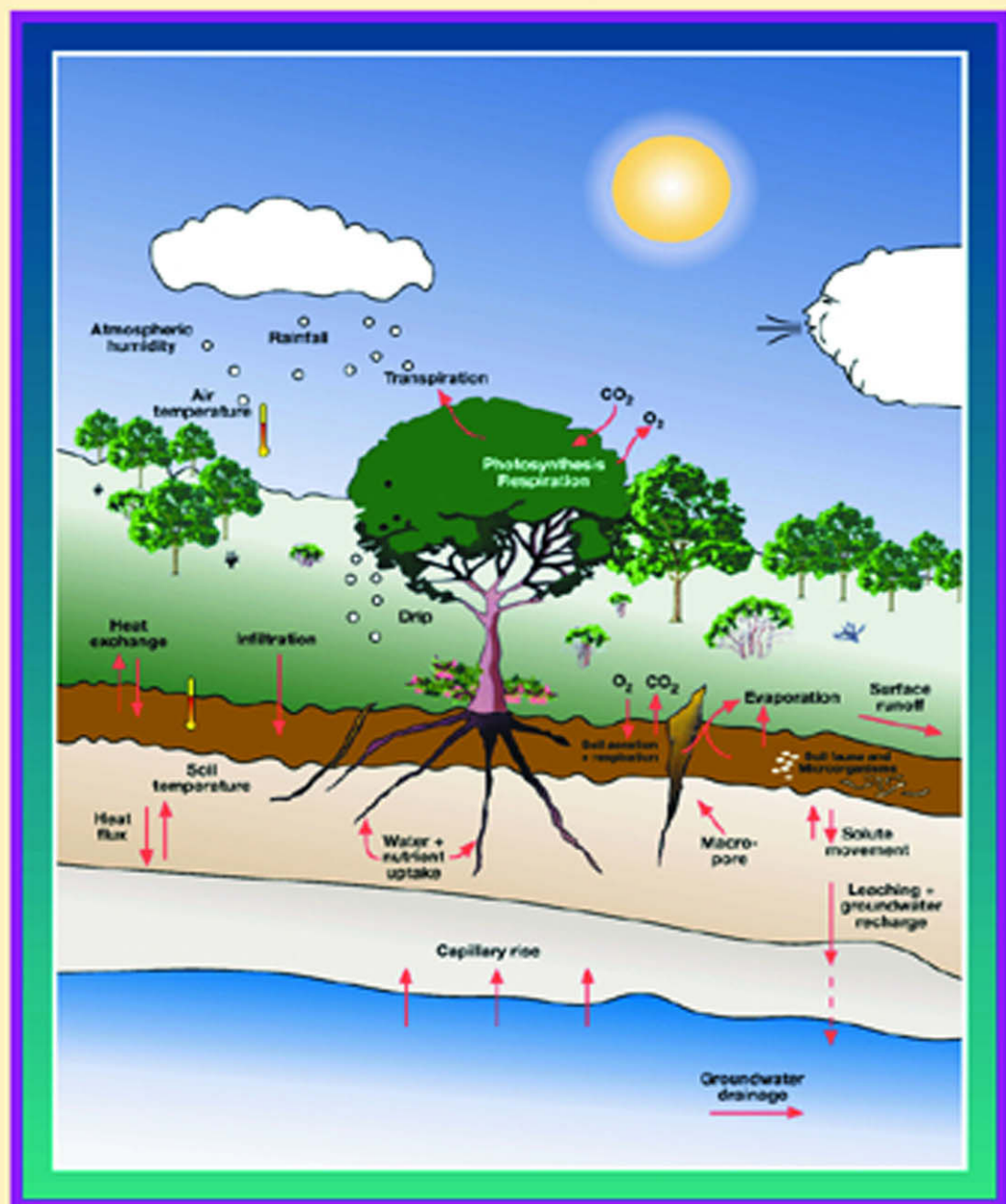


# Introduction to Environmental Soil Physics



Daniel Hillel

*This book is but a clearing at the edge of the woods  
where students might observe a few of the trees  
as they prepare to set forth independently  
to explore the great forest that yet lies beyond, –  
and to care for it.*

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# INTRODUCTION TO ENVIRONMENTAL SOIL PHYSICS

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# INTRODUCTION TO ENVIRONMENTAL SOIL PHYSICS

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*To see a world in a grain of sand  
and heaven in a wild flower  
Hold infinity in the palm of your hand  
and eternity in an hour.  
William Blake (1757–1827)  
Songs of Innocence and Experience*

# PREFACE

What is special about this fragmented and loose outer layer of the earth's continental surface, which we call "soil"? What role does it fulfill in generating and sustaining life on earth, and why do we need to study it?

