CHAPTER

1

Introduction to Soil: Historical Overview, Soil Science Basics, and the Fitness of the Soil Environment

1.1 WHY SOIL ECOLOGY?

A new student of soil ecology might reasonably ask the question that leads this chapter! We felt that for the third edition of Fundamentals of Soil Ecology, we should present our argument for a continued global effort toward the careful study of soil and its ecological properties. We suggest that there are at least four compelling, and somewhat interconnected, reasons for the study of soil ecology, but there are likely many more.

1. Perhaps the most compelling reason to study soil ecology in the 21st century is humanity's dependence upon the products of soil. Current projections of human population on Earth suggest that there will be between 9.6 and 12.3 billion people on earth by the year 2100, and that this growth will continue well into the 22nd century (Gerland et al., 2014). Clearly, all of these billions will rely on food produced on agricultural soils, but the ability of the finite resource of Earth's soils to sustainably provide the service of food production is not completely clear. Understanding the consequences of agricultural expansion or intensification will require a deep understanding of soil and its inhabitants.
2. Soil has been, and remains one of the final frontiers in biodiversity research. As a reservoir of biodiversity, soil offers an amazing opportunity to study the phenomenon of biological diversity. Because soil is by its nature immobile, it must evolve, in place, a biological community that is theoretically capable of dealing with the full set of past climatic/disturbance conditions that may have ever been experienced in a particular location. From cold and dry Antarctic soils to warm and wet tropical soils, soil everywhere harbors bacteria, fungi, and animals, which act and interact in ways that allow ecosystems to function. However, given the dramatic rate of change in climatic conditions currently underway on earth, it is unknown whether the soil biotic communities of the world's ecosystems will have the capacity to adapt and/or evolve to novel combinations of climate, vegetation, and soil. How will soil communities

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respond to changes associated with human forcing of atmospheric processes? The answer will stand as a test of the importance of biodiversity to ecosystem function and the capacity of such diversity to buffer ecosystems against global change, and will be critical with regard to a continuous, sustainable supply of food and fiber for human consumption.

3. Soil is an excellent place to study ecology. In spite of the inconvenient fact that soil is a stubbornly opaque medium, it still provides opportunities to pursue nearly all the subdisciplines of terrestrial ecology: Population, Community, Ecosystem, Stoichiometry, Trophic, Agro-, Disease, Microbial, Restoration, etc. All these avenues of ecological inquiry find a home in soils, and each will be discussed throughout the text. We hope the reader will see that soil—plant—animal ecosystems provide fertile intellectual ground to plow for ecologists of all stripes (Fig. 1.1).
4. Soil ecology is fun! Even at very early ages, children become fascinated with playing in the dirt. Watch any group of children in the outdoors for long enough, and the play will take a turn toward the soil. A hole will be dug, a root excavated, a worm or beetle-grub discovered. Such discoveries elicit strong emotions whether wonder, excitement, or disgust. Children study soil in a semiscientific way, seeking for the perfect clay texture for mud-pies, or for aggregate structure that yields clods suitable for throwing at the neighbor or sibling. All this is correctly called "play," but if the adult scientist can maintain a modicum of childlike inquisitiveness about soil and its many inhabitants, the work of soil ecology can sometimes feel like play, and is undeniably fun!

1.2 THE HISTORICAL BACKGROUND OF SOIL ECOLOGY

The "roots" of human understanding of soil biology and ecology can be traced into antiquity and probably even beyond the written word. We can only imagine hunter—gatherer societies attuned to life cycles of plant roots, fungi, and soil animals important to their diets, their welfare or their cultures, and particularly to environmental conditions favorable to such organisms. Indeed, early agriculture must certainly have

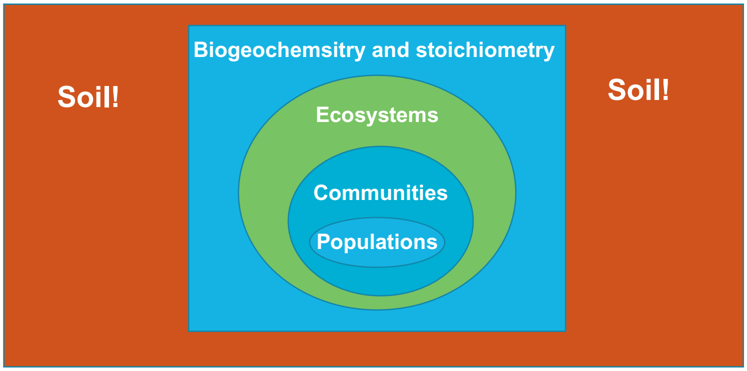

FIGURE 1.1 The full range of opportunities for ecological study within soil.

developed, at least in part, from a practical knowledge of soils and their physical and biological characteristics.

Soil is so fundamental to human life that it has been reflected for millennia in our languages. The Hebrew word for soil is *adama*, from which comes the name Adam—the first man of the Semitic religions who, in these traditions, was formed from clay (Hillel, 1991). Early civilizations had obvious relationships with soils. The Mesopotamian region encompasses present-day Iraq and Kuwait, occupying the valley of the Euphrates and Tigris rivers from their origin as they come out from the high tablelands and mountains of present-day Armenia to their mouth at the Persian Gulf. It had one of the earliest recorded civilizations, the Sumerian, dating from about 3300 years BCE (Hillel, 1991). An inventory taken in the time of the early Caliphates showed 12,500,000 acres (nearly 5,100,000 hectares) under cultivation in the southern half of Mesopotamia (Whitney, 1925). With many centuries of irrigation, this so-called hydraulic civilization was plagued with problems of siltation and salinization, which was written about at the time of King Hammurabi (1760 BCE) (Hillel, 1991). An impressive sequence of civilizations waxed and waned over the millennia: Sumerian, Akkadian, Babylonian, and Assyrian, as cultivation shifted from the lower to central and upper regions of Mesopotamia. Siltation and salinization continue to beset present-day civilizations that practice extensive irrigation-based agriculture with examples worldwide (Rengasamy, 2006).

To the east of Mesopotamia, past the deserts of southern Iran and of Baluchistan, lies the Indus River Valley. Another irrigation-based civilization developed here, probably under the influence of the Mesopotamian civilization. The Indus River civilization probably encompassed a total land area far exceeding that of either Sumeria or Egypt; little is known about it. No written records have been discovered, but its fate, like that of the Sumerian, succumbed to environmental degradation, exacerbated by the extensive deforestation which occurred to provide fuel to bake the bricks used in construction (Hillel, 1991). The bricks in Mesopotamian cities were sun-baked, similar to the adobe style of construction used in the deserts of the southwestern United States.

In contrast, the Egyptian civilization persisted more or less in place, as a result of the annual floods of the Nile River, which renewed soil fertility in vast areas along the river's length as it flowed northward. Over the millennia, from 1 to 3 million people lived along the Nile, and produced enough grain to export wheat and barley to many countries around the Mediterranean rim. Now that the population is some 30 times greater, it must import some foodstuffs and is economically in questionable condition, in spite of the vast areas being irrigated with water from the Aswan high dam.

The ancient Chinese concept of fundamental elements included earth, air, fire, water, and moon. In the Yao dynasty from 2357 to 2261 BCE, the first attempt was made at soil classification surveying. The Emperor established nine classes of soils in as many provinces of China, with a taxation system based upon this system. These classes included the yellow and mellow soils of Young Chow (Shensi and Kansu); the red, clayey, and rich soils of Su Chow (Shantung, Kiangsu, and Anhwei); the whitish, rich salty soils of Tsing Chow (Shantung); the mellow, rich, dark, and thin soils of Yu Chow (Honan); the whitish and mellow soils of Ki Chow (Chili and Shansi); the black and rich soils of Yen Chow (Chili and Shantung); the greenish and light soils of Liang Chow (Szechuan and Shensi); and the miry soils of King Chow (Hunan and Hupeh) and Yang Chow (Kiangsu)

(Whitney, 1925). This system reflects a sophisticated knowledge within early Chinese civilization of soils and their relationship with plant growth. Interestingly, in recognition of the importance of biological activity in soils, the ancient Chinese termed earthworms as "angels of the soil" (Blakemore, 2002).

