of phosphorous from water and soil, and making it available up through the different trophic levels, it is again the soil microbiota which release phosphorous back into the environment through decomposition of dead plants and animals.

Soil formation and weathering

Soil forming processes occur as part of a complex feedback cycle between the mineral fraction of soils, the environment, and the biota within the soil system. Soil formation starts when rocks start to breakdown through weathering, over many years. The type of rock which weathers and from which the soil forms is known as the "parent material".

Early colonizers, such as lichens and other photoautotrophic organisms, fix carbon dioxide from the atmosphere as they grow and start to establish small amounts of organic matter which other organisms can utilise as an energy source. Overtime, the amount of organic matter builds up as more carbon is put into the system through photosynthesis, allowing other organisms to colonise the system. Once there is sufficient organic matter and other nutrients available, higher plants are able to colonise the soil which can then aid and speed up the soil forming process through their roots growing into cracks in rocks and causing cracks to expand thereby increasing the surface area exposed to weathering.

Weathering is the primary source of essential elements for organisms within the soil system, with the exception of nitrogen and carbon. Feedback cycles exist between the soil biota and the weathering process whereby, as weathering occurs, essential elements are released, aiding growth within the soil biota. This in turn adds to the weathering process as the soil biota increases weathering rates. Fungi, particularly saprotrophic and mutualistic fungi, have been shown to increase rates of mineral weathering and are thought to be important in weathering at ecological and evolutionary time scales (Hoffland *et al.,* 2004), and hence influence the cycles of several nutrients within the soil system. Weathering has also been shown to be accelerated by earthworms, including evidence of the transformation of smectite to illite (Carpenter *et al.,* 2007). This highlights the critical role that soil organisms play within soil formation processes.

Waste recycling

Saprotrophic organisms, also known as decomposers, use dead organisms, or dead parts of organisms such as leaves, to carry out the process of decomposition. This is a heterotrophic process whereby the saprotrophs get their energy and nutrients from organic substrates. The primary decomposers are bacteria and fungi although some soil invertebrates such as earthworms are also decomposers.

Other soil invertebrates such as millipedes and collembola are often incorrectly referred to as decomposers. These are more correctly called detritivores as they are not able to digest the wide range of compounds that fungi and bacteria are capable of digesting. Nor are they capable of decomposing organic matter as completely as bacteria and fungi and leave behind organic substances which can than undergo further decomposition into inorganic material.

Bacteria are generally the primary decomposers of dead organisms and fungi are generally the primary decomposers of plant litter. When organic matter becomes available, either in the form of dead organisms, faeces, or through a disturbance event releasing previously inaccessible organic matter, such as when agricultural fields are tilled, bacteria can be capable of rapid growth and reproduction, especially if the organic matter contains relatively simple chemical bonds.

Fungi are able to degrade much more complex chemical bonds including lignin and cellulose. Additionally, as the majority of saprotrophic fungi grow as a branching network of hypahe they are able to penetrate larger pieces of organic matter as opposed to being restricted to growing on the surface. The growth of filamentous fungi is affected by the spatial distribution of substrate within the soil. When substrate is sparsely distributed, fungi can change their foraging strategy to explorative growth, whereby they grow sparsely in order to explore as large an area as possible to increase the likelihood of locating suitable substrate. Upon contact with a suitable substrate fungi can change their growth form, becoming much denser when suitable substrate is available to provide nutrients, allowing them to maximize use of the resource in the competitive soil environment (Ritz and Young 2004).

Fungi usually dominate in forest ecosystems, where the litter is mainly plant based and so contains a high proportion of lignin and cellulose. However, due to their filamentous nature, most saprotrophic fungi are easily damaged by physical disturbance events such as when agricultural fields are subjected to tillage. For this reason, bacteria generally dominate in agricultural systems.

Home for other organisms

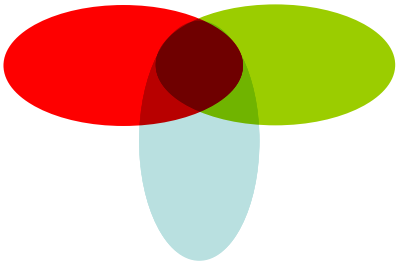
One very important function of soils is as a habitat for other organisms. While most people are aware of larger animals which use the soil as a home, such as moles, rabbits and foxes, many of these are thought of as pests. However, the soil is also a home for many other less obvious organisms, including larval stage of globally important animal groups such as pollinators. Disturbance events, both anthropogenic such as tillage, and natural, such as erosion events, can reduce habitat availability for these important groups. Pollinators are often keystone species for ecosystems, and their removal can lead to the collapse of some ecosystems (Bond 2001).

Functional Redundancy

The phenomenon of functional redundancy relies on the fact that different species are able to perform the same functional role in an given ecosystem. This means that changes in species diversity may *not* affect ecosystem functioning as other species are able to take over the functional role of species which have been lost from the ecosystem. Functional redundancy is possible because it occurs through the overlap of functional processes carried out by different organisms which inhabit different niches. This is different from competition, which is where two different organisms compete for a resource which is in limited supply.

One example of a process where functional redundancy may occur within an ecosystem is nitrogen fixation. As supplies of nitrogen from the atmosphere are all but infinite from the view point of soil microorganisms, there is no competition for this resource. There may be several diverse species of microorganism in the soil environment fixing nitrogen, for example cyanobacteria, *Rhizobium* and some actinomycetes. Loss of one of those species or groups of organisms would not mean that the nitrogen cycle stops within that ecosystem as other organisms are also present and performing that role. This means that there is functional redundancy with regard to nitrogen fixation within this example ecosystem.

To further explain the concept of functional redundancy, consider the following schematic.

