Soils and Soil Fertility

FIFTH EDITION

Frederick R. Troeh
Louis M. Thompson

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SOILS AND SOIL FERTILITY

Preface

This new edition of *Soils and Soil Fertility* is intended as a textbook for the introductory course in soils for students in agriculture and related sciences. Updated and easily readable, it is based on several decades of teaching experience by the two authors. In addition, the text reflects Dr. Troeh's ten years of soil survey experience in Idaho, California, New York, and Iowa plus more than five years of international work in Uruguay, Argentina, and Morocco.

Widely understood terms are used wherever possible so that persons from any field of interest will be able to understand the contents of this book. Necessary technical terms are explained at the point where they are first used and are also included in the glossary, a new feature of this edition.

Special effort has been made to provide a broad viewpoint to match the varied backgrounds and interests of today's students. The book considers both urban and rural land use and includes discussions of lawns, artificial soils for greenhouse use, turfgrass for golf courses, and so forth. Weather, irrigation, and drainage are given a chapter of their own, "Water Management," and environmental concerns are treated in the chapter "Soil Pollution."

The organization both within and among the chapters has been designed to give continuity to the material. Each chapter builds on chapters that have gone before. Chapter 1, "Soil," and Chapter 2, "Soil Formation," provide background for understanding the various components of soils dealt with in the next four chapters. Chapter 6, "Soil Mineralogy," precedes and serves as a basis for "Soil Chemistry," Chapter 7, and "Amending the Soil," Chapter 8. Chapter 9, "Fertilizers," is followed by chapters dealing with the various nutrient elements; and Chapter 16, "Soil Classification and Survey," contains much background material for the succeeding chapters dealing with soil and water management and conservation.

Most students in agriculture take only one course in soils. This book therefore is comprehensive in its coverage of the subject. This broad coverage also makes the book well suited to serve as a background for advanced courses in soils. It can also serve as the basis for a refresher course in soil science.

Experience has shown that a course in college chemistry should be a prerequisite for the introductory soils course. An ideal preparation would include additional courses in organic chemistry, geology, and biology. However, because few students begin their study of soils with such a comprehensive background, this book includes essential information from these related sciences.

Earlier editions used both the metric and the foot-pound-second systems of measurement according to prevailing usage in the United States. In the fourth edition we used the metric system almost exclusively, but for this edition we have reverted to the earlier practice of using the most readily recognized and understood units. Often the smaller units, e.g., the size of soil particles, are expressed in millimeters or grams, but the larger units are expressed in feet or pounds. Material from published literature is usually presented in the units used in the original publication. Where needed, parallel columns are used in tables to provide both systems of units, or the second set is provided in parentheses in the text. Also, an appendix has been included to provide conversion factors between and within the two systems.

The literature on soils has proliferated greatly in recent years. References cited in the text and other selected sources are listed at the end of each chapter, but these items represent only a fraction of the literature that we consulted. The reference lists from the previous edition were culled to allow room for the many more recent references that have been added.

This edition was revised by Dr. Troeh with consultation from Dr. Thompson and others. However, many people, students and colleagues alike, have assisted in the development of this book. Special recognition goes to John Schafer for providing contributions to every chapter. Other colleagues who contributed significantly to the book include Minoru Amemiya, C.A. Black, L. R. Frederick, J.R. George, D.A. Gier, Don Kirkham, Willard Lindsay, T.E. Loynachan, Murray Milford, Larry Miller, W.C. Moldenhauer, Jeff Novak, John Pesek, Don Post, W.H. Scholtes, A. D. Scott, C.H. Sherwood, J.A. Stritzel, Steve Thien, Zahra Troeh, J.R. Webb, and L.V. Withee. Special acknowledgement is given to Miriam Troeh for typing the fourth edition on the computer in preparation for this revision.

Ames, Iowa F.R.T.
L.M.T.

Contents

1
Soil

A thin layer of soil covers most of the earth's land surface. This layer, at most a few feet thick and sometimes only a few inches, might appear insignificant relative to the bulk of the earth. Yet it is in this thin layer of soil that the plant and animal kingdoms meet the mineral world and establish a dynamic relationship. Plants obtain water and essential nutrients from the soil. Animals depend on plants for their lives. Plant and animal residues find their way back to the soil and are decomposed by the teeming microbial population living there. Life is vital to soil, and soil is vital to life.

