Chapter 1

THE SOIL ECOSYSTEM

If one were to imagine the soil ecosystem as a machine, it would have billions of functioning parts. It would be such a complex mechanism that, were it to break, no repairman on earth would be capable of fixing it. Fortunately, in its exquisite design, the soil also contains its own repair mechanism and, even in cases of extreme damage, it can almost always repair itself. The time it takes to recover, however, depends on both the extent of the damage and the conditions that regulate the renewal of life, as it is the soil's biological component that facilitates its ability to heal.

In 1980, the volcano Mount Saint Helens exploded and destroyed the surrounding 234-square-mile area. The soil disappeared under a thick blanket of volcanic ash and rock. Soil life—all life—was annihilated. The devastation from extremely hot ash, pyroclastic flows, blowdowns, and mudflows was severe and seemingly irreparable—but slowly, over the decades, life has begun to reestablish itself. The repair is an ongoing and joint effort of teams of plants, soil organisms, insects and other arthropods, amphibians, birds, and mammals, some of whom work around the clock, 365 days a year.

Restoration probably began by photosynthesizing (autotrophic) bacteria that extracted energy from the sun, combined it with carbon dioxide from the atmosphere and terrestrial minerals, and produced the organic materials necessary for proliferation. As these pioneers of life grew in number, some predator organisms were able to subsist and they, in turn, fed others on the next link of the food chain. Eventually, more and more kinds of organisms began to colonize the devastated area, and organic residues from their activities and expired bodies began to accumulate. Before long, plants were able to acquire the necessities for life. Wildflowers, especially prairie lupines and fireweed, were probably the first to reappear. (The prairie lupine survives and thrives in nutrient-poor soils and, because it's a legume, it works with rhizobacteria to fix nitrogen from the atmosphere for itself and to share with other organisms.) As more and more plants appeared, wildlife began to graze again. Gophers and mice were among the first mammals to migrate into the devastation, and their burrowing activities, through the ash to the soil below, began mixing the horizons. The spread and proliferation of life begun by autotrophic bacteria have brought significant change to an area that, a relatively short time ago, resembled the surface of the moon more than anything on this planet. As more and more life inhabits the devastated soil, it becomes more inhabitable for other organisms, including forest plants. The essential interdependence of life in a functioning ecosystem is an important lesson to learn from Mount Saint Helens, and one that applies everywhere (see Figure 1-1).

The chemical, biological, and physical reactions that make soil functional need air, water, minerals, energy from the sun, and time. The scenic beauty of natural landscapes was not created from a grand plan engineered by a landscape architect and constructed by people in a single season. It evolved over thousands of millennia from organisms in stiff competition that nevertheless created symbiotic alliances. It is that competition and those alliances that must be better understood to engage the soil ecosystem in the creation of a sustainable recreational landscape.

The soil machine can be nudged perhaps, but it cannot be controlled, which is fortunate, because no one really understands the complexities of the soil system well

FIGURE 1-1 Mt. Saint Helens devastated almost 250 square miles of the Pacific Northwest. Photo courtesy U.S. Geological Survey.

enough to govern it. When control is attempted, a part of the machine may be altered or damaged and cease to function properly. In a simple machine, like an automobile engine, malfunctioning parts are noticed almost immediately. But in a complex system, like the soil, dysfunction can go unnoticed for years, decades, or perhaps even centuries. Because the machine is so complex, the cause of a symptom can easily be misunderstood.

SOIL CREATION

To get a sense of how the soil functions—and it will be a superficial sense at best—let's first take a look at how the soil, as we know it, was formed.

Before there was soil, there was rock—perhaps one extremely large chunk called Earth. Eventually, tectonic movement, volcanoes, and other natural forces created pieces of rock, some of which were large and some mere particles of dust (see Figure 1-2). This process of rock size reduction is called *weathering*, and many forces contribute to it. The typical analysis of a well-developed loam (see Figure 1-6) shows that half of the soil's volume is pore space that is (ideally) filled with equal parts of air and water. Most soil solids are minerals derived from rock.

