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Introduction

This introductory chapter discusses the history and the relevance of studying soils, moves on to the principles and processes of soil formation and outlines the importance of soils for forest growth and survival. This is undoubtedly a very broad task. We cannot introduce all the details of all the processes involved and will therefore attempt to offer the reader a good and concise view of the fundamentals of the processes and mechanisms involved.

There is little mileage in trying to put forward a succinct definition of soil. This is mainly because the term ‘soil’ means different things to different people. Sitting at the interface between the atmosphere and the lithosphere, and forming part of the hydro- and biospheres (White 1979), soils have found many uses and hence many definitions. An engineer sees the soil as a loose material providing support; a hydrologist views it as a reservoir and a water purification structure; an ecologist would be interested in all life that it supports; and a farmer would want to know its structure and nutrient content. Naturally, since this is a forest soil ecology book, a forester or a forest ecologist would look at the soil through the prism of the relationship between trees and the underlying soil, how they influence each other and how they form integral parts of any forest ecosystem.

1.1 History of forest soil studies

People have always been interested in how plants grow and what the role of the soil is in this process. This inquisitiveness probably starts with the domestication of plants and the invention of arable agriculture. For example, the Chinese were already using soil fertility as a basis for levying taxes on the landholder in 4000 BC. It is not possible to say when the perception arose that plant and tree growth is somehow related to the soil form. Early farmers must have known that some plants grew better in certain soils, but what we would call a scientific approach to studying soils began with Greek philosophers such as Aristotle (384–322 BC) and Theophrastus (*c.* 371–*c.* 287 BC) (Fisher *et al.* 2000). The knowledge accumulated by the Greeks was then adopted by the Romans and spread across Europe. The notion of soil fertility and how to maintain it was then traded down the generations, but the scientific principles applied by the Greeks and the Romans were lost and not known to Western scholars centuries after the fall of the Roman Empire.

It was not until the latter half of the second millennium that scientific curiosity returned to the study of the soils. In 1563 Bernard de Palissy (*c.* 1510 – *c.* 1589), in his treatise entitled *Recepte Véritable*, introduced the idea that the plants take their nutrients from the soil. Several authors, often working on their own and without reference to others, continued to experiment with simple plant–soil systems to find out the principles of plant growth. Van Helmont (1580–1644) carried out his classic experiment during this time. He grew a willow tree in 200 pounds of soil for five years, meticulously measuring the amount of water he was adding. In the end the willow grew to 164 pounds; since the mass of the soil changed only little, the experiment led him to conclude that the tree gained its mass from the water alone. However, Robert Boyle (1627–1691) rejected this claim in 1666, rightly pointing out that crops and trees do not grow well on poor soil regardless of the availability of water. It was not until the 1800s that the correct conclusion of Van Helmont's experiment was reached by a Swiss plant physiologist, de Saussure (1767–1845), by measuring carbon dioxide and water consumption during photosynthesis.

At around this time, the Industrial Revolution considerably raised living standards, thus increasing the demand for agricultural produce and changing the balance between the rural and urban populations. This meant fewer food producers compared with consumers, resulting in rising interest in soil fertility. Rapid progress in soil science was then made by utilising discoveries in physics and chemistry. Von Liebig (1803–1873) published his *Chemistry Applied to Agriculture and Physiology* in 1840, marking the start of modern soil science. In this landmark publication, he disproved the long-held 'humus theory' and showed that plants absorb nutrients in inorganic form from the soil. During the 1850s, Thomas Way (1820–1883) discovered and described the principles of cation exchange in the soil at the now famous Rothamsted research station. The latter half of the nineteenth century was then marked by the discoveries of the role of microorganisms in the soil, especially the important part they play in organic matter decomposition and the conversion of nitrogen from ammonia to nitrate and vice versa. Russian researchers were prominent in developing certain aspects of soil science during this period; Vasilij Dokuchaev (1846–1903) constructed the first soil classification system in 1886.

