Soil: The Life Supporting Skin of Earth

Kristín Vala Ragnarsdóttir and Steven A. Banwart (eds.)

A book on soil for secondary school students

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Table of Contents

Who are the authors?

Kristín Vala Ragnarsdóttir is a Professor of Sustainability Science at the Institutes of Earth Sciences and Sustainable Development, University of Iceland in Reykjavík, Iceland. She studied geochemistry and worked for a long time on environmental science at the University of Bristol (UK). The last 15 years the unsustainability of the world has worried Vala considerably, and she therefore put her focus on soil research and sustainability, because she would like her grandchildren and future generations to have a good future.

Steven A. Banwart is a scientists and professor working at The University of Sheffield in the United Kingdom. He grew up on a farm in the state of Idaho, USA and still loves being on farms and working outside. His main expertise is using the science of chemistry to study soil and water. Steve is committed to helping prevent and clean up pollution in the environment. He wants to find better ways for people to use soil and water so that all of the benefits that we get from the environment can continue for future generations.

Brynhildur Davidsdottir is professor in environment and natural resources at the University of Iceland. She grew up on a small farm in W Iceland, where she learned to appreciate the wonders of nature. As a child Brynhildur was interested in all the creatures in soils such as earthworms and learned about how incredibly important they are. She has continued this focus into adulthood, and now she concentrates on measuring the benefits we derive from soils, and hopes that such information will help protect soil ecosystems.

Emil Dimitrov – I am a scientist working in Institute of Soil Science in Sofia, Bulgaria. His children´s curiosity was the reason for him to study soils – Where does the rain go? How do seeds become a tree? Where from does the tree get its nutrition? He realised that the major part of our food comes from soil and that beneath our feet exists a whole world, that we cannot see – roots of plants, moles tunnels. He studies processes in the soil and how we can preserve soil diversity, which is important for life beings on our planet.

Jon Örvar Geirsson Jonsson – is a PhD student at the University of Iceland. He is concerned about the relationship between humans and the natural world. For a long time Jon has been very interested in food production and therefore soil, as it is the foundational element for growing food. He wants to help to find ways to preserve soil for current and future generations.

Milena Kercheva is associate professor at The Institute of Soil Science, Agrotechnology and Plant Protection „Nikola Poushkarov” in Sofia, Bulgaria. Her research interests are soil physical properties and climate conditions, which determine the fate of water in soil. These investigations allow estimation of optimal soil physical conditions for plant development, as well as to predict the ecological risks of water availability under different environmental conditions.

Danielle Maia de Souza is a researcher at the Swedish University of Agricultural Sciences in Uppsala, Sweden. She is an environmental engineer and works mainly with environmental management in enterprises and life cycle assessment (LCA) of products. At the European Commission´s, Joint Research Centre, she integrated soil functions into the European Platform on LCA and carried out research on the evaluation of land use change impacts on biodiversity and ecosystem services.

Manoj Menon is a lecturer and soil scientist working at the University of Sheffield. He grew up on a farm in SW India and there he learnt about soil basics. As a scientist, he is fascinated with soil´s complexity. Manoj is interested in understanding how soil aggregates form, how soils interact with biological organisms such as plants and microbes, as well as understanding processes such as water and chemical movement in soils.

Nikolaos Nikolaidis is professor at the School of Environmental Engineering, Technical University of Crete in Greece. He uses mathematical modeling to design sustainable land use practices, that maximize soil services such as food production and soil biodiversity, while reducing the impact of nutrient leaching to the aquatic environment. Living in Crete, which is only 300 km away from the Sahara desert, Nikos studies ways to prevent desertification and find ways to adapt to climate change.

Svetla Rousseva is soil scientists and professor working at the Institute of Soil Science, Agrotechnology and Plant Protection in Sofia, Bulgaria. She is a physicist who applies her background knowledge to study soil and soil degradation threats from the point of view of physics. She is concerned about the fact that soil is a limited non-renewable resource at risk, and that soil protection is essential for food security and our sustainable future.

Toma Shishkov is a soil scientist working at The Institute of Soil Science, Agrotechnology and Plant Protection „Nikola Poushkarov" in Sofia, Bulgaria. His experience started with field surveying, exploring how much one soil differs from another. As an example - if plants colonise particular land form and produce deep rooting, more nutrients and water supply are needed, than if the rorting is shallow. Nowadays, Toma´s expertise is to define soil as it appears (i.e. morphology), diagnosing soil property data (or soil classification), and soil unique evolution in the landscape (or soil genesis).

Preface

Kristín Vala Ragnarsdóttir, University of Iceland

In 2015 the international community is celebrating the International Year of Soils. The United Nations Food and Agriculture Organisation's (FAO) call of action includes: Healthy soils are for healthy life. Therefore we need to protect our soils. Our soils are at danger because of expanding cities, deforestation, unsustainable land use and management practices, pollution, overgrazing and climate change. The current rate of soil degradation threatens the capacity to meet the needs of future generations. We depend on soils. Therefore the promotion of sustainable soil and land management is central to ensuring a productive food system, improved rural livelihoods and healthy environment. As long as soils are at risk, sustainable agriculture, food security and the provision of ecosystem services are compromised.[1] FAO also emphasises that we depend on soils. Healthy soils are the basis for healthy food production; Soils are the foundation for vegetation which is cultivated or managed for feed, fibre, fuel and medical productions; Soils support our planet´s biodiversity and they host a quarter of the total; Soils help to combat and adapt to climate change by playing a key role in the carbon cycle; Soils store and filter water, improving our resilience to floods and droughts; and Soil is a non-renewable resource, its preservation is essential for food security and our sustainable future.

Yet soil was globally not at the top of popularity for neither research or teaching nor funding at the end of the 20th century. In the past decade, however, a push for furthering our understanding of soils has been strong in Europe and further afield. It is therefore fitting that an effort is made by an international soils research team to inform young people about the importance of soil as a natural resource. Soil is the most important natural resource after water. It takes hundreds of years to develop just a few millimetres of soil, yet it can be eroded at an instance in a flash flood. Therefore we are now seeing this important resource being degraded at an alarming rate. In writing this book we took many of the important results from our research project, which involved 15 partners in Europe, USA and China. We hope that the soil issues presented here can help both students and teachers to think in a holistic way about soil - and that many of the students will become intrigued enough to study soil science or natural resource economics and/or policy when they go to University.

2015
International
Year of Soils

[1] http://www.fao.org/resources/infographics/infographics-details/en/c/271187/

1. SOIL AND EARTH'S CRITICAL ZONE

Nikolaos Nikolaidis, *Technical University of Crete and*
Kristin Vala Ragnarsdottir*, University of Iceland*

The 4x40 Challenge for Food, Fuel, Water and The Environment

The world's population has increased sevenfold from 1 billion people in 1800 to 7 billion in 2010 and it is expected to reach 9 billion by 2050. The demographic changes have exerted enormous pressure on agricultural production and it is one of the most significant drivers for environmental change. Further increases in world's population and the improvement of the standards of living in the developing world will also increase food demand and cause intensification in food production. In turn, agricultural intensification is exerting significant pressures on ecosystem resources.

Having the "good agricultural land" already in cultivation, increases in food production are expected by putting into cultivation "marginal lands" that are prone to environmental degradation, leading to depletion of soil carbon and loss of soil fertility. At the same time, the world is experiencing the effects of climate change and increases in the demand for energy and fertilizer required for development. These demand increases coincide with a time in history when the geological sources of energy (coal, oil and natural gas) and fertilizer (phosphate rock) are becoming more difficult and expensive to exploit. This is because the easiest and richest deposits are already exploited. This decline in easy-to-exploit geological resources is termed peak oil and peak phosphorous – or the time in history when the availability and hence extraction rate of these resources has peaked.

Currently nitrogen fertilizer is supplied by converting atmospheric nitrogen gas into concentrated forms that can be used by plants – and the industrial process for this fertilizer production has large energy demands. Oil raw material (the hydrogen in "hydro-carbons") is used for producing nitrogen fertilizer.

Peak energy (including the impact on nitrogen and phosphorus fertilizer production) has led the search for alternative fuel use such as biofuel production, which is taking up "good agricultural land" that could be used for food production. This conflict between food production and energy demand will intensify in the coming decades.

Resolving the conflict between food production and energy demand would require changes in modern agricultural practices that have been using the ''turning oil to food,'' approach which is unsustainable. This is because it uses about 30 times more energy (due to the use of gasoline and oil to operate machinery and produce fertilizers and pesticides) to produce 1 unit of energy of a meat product, and about 10 units more energy for a plant product, and is leading to planetary ecological crisis.

In the next four decades, humanity needs to address four major social and environmental challenges that coincide with a predicted quadrupling in the global economy; this we coin the "4x40" challenge:

1. Doubling of food production,
2. Doubling of energy production,
3. Increasing clean water supply by more than 50%, and
4. Mitigating and adapting to climate change and biodiversity decline.

Given these challenges, the question arises, will we be able to sustain soil fertility and at the same time address the combined effect of these environmental challenges? Suggested solutions to this conflict are not many – and we propose here a new way of thinking that may help us forward on a new and positive path. It is based on the approach of placing soils in the Earth´s Critical Zone and realizing that they are part of a larger system that feeds all life on Earth.

Earth’s critical zone – the central role of soil to meet the 4x40 challenge

The Earth’s Critical Zone is defined as the surface layer from the top of the vegetation canopy to the bottom of underground drinking water sources - “treetop to bedrock.” This is the thin section of our planet that provides almost all life-sustaining resources to humans. These resources include a huge range of beneficial environmental services; essential services that nature does for humanity – so-called ecosystem services - and these include soil ecosystem services. The services from soil include food and biomass production; filtration and transformation of water, nutrients and contaminants; carbon storage; providing biological habitat and maintaining biodiversity.

Figure 1. *A picture depicting an example of Earth’s Critical Zone.*

Figure 1 is a photograph of a vertical cross-section depicting soil on top of bedrock, an example of the Earth’s Critical Zone. A very thin layer of soil, sitting above the bedrock, sustains a healthy and dense forest. This thin soil section of our planet provides all of the biomass production on land this is used to sustain human life. In addition, there are biological and chemical (biogeochemical) interactions with plants and soil when water falls as precipitation and percolates through the soil. Soil has the ability to remove or add dissolved ions such as potassium to the water, and store the ions as mineral nutrients that can be used later as nutrition of plants.

What are the two main geochemical processes in soil? There are two main processes in soils that affect water transformation processes: Ion exchange (taking ions from water and keeping them by adsorption to soil surfaces) and chemical weathering (when minerals dissolve to make

components of the soil water). Mineral- and organic matter surfaces charges in soil depend on pH and give the ability to exchange or adsorb anions and cations from water, and thereby reducing the leaching of cations from the soil and making them bioavailable for plant growth. On the other hand, the process of chemical weathering dissolves the minerals from the soil and transforms them into a new chemical composition within the soil water, also providing elements necessary for plant growth. Important examples include magnesium for chlorophyll and phosphorus for running the plant energy system.

Soil is also important for storage of organic carbon on land, counteracting in this way the impacts of climate change. Plants absorb CO_2, an important greenhouse gas, from the atmosphere through photosynthesis; as plants die and plant litter falls to the ground it is physically broken down by earthworms and other biota into particulate organic matter. This organic matter is composed of the structural components of the plant such as lignin (component of the fiber walls of the vascular plants), cellulose (glucose chains of the cell wall) and hemicelulose (short chain sugars) that form vascular parts of the plant. These plant rests are relatively stable and can store carbon in the soil for a long time. They are the food for microorganisms (bacteria and fungi) in the soil that will eventually break them down to CO_2, water and salts.

What are the microbiota in the soil? They include fungi, bacteria and enzymes that decompose particulate organic matter into smaller molecules which are highly hydrophobic and prefer to adsorb (to stick) on primary soil mineral particles with high surface area such as silts and clays. These organo-mineral complexes have particle sizes that are less than 0.53 μm and they tend to aggregate forming micro-aggregates (size 0.53-250 μm) and then even large macro-aggregates (sizes >250 μm). The sorption of organic materials on silt and clays and the consequent aggregation into larger particles is a significant protection mechanism for carbon (see Chapter 2). Plant roots and fungal hyphae release exudates from the organisms that help bind soil particles into aggregates and the same happens when soil goes through earthworms – and macro-aggregates form. As decomposition within the macro-aggregate takes place, the aggregate breaks down and micro-aggregates are released. In this way, carbon is sequestered in the soil, reducing the amount that is released to the atmosphere and counteracting climate change impacts. Through the many actions of soil, the Critical Zone of our planet plays a central role in meeting the 4x40 environmental challenges, if it is managed properly.

How soil forms and is lost - and how fast

How does soil form? Soils form as a consequence of complex biogeochemical reactions between bedrock, water, plants and soil organisms within the Critical Zone. The rates of these reactions are slow, of the order of several mm depth of soil forming per 100 years, whereas soil degradation in the past decades is 100-1000 faster in agricultural areas – placing an unprecedented stress on agro-ecosystems and making it clear that soil is a non-renewable resource in the time scale of human generations. With the pressure of feeding 7.3 billion people (and rising), humans have now become a geologic force, moving annually 10 times more material than all natural forces and thereby transforming the Earth´s surface. Over 50% of this material movement is due to industrial agriculture. The agricultural losses are due to the physical effect of tillage and too many animal hooves from grazing that breaks the vegetation cover and loosens the soil underneath, breaks down the soil aggregates, and makes soil easier to be swept from the land surface by rain and wind and deposited in areas where it is not useful for agriculture – the processes of erosion.

One of the primary indicators that relates to soil fertility is the organic content of the soil. Loss of organic carbon indicates soil degradation and loss of soil fertility. Figure 2 presents data of soil organic carbon content decline after the conversion from forested land to agricultural land. The figure suggests that once the native land is ploughed to cultivation, the decline of organic carbon content is rapid and the land loses its fertility within 5-10 years without sustainability focused land management methods.