Water, especially when it freezes, is a bull in a china shop when it comes to weathering. In a river, stream, or brook, water constantly washes away surface particles from rocks in its path as it cascades over, under, around, and sometimes through the parent material (see Figures 1-3a and 1-3b). What may seem gentle to the observer is an unrelenting torrent of force to particles clinging to rock surfaces. Those particles snatched by the water's will become unwitting accomplices in tasks downstream, abrasively

FIGURE 1-2 Rock is soil's main ingredient. Over time, natural forces reduce rock size from majestic to sometimes microscopic soil particles.

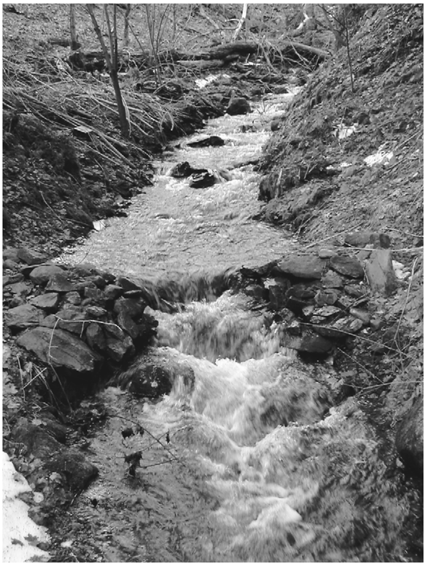

FIGURE 1-3A Flowing water is constantly wearing down rock surfaces and carries liberated particles away.

betraying brethren particles. When gravity's assistance wanes, the water slows, and many of the suspended particles settle to the bottom. Over time, the bottom is built up from these deposits and the water finds a new path, leaving behind beds of sediment—the foundation of a riparian soil.

When the temperature drops below freezing, water changes from liquid to solid and expands with a force few natural materials can contain (see Figure 1-4). One hundred fifty tons of expansive force per square foot can compromise the structure of nearly any rock that allows moisture to enter through cracks, fissures, or pores. If the force of frost separates a boulder from its mother mountain, gravity can assist in the process of weathering as the accelerating rock smashes itself and the surface against which it falls into smaller and smaller pieces.

Wind is another persuasive natural force that not only can coax small particles of rock away from the parent surface but also spread it to areas far and wide. As these pieces ride the wind, they too become unwitting accomplices, blasting free other particles with which they collide. Glaciers, earthquakes,

FIGURE 1-3B As the flow of water slows, suspended rock particles settle and form the basis of riparian soil.

and volcanic eruptions are other forces that produce weathered rock particles.

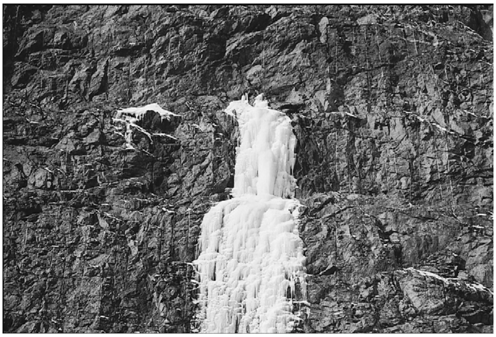

FIGURE 1-4 Water that finds its way into rock expands with a force of 150 tons per square foot when it freezes.

As powerful and persuasive as these physical forces can be, yet another type of weathering also makes significant contributions to the formation of soil. Surprisingly, the largest facility on earth where chemical reactions occur is the natural environment. Naturally occurring elements react with each other regularly to form compounds, many of which then react with other compounds or elements. This constant manufacture and disintegration of chemicals in nature is an integral part of terrestrial functions. One of the effects of this natural chemical activity is an advanced stage of weathering rock into soil.

Water is chemically expressed as H_2O. Its two constituent elements (hydrogen and oxygen) can react chemically with many other elements in nature. The entire water molecule can react in a process called *hydration*. Rock minerals that bond with one or more water molecules become hydrated and are more easily dissolved into a soil system. *Hydrolysis* occurs when a hydrogen atom in water bonds with natural elements, often forming acids that contribute to weathering rock surfaces. Chemical chain reactions, initiated by either the hydrogen or the oxygen in water, can change the original composition of rock; the resulting mineral compounds can have completely different structures and reactive characteristics within the soil.

The formation of inorganic acids, such as sulfuric acid and hydrochloric acid, occurs naturally through reactions between soil chemicals. These acids are extremely effective at separating and dissolving rock components. Carbonic acid, a powerful weathering agent, is formed from the combination of carbon dioxide and water, two relatively abundant substances in the soil.