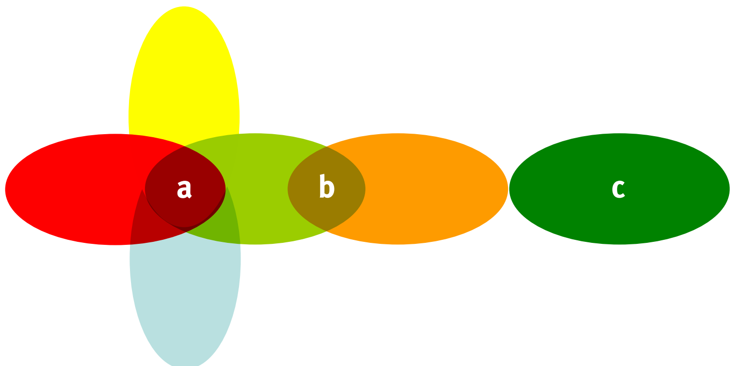


Each ellipse represents the range of functions that can be performed by one part of a given soil community, be it a certain species or group of organisms.

Whilst some functions can be carried out only by a part of the community, overlap between the functions that each group performs exits.

If one part of the community is removed, then some of the functions performed by that community is lost. However, due to the overlap in functions performed by different communities, not all functions are lost. This is Functional Redundancy.

However, it is important to note that some functions carried out in soil have more functional redundancy than others. For example:



a) High levels of functional redundancy exist.
E.g. Breakdown of some forms of organic matter by many species of soil invertebrates, fungi and bacteria.

b) Some levels of function redundancy exists.
E.g. Nitrogen fixation by *Rhizobium,* Cyanobacteria, actinomycetes.

c) No Functional redundancy exists.
Loss of this part of the community means complete loss of this function. E.g. breakdown of some highly recalcitrant or xenobiotic compounds.

Resistance vs. Resilience

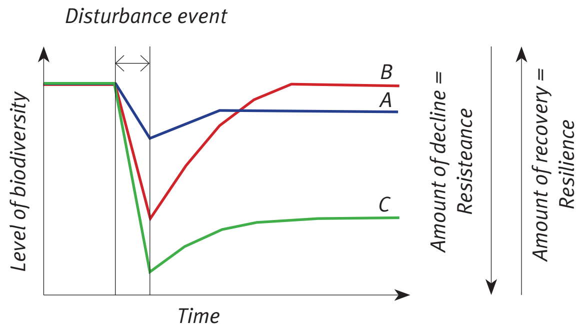
Other important concepts when discussing the effects of soil biodiversity on soil ecosystem functioning (or biodiversity on ecosystem functioning in general), are the concepts of resistance versus resilience.

Resistance refers to a community's ability to 'resist' the effects of a disturbance event. In a soil system this can include both natural phenomena such as an erosion event, or be anthropogenic such as application of pesticide or tillage. The level of resistance in the community is a measure of how much ecosystem functioning is reduced following a disturbance event. A community with high levels of resistance will be affected less by such an event than a community with low levels of resistance.

Resilience, on the other hand, refers to a community's ability to recover back to pre-event levels of functioning after a disturbance. A resilient community will relatively rapidly regain pre-disturbance event levels of functioning whereas a community which has low levels of resilience will take much longer, if indeed it ever recovers to pre-disturbance event levels.

It is important to note that the two phenomena, resistance and resilience are independent, meaning a community with high or low levels of resistance may have either high or low levels of resilience.

For example:



The above figure shows the effect of a disturbance event on three different hypothetical soil communities. Community A shows relatively high levels of resistance but low levels of resilience and over the time frame shown dose not recover back to pre-disturbance levels of functioning. Community B shows relatively low levels of resistance, but much higher levels of resilience and soon after the disturbance event is functioning again at pre-disturbance levels. Community C shows both low levels of resistance and low levels of resilience and its possible that the functioning of this community will dramatically and permanently reduced.

This demonstrates how an identical disturbance event can lead to very different outcomes with regard to different soil communities and highlights the difficulties and importance of having the maximum amount of information possible regarding a soil community when attempting to assess the possible environmental impact of given disturbance event. Some systems will possibly be affected very little whereas other systems may be dramatically affected by the same disturbance event.

The economics of Soil Biodiversity

Soil biodiversity carries a range of values that depend on the perspective from which they are being considered. These include:

• **Functional value,** relating to the natural services that the soil biota provides, the associated preservation of ecosystem structure and integrity, and ultimately the functioning of the planetary system via connections with the atmosphere and hydrosphere.

• **Utilitarian ("direct use") value,** which covers the commercial and subsistence benefits of soil organisms to humankind.

• **Intrinsic ("non-use") value,** which comprises social, aesthetic, cultural and ethical benefits

• **Bequest ("serependic") value,** relating to future, but as yet unknown, value of biodiversity to future planetary function or generations of humankind.

Pimentel *et al.,* (1997) attempted to calculate the economic value of biodiversity, including that of soil biodiversity. This was done using relatively conservative estimates and assumptions. Those processes which are dependent on the soil biota are listed below:

Activity	Soil biodiversity involved in such activity	World economy benefits of biodiversity (x s10^9/year)
Waste recycling	Various saprohytic and litter feeding invertebrates (detritivores), fungi, bacteria, actinomycetes and other microorganisms	760
Soil formation	Diverse soil biota facilitate soil formation, e.g. earthworms, termites, fungi, etc.	25
Nitrogen fixation	Biological nitrogen fixation by diazotroph bacteria	90
Bioremediation of chemicals	Maintaining biodiversity in soils and water is imperative to the continued and improved effectiveness of bioremediation and biotreatment	121
Biotechnology	Nearly half of the current economic benefit of biotechnology related to agriculture involving nitrogen fixing bacteria, pharmaceutical industry, etc.	6
Biocontrol of pests	Soil provide microhabitats for natural enemies of pest, soil biota (e.g. mycorrhizas) contribute to host plant resistance and plant pathogens control	160
Pollination	Many pollinators may have edaphic phase in their life-cycle	200
Other wild food	For ex. mushrooms, earthworms, small arthropods, etc.	180
Total		**1.542**

This *conservative* estimate shows the annual value of ecosystem services provided by soil biodiversity to be $1.5 trillion (Pimentel *et al.,* 1997). This amount rises to $13 trillion once ecosystem good such as crops and timber are included (Constanza 1997). This is approximately 25% of the combined global GDP of 2007! (estimated to be $54.3 trillion: World Bank 2007).