The Greeks believed there were four basic elements: earth, air, fire, and water; and Aristotle, understanding the role of earthworms in organic matter decomposition, considered earthworms to be the "intestines of the earth" (Edwards and Lofty, 1977). In Greek mythology, the champion of mortal men, Heracles, defeated Antaeus, perhaps symbolically ushering in the age of man's dominion over the soil. A wild and dangerous giant, Antaeus, who was the son of Gaia (goddess of the earth), was invincible so long as he maintained physical contact with the soil, but Heracles recognized this and lifted the giant into the air and squeezed him to death in a bear hug. The Greeks and Romans also had a clear differentiation of the productive capacities of different types of soils. They referred to good soils as "fat," and soils of lower quality as "lean" (Whitney, 1925). For the Roman writers, "humus" referred to soil or earth. Virgil (79−19 BC), in his *Georgics*, named the loamy soil *pinguis humus* and used the words *humus*, *solum*, or *terra* more or less interchangeably for the notions of soil and earth. Columella in the 1st century AD noted, "wheat needs two feet of good *humus*" (Feller, 1997; italics added).

The word *humus* seems to have entered the European scientific vocabulary in the 18th century. Thus in Diderot and d'Alembert's Encyclopaedia (vol. 8) in 1765: "Humus, natural history, this Latin word is often borrowed by naturalists (even into French) and denotes the mold, the earth of the garden, the earth formed by plant decomposition. It refers to the brown or darkish earth on the surface of the ground. Refer to the mold or vegetable mold" (translation in Feller, 1997).

By the beginning of the 19th century, the leading authorities with a biological view of soils were Leeuwenhoek, Linnaeus, and other pre-Darwinians, and then Darwin himself (1837, 1881), who "fathered" the modern era. Müller (1879, 1887), cited in Feller (1997), laid the groundwork for the present-day scientific bases of the different forms of humus, and even included a general survey of soil genetic processes in cold and temperate climates. Müller developed terms for the three humus types—Mull, Mor, and MullartigerTorf—the latter equivalent to Moder. *Mull* is mold and *Torf* is peat in Danish. Thus MullartigerTorf is *mold peat* in Danish, and it is viewed as an intermediate form between the two extremes (see Feller, 1997 for more details on the history of these fascinating substances).

The first scientific view of soils as natural bodies that develop under the influence of climate and biological activity acting on geological substrates arose in Russia with the work of Dokuchaev and his followers (Feller, 1997; Zonn and Eroshkina, 1996), in Europe with Müller's (1887) descriptions of soil horizon development (Tandarich et al., 2002), and in England with Darwin's observations on textural sorting through animal activities that resulted in soil horizonation (Johnson and Schaetzl, 2015). In any case, the ecological basis of the Russian tradition is clear in the words of Glinka (1927; cited in Jenny, 1941), a disciple of Dokuchaev, whose view of soil included "... not only a natural body with definite properties, but also its geographical position and surroundings, i.e., climate, vegetation, and animal life." This Russian perspective predates the formal statement of the ecosystem concept by several decades (Tansley, 1935).

During this early period of theoretical development across the Atlantic, soil science in the United States was more concerned with practical matters of agriculture, such as soil productivity and crop growth (Tandarich et al., 2002) and, later, on restoration of soils badly degraded from poor management (e.g., the "dust bowl" in the Great Plains and the severely eroded croplands of the southeastern United States) (Sutter, 2015). It was not until the 1920s that ideas of pedogenesis gained wide recognition in the United States. Within the next decade, Jenny (1941) published his classic work on soil formation, drawing heavily from Dokuchaev's ideas to synthesize pedological and ecological perspectives into the concept of a "... soil system [that] is only a part of a much larger system ... composed of the upper part of the lithosphere, the lower part of the atmosphere, and a considerable part of the biosphere." He formulated this concept into the now famous "fundamental equation of soil-forming factors":

$$s = f(cl,\ o,\ r,\ p,\ t,\ \ldots)$$

where s refers to the state of a body of soil at a point in time; f refers to function; cl to climate; o to organisms; r to relief or topography; p to parent material; and t to time. Jenny, probably more than any North American soil scientist of his era, emphasized the importance of the biota in and upon soils. His last major work, *The Soil Resource* (1980), is now a classic in the literature on ecosystem ecology.

Since Jenny's work, research in soil ecology has experienced a "renaissance" as the significance of biological activity in soil formation, organic matter dynamics, and nutrient cycling have become widely recognized. The post-World War II scientific boom was an important impetus for science generally, including soil science. In the United States, the Atomic Energy Commission (later the Department of Energy), through the national laboratories, funded soil biology in relation to nutrient and radioisotope recycling in soil systems (Auerbach, 1958); more recently, the National Science Foundation's Division of Environmental Biology and the United States Department of Agriculture (USDA) National Research Initiative in Soils and Soil Biology have supported a wide array of research in soil ecology. The International Biological Program (IBP) on the international scene greatly expanded methodologies in soil ecology and increased our knowledge of ecological energetics and soil biological processes (Coleman, 2010; Golley, 1993).

In a concise review of almost a century's work by pedologists and soil scientists, Johnson and Johnson (2010) offered the following passage with regard to a simple, overarching definition of soil in the broadest possible sense, which we endorse here as being perhaps the most succinct expression of these ideas to date:

> So, how should we define soil insofar as it technically is the 'skin' of landforms, an integument of planets, and in the case of Earth primarily biophysically-biochemically produced with an epidermal biomantle? The best scientific definition is one that is most useful and comprehensible to a spectrum of scientists and the lay public. It should be simply expressed, scientifically sound, easily explainable, and cover all cases (Johnson et al. 1997), and ideally have universality. Being applicable to soil on Earth and on all other generally lithic-composed planets and planetoids, a definition that fits these criteria is: ***Soil is substrate at or near the surface of Earth and similar bodies altered by biological, chemical, and/or physical agents and processes*** (emphasis added).

In summary, all of these developments and advances in knowledge, from the ancient to the modern, have led to a vast literature upon which is based our current understanding of the soil beneath our feet and the vital role that this living milieu plays in sustaining life on a thin, dynamic, fragile planetary crust.

1.3 WATER AS A CONSTITUENT OF SOIL

> The occurrence of water is, moreover, not less important and hardly less general upon the land. In addition to lakes and streams, water is almost everywhere present in large quantities in the soil, retained there mainly by capillary action, and often at greater depths. ***(Henderson, 1913).***

Lawrence J. Henderson, a noted physical chemist and physiologist, published a book (*The Fitness of the Environment*, 1913), which was a landmark among books on biological topics. Henderson's thesis is that one substance, water, is responsible for the characteristics of life, and the biosphere as we know it. The highly bipolar nature of water, with its twin hydrogen bonds, leads to a number of intriguing characteristics (e.g., high specific heat), which have enabled life in the thin diaphanous veil of the biosphere (Lovelock, 1979, 1988) to extend and proliferate almost endlessly through the air, water, soil, and several kilometers into the earth's mantle (Whitman et al., 1998).

