Soil, human society and the environment

W. E. H. BLUM¹, B. P. WARKENTIN² & E. FROSSARD³

¹University of Natural Resources and Applied Life Sciences (BOKU), Vienna, Austria (e-mail: winfried.blum@boku.ac.at)
²Oregon State University, Corvallis, USA
³ETH Zurich, Eschikon-Lindau, Switzerland

Abstract: Soils, forming the top layer of the Earth’s crust, are a mixture of mineral particles, organic matter, water, air and living organisms. Processes between these components perform vital functions within ecosystems. The soil forms an interface between the geosphere, the biosphere, the hydrosphere and the atmosphere, and is a largely non-renewable resource. Ugolini & Warkentin show the fruitful relationships which geology and soil science have established since the birth of soil science, and how these two disciplines together could contribute to solve future problems.

The dynamic soil system delivers functions and services vital for human societies and the environment. Soil is the basis for food and biomass production, and plays a central role as a habitat for biota and as a gene pool. Moreover, it stores, filters and transforms a large variety of substances, including water, inorganic and organic compounds, and is a major sink and source for greenhouse gases. Soil provides raw materials for human use. It also serves as the basis for human activities (landscape and heritage) and for our technical and socio-economic infrastructure, delivering materials for their implementation and maintenance.

Soil formation

Soils can be visualized using in a three-dimensional cross-section of the uppermost crust of the Earth, subdivided into different soil horizons (Figs 1 & 2). Soils are produced by physical, chemical and biological weathering processes, starting from solid unweathered rock or loose rock material such as gravel or sand. Chemical weathering is aided by solar energy from radiation and water, in which CO₂ and other atmospheric gases are dissolved, forming acid solutions. Physical weathering processes are based on frost and thaw cycles, direct radiation, and temperature changes, as well as mechanical transport by water, ice or wind. Through those mechanical comminuting processes, the surface area of the rock material is increased, and space is provided for chemical processes, which are mainly reactions at particle surfaces. As soon as the first weathering products, such as clay minerals and oxides are present, biota start to develop, initially forming a very sparse, but later a dense surface vegetation cover, which converts solar energy into biomass. These organic substances are cycled back to the ground after decay, where they are converted into soil organic matter by physical bioturbation and biological/biochemical mineralization and immobilization processes. Through these processes, minerals and organic matter are mixed, forming a soil horizon that contains a high amount of organic matter. The diversity and numbers of soil biota increase with time. These processes continue to increase the weathering depth of soil and form a new substrate, which is totally different from the rock parent material (Duchaufour 1997; Scheffer & Schachtschabel 2002; Sumner 2002).

The weathering rate and type are irreversible soil processes that leave markers in the properties of soil horizons. By studying the properties of these diagnostic horizons, soil scientists gain clues about the processes through which that specific soil was formed. No two soils are likely to be the same, because weathering depends upon the many physical, chemical and biological factors interacting with the specific parent material. The soil management, superimposed on the inherited properties, creates an additional diversity. These processes determine the biological habitat, resulting in biodiversity.

The pore systems of soils

Mechanical pressure exerted by roots, desiccation of areas around roots by plant water uptake, and general wetting and drying, create pores of different sizes. Figure 3 shows macro pores, larger than 50 μm in diameter; small
macropores, 10–50 μm in diameter; medium pores, 10–0.2 μm in diameter; and small pores of less than 0.2 μm in diameter. Pores of different sizes have very different functions in soil processes (Table 1).

Water and solutes are freely transferred through macropores, and water is stored and retained against gravity in the medium pores. In the small pores, the energy of water retention is too high to allow extraction by plant roots; the large and small macropores provide both the space for the growth of plant roots and a habitat for soil biota. The medium pores serve mainly as a habitat for microbial activities, due to the availability of water and air. Small pores are difficult to access by roots or by soil organisms. The water in these pores serves mainly as a medium for forces binding small soil particles, e.g. clays, together. This is the lower level of particle aggregation in a hierarchy that produces the visible soil structure or ‘soil architecture’.

Soil processes occur in the pore space, schematically depicted in Figure 4. The pores form a continuum of sizes, with different materials such as humic substances, clay minerals, carbonates or oxides constituting the pore walls. All these soil components bear electric charges on their surfaces. Reactions such as sorption/desorption and precipitation/dissolution occur between the contents of the pores and the pore walls.