Humanity's contact with soil is so universal that each person has his or her own concept of the nature of soil. To an engineer, it may be a construction material or the foundation material for a building. To the farmer, it is a medium for growing crops. A child may use it to make mud pies, but then it becomes dirt to be washed from hands and clothes. To all of us, soil is the source from which springs our food, clothing, and shelter. Our existence depends on soil.

Liebig and other early chemists considered soil as a storehouse for plant nutrients. Early geologists concluded that soil is weathered rock. These early concepts are not wrong, but neither are they complete. The origin of the word *soil* illustrates another facet of its character. It comes from the Latin word *solum,* which means *floor*. The French word *sol* and the Spanish word *suelo* are still used to mean either soil or floor.

Any definition assigned to a material as complex as soil depends on the viewpoint of the person formulating the definition. An edaphologist, considering soils in relation to their use as media for growing plants, may define soil as *a mixture of mineral and organic matter that is capable of supporting plant life*. A pedologist, studying soil as a distinct entity, can define it as *the natural product formed from weathered rock by the action of climate and living organisms*. The concept of life is vital in these definitions. In one, the soil supports life; in the other, life helps to form the soil. Both viewpoints are correct. Soil supports living organisms and its characteristics are partly determined by the action of the living organisms.

A mass of loose mineral matter lacking the influence of living things is frequently encountered beneath the soil and above bedrock. Such material is properly termed *weathered rock* and is sometimes called *soil parent material,* but it is not the same as soil. The word *regolith* is used as an inclusive term for all the loose material above bedrock.

The Soil Profile

Soils develop distinct layers at varying depths below the land surface. A vertical section of the soil to expose the layering is called a *profile*. The upper layer is usually higher in organic matter and darker in color than the layers below (Figure 1.1). This upper layer is called the *A horizon,* or topsoil.

The middle part of the profile usually contains more clay and has a brighter color than the topsoil. This layer is called the *B horizon,* or subsoil. The A and B horizons together are referred to as the *solum,* or true soil.

The *C horizon,* commonly referred to as the *soil parent material,* occurs beneath the solum and extends downward to bedrock. It may be thick, thin, or even absent. The soil profile includes the A and B horizons and at least the upper portion of the C horizon if a C is present (Figure 1.2).