This demonstrates the vast economic benefits of soil biodiversity and its conservation. Preventing the decline of soil biodiversity must therefore be of paramount importance. Loss of soil biodiversity equates to a loss of value of the soil system by whichever of the four perspectives are used for evaluation.

Whilst any reduction in soil biodiversity may not immediately equate to a loss value due to the previously discussed phenomena of functional redundancy, this may still occur if levels of functional redundancy are low. Even where levels of functional redundancy are relatively high, any loss of soil biodiversity will reduce the functional redundancy of the soil system, thereby reducing its resistance, and so leave it more vulnerable to further loss of value though disturbance events. In some of the worst case scenarios, in the event that the loss of biodiversity from the soil removes a keystone species (that being a species which plays a critical role in a given ecosystem), a collapse of multiple functions and concurrent loss of ecosystem services may occur, dramatically reducing the value of the system.

The biodiversity of the soil system is clearly of immense economic importance. The soil ecosystem is incredibly complex and is still far from being fully understood. Care must be taken that its exploitation for short term economic gain does not turn into a massive long term economic (and ecological) loss. This can only be done with confidence if we completely understand soil biodiversity, its interaction with the soil system and the processes carried out. This highlights the need for further research in this depauperate but highly pertinent area of science.

Soil Biodiversity & Sustainable Agriculture

Agriculture is the science of cultivating soil, producing crops, and raising livestock. Since its development roughly 10,000 years ago, agriculture has achieved unprecedented progress and success, being able to feed an ever increasing global population. Farmers throughout the world have responded to the challenge of rising human needs by increasing the total and per area production levels every year. This agricultural miracle is due to the intensification, concentration and specialisation of agriculture, relying upon new technologies of agricultural chemicals (fertilizers and pesticides), mechanisation, and plant breeding (hybrids and GMO's). Modern agriculture, however, has several undesirable side effects, often resulting in reduced environmental quality and natural resources as well as health concerns and economic insecurity for the traditional family farm. This has led to what is known today as a global "Sustainable Agriculture" movement.

The most important negative effects of conventional agriculture are, for example:

• the indiscriminate use of pesticides and chemical fertilizers which affects human health, wildlife populations and the quality of the environment;

• the excessive reliance on synthetic fertilizers, and the improper use and disposal of animal wastes is leading to the breakup of natural nutrient cycles, affecting also water quality and wildlife in aquatic habitats;

• the trend toward larger farms and plantation-type monocultures is leading to a loss of global biodiversity;

• inadequate farming management practices can led the increase in soil erosion rates, resulting in the loss of productive farmland in many parts of the world and associated off-site problems such as waterway contamination;

• unsustainable irrigation programs throughout the world are resulting in a depletion of freshwater resources and in an undesirable buildup of salinity and toxic mineral levels in one out of five hectares under irrigation.

Sustainable agriculture represents a possible way to avoid, or to reduce, the above listed impacts. In particular sustainable agriculture refers to the ability of a farm to produce food indefinitely, without causing severe or irreversible damage to ecosystem health. As for the more general concept of "sustainability", three key issues are involved: environmental (the long-term effects of various practices on soil properties and processes essential for crop productivity), social and economical. Soil biodiversity is essential for agriculture and food security and its proper management will aid agriculture being carried out using sustainable methods.

The identification of the roles of the soil biota on soil fertility regulation and plant production has been difficult (Anderson, 1994), and still many of the functions associated to different groups are unknown. This is often due to scale problems in research, where crop performance is measured at plot scale and over a growing season, which integrates across (and thus dilutes) the generally smaller scale, shorter term specific effects of the soil biota (Lavelle 2000). In addition, it is difficult to determine the various interactions between above and below ground biodiversity. Nevertheless, there are examples of both positive and negative effects of some functional groups, particularly microorganisms, phytoparasites / pathogens and rhyzophages, plant roots, and macrofauna on plant production.

The beneficial effects of soil organisms on agricultural productivity and ecological functioning include:

• organic matter decomposition and soil aggregation;

• breakdown of toxic compounds, both metabolic by-products of organisms and agrochemicals;

• inorganic transformations that make available nitrates, sulphates, and phosphates as well as essential elements such as iron and manganese;

• nitrogen fixation into forms usable by higher plants.

Organic matter cycling and humification

The decomposition and transformation of organic matter in terrestrial ecosystems relies essentially on soil organisms. This catabolic process is complementary to photosynthesis, and in terms of ecosystems services, has comparable importance. In other words, we can consider the "recycling" activity of the soil biota to be as important as the production of new organic materials.

Decomposition involves the physical fragmentation of organic matter, generally operated by small invertebrates, but also the chemical degradation, transformation and the translocation of organic substrates. The physical decomposition is the first phase of the process and it is followed by the action of enzymes mainly produced by soil microorganisms.

From the transformation of the organic matter in the soil, a peculiar class of organic substances is produced: the humus. This broad and heterogeneous category of organic compounds is not only a long term reservoir of soil fertility, but also plays an essential role in the creation and stabilisation of soil structure, and in the regulation of soil-water interactions.

Soil macrofauna, especially earthworms in temperate regions, have an important impact on soil organic matter dynamics and nutrient cycling is largely determined by their density and behavior (Lavelle *et al.* 1997). Even among a single group of soil organisms, such as earthworms, there can exist vastly different feeding and living habits. For example: epigeic species feed and live on the surface of soil and in the litter; aneic species feed on the surface, but live into the soil, building large gallery networks; and endogeic species live and feed within the soil.

Fertility regulation and nutrient uptake

Chemical fertility can be defined as the availability of nutrients essential for the plants. Soil microorganisms play a fundamental role in soil fertility regulation, increasing plant available nutrients, especially nitrogen and phosphorus, and have been demonstrated repeatedly to have positive impacts on crop yields.