Living organisms, fungi, bacteria, and other biota, up to earthworms and plant roots, actively participate in the soil processes, by absorbing nutrients, shedding dead tissue, and exuding low- or high-molecular-weight compounds (ions, organic acids, polysaccharides, amino acids, proteins, phenolic compounds, antibiotics) that can significantly change the properties of their local soil environment.

The total inner surface of a soil can be estimated on the basis of its constituents. A soil volume of 1 ha (100 m × 100 m) and 20 cm of
Fig. 3. Pore system of the B-horizon of an Amazon Oxisol (Brazil), observe the scale in μm (Blum 2002).

<table>
<thead>
<tr>
<th>Pore size</th>
<th>Hydraulic conductivity water retention capacity (in pF = log cm water column)</th>
<th>Biological activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large macropores</td>
<td>Excellent: 0–1.8 pF</td>
<td>Large plant roots; soil macrobiota</td>
</tr>
<tr>
<td>&gt;50 μm diameter</td>
<td></td>
<td>Small plant roots; fungal spores</td>
</tr>
<tr>
<td>Small macropores</td>
<td>Good: 1.8–2.5 pF</td>
<td>Bacteria; fungal hyphae</td>
</tr>
<tr>
<td>50–10 μm diameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium pores</td>
<td>Very limited: 2.5–4.2 pF</td>
<td>Enzymes; no space for plant roots or soil organisms</td>
</tr>
<tr>
<td>10–0.2 μm diameter</td>
<td>Water is retained against gravity</td>
<td></td>
</tr>
<tr>
<td>Small pores</td>
<td>None: &gt;4.2 pF</td>
<td></td>
</tr>
<tr>
<td>&lt;0.2 μm diameter</td>
<td>Water is retained against plant root extraction forces</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Classification of pore sizes in soils and their physical and biological characteristics (Blum 2002)

Even assuming that only part of these inner surfaces are accessible through the pore system, the large inner surface of the soil becomes one of the very specific and unique characteristics of soil, distinguishing it from stone and rock material. A further specific characteristic of soils is the association between organic compounds, oxides and clay minerals, which provides highly reactive soil particles. Finally, all these surfaces provide living conditions for an enormous variety of soil organisms, which are actively participating in the processes occurring on these inner soil surfaces.

These processes occur in the upper layers of the soil, between the soil surface and the water depth, with a bulk density of 1.5 t m⁻³, forms 3000 t of soil material. Assuming 20% of clay minerals, with an average 200 m² surface area g⁻¹, these 600 t of clay minerals have a total surface area of 120 000 km². If we further assume that this soil contains 3% organic matter with 1000 m² surface g⁻¹, the 90 t of organic substances have a total surface area of 90 000 km². Therefore, the total inner surface of such a soil volume (without counting oxides and other types of minerals) is 210 000 km². For comparison, the total land surface of Italy (301 225 km²), is contained in a soil volume of 120 m × 120 m (c. 1.43 ha) and 20 cm of depth.
table, which are known as the vadose zone. This zone is only partly saturated with water; the remainder of the pore space is filled with air. It is through this vadose zone that water moves down to the water table, transporting soluble and particulate materials which can pollute groundwater. The vadose zone is biologically active because the soil pores contain both air and water.

Vadose zone studies of these processes are carried out by multidisciplinary groups of soil scientists, hydrologists, geologists and environmental engineers. The environmental quality standards and laws of different countries further these studies, in order to provide a high-quality environment for humans. In their paper, Bergström & Djojčić show the importance of soil porosity for phosphate and pesticide transport through soils, and for pesticide degradation. Dosso et al. show the importance of soil distribution in a landscape to the movement of water and copper, relating these movements to vine mortality.

Organic matter in soils

Organic matter is the most active component of soils, with continuous additions and continuing decomposition. The additions are raw plant material from shoots and roots, as well as animal material. The decomposition products are carbon dioxide, plant nutrient elements, and humus, which decomposes at a slow rate. This humus is chemically bonded to clay-sized mineral particles forming the functioning matrix of the soil. The total soil organic matter content is considered one of the most important parameters when rating the quality of agricultural soils. In their paper, Feller et al. propose a historical review of the role of organic matter in agricultural soils and of the role of soils as a source and sink of greenhouse gases. Leifeld presents global data on the greenhouse gases, describes how their production is affected by soil properties and management, and shows the potential of mitigation practices to decrease their concentration in the atmosphere.