Considering the height of the atmosphere, the thickness of the earth's rock mantle, and the depth of the ocean, we note that the soil is an amazingly thin body — typically not much more than one meter thick and often less than that. Yet it is the crucible of terrestrial life, within which biological productivity is generated and sustained. It acts like a composite living entity, being home to a community of innumerable microscopic and macroscopic plants and animals. A mere fistful of soil typically contains millions of microorganisms, which perform the most vital functions of biochemistry. Another amazing attribute of the soil is its spongelike porosity and its enormous internal surface area. That same fistful of soil may actually consist of several acres of active surface upon which physicochemical processes take place continuously.

Realizing humanity's dependence on the soil, ancient peoples, who lived intimately with nature, actually revered the soil. It was their source of livelihood, as well as the material with which they built homes and that they learned to shape, heat, and fuse into household vessels and writing tablets (ceramic being the first synthetic material in the history of technology). In the Bible, the name assigned to the first human being was Adam, derived from the Hebrew word *adama*, meaning "soil." The name given to his mate was Hava (Eve, in transliteration), meaning "living" or "life-giving." Together, therefore, Adam and Eve signified quite literally "soil and life."

The same powerful metaphor is echoed in the Latin name for the human species — *Homo* — derived from *humus*, the material of the soil. Hence, the adjective *human* also implies "of the soil." Other ancient cultures evoked equally powerful associations. To the ancient Greeks, the earth was a manifestation of Gaea, the maternal goddess who, impregnated by Uranus (god of the sky), gave birth to all the disparate gods of the Greek pantheon.

Our civilization depends on the soil more crucially than ever, because our numbers have grown while available soil resources have diminished and deteriorated. Paradoxically, however, even as our dependence on the soil has increased, most of us have become physically and emotionally detached from it. The majority of the people in the so-called “developed” countries spend their lives in the artificial environment of a city, insulated from direct exposure to nature. Many children now assume as a matter of course that food originates in supermarkets.

Detachment has bred ignorance, and out of ignorance has come the arrogant delusion that our civilization has risen above nature and has set itself free of its constraints. Agriculture and food security, erosion and salination, degradation of natural ecosystems, depletion and pollution of surface waters and aquifers, and decimation of biodiversity — all these processes, which involve the soil directly or indirectly, have become mere abstractions to most people. The very language we use betrays disdain for that common material underfoot, often referred to as “dirt.” Some fastidious parents prohibit their children from playing in the mud and rush to wash their “soiled” hands when the children nonetheless obey an innate instinct to do so. Thus is devalued and treated as unclean what is in fact the terrestrial realm’s principal medium of purification, wherein wastes are decomposed and nature’s productivity is continually rejuvenated.

Scientists who observe the soil discern a seething foundry in which matter and energy are in constant flux. Radiant energy from the sun streams onto the field and cascades through the soil and the plants growing in it. Heat is exchanged, rainwater percolates in the intricate passages of the soil, plant roots suck up that water and transmit it to their leaves, which transpire it back to the atmosphere. The leaves absorb carbon dioxide from the air and synthesize it with soil-derived water to form the primary compounds of life: carbohydrates, fats, proteins, and numerous other compounds (many of which provide medicinal as well as nutritional value). Oxygen emitted by the leaves makes the air breathable for animals, which feed on and in turn fertilize the plants.