Nitrogen, which is often the limiting factor for agricultural productivity, can be fixed by several groups of soil microorganisms, both symbiotic and non-symbiotic. Symbiotic nitrogen fixation, operated by bacteria and actinomycetes, can be as high as 400 kg N ha^{-1} yr^{-1}, while the amount of nitrogen fixed by free living bacteria is generally much lower.

Mycorrhiza are the results of symbiosis between specific soil-borne fungi and the roots of higher plants. There are two main types of mycorrhiza known as endomycorrhiza and ectomycorrhiza (Smith and Read 1997). Endomycorrhiza, commonly known as arbuscular mycorrhizal fungi (AMF) physically pentrate the roots of higher plants and can directly affect acquisition of nutrients, such as phosphorus, nitrogen, calcium and magnesium. This symbiosis generally enables the plant to "explore" a higher volume of soil, increasing the mineral uptake several fold. For example, an investigation carried out on sorghum demonstrated that the plants can increase the P uptake more than five times when AMF are present at the roots (Marshner 1995).

The appropriate management of the soil biota is essential for sustainable agriculture, where the limitation of external inputs is one of the fundamental principles. Research carried out in India has shown that the appropriate management of the organic materials and soil organisms (in this case earthworms), can lead to a dramatic increase in tea yields and in profitability of the crop (Senapati *et al.* 1999).

Pest and disease control

Plant pests and disease represent an enormous problem for agriculture production, causing both quantitative and qualitative damages to crop productions. Monetary losses due to soil borne diseases in the U.S. are estimated to exceed $4 billion per year (Lumsden *et al.,* 1995), and losses due to parasitic nematodes exceed $8 billion per year (Barker *et al.,* 1994). Furthermore, the cost of soil borne plant pathogens to society and the environment far exceeds the direct costs to growers and consumers. The use of chemical pesticides to control soil borne pathogens has caused significant changes in air and water quality, altered natural ecosystems resulting in direct and indirect affects on wildlife, and caused human health problems.

Plant diseases may also occur in natural environments, but they rarely run rampant and cause major problems. In contrast, the threat of disease epidemics in crop production is constant. The reasons for this are becoming increasingly evident.

Plant diseases result when a susceptible host and a disease-causing pathogen meet in a favorable environment. If any one of these three conditions is not met, disease does not start or spread. A healthy soil community has a diverse food web that helps to keep pests and disease under control through competition, predation and parasitism (Susilo *et al.* 2004).

Soil-borne diseases often result from a reduction in the biodiversity of soil organisms. Restoring beneficial organisms that attack, repel, or otherwise antagonize disease-causing pathogens will render a soil disease-suppressive. Plants growing in disease-suppressive soil resist diseases much better than in those growing in soils which have a low biological diversity. Beneficial organisms can be added directly, or the soil environment can be made more favorable for them, through correct agronomic management.

Soil structure and soil-water relationships

A good and stable soil structure is one of the main objectives of farmers. A favourable soil structure facilitates the germination and the establishment of crops, helps to prevent water logging, reduces the risks of water shortage and drought and maximises resistance and resilience against physical degradation.

Soil structure, the arrangement of the elemental particles of the soil, is mediated by organic and inorganic substances (microstructure) and by living organisms activities (meso and macrofauna burrowing, root growth, etc.) or structures (roots and fungal hyphae).

Soil macrofauna also play an important role in soil structure modification, through bioturbation and the production of biogenic structures. It is essential to have a suitable balance between organism building and breaking biogenic structures, in order to prevent soil degradation processes, such as soil compaction (Barrios 2007).

The activity of soil macrofauna can have an important influence on water and nutrients dynamic. In a series of experimental activities carried out in Burkina Faso, Mando *et al.* (1996) and Mando and Miedema (1997) showed that by managing the application of organic mulch and manure to the surface of crusted soil surfaces, it was possible to stimulate the burrowing and feeding activities of termites. The holes created in the soil surface helped prevent runoff and aided water infiltration. It has also been demonstrated that the no tillage or minimum tillage management schemes, by promoting the activity of soil engineers, can improve the soil physic characteristics.

Pollination

Two-thirds of the world's crop species depend on insects for pollination, which accounts for 15 to 30 percent of the food and beverages we consume. French and German scientists have estimated that the worldwide economic value of the pollination service provided by insect pollinators, mainly bees, was €153 billion in 2005 for the main crops that feed the world. However, the services provided by pollinators are not limited to agriculture productivity. They are also key to the function of many terrestrial ecosystems because they enhance native plant reproduction.

Several pollinating insect species (belonging to *Hymenoptera, Coleoptera* and other insect orders), spend a part of their life cycle into the soil. American native bees, for example, are among the most important crop-pollinating species and have three basic habitat needs:

• They must have access to a diversity of plants with overlapping blooming times.

• They need places to nest. Most native bees are solitary, and none build the wax or paper structures we associate with honey bees or wasps, but nest in small warrens of tunnels and cells which they construct in the soil.

• They need protection from most pesticides. Insecticides are primarily broad-spectrum and are therefore deadly to bees. Furthermore, indiscriminate herbicide use can remove many of the flowers that bees need for food.

This demonstrates the positive interaction that can be established between soil biodiversity and sustainable agriculture. Sustainable agriculture, thanks to limitations in the use of xenobiotic compounds and external inputs, ensures a higher level of soil biodiversity. At the same time the services provided by more complex and healthy soil communities, feedback and enable the further reduction of external inputs needed by agriculture. Soil biodiversity is therefore of vital importance in increasing the sustainability of agriculture.

Soil Biodiversity and biotechnology

The high levels of biodiversity found in the soil system includes organisms which perform a wide range of ecologically important functions. Soil dwelling organisms, as with above ground organisms, must compete for resources, and try to avoid being prey until they manage to reproduce. The consequences of this is that there are many evolutionary "arms races" occurring within the soil system. This, combined with the high levels of diversity, means that there are an array of functions and compounds within the soil system which can be utilized for biotechnological applications, and potentially there are many more functions and compounds which could be useful which are yet to be discovered. For this reason, an active area of soil biological research is that of biotechnology. These areas of biotechnological research generally fall into one or more of the following areas.