The energy source for soil biota is organic material, produced by the conversion of solar energy into plant biomass (Blum 2001).

Soil biota

The more organic material there is, and the more nutrients it contains, the more biota can live in a soil, if both air and water are present. A soil volume with a surface of 1 ha and a depth of 30 cm may contain about 10 t of bacteria and actinomycetes, 10 t of fungi, 4 t of earthworms and 1 t of other soil animals, such as nematodes and a large variety of insects, making a total of 25 t of biomass. In contrast, only 1.0–1.5 t of farm animals can be nurtured at the top of the soil, assuming two to three livestock units of 500 kg each per hectare.

Ecological soil functions

The soil pore space, the chemical reactivity of the finely divided soil particles, and the presence of numerous living organisms allow soils to perform three main ecological functions.

1. Soils support plant growth, providing food and fodder to humans and animals.
They have the capacity to filter, buffer and transform materials between the atmosphere, the plant cover and the water table. They strongly influence the water cycle at the Earth’s surface, as well as the gas exchange between terrestrial and atmospheric systems. These processes are shown in Figure 5, indicating the filtration of solid and liquid compounds in the pore space (a mechanical process), and the buffering capacity through absorption and precipitation of all kinds of organic or inorganic compounds (physico-chemical reactions on the inner surface of the soil). Last but not least, soils have a microbiological and biochemical capacity for transformation, through the alteration and decomposition of organic materials by mineralization and hydrolytic processes. As long as the soil can maintain these capacities, there is little danger that solid, liquid or gaseous, inorganic and organic compounds, e.g. pollutants, will reach the soil solution. However, if these functions can not be fulfilled any more, higher quantities of heavy metals will reach the soil solution and be transferred to the plant, contaminating the food chain, or being leached beneath the profile and thus contaminating the groundwater. Luster et al. studied the effect of soil formation on heavy-metal transfer from forest soils to the groundwater, whereas Bañuelos & Lin demonstrate how the filtering and buffering functions lost by soils as a result of intensive irrigation, with respect to the transfer of selenium and other salts of geological origin, can be partially recovered by appropriate agro-ecosystem management.

The third important ecological function of the soil is as a biological habitat and a gene reserve for a large variety of organisms. The work conducted by a soil microbiologist, Selman Waksman and his team at Rutgers University in the first half of the twentieth century, resulted in the discovery of streptomycin, a very efficient antibiotic produced by Streptomyces griseus, a drug which is still widely used today. This work,
which was honoured by the Nobel Prize in 1942, illustrates how important soil organ-
isms can be in our daily life. Although it is difficult to use the concept of species when dealing with micro-organisms, the number of bacteria species present in one gram of soil can vary between $10^3$ and $10^8$, while the number of fungal species can vary between 10 and $10^5$. However, the function of most of these micro-organisms remains unclear. This is partly due to the difficulties we have in studying them (95% of soil micro-organisms cannot be cultured). As an example, Jansa et al. discuss the functional diversity of arbuscular mycorrhizal fungi (a group of soil fungi that live in symbiosis with the roots of most plants), and show how these are affected by agricultural management.

**Soil as cultural heritage**

The chapter by Wells describes the functions of soil as an earth cover that protects and preserves the physical artifacts of our cultural heritage. Soil also has more general cultural functions. Soils are a part of us, as we are part of soils – part of the cultural landscape of our minds as well as of the physical world around us. Schama (1996) explores these ideas in his book *Landscape and Memory*. An attachment to ‘home soils’ or a ‘sense of place’ is a cultural attribute developed more strongly in certain peoples or in certain individuals. Pre-Columbian peoples of North America had a strong sense of belonging to the Earth. Their creation myths have people coming from the Earth, rather than from the sky as in many Western myths. A ‘mother earth’ concept was also a part of myths in pre-Greek societies. In 1998, representatives of world religions and cultures met with soil scientists in the Alsace region of France, to discuss the relationship between soil and world religions and cultures (Lahmar & Ribaut 2001).

Artists often view soils as part of the cultural landscape. The French painter Jean du Buffet, half a century ago, in his phase of soil paintings, showed how he saw soils. He painted soils on a micro-scale; some of his works are markedly similar to the thin sections which soil scientists use to study the arrangement of soil components. He stated, ‘The things we truly love, the basis of our being, we never look at. We are unconscious of them because they are so familiar.’