A central fact of soil science is that certain physicochemical relationships of matter in all areas of the biosphere are mediated by water. Thus soil, which we normally think of as opaque and solid, from the wettest organic muck soil to the parched environs of the Atacama, Kalahari, Gobi, or Mojave deserts, is dominated by the amount and availability of water.

Consider water in each of its phases—solid, liquid, and gaseous:

1. *Solid:* In aquatic ecosystems, water freezes from the top down, because it has its greatest density at 4°C. This allows for organismal activity to continue at lower depths and in sediments as well. In soil, the well-insulated nature of the soil materials and water with its high specific heat means that there is less likelihood of rapid freezing. Water expands when it freezes. In more polar climates (and in some temperate ones), soil can be subjected to "frost heaving," which can be quite disruptive, depending on the nature of the subsurface materials.
2. *Liquid:* Water's high specific heat of 1 calorie per gram per degree Celsius increase in temperature has a significant stabilizing influence in bodies of water and soil (Hadas, 1979). The effect of the high specific heat is to reduce fluctuations in temperature. The location of the liquid, in various films, or in empty spaces, has a marked influence on the soil biota.
3. *Vapor:* It is somewhat counterintuitive but true that the atmosphere within air-dry soil (gravimetric water content of 2% by weight) has a relative humidity of 98%. The consequences of this humidity for life in the soil are profound. Most soil organisms spend their lives in an atmosphere saturated with water. Many soil animals absorb and lose water through their integuments, and are entirely dependent upon saturated atmospheres for their existence.

From the pragmatic viewpoint of the soil physicist, we can consider aqueous and vapor phases of water conjointly. Following a moisture release curve, one can trace the pattern of water, in volume and location in the soil pore spaces, in the following manner (Vannier, 1987). Starting with freestanding, or gravitational, water at saturation, the system is essentially subaquatic (Fig. 1.2). With subsequent evaporation and plant transpirational water losses from the soil, the freestanding water disappears, leaving some capillary-bound water (Fig. 1.3), which has been termed the edaphic system. Further evaporation then occurs, resulting in the virtual absence of any capillary water, leaving only the adsorbed water at a very high negative water tension (Fig. 1.4).

The implications of this complex three-dimensional milieu are of fundamental importance for a very diverse biota. Vannier (1973) proposed the term "porosphere" for this intricate arrangement of sand, silt, clay, and organic matter. Primitive invertebrates first successfully undertook the exploitation of aerial conditions at the beginning of the Paleozoic era (Vannier, 1987). This transition probably took place via the soil medium, which provided the necessary gradient between the fully aquatic and aerial milieus. This water-saturated environment, so necessary for such primitive, wingless (Apterygote) forms as the Collembola, or springtails (Fig. 1.2), is equally important for the transient life-forms such as the larval forms of many flying insects, including Diptera and Coleoptera. In addition, many of the micro- and mesofauna (described in Chapter 4, Secondary Production: Activities and Functions of Heterotrophic Organisms—The Soil Fauna) could be considered part of the "terrestrial nannoplankton" (Stout, 1963). Stout included all of the water-film inhabitants, namely: bacteria and yeasts, protozoa, rotifers, nematodes,

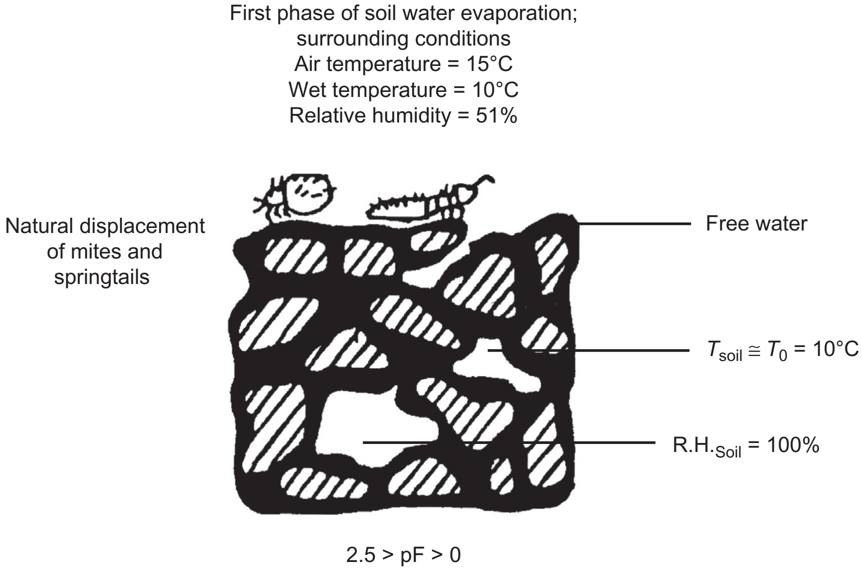

FIGURE 1.2 Gravitational moisture (the subaquatic system) in the soil framework. pF = −log cm H_2O suction; R.H. = relative humidity; 2.5pF = field capacity. *Source: From Vannier, G., 1987. The porosphere as an ecological medium emphasized in Professor Ghilarov's work on soil animal adaptations. Biol. Fert. Soil. 3, 39 − 44.*

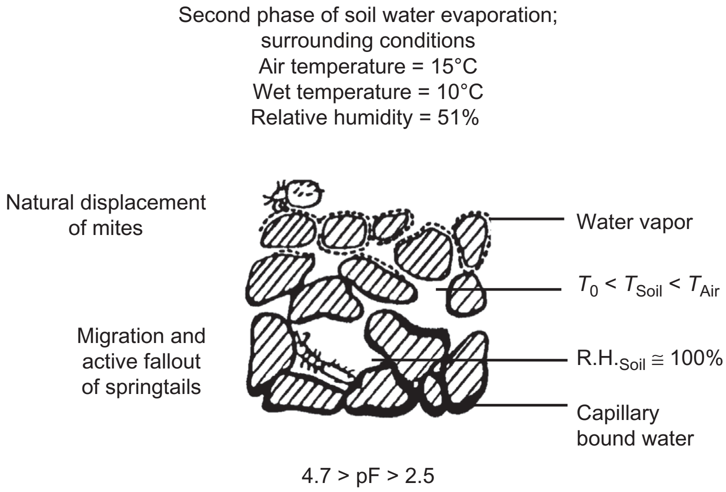

FIGURE 1.3 Capillary moisture (the edaphic system) in the soil framework. 4.7pF = −5 mPa; 2.5pF = −0.03 mPa = field capacity. *Source: From Vannier, G., 1987. The porosphere as an ecological medium emphasized in Professor Ghilarov's work on soil animal adaptations. Biol. Fert. Soil. 3, 39 − 44.*

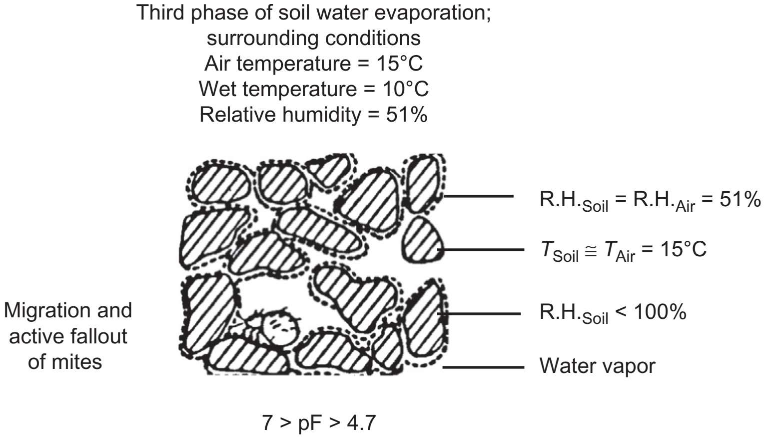

FIGURE 1.4 Adsorptional moisture (the aerial system) in the soil framework. 7pF = −1000 mPa; 4.7pF = −5 mPa; permanent wilting point = −1.5 mPa = 4.18pF. *Source: From Vannier, G., 1987. The porosphere as an ecological medium emphasized in Professor Ghilarov's work on soil animal adaptations. Biol. Fert. Soil. 3, 39 − 44.*

copepods, and enchytraeids (the small oligochaetes also called potworms). Raoul Francé, a German sociologist, made analogies between aquatic plankton and the small- and medium-sized organisms that inhabit the water films and water-filled pores in soils, terming them: "Das Edaphon" (Francé, 1921).