The soil is thus a self-regulating biophysical factory, utilizing its own materials, water, and solar energy. It also determines the fate of rainfall and snowfall reaching the ground surface — whether the water thus received will flow over the land as runoff or seep downward to the subterranean reservoir called groundwater, which in turn maintains the steady flow of springs and streams. With its finite capacity to absorb and store moisture, the soil regulates all of these phenomena. Without the soil as a buffer, rain falling over the continents would run off immediately, producing violent floods rather than sustained stream flow.

The soil naturally acts as a living filter in which pathogens and toxins that might otherwise accumulate to foul the terrestrial environment are rendered harmless and transmuted into nutrients. Since time immemorial, humans and other animals have been dying of all manner of diseases and have then been buried in the soil, yet no major disease is transmitted by it. The term *antibiotic* was coined by soil microbiologists, who, as a consequence of their studies of soil bacteria and actinomycetes, discovered streptomycin (an important cure for tuberculosis and other infections). Ion exchange, a useful process of water

purification, was also discovered by soil scientists studying the passage of solutes through beds of clay.

However unique in form and function, the soil is not an isolated body. It is, rather, a central link in the chain of interconnected domains comprising the terrestrial environment. The soil interacts with both the overlying atmosphere and the underlying strata, as well as with surface and underground bodies of water. Especially important is the interrelation between the soil and the climate. In addition to its function of regulating the cycle of water, soil regulates energy exchange and temperature. When virgin land is cleared of vegetation and turned into a cultivated field, the native biomass above the ground is often burned and the organic matter within the soil tends to decompose rapidly. These processes release carbon dioxide into the atmosphere, thus contributing to the earth's greenhouse effect and to global warming. On the other hand, the opposite action of soil enrichment with organic matter, such as can be achieved by means of reforestation and conservation farming, may help to absorb carbon dioxide from the atmosphere. To an extent, the soil's capacity to absorb and sequester carbon can thus help to mitigate the atmosphere's so-called greenhouse effect.

It takes nature thousands of years to create life-giving soil out of sterile bedrock. It takes but a few decades for unknowing or uncaring humans to destroy that wondrous work of nature. It is for us who do care for future generations to treat the soil with respect and humility, another word derived from *humus*. In the Book of Genesis, humans are said to have been placed in the Garden of Eden for a purpose, "to serve and preserve it." There is a profound truth in that perception. The earth and its soil can be a veritable Garden of Eden, but only if we do not despoil it and thereby banish ourselves from a life of harmony within it.

"To the wise man, the whole world's a soil," wrote Ben Johnson (1573–1637). His thought was echoed by William Butler Yeats (1865–1939): "All that we did, all that we said or sang, must come from contact with the soil."

This book is an abridged and updated version of my earlier book, published in 1998 under the title "Environmental Soil Physics." As such, this version is intended to serve as a basic text for introductory undergraduate courses in soil physics for students in the environmental, agricultural, and engineering sciences. The book is also meant to appeal to a broad range of students and professionals, as well as educated lay readers outside those formal categories, who may wish to acquire a fundamental understanding of the principles and processes governing the ways the soil functions in natural and in managed ecosystems. Those who seek a more detailed treatment of the various topics introduced herewith are invited to consult the larger book (1998), as well as the numerous references listed in the text and the Bibliography.

A textbook on so vital a subject ought by right to capture and convey the special sense of wonderment and excitement that impels the scientist's quest to comprehend the workings of nature, and hence should give some pleasure in the reading. It is my hope that this book might indeed be pondered, not merely studied, that its readers might find within it a few insights as well as facts, and that it will deepen their understandings as well as broaden their knowledge.



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Daniel Hillel  
May, 2003

# Part I

## BASIC RELATIONSHIPS

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# 1. SOIL PHYSICS AND SOIL PHYSICAL CHARACTERISTICS

## SOIL SCIENCE

To begin, we define *soil* as the weathered and fragmented outer layer of the earth's terrestrial surface. It is formed initially through disintegration, decomposition, and recomposition of mineral material contained in exposed rocks by physical, chemical, and biological processes. The material thus modified is further conditioned by the activity and accumulated residues of numerous microscopic and macroscopic organisms (plants and animals). In a series of processes that may require hundreds or even thousands of years and that is called *soil genesis*, the loose debris of rock fragments is transmuted into a more or less stable, internally ordered, actively functioning natural body. Ultimately, this culminates in the formation of a characteristic *soil profile*, which resembles a layer cake. We can visualize the soil profile as a composite living body, in the same way that we think of the human body as a distinct organism, even though in reality it is an ensemble of numerous interdependent and symbiotically coordinated groups of organelles, cells, organs, and colonies of myriad organisms.