Bioremediation

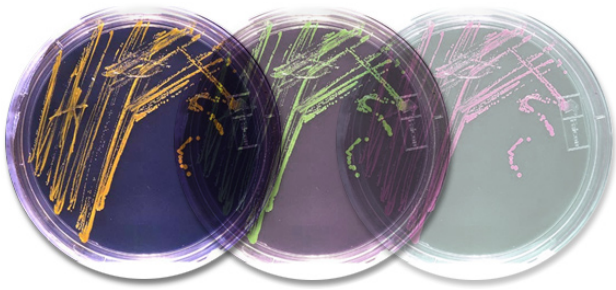
The soil biota is home to many different decomposers. These are heterotrophic organisms which break down organic substances to gain energy and in doing so recycle carbon and nitrogen back into the environment. However, this process can also be utilized as a form of biotechnology known as bioremediation, which is the process of using organisms ("bio") to return a contaminated area back to its pristine state ("remediation"). Despite this broad definition, most bioremediation is actually undertaken through the use of microorganisms due to their ability to utilize a vast range of carbon sources as a substrate.

Different soil decomposers are capable of degrading different types of organic substance. Some, compounds are not recalcitrant and so are susceptible to decomposition by a range of organisms. Other compounds, such as lignin and cellulose are highly recalcitrant and only susceptible to break down but a few select organisms; brown rot fungi in the case of lignin for example. This means that some non-recalcitrant pollutants may only last a short period of time in the environment and be broken down without human intervention. However, many organic pollutants are composed of long chains of carbon and hydrogen and can be structurally similar to complex organic compounds such as lignin. These compounds generally last much longer in the environment but the similarities in structure means that fungi can often be used for the bioremediation of many types of compounds, the key being determination of the correct fungal species for the effective bioremediation of a given compound. The incredible diversity of bacteria means there are often types of bacteria capable of degrading contaminants too. Again determining the correct type of bacteria for a given contaminant is necessary for maximum effectiveness of bioremediation.

Bioremediation occurs, or is undertaken in, three different forms:

- **Intrinsic Bioremediation:** this process occurs naturally in contaminated soil or water and is carried out by microorganisms living at the site of the contamination. No additional organisms or nutrients are required.
- **Biostimulation:** in this process, nutrients and/or oxygen are added to contaminated soil (or water) to encourage the growth and activity of the microorganisms living at the site of the contamination.
- **Bioaugmentation:** is the process of adding organisms, generally microorganisms to soil (or water) to aid the intrinsic bioremediation or to introduce organisms capable of degrading a contaminant which the intrinsic population is unable to.

Bioremediation can be highly effective in removing contaminants from affected sites. In one case an estimated 38,000 m^3 of soil in Canada was contaminated with an oil-tar byproduct containing polycyclic aromatic hydrocarbons, cyanide, xylene, toluene and heavy metals by a gasification plant. After application of a bacteria and nitrogen nutrient mix (a combination of biostimulation and bioaugmentation techniques), the various constituent pollutants of the oil tar were reduced by 40-90% in just 70-90 days (Warith *et al.* 1992).



Antibiotics

The soil contains a complex array of foodwebs and interactions between the diverse groups of organisms found there, with organisms predating each other and competing for resources, and as such a host of processes for both attack and survival have evolved. One of these is the use of chemical substances in a form of chemical "warfare" between soil organisms. It is some of these chemicals which, when isolated, we use for medicinal purposes as antibiotics.

Antibiotics isolated from soil organisms include (but are not limited to): penicillin, isolated from the penicillin fungus which is found in soils and which, along with several semi-synthetic derivatives, is still in wide use. Aminoglycosides, such as streptomycin and kanamycin, as well as tetracyclines were isolated from soil dwelling actinomycetes. Lipopeptides such as daptomycin have also been derived from Steptomyces, a type of actinomycete. Each of these antibiotics has a different mode of action. Some attack the cellular membranes, where as others attack the ribosome or other cellular constituents. It is for this reason that some organisms are susceptible to some antibiotics but not others, depending on whether they have the specific form of cellular constituent which the antibiotic attacks.

Antibiotic resistance

As well as not being susceptible to some antibiotics, microorganisms are also often capable of developing resistance over time. Whilst this is often viewed as a problem for clinical microbiology, precedents for various modes of antibiotic resistance seen in the clinical environment can often be found in the soil environment. This is because soil microorganisms are often exposed to a wide range of compounds in their local environment, some of which may be harmful such as antibiotics, and this places an evolutionary pressure on the organisms to develop resistance or to go extinct. It is also necessary that antibiotic producers must contain some antibiotic resistance mechanisms for example, to prevent them committing suicide through production of their own antibiotic compounds.

The soil environment therefore represents an important pool for research into the underlying mechanisms of antibiotic resistance, including possible mechanisms which are not yet seen in clinical microbiology. Utilisation of this resource to better improve our understanding of the biochemical processes occurring may allow the circumnavigation or reduction of further antibiotic resistance developing. This is an area of research which is just starting to gain prominence (D'Costa *et al.,* 2006; Tomasz 2006). Evolution has even taken antibiotic resistance one step further. Danatas *et al.,* (2008) demonstrated that out of 18 antibiotics that they tested, from 8 major classes of antibiotic of both natural and synthetic origin, 13 to 17 supported the growth of bacteria when the antibiotic was available as the sole carbon source. Microorganisms are clearly highly adaptable, in ways which we are only recently coming to understand.