As noted in Figs. 1.2−1.4, there is a marked difference in moisture requirements of some of the soil microarthropods. Thus another major group, the Acari, or mites, are often able to tolerate considerably more desiccation than the more sensitive Collembola. In both cases, the microarthropods make a gradual exit from the soil matrix as the desiccation sequence described earlier continues.

Other organisms, more dependent on the existence of free water or water films, include the protozoa and nematoda, the life histories and feeding characteristics of which are covered in Chapter 4, Secondary Production: Activities and Functions of Heterotrophic Organisms—The Soil Fauna. In a sense, the very small fauna, and the bacteria they feed upon, exist in a qualitatively different world from the other fauna, or from fungi. Both larger fauna and fungi move in and out of various water films through various pores, which are less than 100% saturated with water vapor, with comparative ease (Hattori, 1994).

In conclusion, this overview of soil physical characteristics and their biological consequences notes the following: "For a physicist, porous bodies are solids with an internal surface that endows them with a remarkable set of hygroscopic properties. For example, a clay such as bentonite has an internal surface in excess of 800 $m^2\ g^{-1}$, and a clay soil containing 72 percent montmorillonite possesses an internal surface equal to 579 $m^2\ g^{-1}$. The capacity to condense gases on free walls of capillary spaces (the phenomenon of adsorption) permits porous bodies to reconstitute water reserves from atmospheric water vapor" (Vannier, 1987). Later, we will address the phenomenon of adsorption in other contexts, ones that are equally important for soil function as we know it.

1.4 ELEMENTAL CONSTITUTION OF SOIL

Many elements are found within the earth's crust, and most of them are in soil as well. However, a few elements predominate. These are hydrogen, carbon, oxygen, nitrogen, phosphorus, sulfur, aluminum, silicon, and alkali and alkaline earth metals. Various trace elements or micronutrients are also biologically important as enzyme cofactors, and include iron, cobalt, nickel, copper, magnesium, manganese, molybdenum, and zinc.

A more functional and esthetically pleasing approach is to define soil as predominantly a sand–silt–clay matrix, containing living (biomass) and dead (necromass) organic matter, with varying amounts of gases and liquids within the matrix. In fact, the interactions of geological, hydrological, and atmospheric (Fig. 1.5) facets overlap with those of the biosphere, leading to the union of all, overlapping in part in the pedosphere. Soils, in addition to the three geometric dimensions, are also greatly influenced by the fourth dimension of time, over which the physicochemical and biological processes occur.

1.5 HOW SOILS ARE FORMED

Soils are the resultant of the interactions of several factors—climate, organisms, parent material, and topography (relief)—all acting through time (Jenny, 1941, 1980) (Fig. 1.6). These factors affect major ecosystem processes (e.g., primary production, decomposition, and nutrient cycling), which lead to the development of ecosystem properties unique to that soil type, given its previous history. Thus characteristics such as cation-exchange capacity, texture, structure, and organic matter status are the outcomes of the aforementioned processes operating as constrained by the controlling factors. Different arrays of processes may predominate in various ecosystems (see Fig. 1.6).

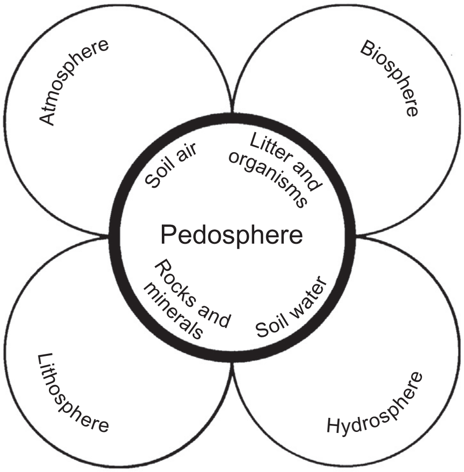

FIGURE 1.5 The pedosphere, showing interactions of abiotic and biotic entities in the soil matrix. *Source: From FitzPatrick, E.A., 1984. Micromorphology of Soils. Chapman and Hall, London (FitzPatrick, 1984).*

1.6 PROFILE DEVELOPMENT

The abiotic and biotic factors noted earlier lead to certain chemical changes down through the top few decimeters of soil (Fig. 1.7A, B). In many soils, particularly in more mesic or moist regions of the world, there is leaching and redeposition of minerals and nutrients, often accompanied by a distinct color change (profile development). Thus as one descends through the profile from the air-litter surface, one passes through the litter (L), fermentation (F), and humification (H) zones (O_i, O_e, and O_a, respectively), then reaching the mineral soil surface, which contains the preponderant amount of organic matter (A horizon). The upper portion of the A horizon is termed the topsoil, and under conditions of cultivation, the upper 12–25 cm is called the plow layer or furrow slice. This is followed by the horizon of maximum leaching, or eluviation, of silicate clays, Fe, and Al oxides, known as the E horizon. The B horizon is next, with deeper dwelling organisms and somewhat weathered material. This is followed by the C horizon, the unconsolidated mineral material above bedrock. The solum includes the A, E, and B horizons plus some of the cemented layers of the C horizon. All these horizons are part of the regolith, the material that overlies bedrock. More details on soil classification and profile formation are given in soil textbooks, such as Russell (1973) and Brady and Weil (2000).

The work of the soil ecologist is made somewhat easier by the fact that the top 10–15 cm of the A horizon, and the L, F, and H horizons (O_i, O_e, and O_a) of forested soils contain the majority of plant roots, microbes, and fauna (Coleman et al., 1983; Paul and Clark, 1996). Hence a majority of the biological and chemical activities occur in this layer. Indeed, a majority of microbial and algal-feeding fauna, such as protozoa (Elliott and Coleman, 1977; Kuikman et al., 1990) and rotifers and tardigrades (Leetham et al., 1982), are within 1 or 2 cm of the surface. Microarthropods are most abundant usually in the top 5 cm of forest soils (Schenker, 1984) or grassland soils (Seastedt, 1984a), but are occasionally more abundant at 20–25 cm and even 40–45 cm at certain times of the year in