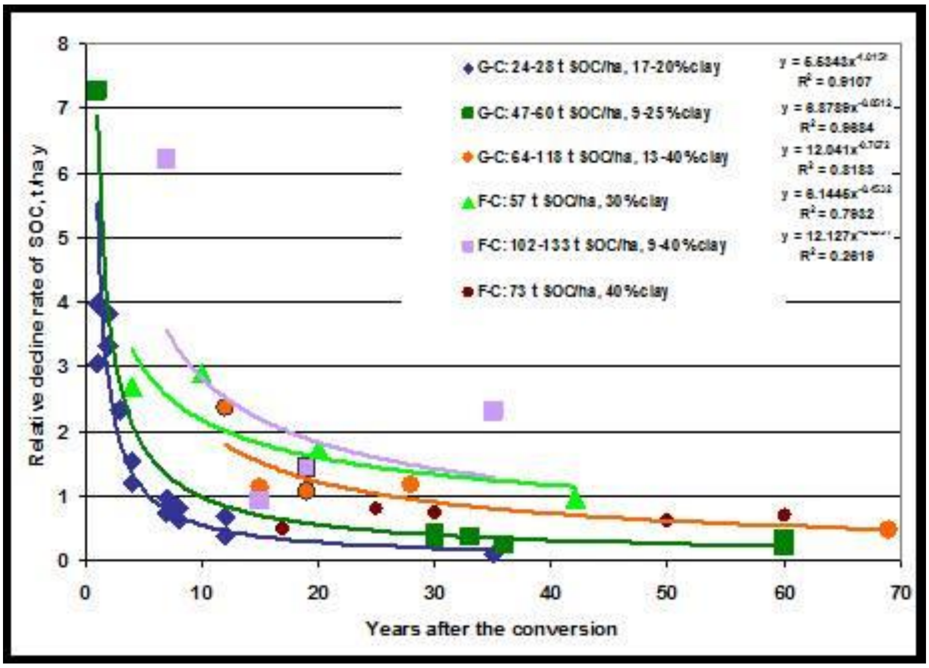

Figure 2. *Soil carbon loss due to conversion of natural forest or grassland to cropland (taken from Stamati, 2012).*

***How can we prevent soil degradation?* To counteract soil degradation and form new soils one needs to add significant amounts of organic matter into the soil on an annual basis. A wide range of techniques have been tested and applied in agriculture – often referred to as agroecological approaches - including reduced tillage (less ploughing), residue management (incorporation of plant residues – roots, leaves, branches, dead grass - into soil), mulching (return of fermented plant remains), crop rotation, crop mixtures, cover crops, the application of manure, sustainable land management, agroforestry with soil improvement through plants and trees that fix nitrogen from the air or soil water, application of permaculture design principles, terrace building, pitting systems (small pits filled soil mixed with manure and grasses), water harvesting techniques, drainage ditches, small dams in valley floors, drip irrigation, and so on to conserve soil and water and to prevent soil degradation and increase crop yields.** Thus man is able to successfully care for agricultural land by applying sustainability principles in soil management.

Soil degradation impacts in Europe and the world

What is the impact of soil degradation? The dynamic interaction of plants, microorganisms and soil generate the desired soil ecosystem functions and services such as food production that humans have depended on for sustenance. The decline of the capacity of the soil to deliver services is referred to as "soil degradation". Figure 3 presents the soil degradation status of the

world. As one can observe, the combination of the three categories of bareland, low and high status of medium to strong degradation characterize the soil services within most of the terrestrial environment. Agricultural cultivation touches 40% of the Earth´s ice-free land and this activity induced transport of 70% of Holocene (time period after Ice Age till presence) sediment.

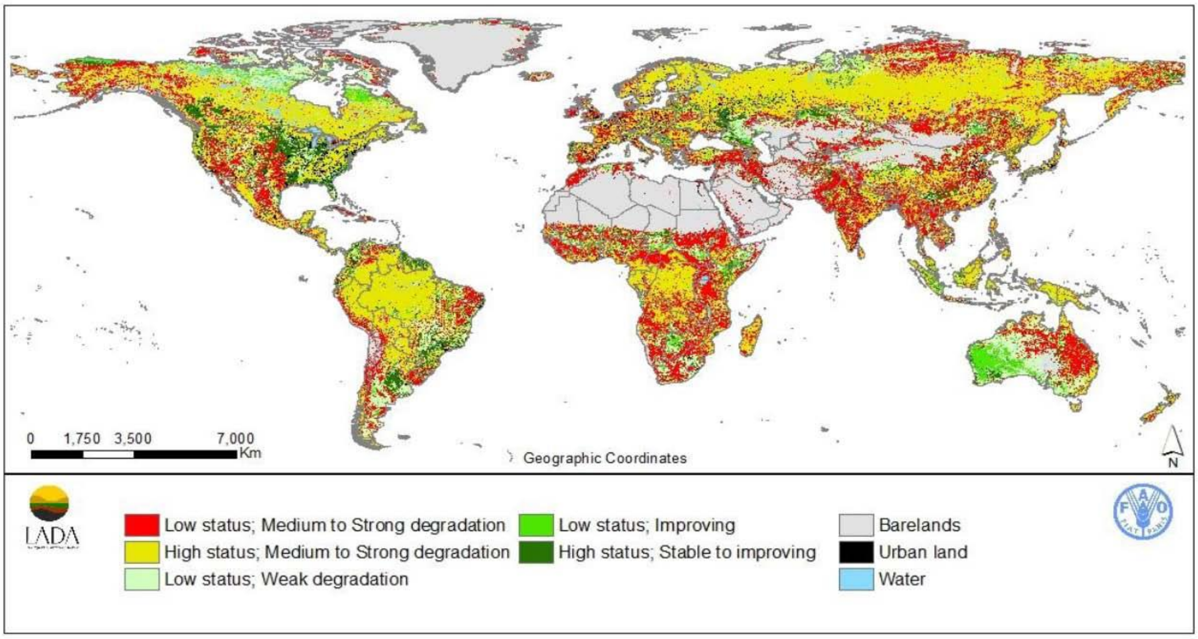

Figure 3. *Soil degradation status of the world (taken from Nachtergaele, 2011).*

The question then arises – ***is the Critical Zone Sustainable?*** Human activities and land use practices have played a significant role in soil degradation throughout human history. It has been claimed that civilizations such as the Mesopotamia and the Harappa (2200 BC) collapsed due to "intense deforestation and soil degradation" which caused decline in food production and consequent social, economic and political upheavals. The sites of the earliest civilizations in Mesopotamia and in the Nile and Indus valleys were characterized by fertile soil, dependable water supplies, low relief, and limited soil erosion. Similar is the story behind the Minoan and the Mycenaean civilizations in 1200 BC in Greece and the Roman in 300 AD. These periods are described as ‘‘Dark Ages’’ and it has been suggested that it takes 500 years for soil ecosystem services to be restored.

Soil degradation and recurrent ecological crisis can be found throughout the human history to the present. There is now a ‘‘historical amnesia’’ regarding the impacts of human practices on the land. Recent soil ecosystem collapse crises include the ‘‘Dust Bowl’’ in the USA in the 1930s, the case of the ‘‘Virgin Land Project’’ in the USSR (1954) “, and the Loess Plateau Watershed Rehabilitation Project” in China in the 1990s. Sensitive forested and grassland ecosystems were converted to cropland, followed by agricultural practices causing fertility decline resulting in the ‘‘dust bowl’” due to drought in the US, ecosystem collapse in the Aral Sea, and extensive soil erosion in China.

What are early messages related to soil degradation? It is of interest to dive into history and find early warning messages related to soil. One of the great early conservationists in the USA, Aldo Leopold, recognized in the 1930s that “the reaction of land to occupancy determines the nature and duration of civilization.” It would appear that the US government was “listening” because soon thereafter, the U.S. President Franklin Roosevelt, warned that “a nation that destroys its soils, destroys itself.”

Who is listening now? It is of prime importance that we learn from history and that land-owners to governments take appropriate action to change behaviour. Solutions and good practices for soil are emerging all over the world.

It has been estimated that moving globally to agro- ecologically attuned farming practices could increase food production significantly. In twenty African countries, more than 10 million farmers have on the average doubled their yields by adopting agro-ecological approaches such as composting, mulching, and careful intermixing of crops. Farmers in Mali (Africa), using non-chemical practices, won a prize for rice yields more than double the world average. Furthermore, organic methods generate one-half to as little as one-third as many greenhouse gas emissions. In the last decade, organic agricultural land has tripled and by moving worldwide to organic practices agriculture could be carbon neutral – releasing no more that it is absorbing. Therefore, in shifting to agro-ecological approaches we will significantly enhance sustainable land care.

These benefits are set against the demand to intensify production and increase yields. Recent studies argue that although organic farming practices offers many solutions to the environmental challenges, the yields that can be achieved are nearly sufficient to meet the present and future demands for food. The conflict between demand and environmental impact crystallises the difficulty of the “4x40” challenge – tough choices are required.

***Can we manage soil sustainably?* We have the knowledge to manage land and soil sustainably within the Earth´s Critical Zone, but the key issue is to transfer knowledge from academics and institutions to farmers and land-owners, and at the same time manage the growing demand for food.** The faster we do that, the more of a chance we have to sustainably manage our soils that are still in good condition and restore the degraded ones. These benefits must also be delivered against a projected doubling in demand for food, which means either more intense production and/or more marginal land being converted to production. Fundamental to all food production is Liebig’s principle: We can only sustainably harvest as much food as we are able to provide nutrients for, either by in-soil production (weathering of nutrients from stone, fixation of nitrogen from the atmosphere) or additions based on returning nutrients after use or from somewhere else. Every citizen’s food supply and every citizen’s environment will be impacted by the decisions that must be made. The future is in the hands of all of us.

Exercises

1. Agro-ecological practices can be used to reverse soil degradation around the world. Using material from the UN FAO and the European Union Common Agricultural Practices that you can readily find available on the web, identify one such practice and describe how it can help improve soil functions and soil services.

2. Using data for your country, estimate the amount of the organic fraction of the municipal solid waste produced, the amount of livestock excreta (animal manure) and the amount of biosolids produced at the wastewater treatment plants. Using literature sources find appropriate conversion factors that describe the content of nitrogen in each organic source and calculate the total nitrogen content from these sources that could potentially be returned to agricultural land and improve soil services. Compare this number with the nitrogen fertilizer use in your country. What is the percentage reduction in inorganic nitrogen fertilization if we recycle these organic byproducts and use them for soil improvements and fertilization?

Further Reading

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2. WHAT SOIL DOES

Manoj Menon**,** *University of Sheffield*

Can we imagine a world without soils? Once we start thinking about it, it will be soon realized that our life and civilization depend on this thin layer of material in the Critical Zone of our planet - the surface layer of our planet, which is critical for our survival (see Chapter 1).

Soil has many uses and, hence, it is viewed in different perspectives. For example, children view soil as something they can play with; soil is home for many organisms such as earthworms, termites and microbes. It provides raw materials (peat fuel, clay minerals for industry). Artists use it to make beautiful sculptures and other objects while engineers use it for construction (e.g. bricks, and as a platform to build on). We use soil to dispose or bury our waste. Perhaps the most important use of soil is produce food, fibre and fuel for our growing population.

Soil is limited resource and in this chapter, we will explore what makes soil such an extra-ordinary material to support our life on this planet? We will go through some of its vital soil functions and how it can be maintained or improved for future generations.

What is Soil?

How can soil be characterised? **Soil can be defined as the loose material on the terrestrial surface of the planet which is formed by weathering – the physical and chemical breakdown of rocks - and that can be put to different uses.** It is a complex, porous material which has distinct physical, chemical, biological and mineralogical properties. The thickness of soil varies from place to place and often it has layers, referred to as horizons. Soils vary in texture, structure, composition, colour etc.

Soil Functions

Soil forms a very thin interface (usually < 2 m) between the continental crust (geosphere) made of rocks or deposited sediments (thickness up to 80 kilometres) and atmosphere (thickness ~35 kilometres), biosphere and hydrosphere. These spheres interact to support all life on the Earth. Together they control water, carbon, nitrogen, other element cycles, gas exchanges and soils act as a temporary reservoir of several resources. Let us examine some of these functions in detail.

The Soil and Water cycle

Soils form an important component of the global water cycle. Nearly half of the total volume of soils is occupied by pores in most soils. **The pores in soils are capable of storage and release of water, which is essential for biological life.** The amount and geometry of pores in soils is a part of soil structure and it is very important in controlling how fast water moves in soil and how much will be retained. Most of the water we receive as rain, is immediately drained via large pores in soils, thus preventing flooding and recharging our groundwater resources. Smaller pores retain water in capillaries and the water becomes available for extraction by plant roots. However, it must be noted that a fraction of the water that plants absorb from the soil is

transpired (transpiration is loss of water from aerial parts of vegetation to the atmosphere – very little in cold climates, and almost all in warm climates). For example, soil needs to supply approximately 1000 litres of its stored water to produce a kilogram of wheat. The ability to store and transmit water in soil will depend on the soil structure and texture and therefore it is important to maintain good soil structure for good water retention between events of replenishment.

A large amount of water is also lost from bare soil through evaporation, which is also an important part of the water cycle. However in vegetated landscapes it is hard to separate evaporation and transpiration and therefore the term evapotranspiration is often used to refer to the combined water loss. Figure 4 shows contributions from various fluxes of water in the global water cycle and it is clearly seen that evapotranspiration is equal to nearly 60% of the precipitation on the land surface.