Antibiotic resistance occurs because antibiotics provide an evolutionary pressure on a given population whereby those organisms with natural resistance can survive and reproduce whereas those organisms which do not have the resistance factor die. Once a resistance factor has developed it can spread rapidly within a population or even a community though horizontal gene transfer where DNA is transferred from one bacterium to another. Transfer of DNA containing antibiotic resistance genes (as well as other genes) can occur through three processes:

- **Transformation.** When a bacterium dies and lyses (splits open), other bacteria which are actively-growing in close proximity can pick up its DNA.
- **Transfection.** Phage, which are viruses that infect bacteria and fungi, sometimes pick up extra genes from the microorganisms that they infect which are then passed on to other organisms which they infect
- **Conjugation.** Bacteria can fuse their cell membranes together and exchange plasmids or fragments of their chromosomes

These processes can occur between distinct 'species' of bacteria meaning that mechanisms of antibiotic resistance may only have to evolve once and can then spread throughout an entire community.

Biocontrol of pests

Biocontrol of pests is the use of natural 'enemies' as biological control agents, such as predators, parasites or pathogens, to control or reduce the population of a given pest. It is often used as an alternative to pesticide use. Broad spectrum pesticide use can be highly problematic as they often act on insects which are beneficial to crops as well as harmful insects. There is also a possibility of these chemicals being washed into groundwater or any nearby waterways causing contamination. Biocontrol is one method which can be used to reduce the need for large scale applications of broad spectrum pesticides.

When the pest is a pathogen, such as in the case of plant diseases, then the biological control agent is often referred to as an 'antagonist'. Biological control generally falls into three different types of strategy, referred to as:

• **Conservation,** where care is taken so that natural biological control agents are not eradicated by other pest control processes;

• **Classical biological control,** where a biological control agent is introduced into an area to control a pest species

• **Augmentation,** which involves the supplemental release of a biological control agent. It is often this third type of biocontrol which utilizes the soil biota. For example, entomopathogenic nematodes are often released at rates of millions or even billions per acre for control of certain soil-dwelling insect pests

Kerr (1982) listed that the ideal biocontrol organisms should include the following characteristics:

1. The organism should survive for an extended period of time in the soil in an inactive or active form.

2. The organism should contact the pathogen either directly or indirectly by diffusion of chemicals.

3. Multiplication in the laboratory should be simple and inexpensive.

4. It should be amenable to a simple, efficient and inexpensive process of packaging, distribution and application.

5. If possible, it should be specific for the target organism; the more specific it is, the less environment upset it will cause.

6. It should not be a health hazard in its preparation, distribution and application.

7. It should be active under the appropriate environmental conditions.

8. It should control the target pathogen efficiently and economically.

Soil biodiversity clearly has many more current and potential uses for biotechnology and this is an area ongoing area of research. One thing is clear, for every organism which goes extinct in the soil environment, as with other ecosystems, some as yet undiscovered biotechnology is also potentially lost. It is vital, therefore, that soil biodiversity is conserved as much as is reasonably possible and that the awareness of this need is raised within the scientific community and public in general.

Soil Biodiversity at the extreme

Microorganisms have been found pretty much everywhere we have looked. This encompasses a vast range of environments including relative extremes in temperature, moisture regime and solar radiation. Whilst microorganisms have been found flourishing in places such as boiling volcanic springs, the soil environment can also be a very extreme environment. Soil communities have been found in many harsh environments on Earth, from freezing Antarctica to baking deserts, including areas of extreme dryness, and exposure to UV. Communities found in such environments often exist at relatively low levels of biodiversity. These low levels of biodiversity can facilitate research as it can often be possible to better elucidate interactions and the relationships between organisms and their physical and chemical environments. Results and insights from these systems can then be applied to more complex systems, such as those found in soil systems in temperate and tropical regions.

The relatively low levels of biodiversity generally found in extreme environments means that communities often contain little or no functional redundancy. This means that they can be particularly susceptible to disturbance events and the removal of a vital function from the community can have dramatic consequences for other organisms of the community possibly leading to large changes in community composition and ecosystem process rates (Wall and Virginia 1999).

Temperature

Hot

Death Valley is one of the hottest places on Earth with daytime temperatures often exceeding 45°C during the summer months, and there are reports of the ground temperature reaching over 93°C (Douglas 2006). However, although the soil biodiversity in Death Valley soil is greatly diminished when compared to temperate soils for example, there are extremophilic bacteria which thrive even there.

Microorganisms in hot deserts have been shown to still function regarding geochemical cycling. Walvoord *et al.* (2003) reported that a large reservoir of bioavailable nitrogen (up to 10^4 kilograms of nitrogen per hectare, as nitrate) has accumulated in the subsoil zones of hot deserts. Natural sources of nitrate in desert ecosystems includes conversion from atmospheric N_2 by N-fixing organisms as well as nitrate in precipitation, eolian deposition of nitrate salts, (Walvoord *et al.* 2003). This demonstrates that ecosystem functioning, driven by microorganisms, still occurs even in the relatively extreme temperatures experienced in the desert environment.

Cold

Antarctic soils are the coldest on Earth (Campbell and Claridge 1981). Mean monthly air temperatures for some areas of Antarctica only rise above 0°C during December and January and don't rise above -20°C in July and August (Delille 2000). These soils represent the only known soil system where nematodes represent the top of the food chain and as such their food webs are unusually simple.

As nematodes are aquatic animals, soil water is a more important factor affecting their survival than the cold. However, nematodes are able to enter a form of cryptobiosis – being a state in which all metabolic activity in an organism is stopped – known as "anhydrobiosis" which is a state entered into by some organisms in the absence of water. Organisms in this state are extremely resilient and are able to survive for extended periods until conditions become favourable once again. In this state nematodes do not function with regards to the cycling of nutrients and this, combined with the relatively slow metabolic activates of microorganisms in the cold temperatures, and the lack of metabolic activity during the coldest months, contributes to an extremely slow rate of nutrient cycling in the Antarctic environment.

Microarthropods in extreme cold environments such as that found in Antarctica survive subzero temperatures through the use of a variety of strategies. Their body fluids are kept in a liquid state through the use of carbohydrate cryoprotectants and in some cases also through the use of antifreeze proteins. These are aided by the removal or masking of ice nucleating agents within their body fluids (Sinclair and Stevens 2006). These strategies prevent the freezing of bodily fluids and concurrent cellular damage that this would cause.