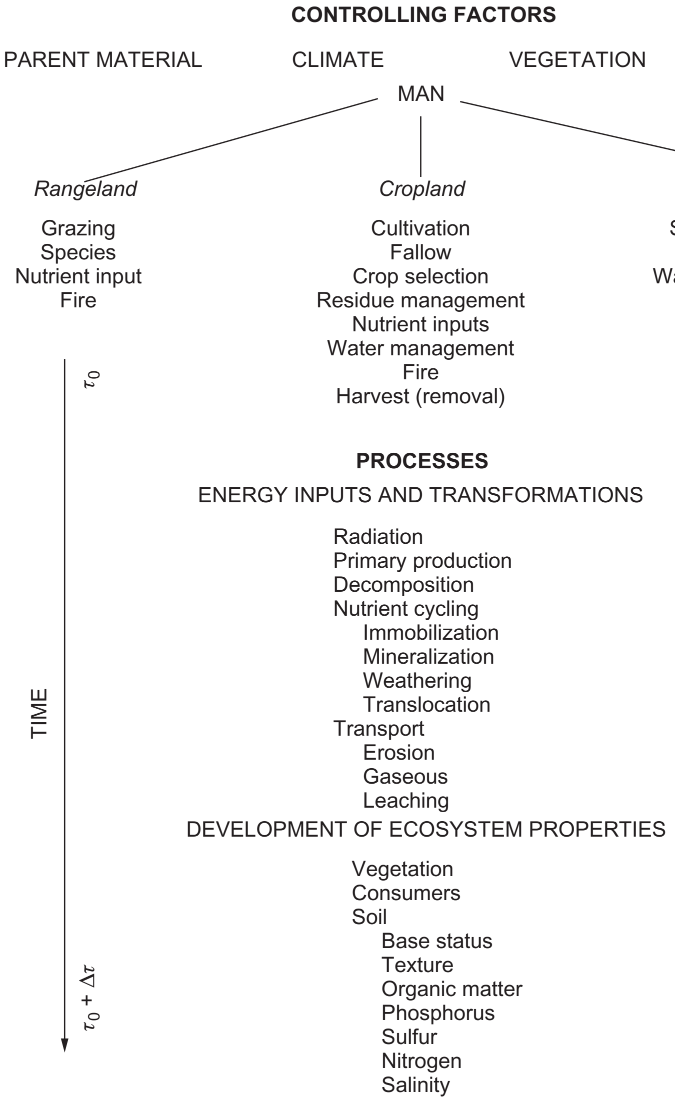

FIGURE 1.6 Soil-forming factors and processes, interaction over time. *Source: From Coleman, D.C., Reid, C.P.P., Cole, C.V., 1983. Biological strategies of nutrient cycling in soil systems. Adv. Ecol. Res. 13, 1 − 55, modified from Jenny, H., 1980. The Soil Resource: Origin and Behavior. Ecological Studies 37, Springer-Verlag, New York.*

tallgrass prairie (O'Lear and Blair, 1999). This region may be "primed," in a sense, by the continual input of leaf, twig, and root materials, as well as algal and cyanobacterial production and turnover in some ecosystems, while soil mesofauna such as nematodes and microarthropods may be concentrated in the top 5 cm. Significant numbers of nematodes may be found at several meters' depth in xeric sites such as deserts in the American Southwest (Freckman and Virginia, 1989).

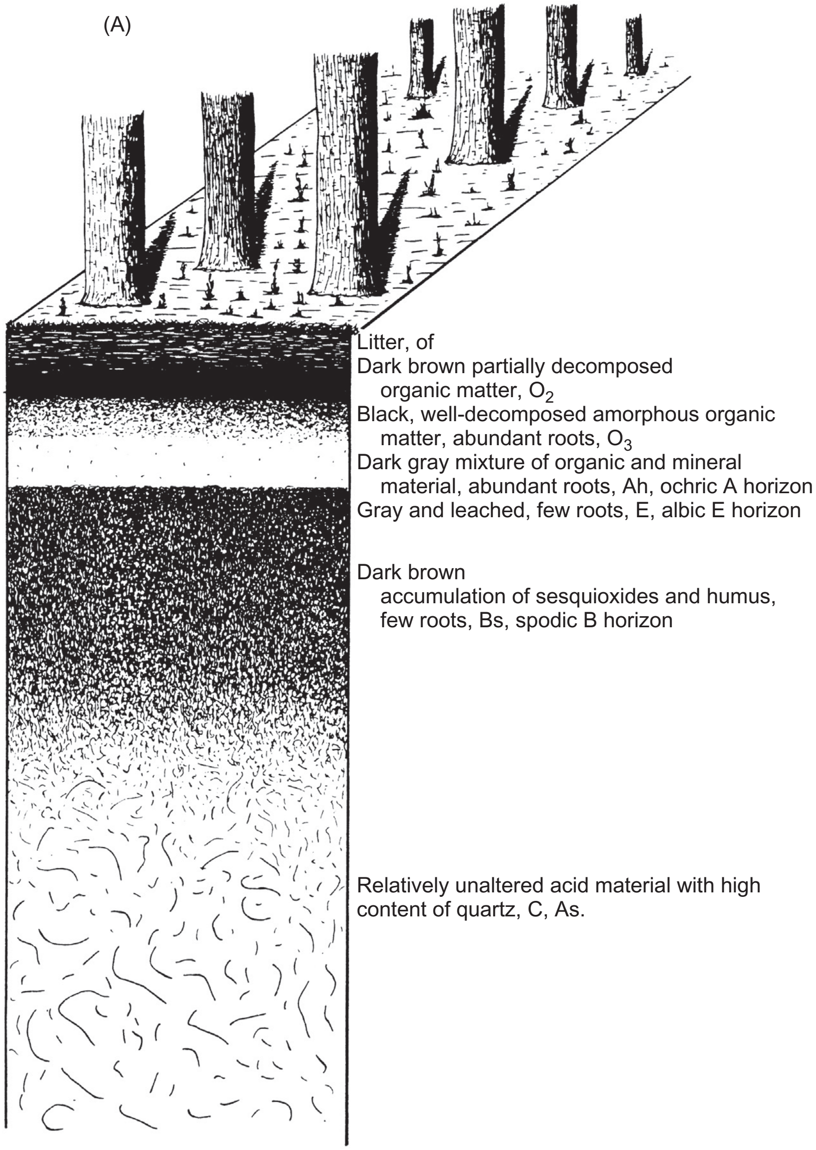

FIGURE 1.7 (A) Diagram of a Podzol (spodosol in North American soil taxonomy) profile with minerals accumulating in subsurface horizons. This is the characteristic soil of coniferous forests. (B) Diagram of a Cambisol profile, with the organic matter well mixed in the A horizon; due to faunal mixing there is no mineral accumulation in subsurface horizons. This is the characteristic soil of the temperate deciduous forests. *Source: From FitzPatrick, E.A., 1984. Micromorphology of Soils. Chapman and Hall, London.*