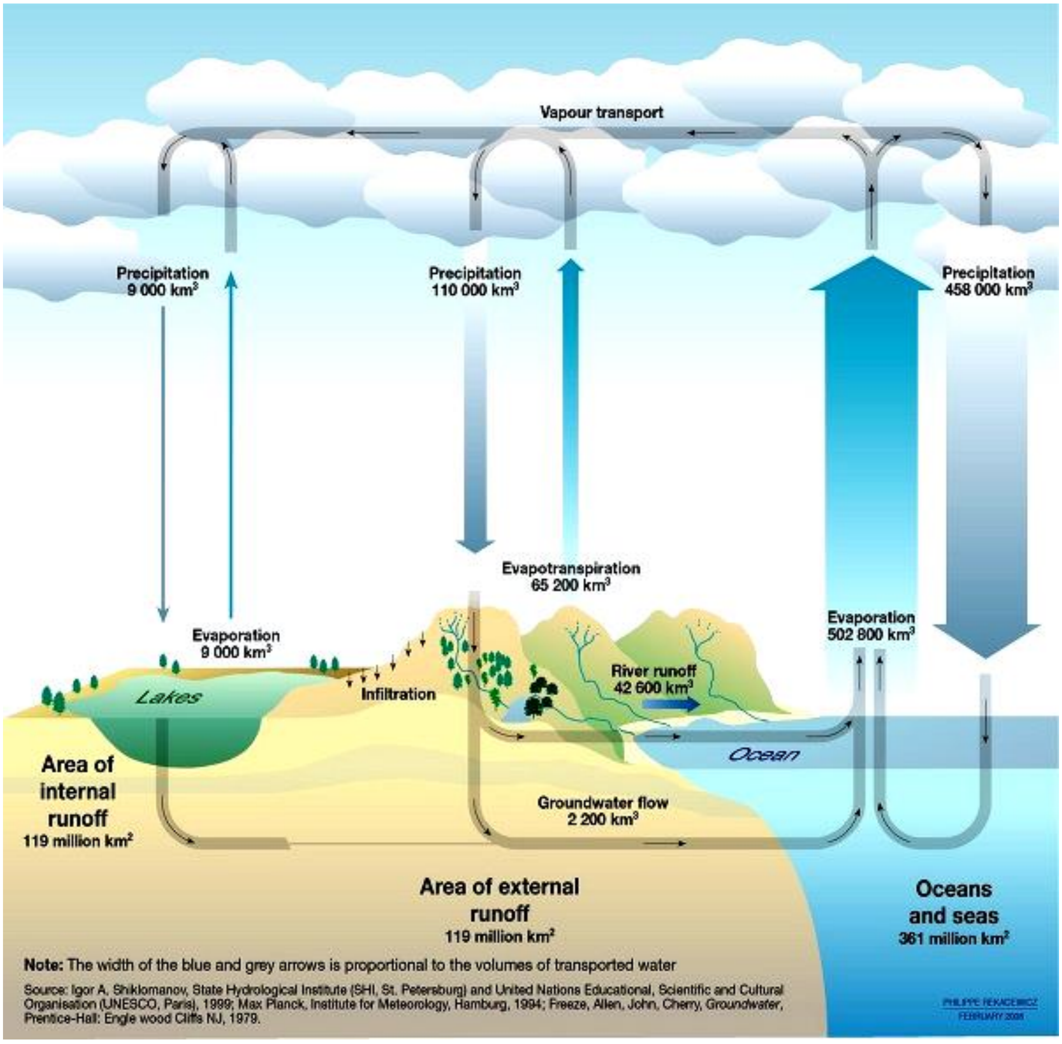

Figure 4. *The global water cycle. Arrows show the direction of water movement. Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and UNESCO, Paris, 1999; Max Planck, Institute for Meteorology, Hamburg, 1994; Freeze, Allen, John, Cherry, 'Groundwater': Prentice-Hall, Englewood Cliffs, NJ, 1979.*

Soil as a habitat

A handful of soil contain billions of microbes that include bacteria, fungi and protozoa and other organisms such as nematodes, earthworms, ants, termites etc., as shown in Figure 5. **Up to five tonnes of animal life can be found live in a hectare of soil.** Soil biota is important for the formation of soils and soil structure, organic matter decomposition, nutrient transformations and breaking down of toxic substances in soils. An example includes heterotrophic bacteria that are involved in nitrogen cycling. Soils support food, fibre and fuel production, help in providing clean drinking water as well as important secondary compounds such as pharmaceuticals and agrochemicals. The first ever antibiotic, penicillin, was extracted from mold derived from soils. Until now we could study and understand roles of only a tiny fraction of the microbial organisms found in soils.

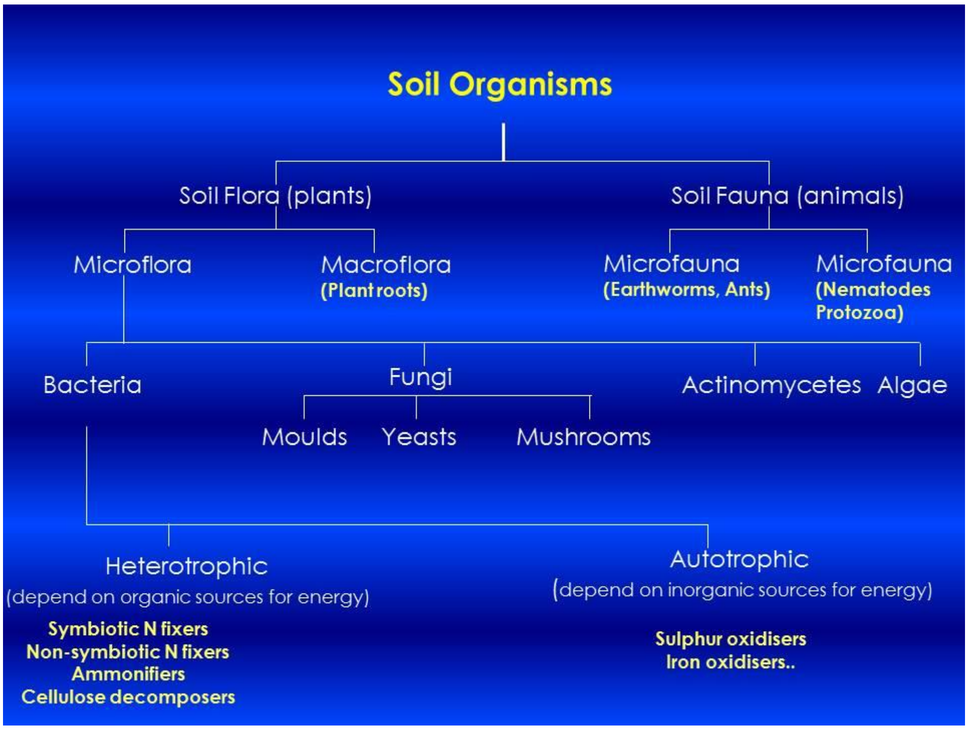

Figure 5. *Classification of soil organisms and biodiversity (Reference: Biswas TD and Mukherjee, S.K. 2001, Textbook of Soil Science, Tata McGraw-Hill Education).*

Soil Carbon Cycle

Soil stores substantial amounts of organic carbon in living and dead, decaying biomass (Figure 6). **Soil stores more carbon than the atmosphere and biosphere combined and therefore plays a significant role in the global carbon budget**, including the amount of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). Both organic and inorganic forms of carbon can be found in soils and the former plays an important role in maintaining soil fertility and productivity. Loss of soil carbon is found to be one of most important soil threats affecting global soils. Organic forms of carbon support the life of soil fauna and their products help to bind soil particles and metals to form the larger soil particles or aggregates (see Chapter 1), which are important in forming soil structure.

The main source of organic carbon in soil is vegetation and the microorganisms that grow when it is decomposed by the soil biota, releasing CO_2 back to the atmosphere. This means soil has the potential to influence the global soil carbon cycle and emission of greenhouse gases (GHGs).

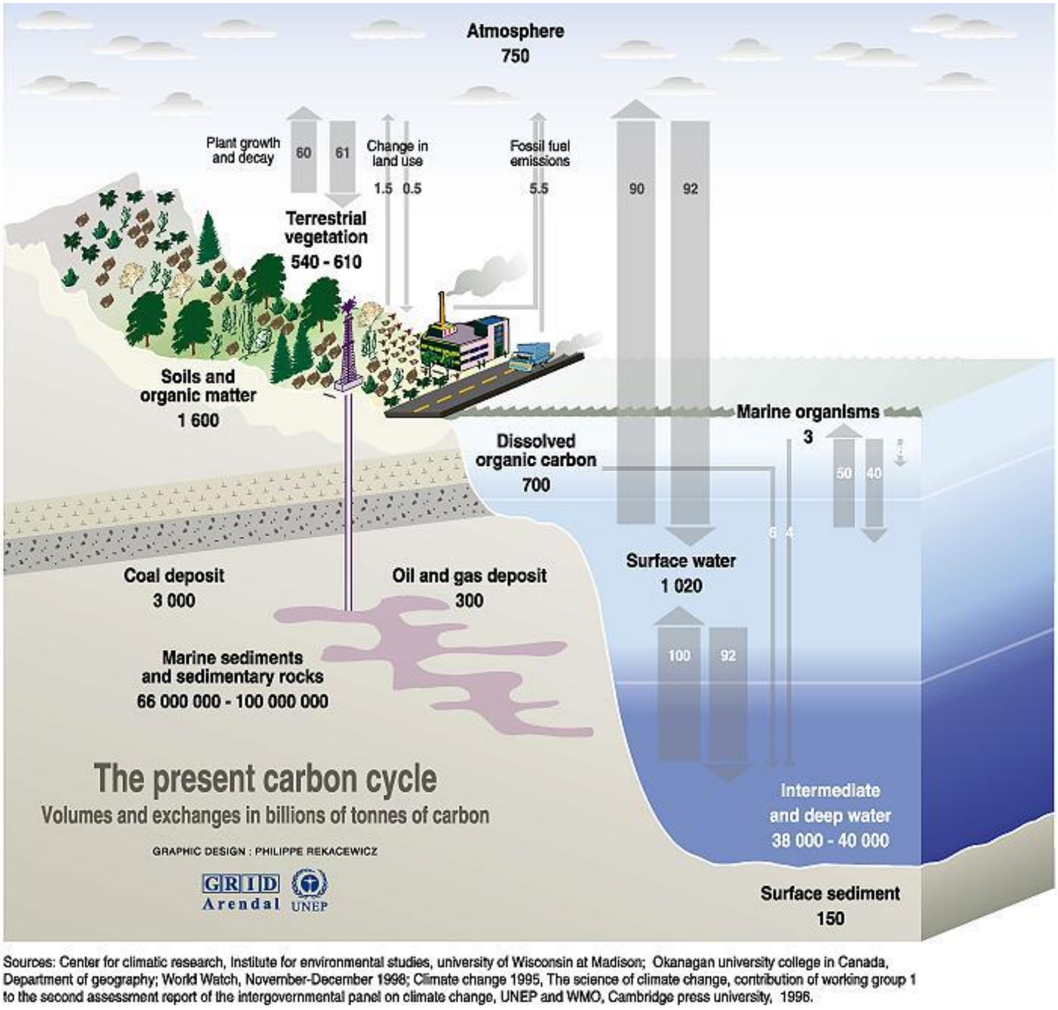

Figure 6. *The global carbon storage and flows. Source: Centre for climatic research, Institute of environmental studies, University of Wisconsin at Madison; Okanagan university college in Canada, Department of geography; World Watch, November-December 1998; Climate change 1995; The science of climate change, contribution of working group 1 to the second assessment report of the IPCC, UNEP and WMO, Cambridge press university, 1996.*

Soil Nutrient Transformations

Soils play vital role in supplying essential nutrients for the growth of vegetation. Among the essential nutrients N, P, S, K, Ca, Mg are called macro nutrients as they are required in large quantities and B, Cl, Mn, Fe, Zn, Cu, Mo and Ni are required in smaller amounts, hence they are called micronutrients. The surface of most particles in soil is negatively charged and therefore can attract and hold positively charged ions such as the calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^{+}) ions. This chemical behaviour of soils is important for the supply of essential nutrients such as potassium to plants and attenuation of contaminants which would

otherwise stay in the pore water and move with it to the groundwater or to streams. Soil pH plays an important role in retention and availability of plant nutrients. pH is a measure of the concentration of hydrogen ions (H^+) in the soil, and these affect how other ions are able to stick (or absorb) on the particle surfaces or remain dissolved in the pore waters. At high H^+ concentration (low pH), the binding of positively charged ions is weaker and the adsorbed ions may be lost from the soil.

Some negative ions such as phosphate (PO_4^{3-}) form such strong chemical bonds with mineral surfaces that they can stick even against the electrostatic repulsion of the negative surfaces. This chemical adsorption to particle surfaces allows ions like phosphate to be stored in the soil where they can be extracted by roots for plant growth.

Nitrogen (N) is one of the most important essential nutrients for the growth of vegetation as shown in Figure 7. Organisms require large amounts of N from the soil along with carbon from the atmosphere as they grow. The N cycle is involves several different steps and many different organisms are involved. N in soils is primarily derived from organic matter or by N fixation by a certain group of microorganisms. Both nitrate (NO_3^-) and ammonium (NH_4^+) forms are found in soils, and are available to plants and microbes for their growth. Soil N can also be released back to the atmosphere via a process called denitrification and one of the products of denitrification is N_2O, a greenhouse gas, which is 300 times more powerful than CO_2 in heating up the atmosphere.

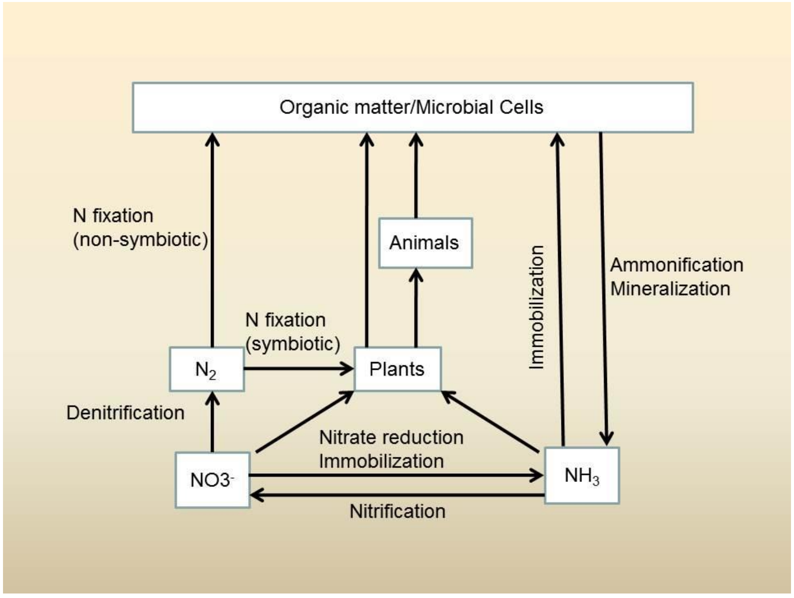

Figure 7. *Nitrogen transformations in soils (Reference: Alexander M, 1991, Introduction to Soil Microbiology (2nd Ed), Krieger Pub Co).*

The nitrate form of nitrogen is not retained in soils and remains dissolved in pore water and moves with the water as it flows to groundwater and to streams. In excessive amounts it is considered a pollutant in groundwater and streams, often causing eutrophication.