*Soil science* is the study of the soil in all its ramified manifestations and facets: as a central link in the biosphere, as a medium for the production of agricultural commodities, and as a raw material for industry and construction. As such, it shares interests with geology, sedimentology, terrestrial ecology, and geobotany as well as with such applied sciences as agronomy and engineering. Because of its varied interests and concerns, soil science itself is commonly divided into several subdivisions, including pedology (soil formation

and classification), soil chemistry, soil mineralogy, soil biology, soil fertility, and soil mechanics. However, such distinctions are often arbitrary, because in fact all of the environmental sciences are inextricably interconnected.

## SOIL PHYSICS

Soil physics is one of the major subdivisions of soil science. It seeks to define, measure, and predict the physical properties and behavior of the soil, both in its natural state and under the influence of human activity. As physics deals in general with the forms and interactions of matter and energy, so soil physics deals specifically with the state and movement of matter and with the fluxes and transformations of energy in the soil. On the one hand, the fundamental study of soil physics aims at understanding the mechanisms governing such processes as terrestrial energy exchange, the cycles of water and of transportable materials, and the growth of plants in the field. On the other hand, the practical application of soil physics aims at the proper management of the soil by means of cultivation, irrigation, drainage, aeration, improvement of soil structure, control of infiltration and evaporation, regulation of soil temperature, and prevention of erosion.

Soil physics is thus both a basic and an applied science, with a very wide range of interests. The study of soil science in general and of soil physics in particular is driven not only by the innate curiosity that is our species' main creative impulse, but also by urgent necessity. The intensifying pressure of population and development has diminished the soil resources of our small planet and has led to their unsustainable use and degradation in too many parts of the world.

Since the soil is not an isolated medium but is in constant dynamic interaction with the larger environment, soil physics is an aspect of the more encompassing field of environmental physics (sometimes called biospheric physics) and of the overall science of geophysics.

The early soil physicists were interested primarily in the engineering and the agricultural aspects of their discipline, hence their research focused on the soil as a material for construction or as a medium for the production of crops. Recent decades have witnessed an increasing emphasis on the environmental aspects and applications of soil physics. Consequently, research in soil physics has expanded its scope to include phenomena related to natural ecosystems and to processes affecting the quality of the environment. Processes occurring in the soil are now seen to affect the entire terrestrial environment, including local and regional climates, the natural food chain, biodiversity, and the fate of the voluminous waste products of our civilization (among which are many pathogenic and toxic agents).

Increasingly, the main concern of soil physics has shifted from the laboratory to the field and from a restricted one-dimensional view to an expansive three-dimensional view interfacing with the domains of sister disciplines such as meteorology and climatology, hydrology, ecology, and geochemistry. The larger domain of soil physics now encompasses greater complexity and variability in space and time, the treatment of which requires reliance on stochastic as well as deterministic methods. Consequently, the science is becoming ever more interesting and relevant.

The task of soil physics is made difficult by the enormous and baffling intricacy of a medium containing myriad mineral and organic components, all irregularly fragmented and variously associated in a geometric pattern that is so complex and labile as to challenge our imagination and descriptive powers. Some of the solid material consists of crystalline particles, while some is made up of amorphous gels that may coat the crystals and modify their behavior. The solid phase in the soil interacts with the fluids, water, and air that permeate soil pores. The entire soil is hardly ever in equilibrium as it alternately wets and dries, swells and shrinks, disperses and flocculates, hardens and softens, warms and cools, freezes and thaws, compacts and cracks, absorbs and emits gases, adsorbs and releases exchangeable ions, dissolves and precipitates salts, becomes acidic or alkaline, and exhibits aerobic or anaerobic conditions leading to chemical oxidation or reduction.