Forest soil science can date its specific origins to the development of German forest science and management during the 1850s. Karl Grebe (1816–1890), a German forester, recognised at around this time that the forest is intricately linked to its soil and that any intelligent forest management must take the soil characteristics into account. Early work concentrated not only on describing forest soils, but also on studying their functioning. Notably, P. E. Müller (1840–1926) carried out his classic studies of the natural types of humus layers and E. Ebermeyer (1829–1908) worked on forest litter, soil organic matter cycling and nutrient dynamics. Texts on forest soils became an integral part of forestry education in Europe, starting with the forestry textbooks of Grebe (1852) in the German language (Wilde 1958).

Forest soil science then proceeded from studies describing the functioning of forest soils in all forest biomes to more applied studies of the impacts of acidification and environmental pollution, as these phenomena became more prominent. At present, great emphasis is placed on forecasting the reaction of forest soils to impending climate change, especially changes in temperature, species composition and carbon fluxes. However, before we unravel these complex mechanisms and dependencies, we have to have a look at the origins of soil: where do soils come from and why do they have their present shape and function?

1.2 Soil formation

All ecological systems found on Earth are essentially open – open to the inward and outward flows of energy and matter (Hoosbeek and Bryant 1992). It is the persistence of these flows that eventually leads to the formation of soils in terrestrial ecosystems. As soon as an otherwise solid rock or mineral deposit is exposed to air – and thus to a free exchange of energy – soil starts to form. Whether through solidification of lava, uplift of sediments, lowering of surface water table or retreat of glaciers, energy stored in rocks and minerals is made available and released during the process of **weathering**. Initially, chemical and physical weathering of ordered crystalline rocks (Table 1.1) leads to their fragmentation and the dissipation of energy from the system, thus increasing its entropy (state of disorder). Weathering and soil formation processes are then greatly hastened by the arrival of living organisms, initially only in primitive forms such as lichens, mosses and liverworts. Any nascent soil therefore contains both mineral and organic components, which will remain its most important constituents for its entire lifetime. However, in order to function, soils need to be organised at various levels. For example, horizontal stratification of soil layers or

Table 1.1 *Physical and chemical weathering processes*

Physical weathering

Freezing and thawing The expansive force of freezing water pushes the mineral structures apart. When the ice thaws, water can reach further into the soil particles; repeated freezing and thawing thus reduces particle size.

Heating and cooling Particles in soil are subjected to heat expansion and contraction. Uneven physical structure or chemical composition causes differential expansion, subjecting particles to internal pressure or shear, eventually leading to disintegration. This process is less pronounced than freezing and thawing, but can become significant in the long term.

Wetting and drying Soils with high content of clay minerals are prone to swelling when wetted and shrinking when dried. This process causes mechanical movement of particles, which leads to abrasion and weathering.

Abrasion Fast grinding or rubbing of particles causes their disintegration. Most obvious in arid and windy environments (blown sands) or in fast-moving water (streams, surf).

Organisms Soil is inhabited by a wide range of organisms. Their actions lead to mixing, aeration, drying or displacement of soil particles, thus enhancing the rate of physical weathering.

Unloading Often linked to the retreat of glaciers or removal of overlying materials. Soils and minerals they contain are prone to uplifting and expansion as soon as the compression agent is removed.

Chemical weathering

Dissolution Certain solid components dissolve in soil water and are removed from the soil if the water supply is sufficient. Limestone formations are especially vulnerable to dissolution, forming spectacular karst landscapes.

Hydrolysis A chemical reaction in which a chemical compound is broken down by reaction with water. This process often involves solutions of salts and their conversion to new ionic species or to precipitates (oxides, hydroxides or salts).

Carbonation Atmospheric CO_2 dissolves in rainwater, forming a weak carbonic acid. This acid, albeit harmless to plants and animals, is able to dissolve certain kinds of rock, such as feldspar and limestone.

Hydration Soil water molecules can attach themselves to the chemical structure of soil minerals, thus altering properties such as their crystalline structure. The most common process of hydration occurs when water is added to cement or gypsum.