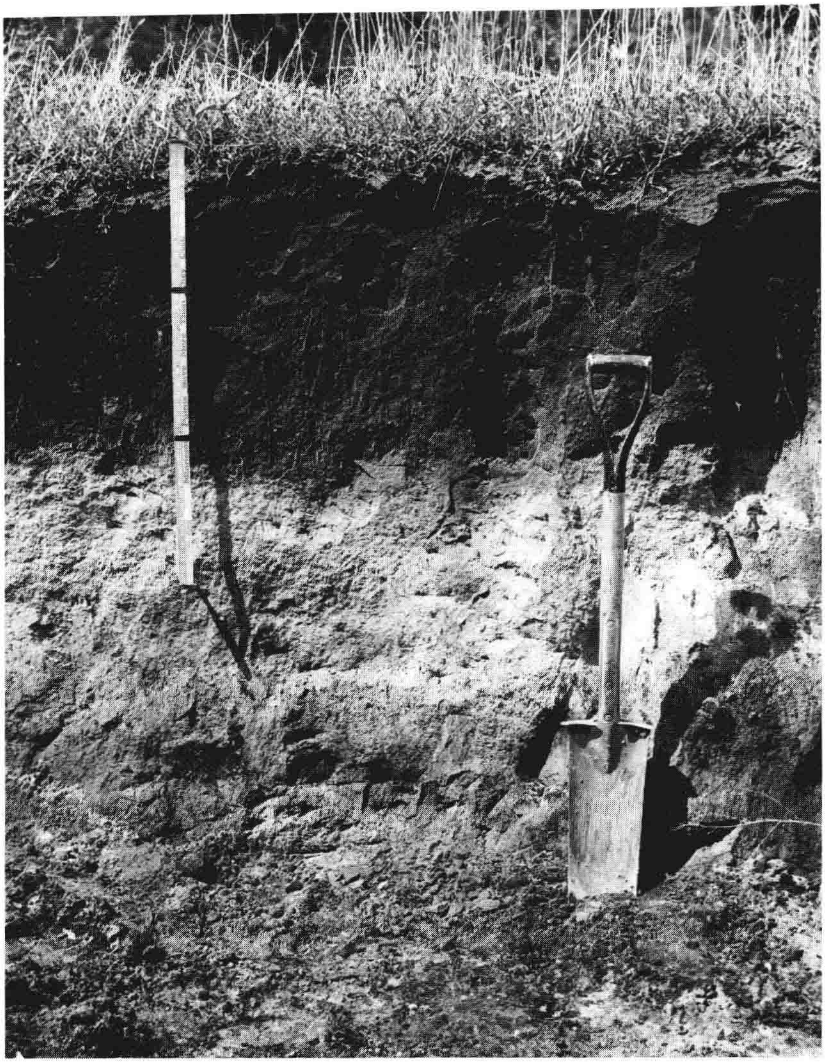

Figure 1.1. A characteristic common to nearly all soils is the darkening of the upper part of the soil by the accumulation of organic matter in and near the surface. (*Soil Conservation Service, USDA*)

How the Soil Profile Develops

The material in the A and B horizons was once part of the C horizon but has undergone many changes. The changes that produce A and B horizons are referred to as *soil development*.

The upper layer became an A horizon as it accumulated organic matter from roots and plant residues. Other changes resulted from forces that cause physical disintegration and chemical decomposition. The A horizon is the portion of the soil most exposed to the weathering action of the sun, rain, wind, and ice and to the action of living things. The more easily decomposed materials weather away first, thus leaving the more-resistant minerals concentrated in the topsoil. The more mature the

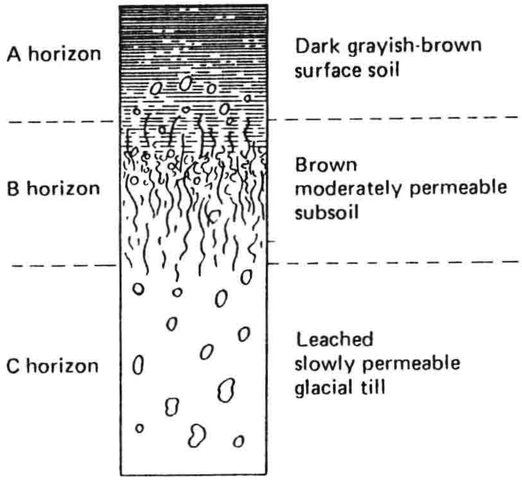

Figure 1.2. A sketch of a typical soil profile formed in glacial till with grass vegetation.

soil—that is, the more it has been influenced by weathering—the more concentrated resistant materials become in the topsoil. This fact is of great significance to plant growth. The more-resistant minerals remaining behind in strongly weathered soils may decompose too slowly to be a good source of plant nutrients. The more-fertile soils are less weathered and still contain minerals that decompose and release new plant nutrients each year.

Weathering processes break down some of the mineral particles in the soil to smaller sizes. Part of the sand is reduced to silt size, and part of the silt is reduced to clay. Some constituents become soluble and are removed from the soil by the leaching action of water. The A horizon is the most leached portion of the soil.

It would be reasonable to anticipate that the clay concentration of the A horizon would gradually increase as weathering action reduces the sizes of mineral particles. There are, however, opposing processes. Some of the clay may weather into soluble materials that are leached from the soil. Another process, generally more important, is the downward movement of solid clay particles in percolating water. The net result is that the percentage of clay in the A horizon is likely to remain about the same for thousands of years. However, clay movement continues even after clay formation slows down; many old soils have lost most of the clay from their A horizons.

The clay content of most B horizons increases with time. Part of the increase is caused by clay from the A horizon being deposited in the B horizon, and part of it comes from the weathering of silt and sand in the B horizon to form clay. Thus the B horizon may accumulate a much higher concentration of clay than either the A or the C horizon of the same soil. Soils with large differences in the clay contents of their A and B horizons are said to be *strongly differentiated*.

In summary, two of the most widespread soil characteristics the world over are the accumulation of organic matter in the A horizon and the accumulation of clay in the B horizon. These characteristics must be considered as norms that fail to occur only when there is some unusual overriding factor.