Regulation of Global Climate

As soil forms the surface layer of the terrestrial environment, it is a significant buffer on air temperature, weather and global climate. Plants roots and other soil organisms need oxygen gas from the atmosphere and release carbon dioxide as they respire. Some other important bacteria related to the N cycle will need nitrogen gas from the atmosphere. Soil therefore acts as an exchange system of gases and in this process, it helps maintain the balance of the gaseous composition in the atmosphere and acts as a filter that can help purify and maintain the beneficial composition of Earth's atmosphere.

The amount of heat stored by soil can vary depending on the composition i.e. proportion of air, water, organic matter and soil minerals. Soils that are wet will have large heat storage capacity compared to the ones that are dry. In vegetated landscapes, however, solar radiation is intercepted by plant canopy. Soil temperature controls the activity of soil microbes and is therefore linked to the decomposition of organic matter. For example, higher organic matter decomposition rates can be found in tropical regions compared to temperate regions.

Soil as a Medium for Plant growth

The ability of soils to control and store water, carbon and nutrients and numerous biota makes soils an excellent growth medium. Soil provides anchorage for plants and provides the necessary nutrients and water for the growth of plants. However, it may take a hundred years to form a cm of soil under natural conditions and can it be lost within a single growing season, or even a single storm or flood, by erosion.

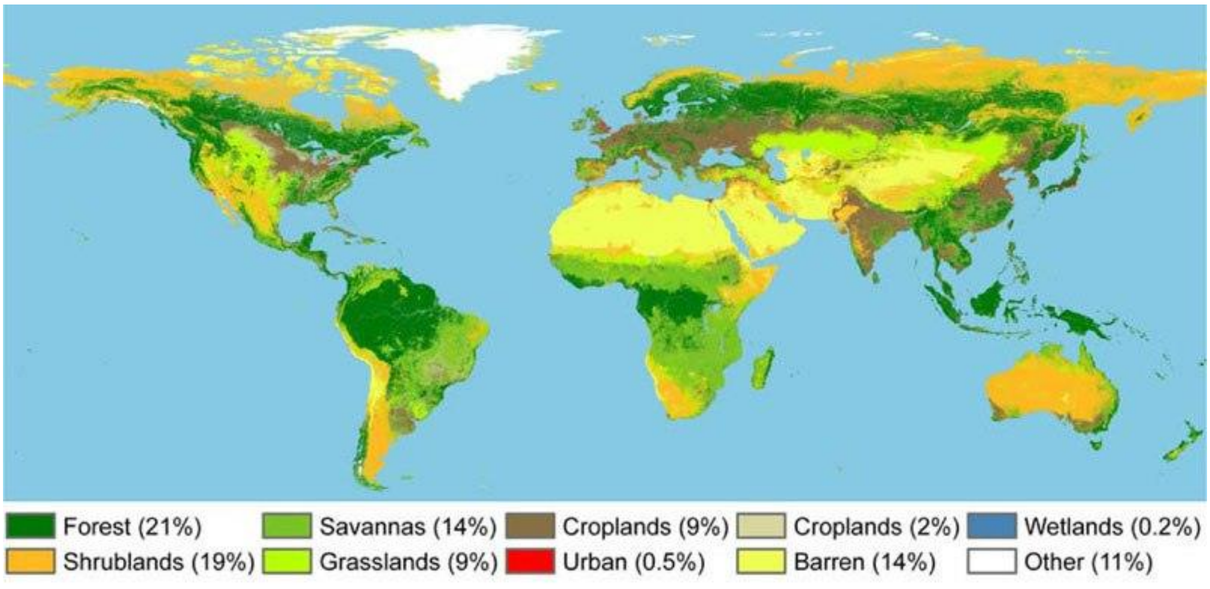

Figure 8. Global land cover in 2000 (source: University of Texas).

Our available land is used for various purposes and Figure 8 shows the distribution of various land covers across the world. Forest still remains the dominant land cover, followed by shrublands, grasslands and croplands. Soil is the most important medium to grow crops (food, fibre and other raw materials) for us. Due to the rapid rise in population, the per capita arable

land i.e. soil that is used for the production of crops, is decreasing due to soil sealing in many parts of the world, as shown in Figure 9 (see also Chapter 3).

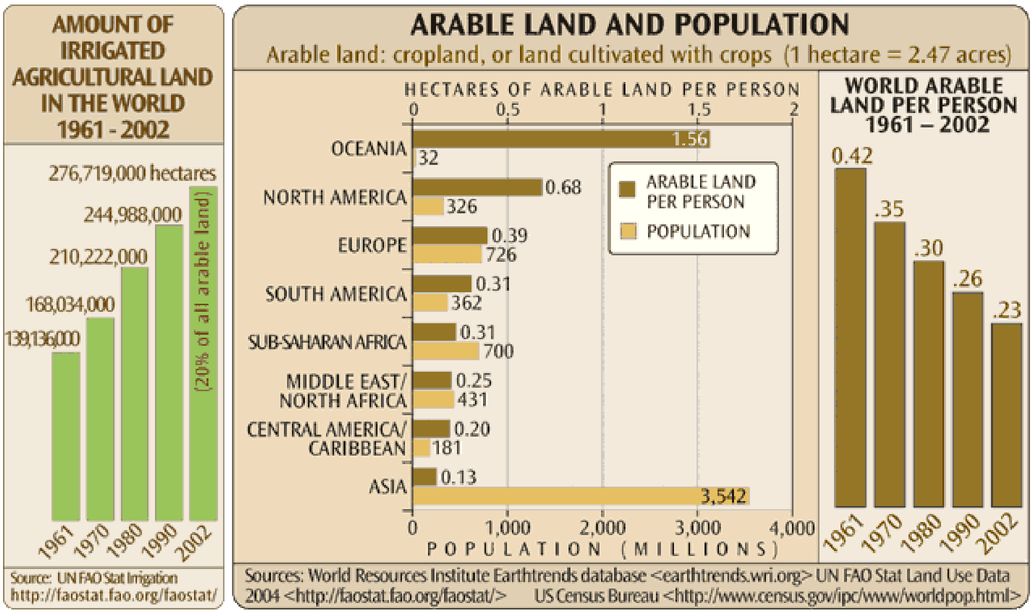

Figure 9. *Trends in irrigated lands in the last 40 years (left) and availability of arable land in regions of the world (middle) and changes in per capita arable land in the last 40 years (right).*

Soil as a Natural Filter

Due to the complex pore structure and the ability of soil minerals and organic particles to bind ions from the soil pore water, soil can regulate the flow of water and it can remove and retain dissolved contaminants such as heavy metals from pore water. **Soil thus acts as a natural filter for water entering our groundwater aquifers and streams that provides safe drinking water for us.** Clay minerals have a very high retention capacity for contaminants and hence soil and/or clay is used as protecting barriers for waste disposal sites. However some ions such as nitrate nutrients cannot be retained to any significant degree in soils, except when they are adsorbed by soil organisms or plants and fixed into biomass. In other cases the capacity of soil particles to retain chemical substances such as pesticides is finite and their use along with nitrate fertilisers must be limited in order to protect groundwater and streams.

Conclusions

Soil performs a variety of key functions that are essential for our survival on this planet. It regulates water, carbon and nutrient cycles and thus helps us to produce food, fibre, biofuels and other raw materials. It helps to transform nutrients required plants and at the same time, it also acts like a natural filter and retains contaminants reaching our precious water resources. With the increasing global population, maintaining these soil functions for future generations is one of the most important needs of today.

Exercises

1. What are the main soil functions? Discuss with your teachers and class-mates.
2. Why is soil important for the carbon cycle? How can we increase carbon storage in soils and help buffer the climate?

Further Reading

1. N.C. Brady and R. R. Weil (2013) *The Nature and Properties of Soils.* Prentice Hall
2. FAO-SOIL Portal http://www.fao.org/soils-portal/en/
3. EU-JRC: http://eusoils.jrc.ec.europa.eu/
4. SoilTrEC: http://www.soiltrec.eu/publications/publicdissemination.html

3. SOIL THREATS

Svetla Rousseva, Toma Shishkov, Milena Kercheva and Emil Dimitrov**,** *Institute of Soil Science, Agrotechnology and Plant Protection N. Poushkarov*

Evaluating the importance of soils

How do we evaluate soils? From ancient times, man has evaluated soil usefulness in terms of crop production; this is referred to as soil fertility. Fertility of the soils is usually determined by the natural conditions. However, soil is under increasing threats from a wide range of human activities. In Europe, the threats are complex and although unevenly spread across regions, their dimension is continental. The main vital environmental services that soil provides are also referred to as the soil functions. If the threats are not countered, soil will lose its capacity to carry out its vital functions and services (see also Chapter 4).

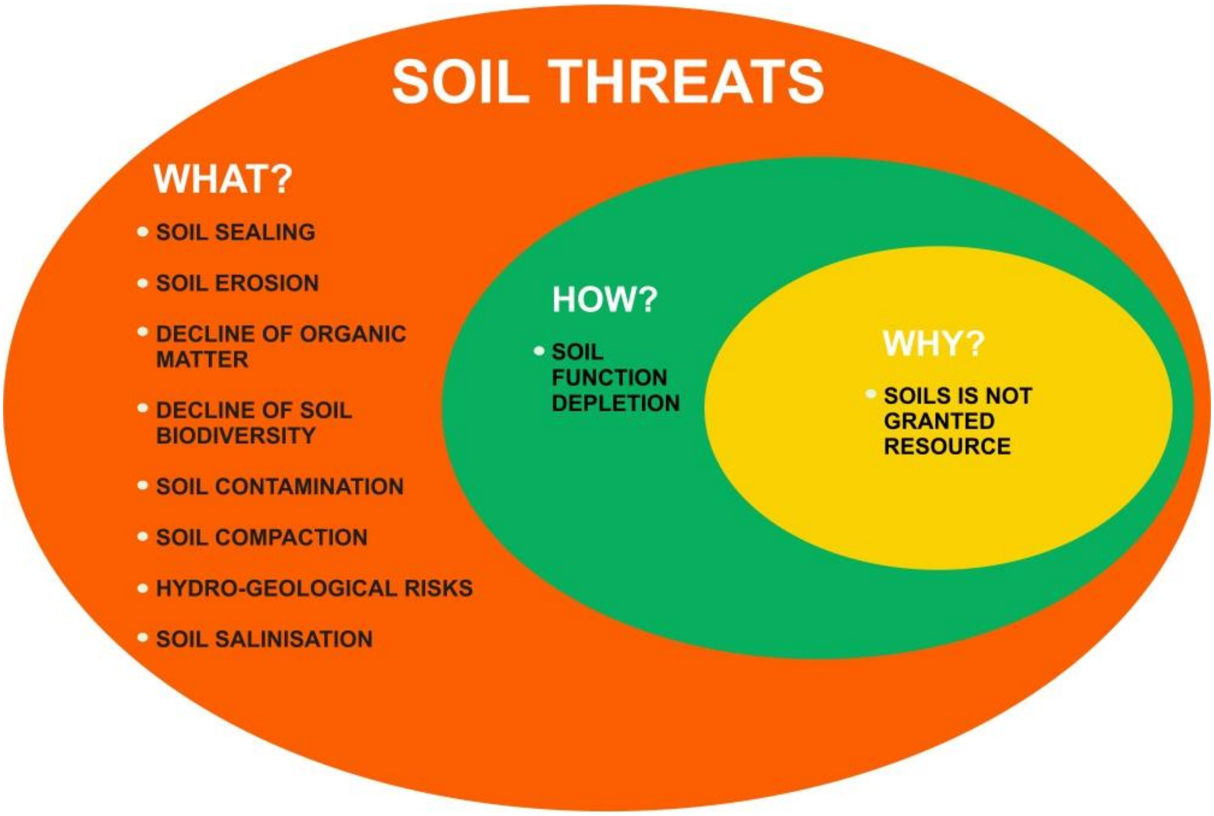

***Figure 10. What** is it a soil threat, **how** do threats impact soils, **why** does it matter today?*

Soil degradation processes

How do soil functions become degraded and lost? Soils are degraded through sealing, erosion, declining organic matter, biodiversity loss, contamination, compaction, hydro-geological risks, and salinization. Each process is described below.

Soil sealing represents the most threatening loss of soil resources due to population rise and accompanying urbanization and industrialization (Figure 11). Soil sealing means permanent covering of soil on land for housing, roads, and societal infrastructures, especially in urban areas. Sealed areas are lost to ecology, agriculture or forestry, while the ecological soil

functions are mostly prevented. Areas surrounding sealed soils may be also impacted by the change in water flow patterns or the fragmentation of habitats. Current studies suggest that soil sealing is nearly irreversible.

Figure 11. *Soil functions impacted by sealing.*

What is soil erosion? Soil erosion means removal of soil and rock particles by water, wind, ice and gravity (Figure 12). Topography, climate and soil characteristics are important physical factors that determine erosion rate. The management of agricultural and forest lands can either significantly reduce soil loss from erosion, or contribute to its considerable acceleration. Soil erosion is regarded as one of the most widespread forms of soil degradation, and as such, poses potentially severe limitations to sustainable land use in Europe. The most dominant effect of erosion is the loss of topsoil, which may not be noticeable but is nevertheless potentially very damaging. Soil loss has a significant on-site and off-site impact on soil functions.

