SOILS AND SOIL SCIENCES

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Keywords: Bulk density, cation exchange capacity, color, mapping unit, organic material, permeability, pH, regolith, soil profile, soil survey, structure, texture, water retention, weathering

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Summary

Soil science is a relatively new discipline which has mainly developed since the 1880s. It uses terms, methods and processes borrowed from other basic disciplines like climatology, geology, chemistry, physics and biology, but with a direct application to soils. At present, it is difficult to speak about one single science but as soil sciences, as they cover several fields including: pedology (or pedogenesis), soil survey (or

mapping), classification and applied soil sciences like soil fertility, soil conservation, land evaluation or soil and land management.

In this chapter an overview is given of the concepts of modern soil sciences. The process of weathering and gradual evolution of a regolith towards a mature soil profile is described. Soil composition and main soil properties, as well as their inter-relations with other characteristics and impact on land use are discussed. Finally, a summary is given of the basic principles of soil survey and soil classification. As an overhead chapter on the topic of soil sciences in this Encyclopedia, this article provides a synthetic overview, with direct references to the more detailed information included in the 17 chapters which make up this topic.

1. Introduction

The term "soil", derived from L. *solum*, has many definitions. Geologists and road engineers consider the soil primarily as an inert unconsolidated weathering product of the underlying rock, a nuisance that must be quarried and removed before reaching the material of their interest, i.e. the basement for construction. Alternatively, soil (or dirt) can also be used for filling excavations or providing foundations. For many other users, however, including farmers and earth science specialists, the soil is primarily a medium for plant growth or crop production and water storage, and a major source of living. Hence, these users and farmers in particular, pay automatically more attention to the inherent characteristics of soils and their management, because to them soil is more than useful, it is indispensable.

Throughout history farmers have learned, through trial and error, to observe differences in soils and to improve, wherever possible, their properties. Long before our era the Greeks were aware of the beneficial effects of applying manure or using ash or sulfur as soil amendments. Since the Roman Empire traditional land use practices have been passed from generation to generation, but always in a conception that soil is a rather inert material to which fertilizers and water has to be added for producing crops. This concept dominated people's minds until as recent as the late nineteenth and early twentieth centuries, and it is only since von Liebig in 1840 discovered the role of nutrients in crop production and Dokouchaiev in 1880 made the link between soil properties and bioclimatic zones that the soil is considered a dynamic body with variable properties and potential depending on variations in climate, vegetation and parent material. In the same line Jenny in 1941 defined the 5 soil forming factors which, still today, guide pedogenetic thinking and research (see: *A Brief History of Soil Science*).

In the present-day concept the soil is considered a product of evolution and changes over time, with an own morphology and properties. The morphology of each soil, as expressed by a vertical section of different layers or horizons, is a direct reflection of the effects of the five genetic factors responsible for its development. This dynamic and evolutionary nature is embodied in the universal definition of soil as:

a natural body, located at the interface between the atmosphere, lithosphere and biosphere, consisting of layers of unconsolidated mineral and/or organic constituents of *variable thickness which have been subjected to and influenced by genetic and environmental factors of: parent material, climate (including moisture and temperature effects), macro- and microorganisms, and topography, all acting over a period of time and producing a product-soil that differs from the material from which it is derived in many physical, chemical, and biological properties and characteristics.*

The upper limit of the soil is air or shallow water. Its lower limit coincides with the lower limit of biologic activity, as reflected by the rooting depth of native perennial plants. This active soil section in between corresponds with what is commonly defined as the *solum***.**

As soils differ in their properties both in the vertical and horizontal sense, their study and characterization should involve both the vertical succession of overlying horizons and spatial variations. The first aspect requires the observation and study of a soil profile pit, approximately 1m x 1m x 1m in size and being considered representative for the soil around. This small basic entity, from which one can observe variations in properties and extract samples for analytical investigations, is called a *pedon***.** It is the smallest volume that can be called a soil, but large enough to exhibit a full set of horizons.

The combination of various pedons with minor differences within a larger landform is called a *polypedon*. Such minor differences may relate to the nature and arrangement of horizons, or to the degree of expression of one or more horizons below the depth of normal plowing. In fact, a polypedon corresponds usually with what is often described as a *soil series*. Soils of the same series have a similar horizon sequence and nearly identical properties of the horizons.