Oxidation Oxygen, whether in soil, water or air, reacts with many soil minerals or compounds, causing a loss of electrons. Structure, chemical composition, appearance or reactivity can all be changed by this process.

Reduction The reverse of oxidation. This occurs when a lack of oxygen in the soil creates conditions in which compounds are prone to acquiring electrons, often inverting the changes caused by oxidation.

Source: Adapted from Soil-net.com, accessed June 2010.

hierarchical foodwebs of soil dwelling organisms will eventually develop. The **organisation of soil** into a functioning unit decreases the entropy of the system and as such requires external input of useful energy. With the exception of primary production of anaerobic bacteria, almost all of the energy available to the soil for self-organisation ultimately comes from the Sun. There are two main types of energy flow that enable organisation in soils: the downward flow of water, and the energy locked into organic matter by the process of photosynthesis. The kinetic energy of water passing through the soil profile enables downward (or upward, depending on circumstances) movement of soil particles or dissolved chemical compounds, thus contributing to stratification of soil horizons and several other processes. In the meantime, the energy stored in the chemical bonds of organic molecules powers the entire community of organisms inhabiting the soil: bacteria, fungi, springtails and worms, to name just a few groups. The functioning of all soils needs constant external energy input, otherwise no living soils would be able to maintain their present state.

There are **five main factors** that take part in the formation of every soil (pedogenesis): climate, relief, parent rock, time, and living organisms and associated organic matter. Before discussing these in greater detail, we have to stress the importance of the mutual dependence of a particular vegetation type, the soil on which it grows and the climate under which they developed. In the case of forest soils, each of these three factors continuously influences the other two, resulting in the development of a particular forest ecosystem and a certain type of soil in a given location, which are at an equilibrium with their environment.

Out of the five factors, **climate** is the one that works at the broadest, sometimes global, scale. Temperature and precipitation patterns strongly influence weathering and movement of fragmented particles. The rest of the agents function at regional or local scales; **relief** (topography) of the landscape has a bearing on site microclimate and the intensity and the direction of matter movement, **parent rock** directly influences the chemical and structural compositions of soils by providing their building materials. Soil formation is generally not a fast process, taking hundreds to thousands of years. The type, stratification and depth of the soil are all dependent on the length of **time** over which the pedogenic processes were at work at any location. The process of soil formation is often reversed or disturbed by climatic events, resulting in complicated patterns of soil horizons or indeed soil types. Finally, **organisms** living on or in the soil greatly affect its formation (Chapter 3). They directly affect mineral weathering, take part in water and nutrient cycling, cause organic matter decomposition and, especially in the case of forests, modify local microclimate. On Earth, the combinations of the five main factors give rise to an almost infinite range of soils (Gobat *et al*. 2004).