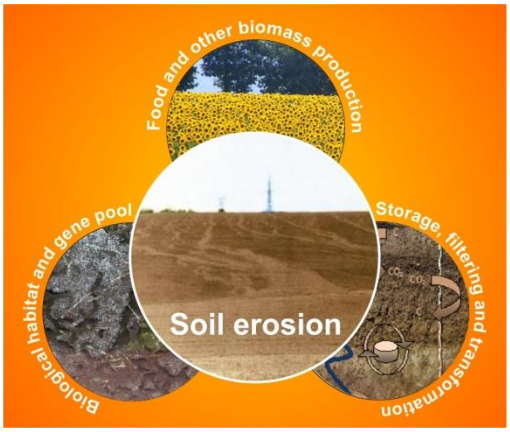

Figure 12. *Soil functions impacted by soil erosion.*

Soil erosion reduces soil thickness, the depth of the rooting layer, the amount of nutrients in the soil, the available soil water, filtering and buffering capacities of the soil, and the content of soil organic matter. Soil loss causes loss of biodiversity, degradation of soil structure, formation of

soil crust, distribution and accumulation of pollutants into watercourses and accumulation of sediments further down in the river system. Some soil erosion is thus soil displacement, where soil is moved from uphill to downhill plains and river-deltas. This soil is not totally lost, and the displacement may have an important ecological role of enriching plains at the cost of eroded soils uphill. When soil is eroded to the sea, the soil is irreversibly lost forever. Soil erosion controls organic carbon stocks and their distribution across terrestrial landscapes, which affects the carbon cycle, the content of carbon dioxide in the atmosphere and global warming. The maintenance of unbroken vegetation cover is a very important tool in preventing soil erosion. Roots of plants are effective in physically holding the soil in place, as well as regenerating it when small damages occur. The vegetation also regulates the hydrology, thus help binding water and even out extreme weather conditions.

Decline in soil organic matter content is more rapid in topsoil due to biological processes, and it can be accelerated by poor management of land (Figure 13). Generally, they include increased mineralization of organic carbon and increased loss of carbon from soils, but can also results from a decline in vegetation growth. Soil organic matter content is very important for soil fertility and thus providing nutrients for plant growth. Decline in soil organic matter contents is the main contributing factor to desertification – the degradation of a soils ability to support vegetation. Desertification and soil degradation is closely linked to changes in land cover and climate. Desertification can result from poor farming practices, and leads to deterioration of soil biodiversity and soil structure, accelerates rates of erosion, impairs infiltration rates and decreases the storage capacity for water.

Figure 13. *Soil functions impacted by decline of organic matter.*

Biodiversity loss is normally aimed at biological diversity among plants and animals, but may also refer to reduction of the main soil vital functions that are supported by the enormous variety of organisms (Figure 14). Soil is derived from the activity of organisms and the soil is their habitat. Soil biota plays fundamental role in delivering key ecosystem services associated with the functioning of the Earth system via connections between the atmosphere and hydrosphere with the biosphere. Healthy soil biota needs a complex mixture of organisms associated with the supply and dynamics of gases, water, solutes and substrates. The most threatening factors

leading to decline in soil biodiversity are use of chemical toxins (herbicides and pesticides), physical erosion, decline of soil organic matter content, contamination, chemical erosion, salinisation and sealing. Unsustainable land management also reduces soil biota communities.

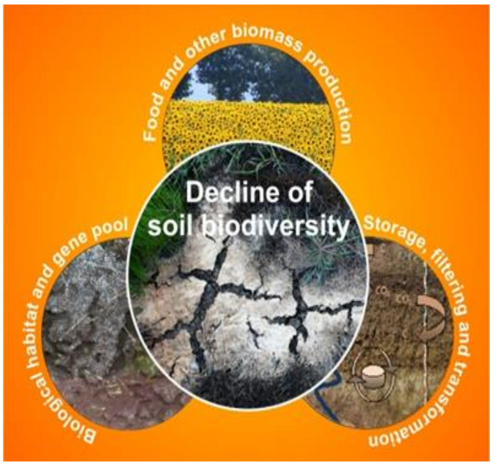

Figure 14. *Soil functions impacted by decline of soil biodiversity.*

Soil contamination can be diffuse or localized to certain areas and is mainly due to industrial production, traffic, through the exploitation of natural resources, such as ores, oil, coal, salts and others, or due to agricultural activities and waste disposal (Figure 15). Soil acts as a sink for almost all substances where soil and is above a certain thickness. Many pollutants accumulate in soil due to its specific filtering and buffering properties. Many substances occur naturally in the environment (e.g. heavy metals). Soil is regarded as "contaminated" when the concentration of these substances in soil is above a certain background value, or so high that it potentially causes a risk to human health, plants, animals, ecosystems or other media (e.g. water). Currently, the most important problems from diffuse sources are airborne acidification from burning of fossil fuels, causing surplus of nutrients through contamination by sulphur, nitrogen and heavy metals. Persistent organic chemicals, radioactive contamination and heavy metals do not compost, degrade, rot or evaporate at significant rates, and damage by these to soils may for many purposes be irreversible. It is therefore better that they never enter soil.

Figure 15. *Soil functions impacted by Contamination.*

Compaction of soil refers to the reorganisation of structural soil aggregates due to high pressure of heavy vehicles or animals on agricultural and forest lands; this has led to subsoil compaction and corresponding impeded drainage (Figure 16). Reduced water infiltration capacity results in increased surface run-off. The higher bulk soil density the higher is soil strength against compaction. These constrain plant root growth at depth and the passage of water and gas through soil. Unlike topsoil compaction, subsoil compaction is a hidden form of soil degradation that develops slowly over the years, decreasing soil biological activity, as well as soil porosity and permeability. More persistent organic fibres in the soil top layers, combined with high calcium saturation on the ion exchange matrix in the soil, tend to give better soil strength against compaction.

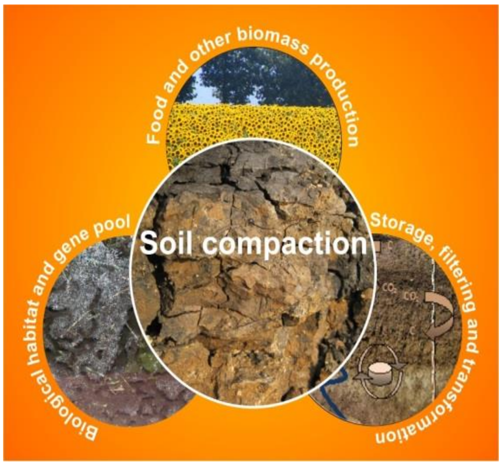

Figure 16. *Soil functions impacted by soil compaction.*

Hydro-geological risks refer to floods and landslides related to extreme climate or weather events, land use and soil cover (Figure 17). According to climate modellers, the probability, frequency, duration, and seriousness of extreme weather events of high temperatures and rainfall are increasing due to global warming and these events will be more common in the future. Man-made large-scale changes in the vegetation may have the same final effect on the soils. The impact of such events depends greatly on the physical and hydro-physical properties of soils. Floods and landslides are natural hazards intimately related to soil and land management. Floods and mass movements of soil cause erosion, pollution and loss of soil resources, with periodic catastrophic impacts for human activities and lives, damage to buildings and infrastructures and loss of agricultural land.

Figure 17. *Soil functions impacted by hydro-geological risks.*

Landslides are complex phenomena, resulting in removal of soil upslope and move downslope under the force of gravity. In cases where a landslide removes all soil material, all soil functions will be lost. Floods can result from soil not performing its role of controlling the water cycle due to compaction, because of a broken vegetation cover or by sealing. Such events are occurring more frequently in areas with highly erodible soil, steep slopes and intense precipitation.

Salinisation refers to the accumulation of soluble salts of sodium, magnesium and calcium in the soil to the extent that soil fertility is severely reduced (Figure 18). It is mainly a regional problem; the areas where it occurs are linked to the unsustainable use of soil and water resources. It occurs when we add more salts than what is removed by the system itself (by runoff with water) or what we remove (by harvest). The main concern is associated with areas under irrigation due to low rainfall and high evapotranspiration rates, and with poor drainage conditions. This causes salt accumulation near the soil surface. Salt rich irrigation water dramatically worsens the problem. Salt prevents, limits or disturbs normal plant cell metabolism and nutrient uptake of plants and soil biota, due to plasmolysis and cell collapse. It also changes the composition of clays, and can make them behave very differently from normal clays, making the soil useless for agriculture.

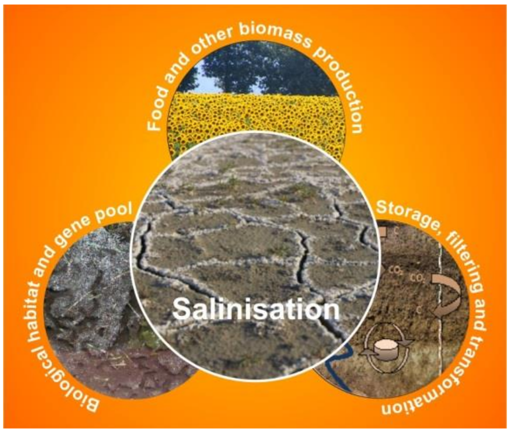

Figure 18. *Soil functions impacted by salinization.*

The chain of impact

What happens when soil functions are degraded and benefits are lost? For human beings soil is a basic natural resource. All natural resources – air and water, plants and organizms, and weathered rock (minerals) have a link to soil. Soil is a global carbon sink and there is a great diversity of soils that has developed in various environments. Soils differ in thickness, colour, productivity, composition and age but all have unique ecological functions. In cases where soil has lost its natural functions, the term ***soil degradation*** is used. Natural soil recovery is nearly impossible, takes a long time and is restricted in space - which means that ***soil is a non-renewable resource***. The reasons that lead to the decline of key soil functions are natural or inflicted by man. Unsustainable use of soils or poor management of land increased soil degradation. To ensure adequate protection of soils in Europe so called key threats to the soil itself have been formulated for policy environmental action, adopted in the so called European Soil Thematic Strategy of 2006. It is aimed at implementing policies to improve Europe's environment, based on evidence that is rooted in understanding soil conditions in Europe. The soil functions and threats are given in Table 1.

Table 1. *Soil functions, soil threats, outcomes of soil function degradation and factors of soil degradation.*

Soil functions	Soil threats	Outcomes of soil function degradation	Factors of soil degradation
Food and other biomass production	*Sealing*	Sealed area, land consumption	Land cover change, Structure of agricultural and forest lands, Soil management and tillage practices, Overgrazing by livestock, Soil wear by walking animals and humans, Soil damage from snow-scooters, tractors and off-
	Soil erosion	Soil loss, reduction of the rooting layer, amount of nutrients, available soil water, degradation of soil structure	
	Decline in soil organic matter	Enhanced mineralization rates and change of soil organic carbon stocks	
	Decline of soil biodiversity	Fragmentation of species diversity and activity	

	Contamination	Deposition of nutrients substances and pollutants, soil acidification	road wehicles, Forest clearing and fires, Protracted conflict Burning of stubbles, drainage condition, Reduction of productivity, desertification
	Soil compaction	Decrease of soil pporosity and physical structure degradation	
	Hydro-geological risks	Depend on type of event	
	Salinisation	Water soluble salts increase, physical structure degradation	
Storage, filtering and transformation	*Sealing*	Loss of soil function	Changes of land cover, Clearing of forests, Land management, Drainage condition
	Soil erosion	Loss of topsoil, reduction of the available soil water, filtering and buffering capacities of soil, the content of soil organic matter	
	Decline in soil organic matter	Rates of change of soil organic carbon stocks	
	Decline of soil biodiversity	Increase of greenhouse gas emissions	
	Contamination	Dispersion of contaminants	
	Soil compaction	Increased surface runoff, reduced filtering capacity	
	Hydro-geological risks	Depend on the type of event	
	Salinisation	Moisture regime	
Biological habitat and gene pool	*Sealing*	Habitat fragmentation	Desertification, Land cover, Overgrasing, Forest clearing, Non-conservation tillage and poor irrigation practice, Inadequate farming practices
	Soil erosion	Loss of topsoil, reducing the amount of nutrients in the soil, the available soil water, the content of soil organic matter, loss of biodiversity, degradation of soil structure	
	Decline in soil organic matter	Reducing the quality of organic matter	
	Decline of soil biodiversity	Microbial respiration rates	
	Contamination	Uptake of contaminants	
	Soil compaction	Reduce of rootability and biological activity	
	Hydro-geological risks	Depend on type of event	
	Salinisation	Spotted stress of species and holding back biodiversity	
Platform for man-made structures	*Sealing*	Sealed area, greenfield use	Socio-economic factors for urbanisation, Drainage condition, Land cover change
	Decline of soil biodiversity	Habitat fragmentation, grow of urban population	
	Hydro-geological risks	Landscape water distribution, loss of soil function	

	Contamination	Waste disposal	
Source of raw materials	*Sealing*	Sealed area, greenland uptake	Shaping physical landscape
	Hydro-geological risks	Rates of soil removing	
Physical and cultural heritage	*Sealing*	Sealed area, greenland uptake	
	Soil erosion	Rates of sedimentation	
	Hydro-geological risks	Depend on type of event	

Feeding 10 billion people

The United Nations expects the population to rise to 9 or 10 billion by 2050. The question arises - ***how can we feed all these people if we do not look after our soils?*** A number of actions can be taken to address the soil threats that are discussed above, and to help maintain soils to meet the growing demand for food and clean water. These include:

- ***Rational land-use planning to enable sustainable management of soil resources;***
- ***Limit sealing of open spaces;***
- ***Redevelopment of brown-fields (old industrial sites) and the rehabilitation of old buildings; and***
- ***Rising public awareness on soil threats impacts on soil functions.***

There is a need to control of soil degradation processes on agricultural land through application of good agricultural practices, including a set of measures for integrated soil and water conservation, which are specific for certain soil, climatic and topographic conditions (see also Chapter 1). These measures aim at:

- ***Maintenance and restoration of soil structure;***
- ***Increasing the stock of soil organic matter;***
- ***Increase of soil infiltration capacity;***
- ***Providing protective cover of vegetation or plant residues on the soil surface during periods of high rainfall and wind erosion.***

Other solutions include the use of machines and technologies for soil tillage with minimal pressure on the soil surface, such as using light weight tractors and farm machinery with large tires that have low inflation pressures, as well as using improved tractor steering systems and adapted ploughs that allow tractors to drive with all wheels on the untilled land, etc. Other soil degradation prevention actions include:

- ***Instead of burning stubbles, use of crop residues as "green manure", through composting or direct incorporation into soil;***
- ***Elimination of the conditions for secondary salinisation, such as irrigation with highly-mineralized groundwater, deterioration of the drainage on intensively irrigated land, or irrigation of land, which is not suitable for irrigation;***
- ***Avoid use of crops from wet tropical climate under arid an desert conditions;***
- ***Always maintain some kind of unbroken vegetation cover;***
- ***Avoid all irreversible damage:***

- ***Elimination of the conditions of loading soils with heavy metals and persistent organic pollutants through the use of pesticides, herbicides, toxic impregnation chemicals, irrigation water, sludge, etc.***
- ***Avoid any radioactive contamination at all cost.***

It is important to stress that most of these measures are also important elements of *environmental protection*. What is good for the soil is good for the land and good for water resources, not forgetting peoples health. Adequate soil and water conservation practices, based on a comprehensive soil or land assessment, can provide an “early warning system” that provides possibilities for efficient salinity (or alkalinity) control, with prevention of environmental stresses and their undesirable ecological, economic and social consequences.