## THE SOIL PROFILE

The most obvious part of any soil is its surface zone. Through it, matter and energy are transported between the soil and the atmosphere. The surface may be smooth or pitted, granular or crusted and cracked, friable or hard, level or sloping, vegetated or fallow, mulched or exposed. Such conditions affect the processes of radiation and heat exchange, water and solute movement, and gaseous diffusion.

Important though the surface is, however, it does not necessarily portray the character of the soil as a whole. To describe the latter, we must examine the soil in depth. We can do this by digging a trench and sectioning the soil from the surface downward, thus revealing what is commonly termed the *soil profile*.

The soil profile typically consists of a succession of more-or-less distinct strata. These may result from the pattern of deposition, or sedimentation, as can be observed in wind-deposited (*aeolian*) soils and particularly in water-deposited (*alluvial*) soils. If, however, the strata form in place by internal soil-forming (*pedogenic*) processes, they are called *horizons*.

The top layer, or *A horizon*, is the zone of major biological activity and is therefore generally enriched with organic matter and darker in color than the underlying soil. Here, plants and animals and their residues interact with an enormously diverse and labile multitude of microorganisms, such as bacteria, protozoa, and fungi, millions of which can be found in a mere handful of topsoil. In addition, there are usually varied forms of macroorganisms (including earthworms, arthropods, and rodents) that burrow in the soil. The A horizon is generally the most fertile zone of the soil, but it is also the zone most vulnerable to erosion by water and wind (especially if it is denuded of vegetative cover or its protective residues).

Underneath the A horizon is the *B horizon*, where some of the materials (e.g., clay or carbonates) that are leached from the A horizon by percolating water tend to accumulate. The B horizon is often thicker than the A horizon. The pressure of the overlying soil tends to reduce the porosity of the deeper layers. In some cases, an overly dense or indurated B horizon may inhibit gas exchange, water drainage, and root penetration.

Underlying the B horizon is the *C horizon*, which is the soil's parent material. In a soil formed of bedrock in situ (called a *residual soil*), the C horizon consists of the weathered and fragmented rock material. In other cases, the C horizon may consist of alluvial, aeolian, or glacial deposits.

The character of the profile depends primarily on the climate that prevailed during the process of soil formation. It also depends on the parent material, the vegetation, the topography, and time. These five variables are known as the *factors of soil formation* (Fanning and Fanning, 1989). Mature soils are such that have been subjected to those factors for a sufficient length of time so that full profile development has taken place. The A, B, C sequence of horizons is clearly recognizable in some cases, as, for example, in a typical zonal soil (i.e., a soil associated with a distinct climatic zone), such as a *podzol* (also known as a *spodosol*). In other cases, no clearly developed B horizon is discernible, and the soil is then characterized by an A,C profile. In a recent alluvium, hardly any profile differentiation is apparent.

The typical development of a soil and its profile, called *pedogenesis* (Buol et al., 2003), can be summarized: It begins with the physical disintegration of an exposed rock formation, which provides the soil's parent material. Gradually, the loosened material is colonized by living organisms. The consequent accumulation of organic residues at and below the surface brings about the development of a discernible A horizon. That horizon may acquire an aggregated structure, stabilized to some degree by glue-like components of the organic matter complex (known as *humus*) resulting from the decomposition of plant and animals residues. Continued weathering (decomposition and recombination) of minerals may bring about the formation of clay. Some of the clay thus formed tends to migrate downward, along with other transportable materials (such as soluble salts), and to accumulate in an intermediate zone (the B horizon) between the surface zone of major biological activity and the deeper parent material of the so-called C horizon.

Important aspects of soil formation and profile development are the twin processes of *eluviation* and *illuviation* ("washing out" and "washing in," respectively), wherein clay and other substances emigrate from the overlying eluvial A horizon and accumulate in the underlying illuvial B horizon. The two horizons come to differ substantially in composition and structure.