2. Soils and Soil Science

Soil science is the study concerned with observing and describing, collecting, establishing and systematizing facts, principles and methods in order to acquire an in-depth knowledge of the soils, their properties and potential for production and conservation. Soil science uses an integrated multidisciplinary approach in the sense that it borrows concepts, techniques and processes from other sciences, but with a focus on soils. Soil science relies on 7 major supporting sciences or sub-disciplines (Figure 1):

- Climatology which affects the pedo-climate in terms of moisture and temperature conditions in the solum, and thus influences physical and chemical soil processes and plant and animal life;
- Geology which determines the nature and constitution (mineralogy) of the parent material from which the soil profile develops;
- Geomorphology (landform evolution) and hydrology which have a major impact on runoff, erosion and sedimentation processes, and differential warming up of soils;
- Physics, the basic laws of which determine the nature, intensity and interrelationships between the solid, liquid and gaseous soil components;
- Chemistry, concerned with the chemical constitution, chemical properties and chemical reactions in the soil, and their direct effect on soil fertility and nutrient supply to plants; and

- Soil (micro) biology dealing with the soil fauna, the vegetation above and below the soil surface, as well as the microscopic soil population, and their role in various transformations and the liberation of nutrients.

Soil science as a discipline is relatively young compared to other sciences like mathematics or astronomy, the origin of which dates back for more than 2 000 years. The first who started to systematically study soils was the Russian geographer Dokouchaiev in the late 19th century, but his work became only known at the international floor after it had been published in German and disseminated by Marbut and Jenny in the USA (see: *A Brief History of Soil Science*).

The disastrous Dust Bowl in the Mid West in the 1930s gave an additional impetus to the study of soils and was the start of the Soil Conservation Service in the US. Elsewhere in the world the growing interest in soils work received a major push after World War II when in a number of European countries a national soil survey institute was established (in 1947 in Belgium, 1952 in France, 1966 in The Netherlands, etc.) while in the tropics the rapid development and increased demand of plantation crops asked for an better knowledge and understanding of soil-plant relations in these areas.

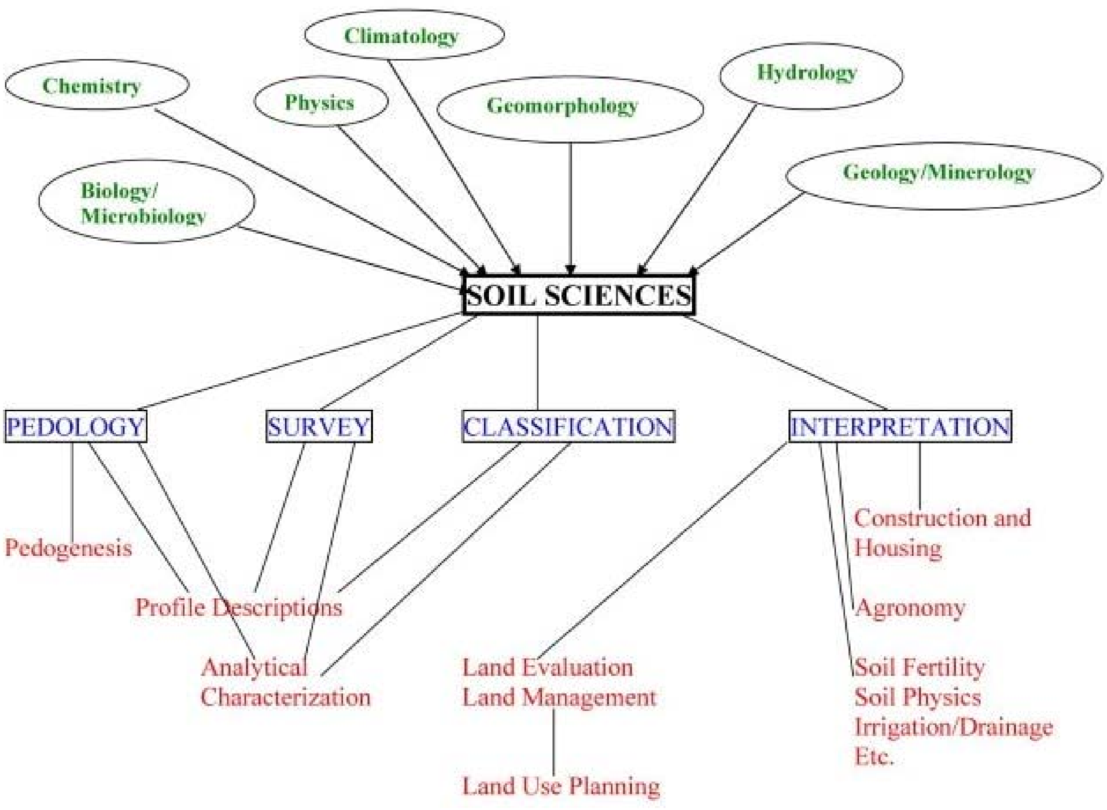

Figure 1: Supporting basic sciences and current sub-disciplines of soil science

At present, there are four major disciplines within soil science focusing on different applications and users (Figure 1):

- Pedology, focusing on the formation (pedogenesis) and development of soils as recognized in the characteristics of the soil profile. It deals with fundamental and academic research aspects of soils, and includes the description and analytical characterization of the soil;