Exercises

1. Draw a diagram with all the major soil erosion processes. What are they? Can you find areas in the world where they are affecting soils quality?
2. How can we better protect soils? Do you know a practice in your area where the soil is being improved?

Further reading

1. Tóth G., Montanarella L. and Rusco E. (eds.) (2008) Threats to Soil Quality in Europe, http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR23438.pdf
2. Soil threats maps http://eusoils.jrc.ec.europa.eu/library/themes/ThreatsMaps.html
3. The State of Soil in Europe (2012) JRC/IES, EUR 25186 EN http://ec.europa.eu/dgs/jrc//downloads/jrc_reference_report_2012_02_soil.pdf

4 GLOBAL SOIL SUPPLY CHAIN–TRADE NETWORKS AND SOIL IMPACTS

Danielle Maia de Souza[1], Steve Banwart[2]
[1]European Commission, Joint Research Centre, Institute of Environment and Sustainability. [2]University of Sheffield, Croto Institute

The interconnectedness of land use through trade

How is soil related to trade? There has been an intensive transformation of natural areas in the last 50 years, mainly driven by population rise and associated economic growth and agricultural intensification. This transformation has been supported by technological development and has resulted in the loss of important environmental assets. Land has been used for the production of goods and services, often involving different environmental pressures, which are mostly difficult to account for. These range from impacts on provisioning ecosystem services, such as food and freshwater, with economic interest to humans, to the loss of nature's intrinsic values and natural assets, such as biodiversity. **The global configuration of supply chains may affect land use management practices and soil functions in different parts of the world and hinder the prediction of potential impacts, such as soil loss, and their location.**

The increasing rates of land conversion in the last decades led to a stronger engagement of different actors (e.g. scientists, policy makers) to enhance sustainability of commodity supply chains and the need to develop and implement tools to better understand the influence of supply chains on land use problems. In this context, the analysis of interconnected chains and linkage with specific policy are key steps on the assessment of environmental impacts. Life Cycle Assessment is a widely applied method to assess the potential environmental impacts and can be applied as a decision-making tool and as a support to environmental policy development.

Including land impacts in life cycle assessment of products

In the last decades, the focus on the evaluation of impacts from the life cycle of products, processes and services has been the focus of many national policies, in order to reduce resource use and the impacts on the environment. In Europe, for example, different legal instruments indicate the use of life-cycle-assessments on the evaluation of alternatives to reach a better environmental performance of products and services. These instruments emphasize the need to look at resources over their whole life cycle, taking into account not only the impacts generated from cradle-to-grave, but also their value chain, in order to reach more efficient use and sustainable consumption and production patterns.

Life cycle analysis: from resource extraction and energy use to environmental impacts

The term "life-cycle" refers to all the major stages of a product life span, from the extraction of resources (e.g. minerals, water, wood). The simplified representation of the life cycle of a product (e.g. computer desktop) is illustrated in Figure 19 with input flows of raw materials, energy, land interventions and water and output flows of emissions, wastes and co-products.

Figure 19. *Schematic representation of the stages of the life cycle of a product (here a computer desktop), with general input flows (raw materials, energy, land interventions, water use) and output flows (emissions, waste, co-products) and life cycle stages, from resource extraction to final disposal of product parts and elements.*

For decision support, Life Cycle Assessment (LCA), also called Life Cycle Analysis, is used by industry and businesses as a tool to understand the potential environmental concerns associated with the life cycle of a product or a service, in order to reduce impacts on the supply chain. It allows the quantitative evaluation of impacts from cradle-to-grave, i.e. from raw-material extraction to end-of-life alternatives, such as recycling, incineration and landfilling, and therefore, the assessment of how different life cycle stages and processes may be associated with different environmental impacts. It can be used to analyse the environmental impacts of a single product (e.g. a 750 mL glass bottle, a laptop, 1L of gasoline) or to compare products used for a similar purpose (e.g. glass *versus* plastic *versus* paper cup). The comparative assertion is usually carried out in order to compare potential impacts of similar products.

Some of the main applications of LCA in decision-making are the comparison of impacts between different products (e.g. plastic versus glass bottles), the identification of major contributing processes (e.g. transportation, manufacturing) and the quantification of specific environmental areas of concern (e.g. climate change, land and water use) associated with a specific life-cycle or process.

A LCA study consists of four steps (Figure 20), from the description of the product system, process or service to the interpretation of the results of the study: (1) Definition of goal and scope; (2) Life cycle inventory; (3) Life cycle impact assessment; and (4) Interpretation of result. It can be applied to the assessment of impacts from single products, with a short life cycle, to large-scale policy decision contexts.

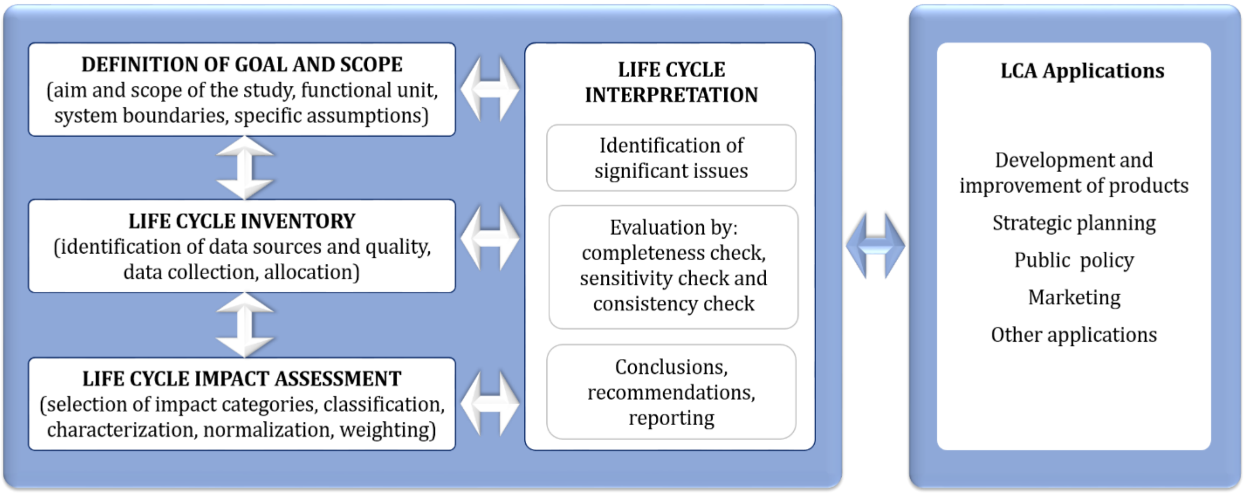

Figure 20. *The four steps of life cycle assessment: (1) Definition of goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, (4) interpretation of results. Some of the main applications of LCA are represented in the box on the right (Adapted from ISO standard 14040 (2006a).*

The first step, *goal and scope definition* - consists of the definition of the aims of the life cycle study (e.g. comparative assertion between two or more products), and contains the description of the product system (what is the product being analysed and which function it fulfils) and the definition of system boundaries (which processes and life cycles stages are relevant to be included). During the *life cycle inventory* (LCI) data is collected on input (e.g. abiotic resources, energy) and output flows (waste, emissions) at each phase of the life cycle. These flows are then associated with potential environmental impacts (impact categories), such as global warming, acidification, eco-toxicity and land use. This step is called *life cycle impact assessment* (LCIA). Results are then interpreted in order to identify significant issues, i.e., data that contribute the most to the results, and evaluate the outcomes obtained. The conclusions and recommendations are reported following the specifications of the scope of the study.

Figure 21 presents some of the impact categories used in LCA studies, at midpoint level (intermediate impacts), and examples related life cycle inventory substances and flows (CO_2,PAH, water, land occupation, etc). Each of these midpoint impact categories are associated with a specific area of protection or damage category, located at endpoint modelling (end of impact chain). As an example, when a land is transformed, from a forest area into an agricultural area, soil functions may be affected and a later impact on ecosystem quality may be computed, such as damage to certain ecosystem functions.

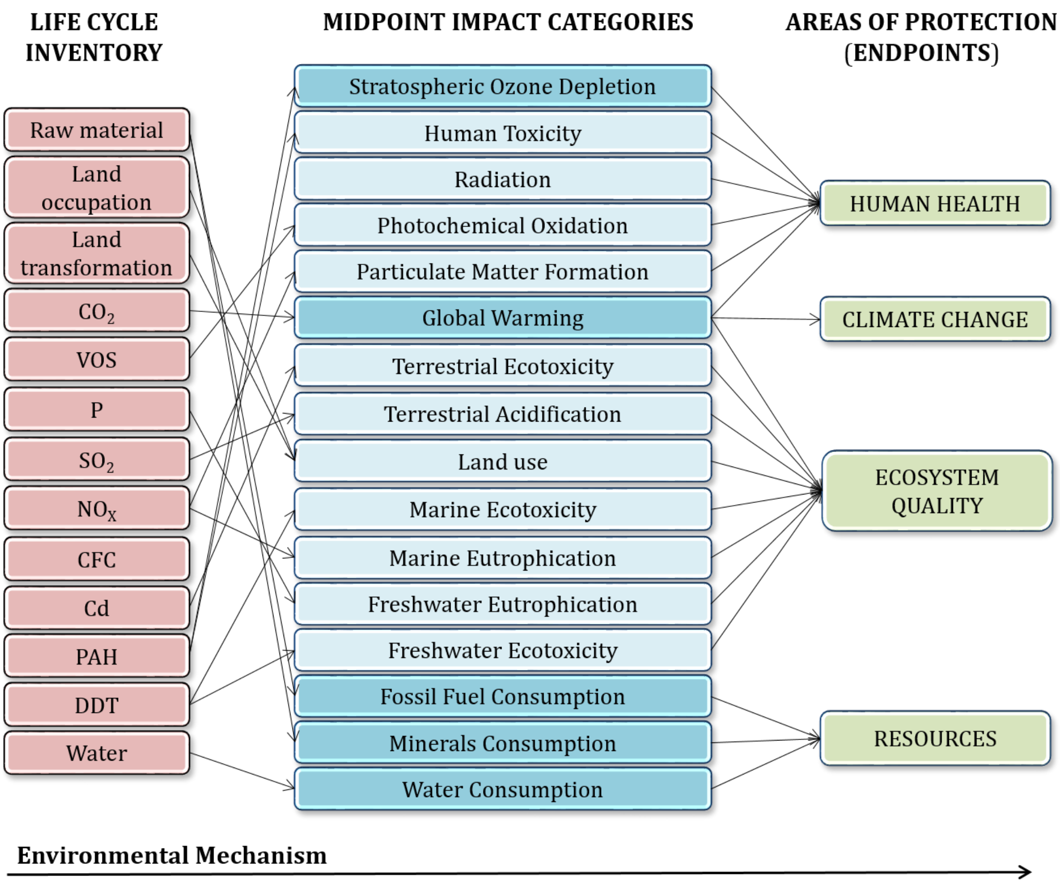

Figure 21. *Example of a simplified environmental mechanism (i.e. the cause-effect chain, from the life cycle inventory to the endpoints), from life cycle inventory data (in red), i.e., emissions, natural resources and land interventions, to endpoint modeling. The illustrated impact categories (in blue), such as "stratospheric ozone depletion" and "land use" are located at midpoint level. 'Human health', 'Climate change', 'Ecosystem quality' and 'Resources' are located at the end of the environmental mechanism and are considered 'endpoints' (in green).*

The *selection of impact categories* is based on scientific knowledge on **environmental processes** (e.g. radiative forcing, soil processes) and to each of them are assigned the LCI results. During the *characterization*, equivalency or conversion factors (so called 'characterization factors') are used to combine LCI results (energy and matter flows) into *category indicators*, which are the quantified representation of impacts associated with a specific impact category. By means of a specific indicator and the characterization model, it is possible to calculate the potential impact associated with an impact category. Figure 22 illustrates the LCIA elements for the land use impact category, for which different indicators exist (e.g. biodiversity, **soil quality**).

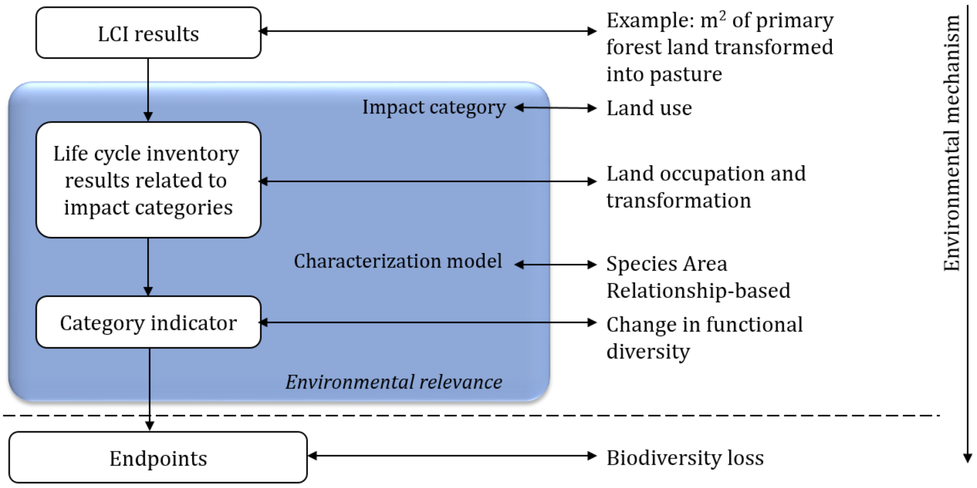

Figure 22. *Example of LCIA elements for the impact category "land use". The LCI results are expressed in terms of land area occupied or transformed. The characterization for this category may be done by means of different indicators, such as habitat loss and change in soil quality parameters (e.g. increase/decrease in soil erosion). Endpoints are, respectively, biodiversity loss and soil loss. Source: Udo de Haes and Lindeijer (2002).*

The chain of impact, soil and ecosystem indicators for life cycle analysis

Land use impacts have been a topic of research in LCA for more than 15 years. However, due to the lack of consensus, it is not a common practice to fully include land use impact assessment in LCA studies, in evaluation of industrial systems. As a consequence, the importance of soil and its close relation with farming activities is mostly ignored in LCA studies. Soil is a non-renewable resource and changes in its quality and availability affect future productivity of the agricultural systems.