More generally, soil was one of the important factors determining human migrations, affecting why people moved and why they settled, what lifestyles were possible for them, and how they used their resources. This is the realm of soil geography.

**Soil: a threatened resource**

Soil conservation is a major concern for the sustainable use of soils by society. Soils are primarily used for agricultural production, but also for building sites and the extraction of resources, such as gravel. Burghardt shows that an urban soil can retain some of its functions, and argues for a more reasonable use of the soil resources in urbanized areas. Degradation through desertification is an issue on a broad scale, with global effects. Loss of soil functions, due to compaction of surface soil by agriculture; or heavy-metal pollution in industrial areas, may represent a more local problem.

Soil degradation has increased dramatically over the last few decades. Lal (1994) estimates that between 1945 and 1996, the percentage of soil surface that was moderately, strongly or very strongly degraded worldwide reached 10.5% (1215106 ha), with 16.7% in Europe (158106 ha) and 14.3% in Africa (320106 ha). While continuing soil degradation will not immediately endanger total worldwide food production (Penning de Vries 2001), the situation is worse in developing countries, where soil is often one of the only assets of resource-poor farmers. In these areas, any increase in soil degradation will result in rising poverty and food insecurity.

Soil degradation has many causes. Agricultural management systems not adapted to their environment lead to erosion, soil structure deterioration from compaction; salinization; loss of organic matter and of biodiversity; nutrient mining and the input of toxic minerals and organic compounds. Although excess accumulation of nutrients, such as nitrogen or phosphorus, may not threaten soil fertility, the excess phosphorus in the soil may be lost to surface water or wind erosion, and excess nitrogen may be leached into the ground-water, leading to water- and air-quality degradation. Bergström & Djodjic discuss the leaching of nitrate and phosphate from agricultural soils. Our entire society contributes to soil degradation or destruction, through careless disposal of waste in the soil, or the emission of pollutants into the air, which enter the soil at some stage.

Soil disturbance during the construction of buildings leads to increased erosion, with the soil moving to places where it interferes with drainage and causes turbidity in surface water. In Switzerland, for example, 1 m$^2$ of soil disappears each second under construction, 10 000 ha are considered to be polluted and 10
to 40% of the agriculturally cropped surface is threatened by erosion (Stamp et al. 2002).

Soil management systems have changed, in order to take advantage of erosion on a geological scale. While removal of topsoil from a field decreases yields, this topsoil may be transported to flatter land, more suitable for agricultural crops. Nevertheless, erosion also has a lot of off-site effects which must be controlled, such as water pollution and mud accumulation on road and residential areas.

Many methods have been tested to decrease soil loss by erosion or loss of soil functions by degradation. The application of these methods involves changing soil management practices. The adoption of control practices has become a social or cultural issue, through education and government policy. Montanarella presents some policies which have been adopted for soil protection, as well as the European strategy for soil protection. Landa shows the importance of education in soil science, and how an alliance with geology could contribute to improving education in the earth-sciences, and Hazelton explains why public awareness of the importance of soils should be increased. Finally, besides policies and education, it is also important to ensure that soil use is sustainable. Inácio et al., and Menzi & Gerber propose appropriate tools for this purpose. Inácio et al. propose low-density geochemical exploration to assess changes in heavy-metal concentration in upper soil horizons at a country scale. Menzi & Gerber suggest the use of nutrient balances to assess, on soil horizons at a country scale. Menzi & Gerber propose appropriates tools for this purpose. Inácio et al. propose low-density geochemical exploration to assess changes in heavy-metal concentration in upper soil horizons at a country scale. Menzi & Gerber suggest the use of nutrient balances to assess, on a farm scale, whether nutrient depletion is occurring or whether the nutrient load is excessive. By doing so, they increase the awareness among farmers about the use of non-renewable resources, such as phosphate.

In the longer term, climate change might also affect soil development and soil properties. Increased temperatures and changes in water dynamics in the colder regions (in mountainous areas and at high latitudes), will lead to increased organic-matter mineralization, plant growth and weathering rates (Robert 1999). While changes in precipitation regimes, such as those observed in Switzerland, with more rainfall in winter and less in summer, will also increase erosion and nutrient losses by leaching, runoff and gaseous losses.

Altogether, we urgently need to limit soil degradation by implementing pro-soil national policies; by improving education about soil for all stakeholders involved with soil, and by improving public awareness of soil.

References