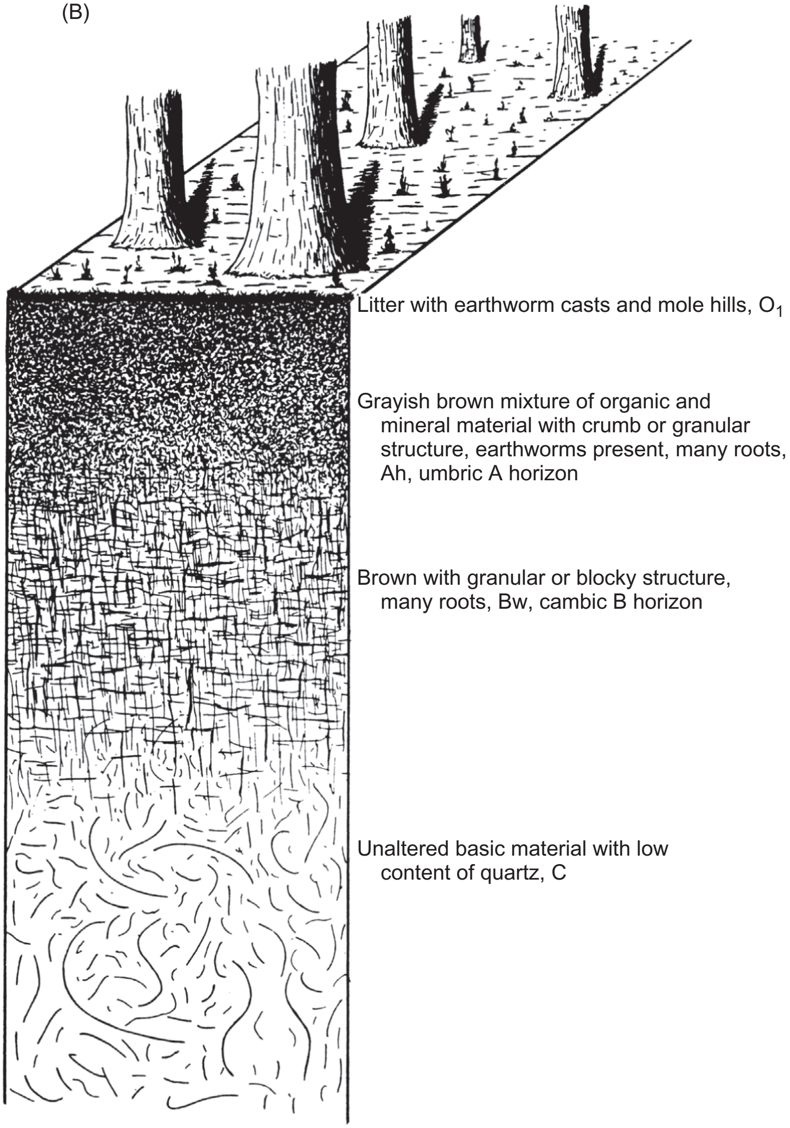

FIGURE 1.7 (Continued).

1.7 SOIL TEXTURE

Historically, texture was a term used to describe the workability of an agricultural soil. A heavy, clay soil required more effort (horsepower) to till than a lighter, sandy loam (Russell, 1973). A more quantifiable approach is to characterize soils in terms of the sand, silt, and clay present, which are ranged on a spectrum of light–intermediate–heavy or sandy–silt–clay. The array of textural classes (Fig. 1.8) shows percentages of sand, silt, and clay, and the resulting soil types such as sandy, loamy, or clayey soils.

The origin and mineralogical composition of mineral particles in soil is a most interesting and complex one. The particles are in two major categories: (1) crystalline minerals derived from primary rock, and (2) those derived from weathering animal and plant residues. The microcrystalline forms comprised calcium carbonate, iron, or aluminum oxides, or silica.

The clay fraction, so important in imparting specific physical properties to soils, to microbial life, and to plant activity via nutrient availability, comprised particles less than 2 μm in diameter. Unlike the sand–silt minerals, clays are weathered forms of primary minerals, and hence they are referred to as secondary minerals. Coarse clay particles (0.5 μm) often are derived from quartz and mica; finer clays (0.1 μm) are clay minerals or weathered products of these (such as hydrated ferric, aluminum, titanium, and manganese oxides).

No matter what size the particle is, microorganisms in unsaturated soil exist in a world dominated by the presence of extensive surfaces. There seems to be a general advantage to microbes living at these interfaces in terms of enhanced nutrient concentrations and the potential to use many of the physical substrates themselves as energy or nutrient sources. The thickness of water films in unsaturated conditions allows the microbes little option except to adhere to the surfaces (Mills, 2003). We discuss some of the microbial dynamics and interactions with soil organic matter in Chapter 3, Secondary Production: Activities and Functions of Heterotrophic Organisms—Microbes.

The roles of coarse and fine clays in organic matter dynamics are under intensive scrutiny in several laboratories around the world (Oades and Waters, 1991; Six et al., 1999). It is possible that labile (i.e., easily metabolized) constituents of organic matter are preferentially adsorbed onto fine clay particles and may be a significant source of energy for the soil microbes (Anderson and Coleman, 1985). For more information on the environmental attributes of clays, see Hillel (1998).

1.8 CLAY MINERAL STRUCTURE

The clay minerals in soil are in the form of layer-lattice minerals, and are made up of sheets of hydroxyl ions or oxygen. The clay minerals fall into two groups: (1) those with three groups of ions lying in a plane (the 1:1 group of minerals), and (2) those with four groups of ions lying in a plane (the 2:1 group of minerals). The type mineral of the 1:1 group is kaolinite, which typically has a very low charge on it. In contrast, the 2:1 type mineral, for example illite, carries an appreciably higher negative charge per unit weight than the kaolin group. More detailed information on the clay particles, their composition, and charges upon them is given in Theng (1979) and Oades et al. (1989).

A key concern to the soil ecologist is the extremely high surface area found per gram of clay mineral. Surface areas can range from 50 to 100 $m^2\ g^{-1}$ for kaolinitic clays, from 300 to 500 $m^2\ g^{-1}$ for vermiculites, and from 700 to 800 $m^2\ g^{-1}$ for well-dispersed smectites (Russell, 1973). These impressively large surface areas can play a pivotal role in adsorbing

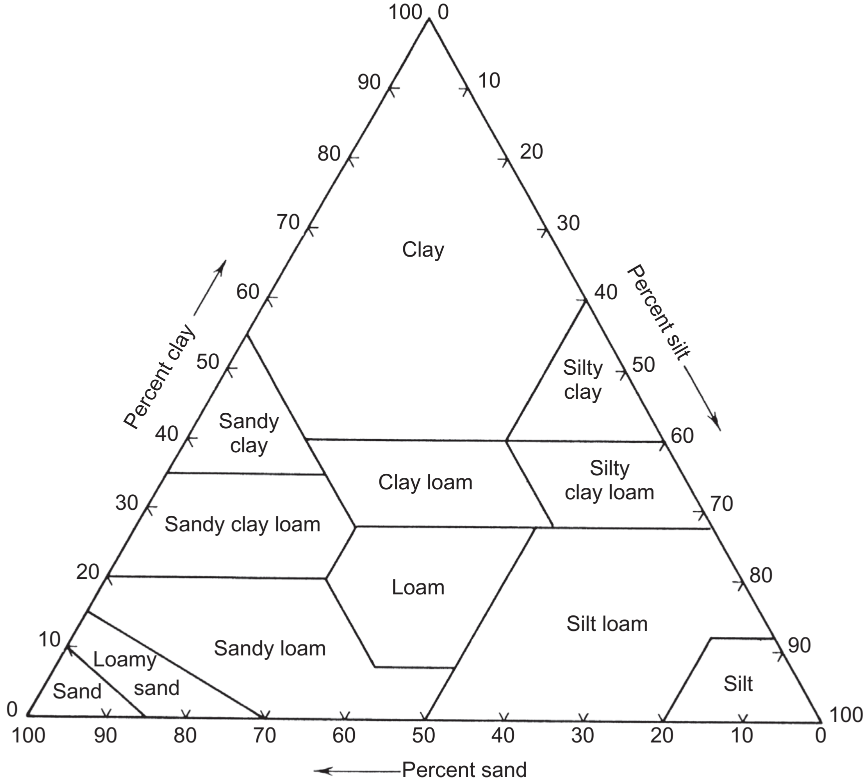

FIGURE 1.8 The soil texture triangle. Using this diagram, the textural name of a soil may be determined from a mechanical analysis. The points corresponding to the percentages of sand, silt, and/or clay present in a given soil sample are located on their respective axes. Lines are then projected inward, based on the relative abundance of these particles (only two of the three must be known). The name of the compartment in which the two lines intersect is the class name of the soil in question. *Source: Modified from Buckman and Brady (1970).*

and desorbing inorganic and organic constituents in soils, and have only recently been treated in an appropriately analytical fashion as an integral part of the soil nutrient system (Oades et al., 1989; Tisdall and Oades, 1982).