Composition of Soil

Soil inherits mineral matter from its parent rock and organic matter from its living organisms. These materials constitute the solid portion of the soil and form its skeleton. Voids known as *pore spaces* occur between the solid particles. The pore space usually constitutes about half of the volume of the A horizon and somewhat less than half the volume of the B and C horizons. Water and air share the pore space in variable proportions. The smaller pores are more likely to fill with water, and the larger pores are more likely to contain air. The shape and continuity of the larger pores determine to a large extent how well the soil is aerated.

It is desirable for the water that enters the soil to continue moving downward through the profile until the pore space contains about two-thirds water and one-third air. Soils with high clay contents, especially those low in organic matter, may hold so much water that they are poorly aerated. Sandy soils may let the water pass through too rapidly and not retain enough water to support plant growth through a dry period. Desirable proportions of air, water, and solids are illustrated in Figure 1.3.

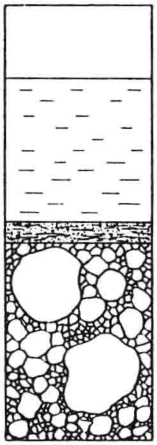

Figure 1.3. The relative volumes of soil components in a typical A horizon at the maximum desirable water content.

Mineral Components of Soils

The mineral particles in soils range in size from submicroscopic clay to stones several feet across. The pieces over 3 in. (76 mm) in diameter are referred to as *stones,* and those smaller than stones but over 2 mm in diameter are called *pebbles* or *gravel*. Stones and gravel are inert in terms of providing fertility for plant growth but can affect physical properties such as permeability and erodibility and can be limiting factors for tillage operations.

Mineral particles smaller than 2 mm in diameter are divided into sand, silt, and clay. *Sand* particles, according to U.S. Department of Agriculture (USDA) standards, are between 0.05 and 2 mm in size. Sand gives soil a gritty feel, and individual sand grains are easily seen by the unaided eye. *Silt,* by USDA standards, includes the particles from 0.002 to 0.05 mm in diameter; only the coarse silt particles are visible to the eye. When silty material is rubbed between the thumb and fingers, it has a smooth feel like flour or talcum powder. Those particles smaller than 0.002 mm in diameter are classified as *clay* by the USDA standards. Clay feels gritty and hard when dry but becomes sticky and plastic when wet. Certain types of clay swell considerably by absorbing water and then shrink and cause the soil to crack open when it dries. Clay is much more active chemically than sand and silt. Available plant nutrients are stored by the clay and the soil organic matter.

The elemental composition of the mineral matter is over half oxygen by weight. In fact, oxygen and hydroxyl ions are the only anions (negatively charged ions) in the most abundant soil minerals. The principal cations (positively charged ions) in their usual order of abundance are silicon, aluminum, iron, potassium, calcium, magnesium, and sodium. All other elements found in the mineral portion usually total less than 5 percent of its weight. The most abundant of all minerals are called *silicates* or *aluminosilicates* because of the predominance of oxygen, silicon, and aluminum in their composition. Another important group, known as the *oxide minerals,* is dominated by iron, aluminum, and silicon oxides. The oxide minerals are most abundant in highly weathered materials in tropical areas. Minerals are discussed more fully in Chapter 6.

Organic Components of Soils

Organic matter constitutes between 1 and 6 percent of the topsoil weight of most upland soils. Topsoils with less than 1 percent organic matter are mostly limited to desert areas. At the other extreme, the organic-matter contents of soils in low wet areas may be as high as 90 percent or more. Soils with more than 12 to 18 percent organic carbon (approximately 20 to 30 percent organic matter) are called *organic soils* (see Chapter 5 for details).

Soil organic matter is partly alive and partly dead. Living plant roots are usually excluded, but both fresh and partly decomposed residues of plants and animals are included, along with the tissue of living and dead microorganisms.

It should be obvious that the soil organic matter contains some of every element needed for plant growth because it "inherits" the components of the plant residues. These elements are released and made available to plants as the organic matter decomposes, but not all at the same time and rate. Almost all the nitrogen utilized by growing plants must come via an organic source (unless supplemented by fertilizer) because the primary minerals contain only traces of nitrogen. Decomposing organic matter is also an important source of phosphorus and sulfur. Furthermore, the decomposition of organic matter produces acids and other substances that cause soil minerals to decompose and release plant nutrients.

Supplying plant nutrients is one of the important functions of organic matter in soil. Another is to help bind the mineral particles into aggregate units providing a more open structure with adequate pore space for good aeration. Structure is especially important in soils having moderate to high clay contents.