- Soil survey which describes the soil properties (making use of field and laboratory observations as referred to above) and delineates the geographical distribution of the different soils;
- Soil classification which organizes the soils and their particular properties on the basis of a hierarchical system of pre-defined criteria and classes. Though these criteria may vary as a function of the objectives, most international classification systems have a pedogenetic background; and
- Applied soil sciences which interpret the soil properties in function of their ranking and potential for a specific objective. This includes applications (1) for housing and construction, focusing mainly on physical and much less on chemical properties; (2) for agronomic and crop production objectives, including soil fertility, suitability for drainage and irrigation, etc.; (3) for soil conservation and the protection of soils against physical loss by erosion or by chemical deterioration; and (4) land evaluation which assesses the production and use potential of the soil, including the development and monitoring of land use practices. The latter domain has since the 1980s gradually become a key issue for land resource management and land use planning.

The various aspects of soil sciences described above are discussed at large in different separate chapters in this section: *Soil Physics, Soil Chemistry and Soil Fertility, Soil Biology and Microbiology, Soil Biochemistry, Soil Mineralogy.*

3. Soil Formation and Soil Forming Processes

Soil formation takes place in two consecutives stages, starting with a simple weathering (disintegration and decomposition) of rocks and minerals giving rise to an unconsolidated regolith (from Gr. *rhegos*, covering, and *lithos*, stone), and followed by a soil profile development, whereby the regolith material is gradually modified and a horizon sequence develops under the combined action of climate, vegetation, topography and time.

3.1. Weathering and Regolith Formation

Weathering is basically a combination of destruction and synthesis. It breaks up rocks, modifies or destroys their physical and chemical characteristics, and carries away the soluble products and some of the solids. These changes are accompanied by a continuous decrease in particle size and by the release of soluble constituents, which are subject to loss in drainage waters or recombination into new (secondary) minerals.

There are three major forms of weathering: physical, chemical and biological weathering. Physical or mechanical weathering takes places under conditions where water is no active agent to enhance chemical reactions. It is particularly active in deserts or in polar areas where temperature changes create internal pressures in the rock and produce cracks (see: *Dry Lands and Desertification, and Soils of Arid and Semi-Arid Areas*). Chemical weathering is mainly related to the concerted action of water, oxygen and organic chemicals released by higher plants and microorganisms. While physical weathering results generally in a broad breakdown of soil and rock components, chemical weathering affects much more intensively the composition of soil material. The three major weathering processes related to water are hydrolysis (the dissociation from H^+ and OH^- ions from H_2O), hydration (addition of a water molecule to the mineral) and dissolution (the solubility of a compound and its elimination from the environment).

Biological weathering processes are activated by living agents (animals, higher plants, microorganisms) and are mainly responsible for both the decomposition and disintegration of rocks and minerals. The processes related to these weathering forms have been discussed at large in: *Dry Lands and Desertification*.

3.2. Soil Profile Formation and Horizon Development

Soil profile development is basically a re-arrangement of soil particles into soil horizons, each of them with specific properties. Soil formation can proceed rather fast in aggressive humid tropical climates, but is much slower in cold or dry climates; when the surface layers are eroded, the (active) root zone comes nearer to the regolith and soils are rejuvenated. Conditions that hasten the rate of soil development are: (1) a warm, humid climate, (2) forest vegetation, (3) permeable unconsolidated material low in lime content, and (4) flat or lowland topography with good drainage. Factors that tend to retard development are: (a) a cold or dry climate, (b) grass vegetation, (c) the presence of impermeable consolidated material high in lime, and (d) a steeply sloping topography.

Weathering and soil formation can be studied by changes of color, structure and texture in the field, by laboratory analyses and by microscopic observations and techniques (see: *Soil Mineralogy*, and *Soil Microscopy and Micromorphology*). The processes involved in soil profile formation and horizon development are: (a) gains or additions of water, organic and mineral material, (b) losses of such material from the soil, (c) transformation of mineral substances within the soil, and (d) translocation or movement of soil material from one point to another, involving movement in solution (leaching) or in suspension (eluviation) of clay, organic matter or hydrous oxides. Conditions that retard or offset horizon differentiation are due to: (a) mixing of material by burrowing animals, (b) removal of surface soil by water or wind, (c) creep, and (d) accretion of sediments in floodplains.

There are 9 fundamental processes that affect profile differentiation:

Humification - The process of transformation, i.e. decomposition of raw organic material into humus under the influence of soil microorganisms. During this process, the soluble organic substances regroup themselves into large molecules and become poorly soluble. In the strict sense, the term focuses in particular on the phase which follows the decomposition of the organic debris and which consists mainly of processes of synthesis and building up of new molecules through microbial or physicochemical pathways.