Throughout these processes, the profile as a whole deepens as the upper part of the C horizon is gradually transformed, until eventually a quasi-stable condition is approached in which the counterprocesses of soil formation and soil erosion are more or less in balance. In the natural state, the A horizon may have a thickness of 0.1–0.5 meters. When stripped of vegetative cover and pulverized or compacted by tillage or traffic, this horizon may lose half or more of its original thickness within a few decades.

In arid regions, salts such as calcium sulfate and calcium carbonate, dissolved from the upper part of the soil, may precipitate at some depth to form a cemented *pan* (sometimes called *caliche*, from the Spanish word for "lime"). Erosion of the A horizon may bring the B horizon to the surface. In extreme cases, both the A and B horizons may be scoured off by natural or human-induced erosion so that the C horizon becomes exposed and a new cycle of soil formation may then begin. In other cases, a mature soil may be covered by a new layer of sediments (alluvial or aeolian) so that a new soil may form over

a “buried” old soil. Where episodes of deposition occur repeatedly over a long period of time, a sequence of soils may be formed in succession, thus recording the pedological history — called the *paleopedology* — of the region (including evidence of the climate and vegetation that had prevailed at the time of each profile’s formation).

Numerous variations of the processes described are possible, depending on local conditions. The characteristic depth of the soil, for instance, varies from location to location. Valley soils are typically deeper than hillslope soils, and the depth of the latter depends on slope steepness. In places, the depth of the profile can hardly be ascertained, because the soil blends into its parent material without any distinct boundary. However, the zone of



### BOX 1.1 Soil Physics and the Environment

As human populations have grown and living standards have risen, the requirements for agricultural products have increased enormously. More land has been brought under cultivation, including marginal land that is particularly vulnerable to degradation by such processes as erosion, depletion of organic matter and nutrients, pollution, waterlogging, and salination. Other forms of land use — towns, roads, factories, airports, feedlots, waste disposal sites, and recreational facilities — usurp ever more land.

Consequently, the domain remaining for natural ecosystems has shrunk and been divided into smaller enclaves, to the detriment of numerous species. The mutual checks and balances that have long sustained the rich diversity of life on earth are now threatened by the human appetite for resources and the wanton way they are used and their waste products discarded. The task therefore is to supply human needs in ways that are sustainable locally and do not damage the larger environment.

Two alternative approaches have been proposed to prevent further destruction of the remaining natural ecosystems and to relieve pressure on fragile marginal lands. One way is to restrict human activities to choice areas, where production can be intensified. This calls for optimizing all production factors so as to achieve maximum efficiency in the utilization of soil, water, energy, and other necessary inputs (e.g., nutrients and pest control measures). The problems are that soil processes are difficult to control, and, because the soil is an open system in constant interaction with its surroundings, the time-delayed and space-removed consequences of soil processes are difficult to predict. Full control of agricultural production can ultimately be achieved only in enclosed spaces such as greenhouses or in confined fields.

Another approach is to devise more naturalistic modes of production that are compatible with the environment and do not require the drastic isolation of production from neighboring ecosystems. This agro-ecosystem approach is exemplified by the trends toward organic farming and agroforestry.

Either way, the physical attributes and processes of the soil are of prime importance. Physical factors strongly affect whether the soil is to be cool or warm, anaerobic or aerobic, wet or dry, compact or highly porous, hard or friable, dispersed or aggregated, impervious or permeable, eroded or conserved, saline or salt free, leached or nutrient rich. All these, in turn, determine whether the soil can be a favorable or unfavorable medium for various types of plants and other living organisms as well as for alternative modes of production; in short, whether the soil can be managed productively and sustainably while neutralizing — rather than transmitting — environmental pollutants.



biological activity seldom extends below 2–3 meters and in many cases is shallower than 1 meter.