A methodology for assessing soil functions in LCA takes into account soil characteristics and functions over space (different locations) and time. Figure 23 shows some of the pressures (*e.g.* soil compaction) and state (*e.g.* altered soil functions as water infiltration capacity) of soil functions and what these functions may affect (*e.g.* potential for agriculture and altered life-support functions of natural systems). Some indicators of impacts on soil function can be degree of soil compaction and soil erosion, soil organic carbon content and altered soil functions, such as water filtration capacity.

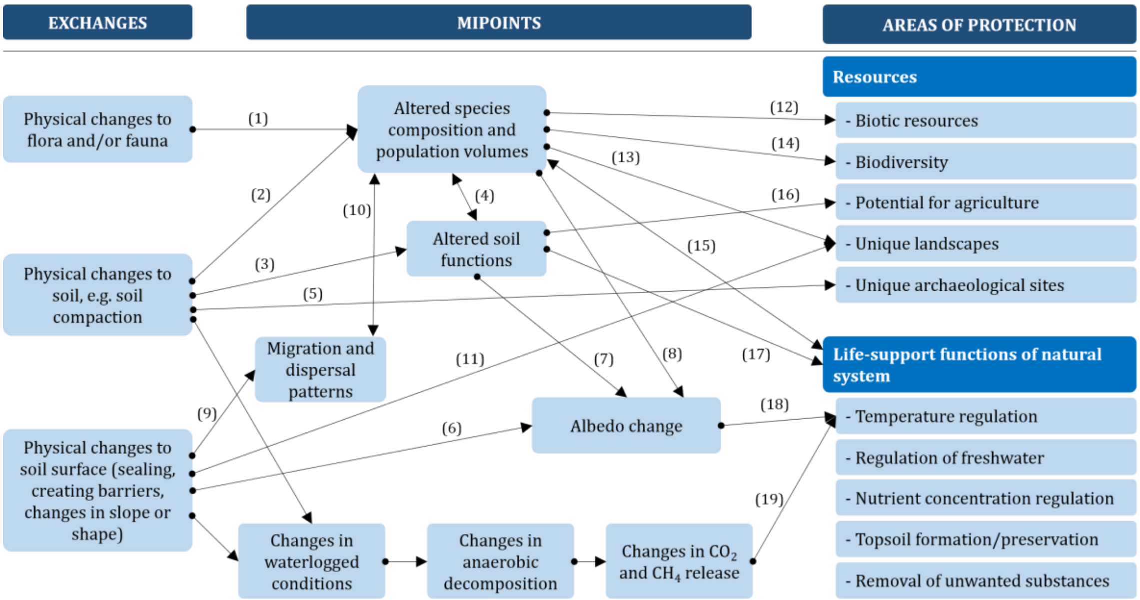

Figure 23. *Scheme of environmental mechanism proposed by Weidema and Lindeijer (2001). The numbers represent different mechanisms in the cause-effect chain of impacts. Midpoints are affected by physical changes in the environment and cause further damage to resources and life support functions of natural system.*

Changes in soil organic matter may also affect life support functions and be used as an indicator of impacts on soil functions in LCA, as SOM has important roles on biotic production, climate regulation and maintenance of substance cycles.

Exercises

1. Do you think that life cycle analysis could be useful for soil conservation? If yes, why?
2. Which areas of protection (human health, ecosystem quality, resources, climate change) can be affected when soil functions are impacted? Explain why.
3. Cite some indicators used in LCA to indicate impacts on soil functions.

Further reading

1. United Nations Environment Program/Society for Environmental Toxicology and Chemistry Life Cycle Initiative: http://www.lifecycleinitiative.org/
2. European Platform on LCA: http://eplca.jrc.ec.europa.eu/
3. United States Environmental Protection Agency: http://www.epa.gov/nrmrl/std/lca/lca.html
4. OpenLCA project: http://www.openlca.org/

5. THE VALUE OF SOIL ECOSYSTEM SERVICES

Jon Orvar Geirsson Jonsson, Brynhildur Davidsdottir and Kristin Vala Ragnarsdottir,
University of Iceland

1. Introduction

"It suddenly struck me that that tiny pea, pretty and blue, was the Earth. I put up my thumb and shut one eye, and my thumb blotted out the planet Earth. I didn't feel like a giant. I felt very, very small" Neil Armstrong.

Ecosystems and their importance

From space it is obvious to see that the Earth is what is called a closed system; there are no significant inputs coming from the outside except the energy from the sun. The sun is the basis for the living ecosystems and humans use energy and raw materials from natural systems to build their societies and economies. As the laws of thermodynamics prescribe, energy and materials can neither be created nor destroyed, and therefore any waste that human economies produce goes back to the surrounding natural systems. Furthermore, **the physical inputs derived from natural systems are limited, as the Earth is a closed systems, and so is its capability to assimilate waste.** This means that how human economies operate and what rules they operate by has tremendous consequences for the biosphere. The condition of the biosphere also has consequences for human wellbeing and economic development. **The Millennium Ecosystem Assessment clearly illustrated the importance of maintaining functioning of the natural systems, to ensure continued human wellbeing.** In the book *Limits to Growth* the consequences of the interaction of population rise and limited resources were studied with systems dynamics models, showing that endless growth is impossible. The results from this study are still relevant today, but the results clearly illustrate the problems that arise with limited resources and increased environmental impact of human actions.

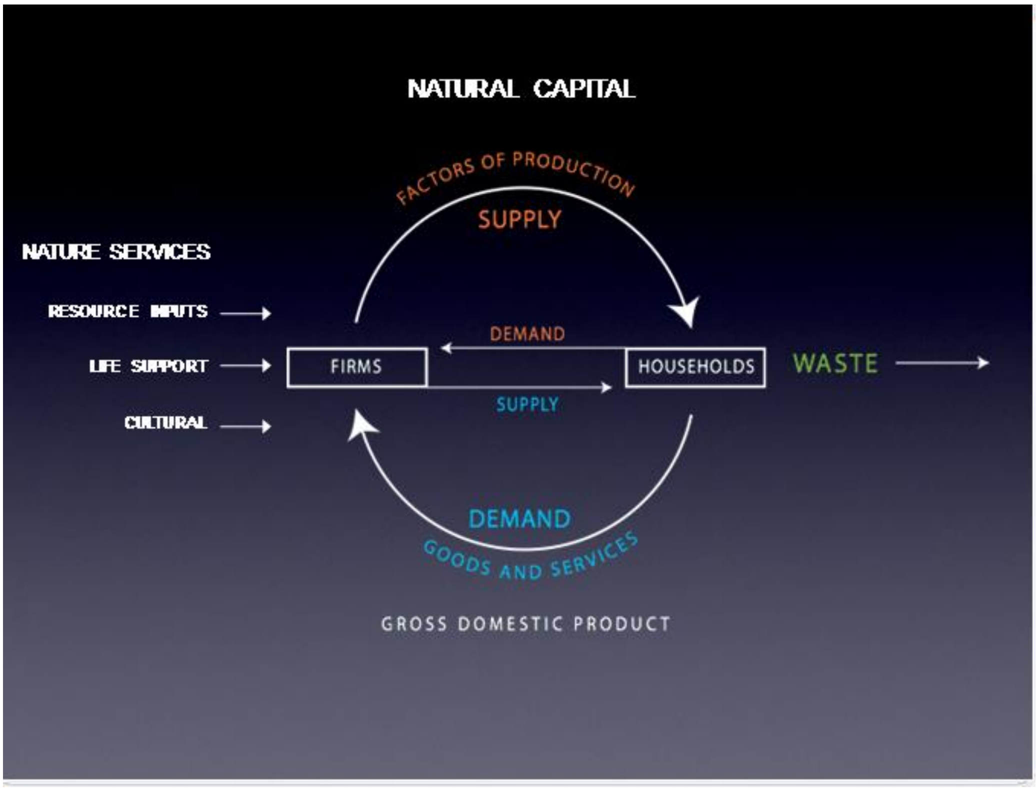

Figure 24. *The economy imbedded in natural systems.*

Natural capital and ecosystem services

What is natural capital? Ecological economists refer to natural systems, as natural capital (Figure 24). Natural capital, as other forms of capital (financial capital, human capital, built capital and social capital), yields a flow of goods and services of what has been collectively called ecosystem services***. Ecosystem services are simply put the benefits that humans derive from nature/natural capital.*** Humans use these services both directly and indirectly in their social and economic systems. **A direct service is something that is visible and often tangible, for example a food item such as fruit, fibres such as cotton, fresh water, energy and materials. Indirect services, however, are often invisible and intangible but no less important. Examples include; carbon sequestration in plants and in the soil, the formation of soil by natural processes, filtering and provisioning water which takes place out of sight by for example forests, wetlands and soils, and the sustenance of biodiversity.** An ecosystem can provide simultaneously many different ecosystem services that vary both spatially and temporally. If natural capital is degraded it loses its ability to provide us with the services needed for humans and other living beings to thrive, affecting wellbeing of all. This relationship was clearly illustrated in the Millennium Ecosystem Assessment as shown in Figure 25.

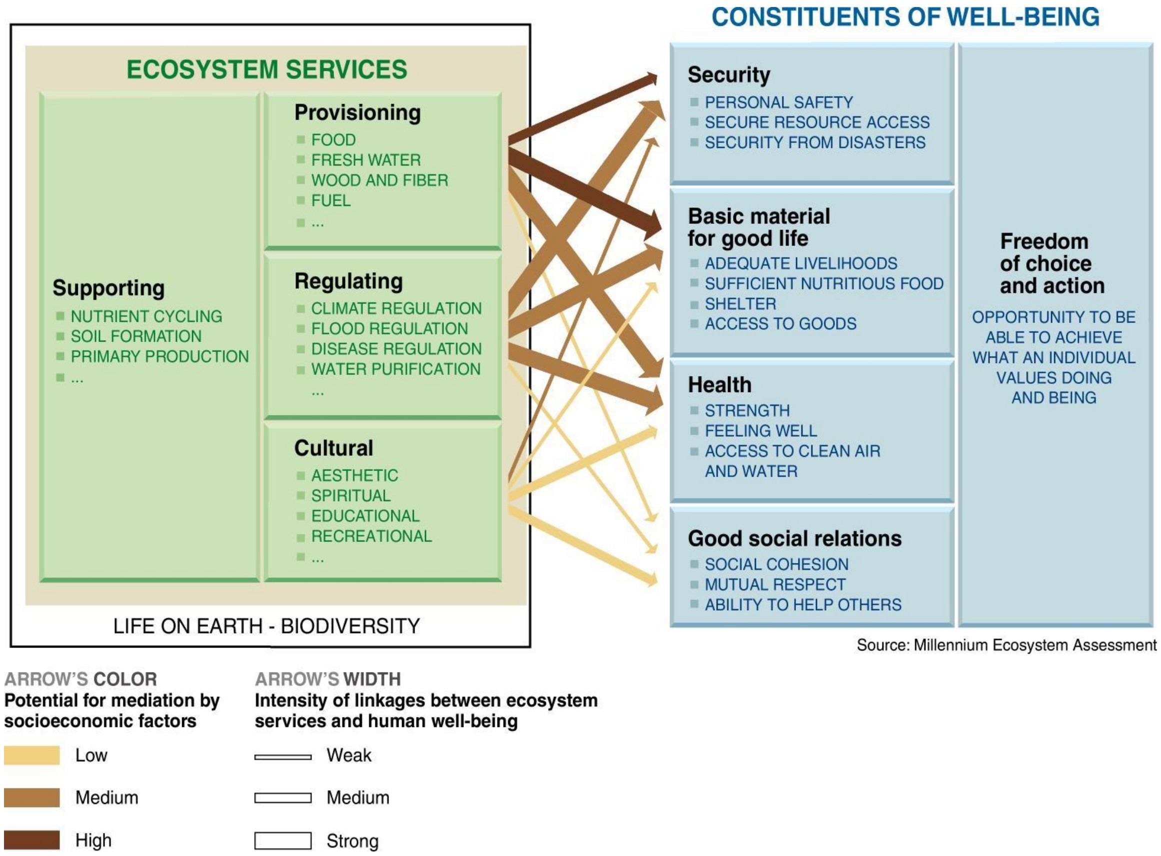

Figure 25. *The relationship between ecosystem services and human well being (Source: Millennium Ecosystem Assessment 2005).*

In the Millennium Ecosystem Assessment ecosystem services were categorized in four main groups depending on what services they provide. The groups are: supporting, regulating, provisioning and cultural services. ***Supporting services*** provide the necessary intermediate services for the other service groups, and include primary production, nutrient cycling and creating the living conditions for biodiversity. ***Regulating services*** are services that maintain and regulate essential ecological processes and life support systems through bio-geochemical cycles and other biospheric processes. Regulating services include climate regulation through for example carbon sequestration, flood prevention, prevention of outbreaks of pests and diseases and water purification. ***Provisioning services*** are services that provide direct inputs into social and economic system such as food and fibre, raw materials and energy. ***Cultural services*** are the nonmaterial benefits obtained from ecosystems such as recreational, educational, spiritual and aesthetic services. Maintaining and nourishing our natural systems and thereby growing our natural capital, will ensure that we continue enjoying the services provided by nature. As a result, **maintaining natural capital is necessary for continued human wellbeing.**

Soil ecosystem services

What are soil ecosystem services *(Figure 26)* ***?*** Soils are an important type of natural capital that has specific functions that provide multiple important ecosystem services (see also Chapter 2). ***Some even call soils the living skin of the Earth.*** **Around 99% of all our food comes from the land and the soil. Soils filter and clean our drinking water, they deliver the nutrients that plants need for growth and decompose them when they die. Soils provide**

habitats for millions of species where they can grow and flourish and if you would take teaspoon of soil from you backyard there probably would be billion/millions of microbes, thousands of funguses in that single teaspoon. Soil stores twice as much carbon as the biosphere and the atmosphere combined. Soils help to keep our climate stable by sequestering and releasing greenhouse gases like CO_2, they also can buffer heat waves and ameliorate local climate. Soils also regulate water flows and thereby prevent floods. Soil thus acts as a natural filter for water ensuring safe drinking water for us. Soil particles help with cloud formation released from the Earth´s surface through intensive agriculture and deforestation and provide nutrients for the smallest creatures in the ocean. Soils provide us with materials, which we use to build our cities and industries as well as provide the structural foundation needed. They provide us with medicine, probiotics and antibiotics, which makes us healthy. Immune systems of healthy adults "remember" germs to which they have never been exposed.