Dry

As well as being the coldest soils on Earth, Antarctica is also home to the driest soils in the McMurdo Dry Valleys. Outside of Antarctica, the driest place on the planet is the Atacama Desert of Chile. Here, some areas receive less than 5 mm of rainfall per year and there can be decades with no rain at all (Warren-Rhodes *et al.* 2006). However, limited levels of biodiversity are still found here. In areas with less than 75 hours a year of available liquid water, cyanobacteria, which are capable of photosynthesis, are still found. This appears to be the limit of photosynthesis with regard to water availability. Due to the restrictions on photosynthesis and metabolism imposed by the severe restrictions of water, it has been estimated that organic carbon within the soil communities found in this environment has a turnover time of 3,200 years (Warren-Rhodes *et al.* 2006). This compared to turnover rates of gener

ally less than 100 years in arable soils (Yamashita *et al.* 2006).

Solar radiation

Solar radiation is confined to the extreme surface of soils. It has been demonstrated that even sandy soils which have relatively large pores only allow the transmittance of 0.3% of solar radiation down to 2 mm deep and this transmittance is reduced to just 0.2% at 1 mm depth in a silty clay soil (Benvenuti 1995).

While light is vital for photosynthetic organisms, restricting photosynthesis to the extreme surface of the soil system, solar radiation also contains UV which is harmful to life. Hughes *et al.* (2003) demonstrated that UV radiation inhibited the growth of fungal hyphae, with the inhibition of growth increasing with decreasing wavelength.

Organisms which are exposed to sunlight normally produce pigments to protect themselves from the harmful effects of UV. For example, increased melanisation is witnessed in collembola which dwell nearer to the soil surface as a direct correlation to their increased exposure to UV (Hopkin 1997).

Perhaps counterintuitively, Arrage *et al.* (1993) demonstrated that many of the subsurface microorganisms they studied exhibited the same levels of UV resistance as surface microorganisms. This is perhaps a consequence of the highly dynamic nature of the soil system meaning that any soil microorganisms cannot 'rely' on being protected from UV and may become exposed after erosion events. In order to survive such events it is necessary for subsurface organisms to possess the necessary protective mechanisms even if they are not utilized for the majority of the time.

Mechanisms for coping with extremes

Cryptobiosis

The cryptobiotic state is characterised by an undetectable metabolism and the induction of physiological and morphological changes in the organism. Some organisms, including many species of bacteria and nematodes, are able to enter a cryptobiotic state at any stage during the lifecycle when environmental conditions become too harsh to support active life.

Organisms in the cryptobiotic state become extremely resistant to environmental conditions. Nematodes in this state, for example, have been shown to be resistant to extremely low temperatures, desiccation where the relative humidity reaches 0%, vacuum and nematicides. However, they are still able to quickly revive to an active state when favourable environmental conditions return (Freckman and Womersley 1983).

Use of proteins

Proteins have been shown to be able to function to protect organisms from extremes of either heat or cold. Proteins which help protect organisms from the effects of heat are called heat shock proteins. These proteins function as 'chaperones' to other proteins, aiding their folding and helping to prevent denaturation which would otherwise be caused by the heat.

Conversely, proteins which help protect organisms from the cold are called cold shock proteins. The mode of function of cold shock proteins is less certain than that of heat shock proteins, but it appears many are capable of binding to DNA and so possibly aid the organization of the chromosomes or act as RNA 'chaperones'. Some organisms which are able to survive in sub zero environments are also capable of producing antifreeze proteins. These function by binding to any ice crystals which form and inhibiting their growth.

Cyst formation

Many microorganisms, including bacteria, protozoa and fungi are also capable of undergoing a process called 'encysting' in which they form 'cysts'. Cysts are basically dormant and resilient forms of the organisms characterised by very little or no metabolism and thicker cells walls. Cysts are more resilient to extremes of temperature, pH and desiccation. Once conditions again become favourable, the organisms are able to come out of their cyst form and again start metabolizing, growth and reproduction.

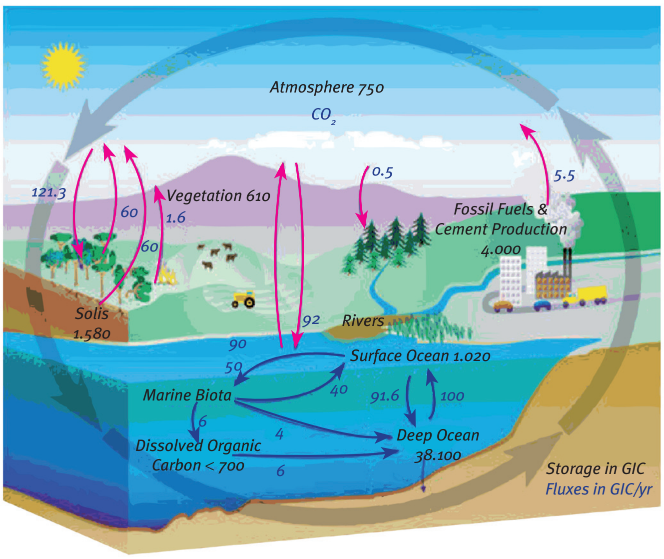
Soil Biodiversity and Climate Change

Climate change and its possible effects is currently an area of intensive research. The global system is incredibly complex with a virtually infinite number of interactions occurring at different temporal and spatial scales. While a reductionist approach to understanding such a large, complex and dynamic system is not possible, gaining a better understanding of the functions occurring in many of the different ecosystems found on the planet and their implications for climate change is clearly very important.

Soil is one system which has the potential to have a massive influence on climate change due to the large amounts of carbon stored there, more than twice the amount present in the atmosphere, which is found in the soil system in the form of organic matter.

Carbon dioxide is continuously removed from the atmosphere through photosynthesis by plants and other photosynthetic organisms such as algae and cyanobacteria. However, it is also generally being emitted from soils as the carbon which is present in soil is utilized as an energy source with CO_2 being emitted as a by-product of respiration. This is the essence of the carbon cycle, albeit in highly simplified form.