Thousands of Different Soils

Parent material, climate, living organisms, topography, and time are known as the *factors of soil formation*. The characteristics of a soil result from the integrated action of these five factors. There are thousands of different soils because the soil-forming factors occur in different kinds and degrees that can be combined in thousands of different ways. Each combination produces a different soil with its own unique properties. Fortunately, many soil properties can be predicted from a study of the five soil-forming factors as they pertain to individual soils.

Parent Material

Soils inherit dozens of different minerals from their parent materials. These minerals have a wide variety of chemical compositions and a wide range of weathering rates. The individual particles differ greatly in size and shape. The arrangement and the amount of consolidation or binding together of the individual particles also vary widely. Thus a particular soil may originate from a parent material that is distinct, at least in some measure, from all other soil parent materials.

Climate

The weathering forces that attack the parent materials are as varied as the materials. The complexity of climate is seldom overstated. It is true that precipitation and temperature are the basic components, but neither of these is adequately described by citing averages. Type, timing, and intensity of precipitation are all significant. Maxima, minima, and seasonal variations are vital characteristics of temperature. The coordination of the temperature and precipitation patterns must be considered. Does the soil become thoroughly dry at some time during the year? If so, it will differ from another soil that remains moist. Does it freeze? To what depth? Is the precipitation intense enough to cause runoff and erosion? Is there ever enough water present at any one time to percolate through the entire solum into the C horizon and rock layers beneath? The answer to this last question is one of the most important features of the climate. Materials are leached from the solum if there is even a temporary excess of water over the amount the soil can absorb.

Living Organisms

Plant and animal life of both macroscopic and microscopic forms take part in soil formation, working with climatic forces to alter the parent material and help make it into soil. Generally the most obvious variable in this factor is the vegetation. An easily noted difference between grassland soils and forested soils is in the distribution of organic matter within the soil. The organic-matter concentration in most grassland soils is highest near the surface and declines gradually with depth through the solum. This pattern closely follows the distribution of grass roots because much of the organic matter comes from the annual death and regrowth of grass roots.

The top part of a forested soil may be as dark colored and contain as much organic matter as the corresponding part of a grassland soil, but the A horizon of a forested soil is normally much thinner than that of a grassland soil. Most forested soils have an additional E (eluviated) horizon between the A and B horizons. E horizons are lighter colored than the A above and the B below because eluviation has removed much material from them and left them low in organic matter (Figure 1.4) and other coloring agents. Tree roots tend to live for a long time and therefore add little organic matter to the soil year by year.

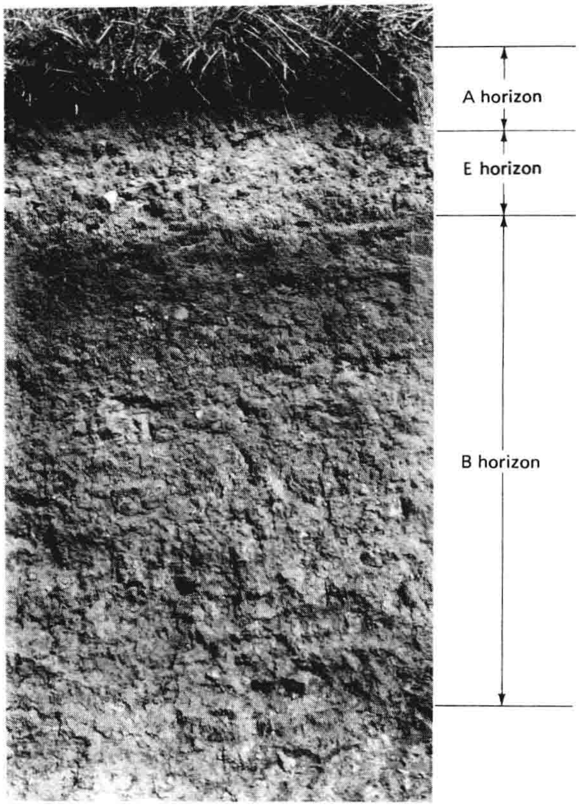

Figure 1.4. A soil formed under forest vegetation showing a lighter-colored E horizon between the A and B horizons. This profile may be contrasted with the grassland soil shown in Figure 1.1. (*Courtesy of Wells Andrews*)

Trees deposit leaves and twigs as litter on the soil surface. The litter decomposes gradually. Part of it becomes mixed into the upper layer of soil and helps to produce the thin, dark-colored A horizon. The decomposition processes produce organic acids that leach down through the soil and tend to make forested soils more acid than grassland soils. Intense acid leaching often causes more clay movement from the A to the B horizons in forested soils than in grassland soils.