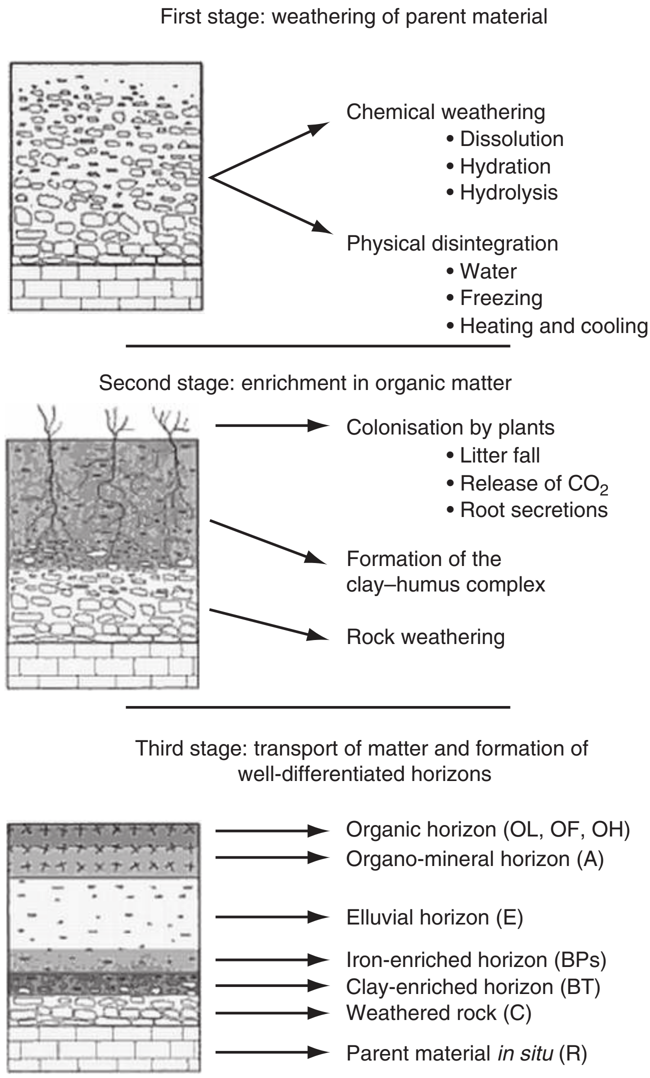

Figure 1.1 Three main stages of soil formation: weathering of parent material, organic matter deposition by living organisms, and movement of materials. Adapted from Soltner (1996).

Inevitably, the influence of all soil formation factors does not cease once the soil has been formed; they do continue to play a part in, and influence, normal soil functioning. It is very difficult, if not impossible, to distinguish the boundaries of soil formation. Nearly all the processes involved are continuous; the only change is the relative strength of their influence once the soil has reached an equilibrium with its environment. Despite this continuum, it is possible to distinguish **three major phases of soil development**, as illustrated in Figure 1.1.

The first phase takes place during solid rock disintegration and results in a layer of loose mineral particles commonly defined as sand, silt and clay (Chapter 3). Mineral transformation may take place during this phase, but the primary process taking place is weathering. The second stage is characterised by the colonisation of loose matter by organisms and by the incorporation of dead organic matter into the soil. As mentioned before, the processes driven by the actions and outputs of living organisms take place during the soil formation and during its entire existence – as long as the inputs of organic matter continue. When organic matter enters the soil, it undergoes one of the following three types of transformation: mineralisation, humification or assimilation by microorganisms (for more details about organic matter, see Chapter 6). The third stage of soil development can then be defined as horizon formation (stratification). Several soil-forming processes take place during this phase, all dependent on external energy input. Each soil will eventually develop its own sequence of horizons, depending on the interplay between the five soil formation factors. However, there are similarities enabling us to group similar soils into various classes and types through soil classification (Chapter 3).

Soil-forming processes

All processes that take part in the formation of soil can be, in one way or another, connected to the movement and transformation of particles found in the soil. None of these principal processes is unique to soil formation; they do continue to operate once the soil has been formed and become part of normal soil functioning. Specific site and climatic conditions may exclude certain soil formation processes, but if the environmental conditions change they may be activated. Generally, the presence or absence of water in the soil and the prevailing temperature drive the direction and the rate of any soil formation process. Mineral weathering in arid environments often consists of physical disintegration of rocks with little chemical transformation. If evaporation exceeds rainfall, soluble chemicals are often carried upwards with capillary movement of water and accumulate at or near the soil surface, giving rise to saline soils. Humid environments, on the other hand, are characterised by strong transformation and movement of the products of weathering. Processes such as **leaching**, **elluviation** and **illuviation** take place when the supply of water is plentiful. Leaching, the removal of soluble components of the soil, occurs when downward movement of water results in a net loss of chemical compounds, either from a single horizon or from the entire soil column. Elluviation and illuviation relate to the movement of clay or silt particles suspended in water, often from one horizon to the next. Soil-forming processes often take place in combination, giving rise to a very characteristic type of soil. Podzolisation is a good example of such a combination: chemical and physical elluviation and illuviation take place concurrently within the soil column,

Figure 1.2 Typical profile of a podzolic soil developed on aeolic sediments in Central Russia. Soil horizons are clearly separated by colour as a result of downward water movement. (Photo: authors.)

resulting in a typical arrangement of a bleached elluvial horizon and an enriched illuvial one just below it (Figure 1.2).