Eluviation and illuviation - The process of removal of soil constituents in suspension or in solution by percolating water from the upper to the lower layers. It encompasses mobilization and translocation of mobile constituents (mainly clay) resulting in a textural differentiation, or leaching of soluble elements like salts.

Calcification and decalcification- The movement of soluble calcium carbonate in the soil, involving their leaching, movement, precipitation and accumulation in various soil layers. The general reaction which controls the movement of carbonate is:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$$

If CO_2 and H_2O are present, i.e. under an active biological activity, the reaction proceeds in the right direction, with the formation of soluble bicarbonate. When CO_2 and water are not active, i.e. in the dry season when the biological activity is largely reduced, the reaction proceeds to the left and insoluble calcium carbonate precipitates. This is, for example, what happens in Mediterranean soils which develop under an alternate humid winter and dry summer period (see: *Mediterranean Soils*).

Podzolization - The process of extreme leaching of bases in an acid environment, relatively poor in weatherable minerals, characteristic of regions with a (very) humid boreal or tropical climate. It involves the eluviation of acid and complex-forming humus that becomes mobile and gets leached from the upper part of the profile, and their subsequent deposition in the lower horizons. The process is the most active under pine tree forests (see: *Forest, Range and Wildland Soils*).

Lateritization (currently replaced by the connotations allitization and ferrallitization) - The process that removes silica and soluble bases from the upper layers of the soil, creating a relative accumulation and concentration of sesquioxides (Fe and Al-oxides) in the soil. As the alkaline bases are removed from the seat of their formation, the residual soil is acidic in reaction. Though considerable eluviation takes place, there is no marked horizonation as the eluviated materials are not re-deposited in the lower layers. Depending on the intensity of the weathering process the residual soils are dominated by Fe and Al compounds (ferrallitization) or by Al-(hydr)oxides only (allitization). These processes act most intensively in warm and humid tropical climates with 2000-2500 mm annual rainfall and high temperatures (>22°C) throughout the year (see: *Soils of the Humid and Sub-Humid Tropics*).

Gleization - A process of soil formation under an anaerobic environment and leading to the development of a gley horizon with green-blue colors, related to the reduction of soluble ferrous iron under water-logged conditions. Where the groundwater fluctuates considerably with the season, the gley shows distinct mottling of yellow and rusty brown colors caused by alternate oxidation and reduction phenomena.

Salinization - The process of accumulation of salts, such as sulfates or chlorides in the form of a salty horizon. It is active under conditions of highly saline or brackish groundwater, and evaporation being higher than precipitation, so that salts move up by capillary action from the groundwater. Desalinization is the removal, by leaching of excess soluble salts from horizons that contain enough soluble salts to impair plant growth (see: *Salinity and Alkalinity Status of Arid and Semi-arid Lands*).

Alkalinization - A process involving the accumulation of sodium ions on the exchange complex of clays, resulting in the formation of a sodic soil (Solonetz). At this moment a high soil pH (>8.5) develops, soil colloids are dispersed and a very poor soil structure develops. The organic matter dissolved under alkaline conditions forms black organo-clay coatings on the ped surfaces giving the soil a dark-colored appearance (Black Alkali Soils).

Solodization or de-alkalinization - The removal of Na^{+} from the exchange sites and the dispersion of clay, promoted by the addition of Ca^{2+} to the formerly alkaline soil, often under the form of easily soluble gypsum (see: *Dry Lands and Desertification*).

Pedoturbation - The process of mixing the soil due to faunal activity (ants, earthworms, moles, termites, etc.), plant roots, natural swell-shrink processes or by man-made land management practices. It is very active in boreal areas covered by long-time and usually undisturbed forest vegetation (see: *Forest, Range and Wildland Soils*).

The rate of soil development varies with the intensity of the processes involved, and with the age of the soil. In dry climates there is almost no water for either chemical processes or organic material production. Hence, soil formation is mainly limited to an incomplete physical breakdown of soil components. In a humid, warm climate hydrolysis, dissolution and leaching are much more intensive, and soil properties rapidly change into a material that is composed of stable mineral components.

Individual processes vary also in intensity over time. Under ideal conditions a recognizable soil profile may develop within a couple of centuries. But under less favorable environments, as is the case in deserts, the time taken for soil development may extend over several thousand years.

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Biographical Sketch

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He has been active for more than thirty-five years, both in the academic world, as a professor/ research director in soil science, land evaluation, and land use planning, and as a technical and scientific advisor for rural development projects, especially in developing countries. His research has mainly focused on the field characterization of soils and soil potentials and on the integration of socio-economic and environmental aspects in rural land use planning. He was a technical and scientific advisor in more than 100 development projects for international (UNDP, FAO, World Bank, African and Asian Development Banks, etc.) and national agencies, as well as for development companies and NGOs active in inter-tropical regions.