There are, of course, many different kinds of grasses and trees. Each kind has its own influence on soil formation. Evergreen trees, for example, usually produce a more acid leachate than do deciduous trees. Various types of grasses, bushes, and other plants produce different kinds and amounts of soil organic matter. Each soil reflects the vegetation under which it formed.

Vegetation is a very important variable in determining the type of soil that forms in a particular place, but it is not a completely independent variable. The climate of an area has much to do with the type of vegetation that will grow there. Also, the nutrient-supplying capacity the soil inherits from its parent material helps determine the kind of vegetation and influences the amount of growth produced on the soil. Soil and vegetation are each influenced by the other and by the action of climate and other factors.

The importance of animal activity as a component of the living organisms factor of soil formation is often observable, though easy to overlook. A bumpy lawn is likely evidence of the activity of earthworms and moles. Anthills often represent a more drastic alteration of soil material. Various types of rodents, snakes, and insects that burrow in the soil all leave the marks of their presence. Furthermore, these and other forms of animal life return their bodies to the soil organic matter when they die.

Topography

Another two-way relationship exists between soil and topography. Some soils erode easily and readily permit wide valleys to form. Other soils resist erosion and may cause narrow valleys and steep slopes. In turn, the steepness of slope influences how fast the soil erodes. Rapid erosion keeps soils shallow and young. Slower erosion allows the formation of deeper soils with more strongly differentiated horizons.

Nearly level areas where there is little or no erosion are likely to produce soils with strong differentiation of A and B horizons. Water tends to accumulate in these soils and make them wetter than the sloping soils. Level soils tend to have poor drainage both externally and internally. The wetness often results in a lush growth of water-loving plants. Poor aeration in the wet soils causes organic matter to accumulate and produce dark colors.

Soils on steep slopes are drier, are usually shallower, and have lighter, often redder, colors than soils on gentle slopes. These characteristics are especially prevalent in soils that face toward the early afternoon sun. South-facing (in the Northern Hemisphere) and west-facing soils lose water first by runoff and second by rapid evaporation. Vegetative growth is sparser, and decomposition is more rapid than elsewhere. The soil organic-matter contents are therefore relatively low on the slopes with the warmest soils.

Time

Soil formation is a slow but continuing process. The soils change as the years, centuries, and millennia pass. The nature of the soil today at any one place therefore depends partly on how long it has been exposed to weathering. Young soils are similar to their parent materials, whereas older soils become strongly differentiated. Too much differentiation is unfavorable because the clay in the B horizon of an old soil makes it too hard and poorly aerated for plant roots to penetrate easily.

Declining fertility is another unfortunate characteristic usually associated with old soils. Fertility, however, can be improved by the proper use of fertilizers.

Naming Soils

It has become standard practice to give each soil the name of a town, school, church, stream, or other geographic feature located near the area where the soil is first identified. Soil names such as *Amarillo* and *Fargo* automatically infer soils of northwestern Texas and North Dakota, respectively. The same name is given to all soil areas that have profile characteristics falling within its defined limits. The unit thus formed is known as a *soil series*. Theoretically, any two areas that combine the same type and degree of each of the five soil-forming factors will have the same soil series. This principle applies theoretically whether the two areas occur near each other or on separate continents. In practice, a soil series name is usually used in only one country because of political and organizational problems. Certain broad units of soil classification, however, are in almost worldwide use.

Some range of characteristics must be allowed within each soil series because differences can be found between any two soil profiles. But these ranges must be carefully defined. The limits must be narrow enough to permit interpretations to be made for agricultural, engineering, and other uses, yet broad enough to permit significant areas of soil to be called by the same name.

Soil series names are given to areas, not points. Surface features such as slope and roughness are soil characteristics to be considered in naming a soil. A soil profile by itself does not qualify because it essentially represents a point on the landscape having a vertical dimension but lacking area and volume. The *pedon* is the three-dimensional soil unit defined to have all the characteristics of a soil. It corresponds to an individual plant or animal as the smallest individual unit of the soil series. Arbitrarily, each pedon covers an area of one square meter except in certain special circumstances where it must be larger to fully represent the soil.