1.9 SOIL STRUCTURE

Structure refers to the ways in which soil particles are arranged or grouped spatially. The groupings may occur at any size level on a continuum from either extreme of what are nonstructural states: single grained (such as loose sand grains) or massive aggregates of aggregates (large, irregular solid).

An additional aspect of aggregates, their stabilization once they are formed, is significant for soil ecology. Stabilization is the result of various binding agents. Plant and microbial polysaccharides and gums serve as binding agents (Cheshire, 1979; Cheshire et al., 1984; Harris et al., 1964). A variety of other organic compounds act as binding agents (Cheshire, 1979), and some biological agents such as roots and fungal hyphae (Tisdall, 1991; Tisdall and Oades, 1979, 1982) play a similar role.

The implications of soil structure refer not only to the particles but also extend to the pore spaces within the structure, as noted earlier. Indeed, it is the nature of the porosity that exists in a well-structured soil that leads to the most viable communities within it. This in turn has strong implications for ecosystem management, particularly for agroecosystems (Elliott and Coleman, 1988). There is a very active area of research in soil ecology related to dynamics of micro- and macroaggregates, in relationship to drying−wetting cycles and tillage management. Denef et al. (2001) measured marked differences in aggregate formation and breakdown as a function of amount of bacterial and fungal activity in soils with ^{13}C-labeled crop residues. They traced differences in fine intraaggregate Particulate Organic Matter (POM) to variations in wetting and drying regimes versus those soils not experiencing such environmental fluctuations. We discuss the aggregate formation process further in Chapter 3, Secondary Production: Activities and Functions of Heterotrophic Organisms—Microbes on microbes and their effects on ecosystems.

Several types of structural forms are found in soils. The four major types are platelike, prismlike, blocklike, and spheroidal (Fig. 1.9). All of these are “variations on a theme,” as it were, of a fundamental unit of soil aggregation: the ped. A ped is a unit of soil structure, such as an aggregate, crumb, prism, block, or granule, formed by natural processes. This is distinguished from a clod, which is artificial or man-made (Brady and Weil, 2000). Soils may have peds of differing shapes, in surface and subsurface horizons. These are the result of differing temperature, moisture, and chemical and biological conditions at various levels in the soil profile.

Another concept is helpful in soil structure: the pedon. This is an area, from 1 to 10 m^2, under which a soil may be fully characterized. Later in the book, we will consider the arrangement of soil units in a landscape, and in an entire region. Next, we will examine some of the causes for the formation, or genesis, of soil structure.

Input of organic matter to soil is one of the major agents of soil structure. The organic matter comes from both living and dead sources (roots, leaves, microbes, and fauna). Various physical processes, such as deformation and compression by roots and soil fauna, and freezing−thawing or wetting−drying, also have significant influences on soil structure. It is generally recognized that plant roots and humus (resistant organic breakdown products) play a major role in the formation of aggregates (Elliott and Coleman, 1988; Paul, 2015). However, bacteria and fungi and their metabolic products play an equally prominent role in promoting granulation (Cheshire, 1979; Foster, 1985; Griffiths, 1965). We will explore organic matter dynamics in the sections on soil biology.

The interaction of organic matter and mineral components of soils has a profound influence on cation-adsorption capabilities. The interchange of cations in solution with cations on these surface-active materials is an important phenomenon for soil fertility. The capacity of soils to adsorb ions (the cation-exchange capacity) is due to the sum of exchange sites on both organic matter and minerals. However, in most soils, organic matter has the higher exchange capacity (number of exchange sites). For a more extensive account, see Paul (2015).

There is a hierarchical nature to the ways in which soil structure is achieved, and it reflects the biological interactions within the soil matrix (Elliott and Coleman, 1988; Six

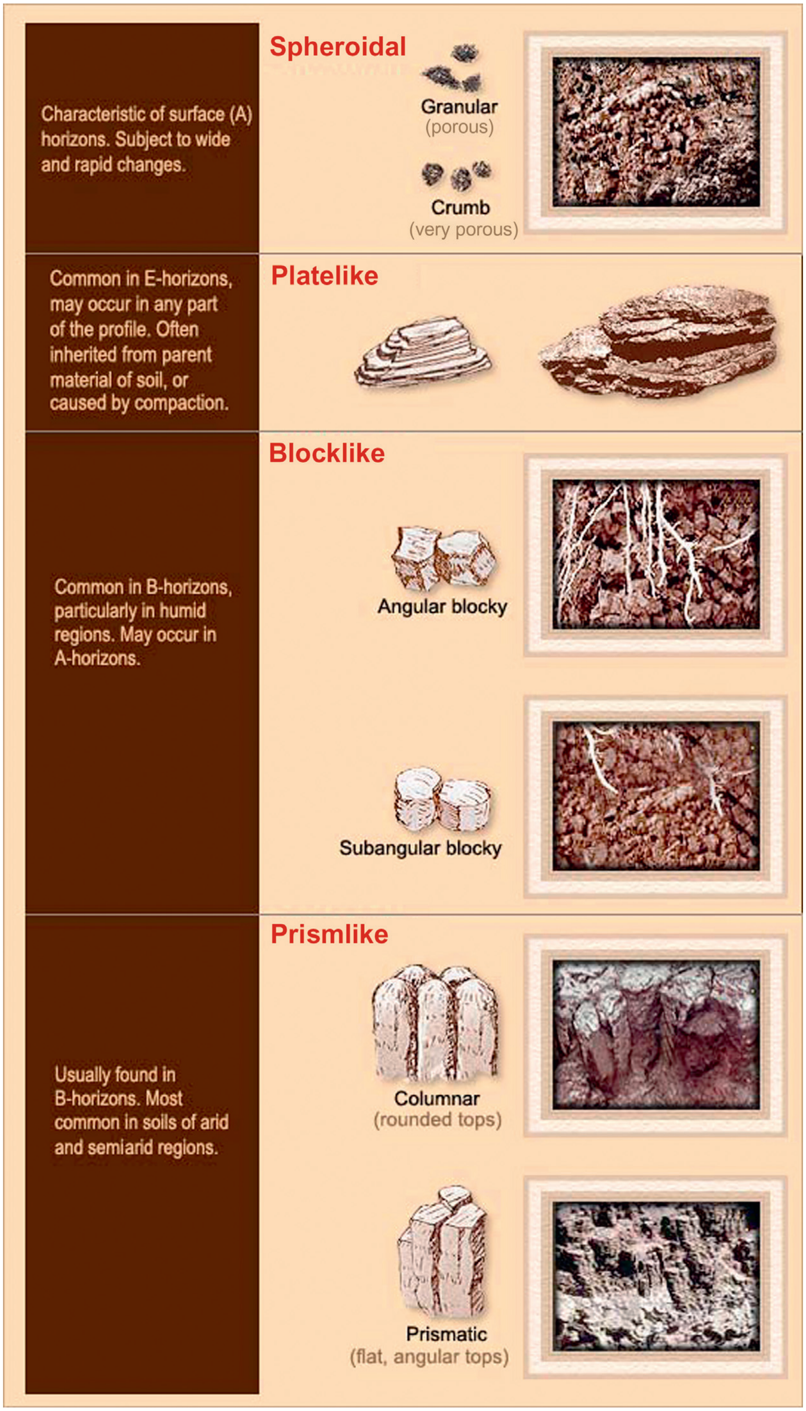

FIGURE 1.9 Various structural types found in mineral soils. Their location in the profile is sugested. In arable topsoils, a stable granular structure is prized. *Source: From Brady, N.C., 1974. The Nature and Properties of Soils, eighth ed. MacMillan, New York (Brady, 1974).*