## SOILS OF DIFFERENT REGIONS

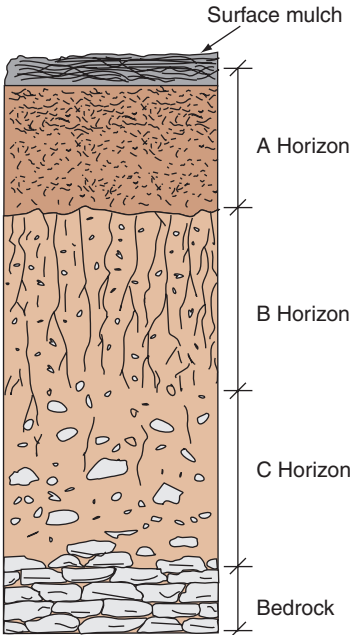
Each climatic zone exhibits a characteristic group of soils. In the humid tropics, there is a tendency to dissolve and leach away the silica and to accumulate iron and aluminum oxides. As a result, the soils are typically colored red, the hue of oxidized iron. Chunks or blocks excavated from such soils and dried in the sun may harden to form bricks; hence these soils are called *laterites*, from the Latin word *later*, meaning “brick.” On the other hand, soils of the humid cool regions often exhibit an A horizon consisting of a thin surface layer darkened by organic matter and underlain by a bleached, ashlike layer; in turn, this overlies a clay-enriched B horizon. These soils were called *podzols* by the early Russian pedologists (from the Russian words *pod* = “ground” and *zola* = “ash”) and are known as *spodosols* in the current American system. Soils that are poorly drained (“waterlogged”) may exhibit conditions of chemical reduction in the profile, indicated by streaks of discoloration (“mottling”).

In contrast with the soils of humid regions, from which nearly all readily soluble salts have been leached, the soils of arid regions tend to precipitate the moderately soluble salts of calcium and magnesium. (Especially prevalent are accumulations of calcium carbonate [lime] and calcium sulfate [gypsum].) Under certain conditions, arid-zone soils may even accumulate the more readily soluble salts of sodium ( $\text{NaCl}$  and  $\text{Na}_2\text{CO}_3$ ) and of potassium. Such soils are prone to excessive salinity, in extreme cases of which they become practically sterile. Irrigated soils in poorly drained river valleys of arid regions are particularly liable to undergo the process of salination. When such soils are leached of excess salts, they must be treated with soil amendments (such as gypsum) to replace the exchangeable sodium ions with calcium, lest the sodium ion cause dispersion of the clay and the breakdown of soil structure.

An outstanding soil formed naturally in some intermediate semihumid to semiarid regions (e.g., Ukraine, Argentina, and the prairie states of North America — the so-called “corn belt” of the United States) is the soil classically called *chernozem* (Russian for “black earth”) with its unusually thick, humus-rich, fertile A horizon.

Whereas Russian pedologists were the first to develop a universal classification system of soils over a century ago, other schools of pedology have since offered alternative taxonomies, claimed to be more detailed and comprehensive. Notable among these is the systems offered by the U.N. Food and Agriculture Organization and the one developed by the U.S. Soil Survey. Each system recognizes hundreds of soil types and their variants.

By way of illustration, we present a hypothetical soil profile in Fig. 1.1. This is not a “typical” soil, for among the myriad of differing soil types recognized by pedologists no single type can be considered typical. Our figure is only meant to suggest the sort of contrasts in appearance and structure among different horizons that may be encountered in a soil profile. Pedologists classify soils by their mode of formation (genesis) and recognizable properties (see Fig. 1.2).



**Fig. 1.1.** Schematic representation of a hypothetical soil profile. The A horizon is shown with an aggregated crumblike structure, the B horizon with columnar structure, and the C horizon with incompletely weathered rock fragments.

<div><div>↑</div><div>0 horizon (plant residues)</div><div>↑</div><div>A horizon (zone of eluviation)</div><div>↓</div><div>Solum (true soil)</div><div>↑</div><div>B horizon (zone of illuviation)</div><div>↓</div><div>C horizon (parent material)</div><div>↑</div><div>R layer (bedrock)</div><div>↓</div><div>Regolith (weathered material)</div></div>	01	Undecomposed litter
	02	Partly decomposed debris
	A1	Zone of humus accumulation
	A2	Zone of strongest leaching
	A3	Transitional to B horizon
	B1	Transitional to A horizon
	B2	Zone of maximum illuviation
	B3	Transitional to C horizon
	C	Unconsolidated rock
	R	Consolidated rock

**Fig. 1.2.** Descriptive terminology for soil profile horizons.