Given enough time, and depending on the particular combination of soil formation factors, a **mature soil** will develop. The soil is considered mature when a sufficient length of time has passed for a fully stratified soil to develop. This does not mean that the soil is not developing further or that it is in an absolute equilibrium. Any change in climate or vegetation, natural or anthropogenic, will alter the fluxes of energy and materials. This has a great effect on soil functioning, shifting the existing soil equilibrium and changing the speed and the direction of soil development.

1.3 Trees and soil environment

As already explained, a forest and its soil are intimately linked. Little is to be gained by considering the soil without the plants, and vice versa. Because of their varying characteristics, different forest soils support different forest types. However, the very same forests shape the development and the formation of forest soils. If we intend to study forest soils and their ecology, we have to solve the dilemma of where the forest finishes and the soil starts. The solution, of course, is that there is no functional boundary between the two; both are parts of a forest ecosystem and share common cycles of matter and energy. When looking at the ecology of soil-dwelling organisms, we always need to take the trees into account, especially since they are a dominant part of this system. Another important point is the complexity of the interactions between the forest and the soil: even if we were able to describe every individual relationship and process, the functioning of the whole system would be far from understood.

A forest does influence the soil through a variety of mechanisms, for example by defining the type and the amount of organic matter that enters the soil, by utilising water for evapotranspiration or by altering the site microclimate. Substituting native broadleaved woodland with conifer plantations to increase wood production often results in a rapid increase in soil acidity, especially on nutrient-poor soils. In a pollution free environment, the main factor driving acidification is the change of forest litter from readily decomposable and relatively nutrient-rich leaves to resilient and nutrient-poor conifer needles. Similarly, removing the trees from a site prone to waterlogging increases the risk of the soil conditions becoming permanently anaerobic. While growing, the trees extract large quantities of water to supply photosynthesis and to acquire nutrients. If this flux is severed, water accumulates in the soil, potentially turning an otherwise well-aerated soil into a waterlogged one.

A great proportion of soils that today are used for agriculture originally developed under a forest. We tend to think that the forests are linked to nutrient-poor soils on difficult sites, but this is the case only because deforestation happened predominantly in easily accessible locations and where the soils were the most suitable for agriculture. Generally, if the soil is left untended and the disturbance associated with agriculture ceases, any deforested site will start reverting back to woodland and the soil will again develop its typical stratification and its ecology. This process is in evidence in Europe and North America, where large parts of temperate forests are the result of secondary, post-agricultural, succession. Excluding any changes in climate, the soils on such sites would revert to an equilibrium found before deforestation and acquire their typical forest soil characteristics.

2

Soil properties

The properties of any soil are dependent on its constituents, their proportions, and their flows and fluctuations both in space and in time. The soil is an interlinked system where all constituents influence each other through a myriad of interactions, making it nearly impossible to separate, describe and study individual physical, chemical and biological processes. This chapter describes the scientific underpinnings of soil science; it then defines the basic soil properties, the methods used to measure them and their relevance to the forest ecosystem and its functioning.

Any soil typically consists of three phases: solid, liquid and gaseous. The **solid phase** is represented by mineral or organic particles of various shapes and sizes, the **liquid phase** by water with varying concentrations of soluble compounds and the **gaseous phase** by soil air. All are essential parts of soil formation and functioning; however, we can imagine a soil without its liquid or gas constituent. A temporarily dried out or completely flooded soil would still be considered a soil, but we would not define a material as soil if it was lacking the solid phase. We therefore start the description of soil properties by discussing the solid phase and its most important property: texture.

2.1 Physical properties

2.1.1 Texture

Texture describes the relative proportion of solid soil constituents according to their size. The term **mineral texture** refers to the size distribution of mineral particles, which can be determined by a simple granulometric analysis. The array of solid particles found in forest soil can span several orders of magnitude. The particles are, somewhat arbitrarily, divided into several