Figure 26. *Ecosystem services provided by soils (source: http://www.nature.com/scitable/knowledge/library/what-are-soils-67647639)*

Soils store our history, in buried ruins and sediments and they give us the opportunity to look into the past by studying layers of soil (pedology), so we can educate ourselves about our ancestors' discovery. Examples include the people preserved in peat bogs and clay-covered graves in Denmark and Germany for 3,000 years, with skin, hair and clothes conserved. The soil is our largest historical archive, and most of the artifacts stored have yet not been seen, read or discovered. This applies for all countries on Earth. If the soil is damaged or destroyed, then our largest historical archive are harmed.

Soils build and support magnificent landscapes and give us the chance to experience the marvels of nature. They have been a source of entertainment for children through the ages (play in the mud anyone?!?) and a source of recreation for old and the young - both easy going like gardening or intense like dirt bike racing. They are a fundamental part of our religion, the indoeuropean pantheon, later also the Judeo-Christian faith (God created man from soil) and

our connection to the deity, for instance the ancient Mayan culture believed the soil was a gift from the ancestors. For the Incas of ancient Peru, the Earth Goddess (Pachamama), personified the Earth. The religions of the Middle East had their Earth Goddesses (Artemis, Asshera, Astarte, Demeter, Kybele, Ninhursagh) and Earth Gods (Enki, Ea). Derived from this discussion you can clearly see how soils contribute to all service categories as defined by the Millennium Ecosystem Assessment.

Given the importance of the multiple services derived from soils, it is clear that they need to be maintained and the only way to do that is to protect our soil natural capital. Soil, the skin of the Earth, is delicate; it is thin (on the average 15 cm) and forms slowly. It can take over 1000 years for 15 cm of soil to form in some areas but it can disappear in an instant, for example, during flash floods (see Chapter 3). Unfortunately, soil, as other types of natural capital, is coming under increased pressure because of human activities. We pave over them, pollute them with toxic substances, compress them with heavy agricultural machinery so they are as hard as concrete, leave them unprotected from the sun and let the wind blow them away and the rain wash them away.

International agencies tell us that desertification, land degradation and drought have an negative impact on more than 1.5 billion people in over 110 countries, 90% of them live in low-income countries, and that every year around 10 million hectares of agricultural land are lost because of soil erosion; this is equivalent to 1.5 times the size of Lake Victoria, Africa´s largest lake. Given how soils have been treated in the past **it is as if our economic decision-making frameworks do not recognize the multiple importances of our soil natural capital and its derived ecosystem services.**

Value and soil ecosystem services

Ecosystem services are fundamentally important for economic prosperity and human well-being. In the market economy, a dominant form of an economic system in the western world, decision-making is largely based on signals provided by the market through prices. Prices of goods and services are set by the interaction of supply (sellers) and demand (buyers), determining optimal quantities of output, as well as the optimal use of various inputs to the production process. Value is derived from the willingness to pay for a particular good or a service, illustrating relative economic importance and its relative scarcity.

Unfortunately, not all goods and services are captured by markets, and this is specially the case with many goods and services derived from natural capital. Such services are called non-market goods; **soils as natural capital and many soil ecosystem services are considered non-market goods and services. Their nature does not easily lend itself to be traded in markets and thus they have no market price, but are regardless immensely important for our economy**.

The value of non-market ecosystem services has been evaluated since the 1990s. It was found that for the entire biosphere, the value (most of which is outside the market) is estimated to be in the range of US$16–54 trillion ($10^{12}$) per year, with an average of US$33 trillion per year. Because of the nature of the uncertainties, this must be considered a minimum estimate. Global gross world product total in 1994 was around US$18 trillion per year – indicating that nature gives us for free at least as much value as global production of goods and services. Since then

many estimates have been conducted for ecosystem services, further supporting the importance of formally accounting for these services in economic decision-making through valuation.

Unfortunately as our economies are managed as market economies, non-market goods are invisible in the market and thus are largely excluded from economic decision-making. This fact has often resulted in misguided economic decisions as they are based on incomplete information, resulting in the degradation of natural capital such as soils.

This absence of value can be addressed with assessment methods that relate to how economics treat the concept of value. The theory of value in economics relates to the idea of human well-being and that well-being is based on economic benefits which economic decision making aims to maximize. **Economic benefits, and thus value is assessed through our willingness to pay for a particular good or a service.** This notion of willingness to pay is used to assess the value of non-market goods and services derived from natural capital.

Values derived from natural capital such as soils are broken into several types. The two main types of values are what are called **use value and non-use value.** Use values are broken into direct and indirect use values. Direct use values include consumptive uses such as food (collection of berries, mushrooms, herbs and plants) and fibre, whereas non-consumptive uses include for example recreation, photography and view from a dwelling. Indirect use values include use values that are not consumed such as carbon sequestration, hydrological buffering, filtering of nutrients and contaminants and biological control of pests and diseases.

Non-use values include *option*, *bequest* and *existence* values. The concept of non-use value refers to the value that people assign to economic goods and services (including public goods, public assists or public resources) even if they never have and never will use them. Option value is individual willingness to pay for maintaining natural capital such as soils even if there is little or no likelihood of the individual actually ever using its derived services, but there is value in maintaining the possibility that it may someday be used. Bequest value is the willingness to pay for maintaining or preserving natural capital that has no use now, so its services are available for future generations. Existence value reflects the benefit people receive from knowing that a particular natural capital and its associated services exist. The total economic value of soil ecosystem services is the sum of all use and non-use values.

Economic valuation methods

The notion of value used to **obtain use value and non-use values relies on people's willingness to pay for ecosystem services, reflecting their importance** (Figure 27). Several valuation methods exist, varying what they measure and the data required. The methods are categorized according to whether preferences and thus willingness to pay are expressed in surveys or revealed through actual behaviour.

Revealed preference techniques base the value of ecosystem services on actual observed behaviour linked to the service or associated services or products or the revealed willingness to pay for a mechanism or a product that somewhat replaces the ecosystem service. The main methods are: *Market prices*; most commonly used to value provisioning services, *Cost based metrics;* including avoidance cost, replacement cost, and *damage expenditures*; most

commonly used to value supporting and regulating services, *Travel cost*; used to value cultural services such as recreational value, and *Hedonic pricing*; used to value cultural services such as amenities.

Stated preference techniques elicit values directly through survey methods where subjects are asked about their willingness to pay to conserve a particular ecosystem service or to conserve an entire ecosystem or their willingness to accept a fee for losing a service or an ecosystem. Contingent valuation methods or choice experiments are the most commonly used stated preference methods, and are used to capture non-use values such as existence value as well as they can be used to assess all use values.

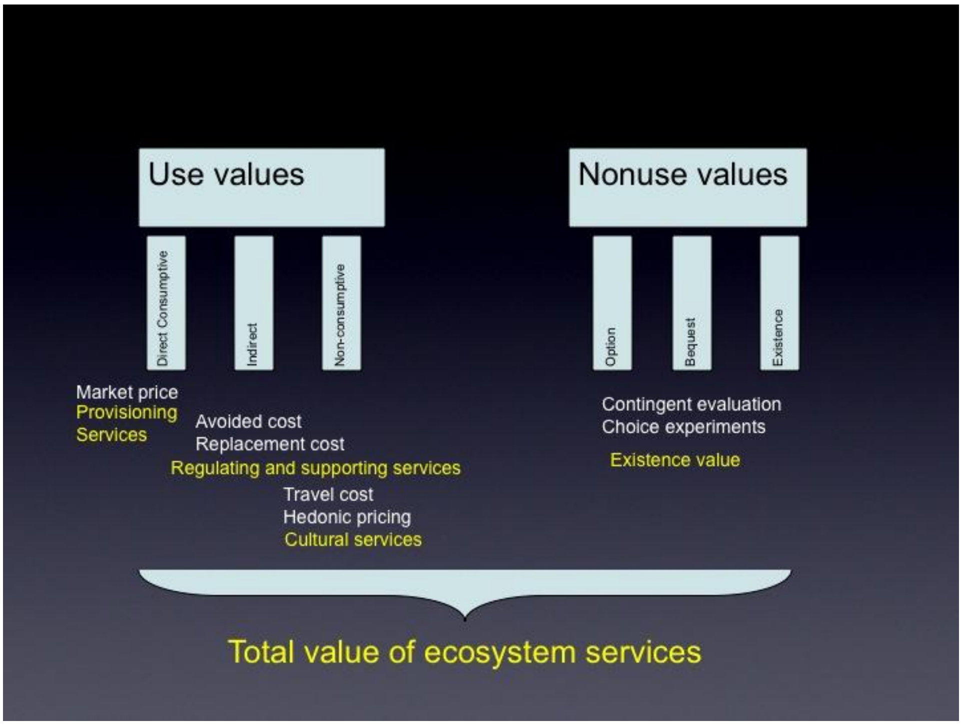

Figure 27. *Types of values derived from ecosystem services and valuation methods.*

Decision-making regarding sustainable land use and soil management

As with many other natural systems, the **services from soils suffer from the lack of proper economic valuation,** be it monetary or some other and many of the soils services are not even taken into consideration when ecosystems are analysed with the conventional ecosystem services approach.

In the next 50 years we need to grow more food than we have done for the last 10 thousand years and we have to do that with less land. This will put enormous pressure upon soils. **What decisions we make regarding land use and soil management are therefore of the outmost importance.** If we continue to overexploit the land and degrade the soil this will lead to reduction in the future provision of the services soils provide.

We need to change our design of decision making processes in such a way that the essential services that soils provide are factored into the process and that it results in decisions that sustain healthy and functioning soils. Valuing soils with some of the methods mentioned in this chapter is a step towards such a change, though of course we cannot fully price the total value of the natural world, nor do we want to. **By using the tools of economics that are at our disposal, along with other social and environmental tools such as soil sustainability indicators we can move towards more holistic approach regarding sustainable soil and land management.**

Beyond money

Existential values of soil beyond money also exists, where the value is determined in the expressions of Shakespeare's character Hamlet's fundamental question "to be or not to be." In face of existence or not existence, if society cannot persist with a certain type of consequence, then any form of money or discussion thereof is redundant, and we have to make a decision based on existential and ethically based choices.

Discussion

Natural capital such as soil is very important for our continued wellbeing. Soils provide us with essential soil ecosystem services that must be maintained, and the only way to secure their maintenance is to protect soil natural capital. Since many soil ecosystem services do not carry a market price, we do not think about them when making decisions every day. Therefore, soils tend to be overused, and soil natural capital degraded. To get us to think about the economic importance of soil natural capital, economists have recently developed methods to assess the economic value of soil ecosystem services. Hopefully such assessments will illustrate the immense economic importance of soils, and enable us to reverse the trend of soil degradation that is bound to harm our future well-being.

Exercises

1. Think about all the different things soils do for you and your wellbeing and try to place them in the classes defined by the Millennium Ecosystem Assessment. What is the service that is the most important to you and why?
2. Go to your local gardening shop or online and find how much we pay for soils in our daily lives. Considering that soils form at the rate of only millimetres per 100 years, do you think that the price of soil in the market reflects their value?

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6. CONCLUDING REMARKS

Kristín Vala Ragnarsdóttir, University of Iceland

As can be seen in this book, soils are one of our most important natural resources and yet we do not look after soil as we should. The reasons are many as highlighted in the five chapters above. It would appear that we did not learn from history as outlined in Chapter 1. There are many agro-ecological approaches that can be adopted that have been shown to increase both soil resilience and stability, but also crop yield. Chapter 2 outlines what soil does for us, soil function, soil impact on the water cycle and regulation of the global clime, soil provision of habitat, importance of soil for the carbon cycle, soil nutrient transformations and medium for plant growth and soil as a natural filter. In Chapter 3 the processes that cause soil degradation are outlined and solutions are suggested for soil protection. In Chapter 4 we consider the importance of understanding the life cycle of soils as well as steps to assess impacts on soil quality. Finally in Chapter 5 natural capital is introduced, the concept of soil ecosystem services is outlined, showing the many services they provide: They provide food, filter our drinking water, deliver nutrients for plants, and decompose organic matter in soil. Soils provide habitats for millions of species, stores twice as much carbon as the biosphere and atmosphere combined. Soils buffer climate and heat waves. Soils regulate water, soil particles aid in cloud formation, provide building material and structural foundations. They also provide us with medicine, and strengthen our immune system.

Given the importance of soils for survival of ecosystems and humans alike, what would you as a pupil at school suggest that we do to change direction?

Exercises

1. What are the agroecological approaches that you think are the most important for soils in your area? If you live in the city, focus on the soils in your garden, nearby park or allotments.
2. Have you ever gone into your garden and played in the soil? What did you see?
3. Does your family have a compost bin? If not could you sent one up?
4. Does your school have a garden? Have you ever tried to grow anything in soil? If not, why not try?
5. What are the most important soil erosion processes that you have seen in your area?
6. Have you ever thought about what life cycle assessment of a product or a service?
7. Do you think that it is important to economically value soil and their services?
8. How come that soils are not better protected for our own well being and future generations? What can you do to help protect soils?

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