This is a schematic representation of the **Carbon Cycle:**



Schematic showing the carbon cycle highlighting both quantities of carbon stored in, and fluxes of carbon moving between different global systems.
Source: NASA (2008) http://earthobservatory.nasa.gov/Features/CarbonCycle/carbon_cycle4.php

Although this figure is also simplified, the numbers are all well established and relatively uncontroversial. Figure 1 shows is that if all inputs of carbon into sinks are added together the total amount of carbon going into sinks from the atmosphere is 213.35 Gt per year. Conversely, when all of the carbon emitted into the atmosphere from non-anthropogenic sources are added, they total 211.6 Gt per year. This equates to a net loss of carbon from the atmosphere of 1.75 Gt carbon. It is for this reason that the relatively small flux of CO_2 from anthropogenic sources (5.5 Gt per year) is of such large consequence as it turns the overall carbon flux from the atmosphere from a *loss* of 1.75 Gt per year, to a *net gain* of 3.75 Gt carbon per year!

The Impact of Soil Biodiversity on CO_2

The feedback between soil carbon and atmospheric CO_2 is a process which is still not fully understood. However, it is generally accepted that the soil biota plays the dominant part in this interaction. Soil biological processes therefore can clearly have a large effect on the global carbon cycle. This is because soils currently contain approximately twice the amount of carbon as is found in the atmosphere, and fluxes totaling in the hundreds of gigatonnes of carbon occur between the soil and the atmosphere on an annual basis. A complete understanding of the Carbon Cycle is vital in increasing our understanding of the feedback of carbon between the soil and the atmosphere and if, or how, this may be controlled.

Bellamy *et al.* (2005) found that an estimated 13 million tons of Carbon are lost from UK soils annually. This is the equivalent to 8% of total UK carbon emissions. As losses of soil organic carbon (SOC) were found to be independent of soil properties, this has lead to the formation of the hypothesis that the stability of SOC is dependent on the activity and diversity of soil organisms (Schulze & Freibauer 2005). There is evidence, however, that soils function as a sink for CO_2 in some areas as more carbon is put into the soil system through photosynthesis than is removed via respiration.

Studies at different latitudes have shown that the rate of soil organic matter decomposition doubles for every 8-9°C increase in mean annual temperature (Ladd *et al.*, 1985). While this is greater than the predicted increases due to climate change, all other things being equal, it is apparent that increased global temperatures will speed up soil organic matter decomposition rates. This then has the potential to feedback into even greater losses of CO_2 from soil.

Soil biodiversity can also have indirect effects as to whether soil functions as a carbon sink or source. It has been demonstrated repeatedly that soil biodiversity affects the erodibility of a soil due to a number of mechanisms including extracellular exudates, and physically binding soil particles together with fungal hyphae. This process is important with regard to climate change as it has been shown that soil erosion can turn soil from carbon sink to a carbon source (Lal and Pimentel 2007). However, how large an effect this is remains controversial and is an area of ongoing research.

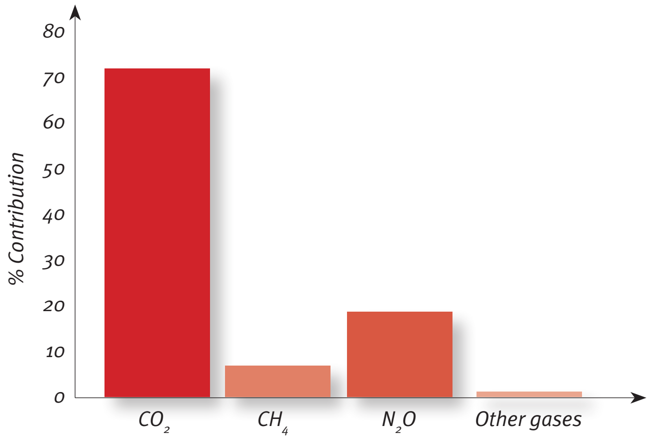
The impact of Soil Biodiversity on other Greenhouse Gases

Methane (CH_4) production also occurs as a part of the carbon cycle. It is produced by the soil microbiota under anaerobic conditions through a process known as methanogensis. Methane is about 21 times more potent as a greenhouse gas than carbon dioxide.

Nitrous oxide (N_2O) is produced as a part of the nitrogen cycle through processes known as nitrification and denitrification which are carried out by the soil microbiota. Nitrous oxide is 310 times more potent as a greenhouse gas than carbon dioxide.

Of the totals emitted, 80% of N_2O and 50% of CH4 emitted from are produced by soil processes in managed ecosystems.

Whilst these gases are potentially more potent greenhouse gases than CO_2, only approximately 8% of emitted greenhouse gases are CH_4 and only 5% are N_2O, with CO_2 making up approximately 83% of the total greenhouse gases emitted. The actual percentage contribution of these gases to global warming can be seen in the figure below (Source: US EPA Inventory of Greenhouse Gas Emissions and Sinks).



Relative contributions of different green house gases to global warming
Source: Greenhouse Gases and Global Warming Potentials. U.S. Environmental Protection Agency (2002)

This provides strong evidence that the soil system has the potential to play a very important role in either causing or helping to mitigate the effects of climate change. It is therefore very important that we fully understand the soil system, and its feedback with greenhouses gases in the atmosphere, to allow us to make accurate predictions regarding climate change and the possible impacts of various land management practices.

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Abstract

What is biodiversity? Biodiversity has different meanings depending on the situation being discussed and the target audience. For example, the Oxford English Dictionary defines biodiversity as being. The variety of plant and animal life in the world or in a particular habitat. This is definition is clearly sufficient for non-specialists. However, when looking more specifically at biodiversity, it becomes evident that thought needs to be given to other groups such as fungi, bacteria and archea. As soil is such as diverse system when considered biologically (as well as physically or chemically) it is necessary to include all taxonomic groups. Therefore, throughout this booklet, when referring to soil biodiversity it will be in reference to the variety of all living organisms found within the soil system.

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