Classifying Soils

There are thousands of soil series—too many for any one person to be acquainted with all of them. More inclusive soil names are needed to group soils into a smaller number of classes. Several systems of classification are used for this purpose in various places. Both the new and the old soil classification systems of the USDA are explained in Chapter 16. Many other countries have classification systems that are closely related to one or the other of these systems.

One of the best-known higher levels of soil classification is called a *soil order*. Most soils can be fitted into one or another of the 11 soil orders of the United States Department of Agriculture (USDA) system of soil taxonomy. Generalized descriptions of these 11 orders are given in Table 1.1. Each soil order includes many different soil series that have several important characteristics in common. For example, the soil in Figure 1.1 is a Mollisol because it has a thick, dark-colored A horizon characteristic of soils formed under grass vegetation in subhumid temperate climates. The soil in Figure 1.4 is an

Alfisol, formed under forest vegetation in a humid temperate climate. These and other soil names will be used in various parts of this book wherever needed to illustrate specific concepts.

World Soil Resources

The land area of the world is about 13.4 million hectares, or about 33.1 million acres. About 1.5 million hectares (11 percent of the total) are presently cultivated (Larson, 1986). A large proportion of the world's Mollisols are cultivated because their average productivity is the highest of any of the soil orders. The Spodosols and Oxisols are among the least favored soils because of their low fertility.

Table 1.1. Generalized Descriptions of the Orders in Soil Taxonomy

Order	Description
Alfisols	Soils with medium- to light-colored A horizons and with significant clay accumulations in their B horizons. Most Alfisols formed under forest vegetation.
Andisols	Soils with relatively high contents of glass and/or extractable aluminum and iron. Most Andisols are formed in relatively young volcanic ash materials.
Aridisols	Soils of arid regions. Aridisols are light colored and most are alkaline in reaction.
Entisols	Very young soils that have little or no horizon differentiation.
Histosols	Soils dominated by organic materials. Histosols form in wet and/or cold conditions.
Inceptisols	Soils in an early stage of development that lack significant clay accumulations. Most Inceptisols formed under forest vegetation in humid climates.
Mollisols	Soils with thick, dark-colored A horizons. Most Mollisols formed under grass vegetation in temperate climates.
Oxisols	Very highly weathered soils. Most Oxisols occur in the tropics and have low natural fertility.
Spodosols	Very strongly leached soils of cool, humid areas. Spodosols have bright colors, high acidity, and low fertility.
Ultisols	Strongly weathered soils formed in warm, humid regions under forest vegetation. Ultisols are redder and less fertile than Alfisols.
Vertisols	Soils high in clay that form deep cracks at least 1 cm wide during dry seasons.

Aridisols are fertile but their productivity is limited by lack of water unless they are irrigated. Each of the other soil orders has its own possibilities and limitations that influence land use.

The total amount of tillable land is estimated to be approximately 3 million hectares (double the amount now cultivated), but the additional areas have lower yield potentials than those already tilled. Furthermore, these additional areas are already in use, mostly as either grazing land or woodland. Increasing the area of cropland therefore decreases the area available for grazing livestock and producing wood products.

Cropland is being lost to erosion and diverted to other uses such as roads and buildings nearly as fast as new areas are being added (Larson, 1986). Increased agricultural production to feed the growing population of the world therefore has to come from increased yields. New crop varieties, higher fertilizer rates, and improved management practices make yield increases possible, but they must be combined with soil conserving practices that retain cropland in good condition for future as well as present use.

Contributions of Soil to Plant Growth

Soil provides higher plants with many essentials for their growth. Principal among these are mechanical support, plant nutrients, water, and oxygen for root respiration.

Plants produce sugar and give off oxygen in the process of photosynthesis. This complex reaction may be shown in abbreviated form as follows:

$$\text{Light energy} + 6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

An important aspect of photosynthesis is that it takes place only when and where light energy strikes plant tissue containing chlorophyll or some similar substance.

Plants also carry on respiration and utilize some of the energy stored in the sugar produced by photosynthesis by the following generalized reaction:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

Respiration is carried on in all living tissue. The