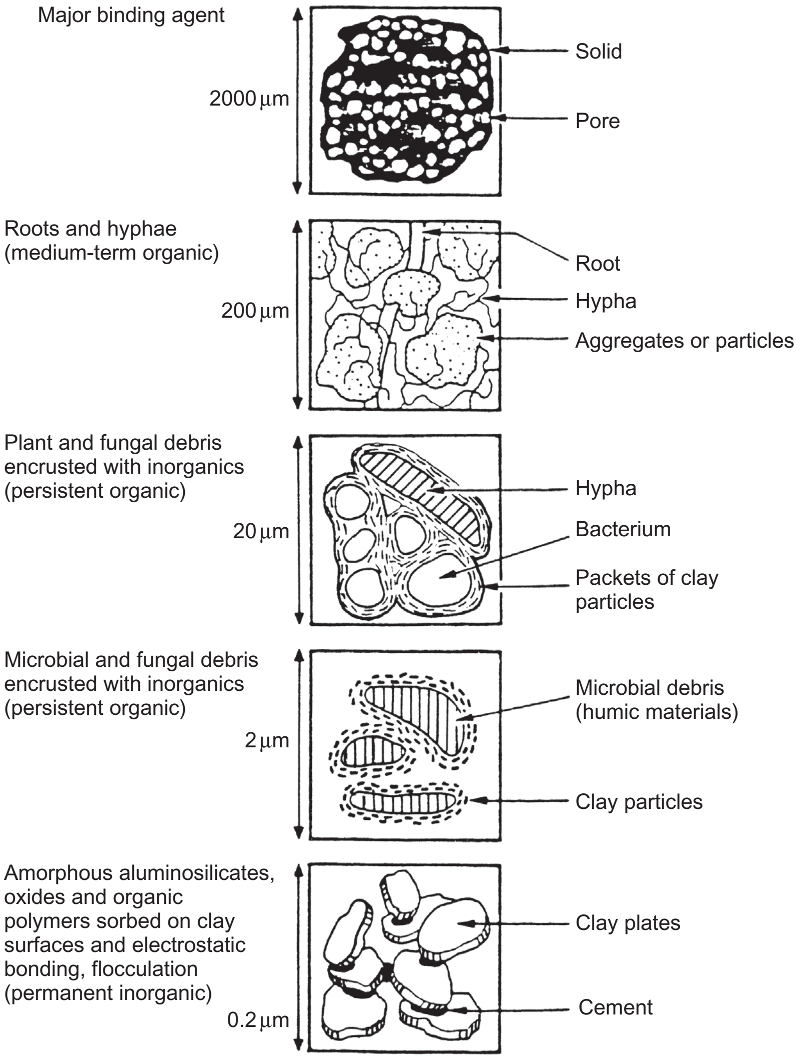

FIGURE 1.10 Soil microaggregates, across five orders of magnitude, beginning at the level of clay particles, through plant and fungal debris, up to a 2-mm diameter soil crumb. *Source: From Tisdall, J.M., Oades, J.M., 1982. Organic matter and waterstable aggregates in soils. Eur. J. Soil Sci. 33, 141 – 163.*

et al., 2002a). Several Australian researchers (Oades, 1984; Tisdall and Oades, 1982; Waters and Oades, 1991) have noted how the processes of structuring soils extend over many orders of magnitude, from the level of the individual clay platelet to the ped in a given soil. For most of the biologically significant interactions, one can consider changes across a range of at least six orders of magnitude from <0.01 µm to <1 cm (Tisdall and Oades, 1982) (Fig. 1.10). Not all soils are aggregated by biological agents; for heavily weathered

Oxisols with kaolinite-oxide clays, there seems to be no hierarchy of organization below 20 μm, because only physicochemical forces predominate there (Oades and Waters, 1991). Studies in our Horseshoe Bend agroecosystem project at the University of Georgia have uncovered significant differences between tillage regimes (conventional, moldboard plowing vs no-tillage, direct drilling of the seeds into the soil). The aggregates in the 53−106 and 106−250 μm categories are most affected by fungal growth and proliferation, reflecting physical binding and the increased amounts of acid-hydrolysable carbohydrates, which are more prevalent in the no-tillage treatments as compared with the bacteria-dominated conventional tillage systems (Beare et al., 1994a, 1994b, 1997).

It is the interactions between physical, chemical, and biological agents in soils that are so fascinating, complex, and important to consider as we increase the intensity of management of terrestrial ecosystems, or alter their usage in response to increased human concerns about their use, and also strive for effective sustainability of them worldwide (Coleman et al., 1992, 1998). Indeed, Lavelle (2000) observed that soil ecology can be considered to have arisen from the convergence of three major approaches: (1) the development of enormous databases on communities of microorganisms and invertebrates and their energy budgets via the International Biological Program (e.g., Petersen and Luxton, 1982); (2) the placement of decomposition processes on center stage, bridging soil chemistry with soil biology (Swift et al., 1979); and (3) an appreciation of the effects of soil organisms on soil structure, including the influence of macrofauna as ecosystem engineers (Bal, 1982, Jones et al., 1994). We would add a fourth dimension, that of soils and sediments as repositories or libraries of DNA. In Siberia, several permafrost cores dating from 10,000 to 400,000 years old have yielded at least 19 different plant taxa, as well as megafauna sequences of mammoth, bison, and horse (Willerslev et al., 2003). Temperate cave sediments from New Zealand yielded 29 taxa characteristic of the prehuman environment, including two species of ratite moas. These genetic records of paleoenvironments will add to our understanding of past ecosystem structure and, possibly, function.

1.10 SOILS AS SUPPLIERS OF ECOSYSTEM SERVICES

Soils are large repositories of mineral and organic wealth, available for both the use and misuse by civilizations on this planet (Hillel, 1991). Levels of soil carbon have dropped by as much as 50% after 50−100 years of intensive farming in the North American Great Plains (Haas et al., 1957). Similar concerns were expressed about loss of organic matter and erosion of soils in the Mediterranean region at the time of Plato in the third century BCE, as noted earlier (Whitney, 1925).

An example of the monetary value of what soils provide is given by the costs of raising crops in intense nonsoil conditions using hydroponic culture. Construction of a modern hydroponics system in the United States, including pumps and sophisticated computer control systems, costs upward of $850,000 per hectare (FAO 1990, cited by Daily et al., 1997). Soils also play significant roles in the regulation of global greenhouse gases such as carbon dioxide, methane, and nitrous oxides (Schimel and Gulledge, 1998). As we present in detail in later chapters, the cleansing and recycling role that soils play in processing organic wastes and recycling nutrients constitutes one of the major benefits provided "free" to humanity and all the biota (outside the market economy) but worth literally trillions of dollars per year as one of the major ecosystem services (Costanza et al., 1997) on Earth.

1.11 SUMMARY

The physical properties of the soil are the production of continued interactions between soil biota and their abiotic milieu. Water, the "universal solvent," exerts a strong influence on the biota because many of the biota are adapted to life in a saturated atmosphere. The interplay between liquid and gaseous phases of water, in turn, is largely determined by pore size. The arrangement of particles in soils (the porosphere) is an important determinant for the ecology of the soil microbes (Archaea, bacteria, fungi) and fauna.

Soil formation—the product of climate, organisms, parent material, and topography, over time—leads to various soil types. Profile development and soil texture are the product of interactions of these factors. The capabilities for nutrient retention, important for primary producers in all soils, are affected by both mineral content and soil organic matter, with organic matter usually having the higher number of exchange sites. The aggregate structure of soils is biologically mediated in many soil types. Soils play major roles in both recycling matter and nutrients, as well as being important sources and sinks of global greenhouse gases. It is apparent that soil ecology is being considered much more centrally in ecological studies and in ecosystem management as well.