The different types of parent material determine the rate at which rock is weathered and, to a large extent, the size of the resulting particles found in the soil. Limestone, for example, is a rock that is easily weathered and can eventually dissolve so completely that few particles can be found. Quartz, on the other hand, weathers slowly; because of its structure, it is difficult for nature to completely weather it into its molecular components.

Another factor that influences weathering is surface area. The greater the surface area exposed to soil acids, the faster rock particles can be dissolved. A fist-sized stone may have several square inches of surface area when intact, but when it is ground into a fine powder, the overall surface area increases to several *acres*. The amount of time it takes for nature to weather the material is measured in years for the powder, compared to centuries for the intact stone.

Rocks composed predominately of aluminum, potassium, or magnesium silicates (generally insoluble compounds) are commonly weathered into tiny (<0.002-inch diameter) platelike particles classified as *clay*. Because of complex substitutions of ele-

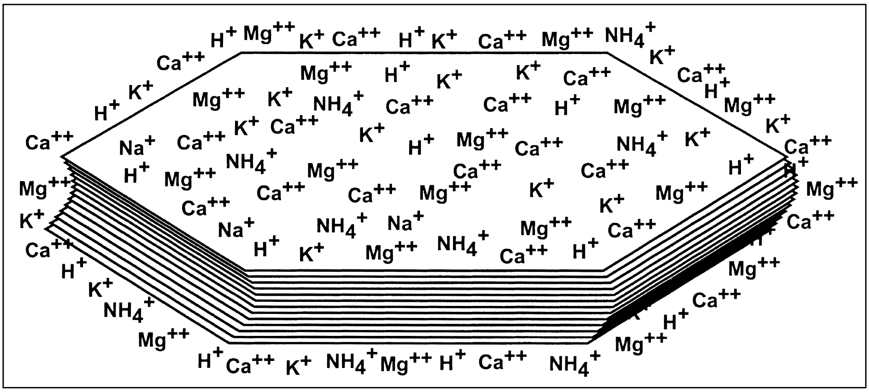

FIGURE 1-5 Clay Particles. Negatively charged clay particles shown with a typical platelike appearance and swarm of adsorbed cations.

ments within their molecular structure, many clay particles inherently have a negative electromagnetic (anionic) charge that enables them to adsorb positively charged ions (cations) such as potassium (K), calcium (Ca), and magnesium (Mg) (see Figure 1-5). This magnetic ability is described as *colloidal* (from the Greek *koll*, meaning "glue," and *oid*, meaning "like") and is inherent in humus particles as well. Colloidal particles play a crucial role in the soil system. Soil environments devoid of either clay or humus—like pure sand fields—have a greatly diminished capacity to hold plant nutrients and, consequently, do not naturally support an abundance of plants or other biological life.

Soils formed from rock are called *mineral soils*; this is the most common type of soil on earth. An analysis of a well-developed mineral soil might reveal around 90 percent rock particles on a dry basis (see Figure 1-6). Volumetrically, 50 percent of this type of soil is made up of air and water. In a rich, healthy soil, an average of only 5 percent is organic matter. Natural levels of organic matter vary considerably.

There are about 90 naturally occurring elements on earth; most are found, at least in trace amounts, nearly everywhere. The most common elements found in the min-

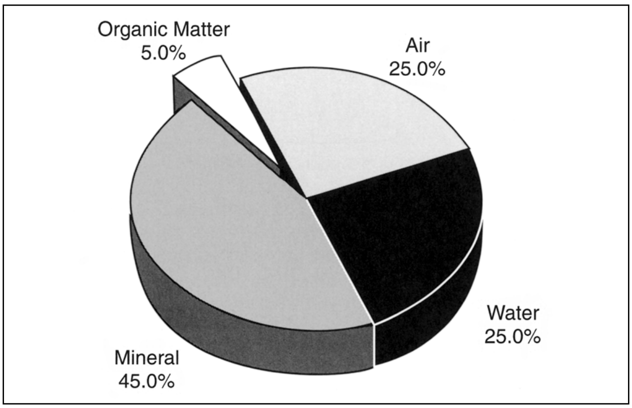

FIGURE 1-6 Soil Structure. Typical analysis of a well developed loam.

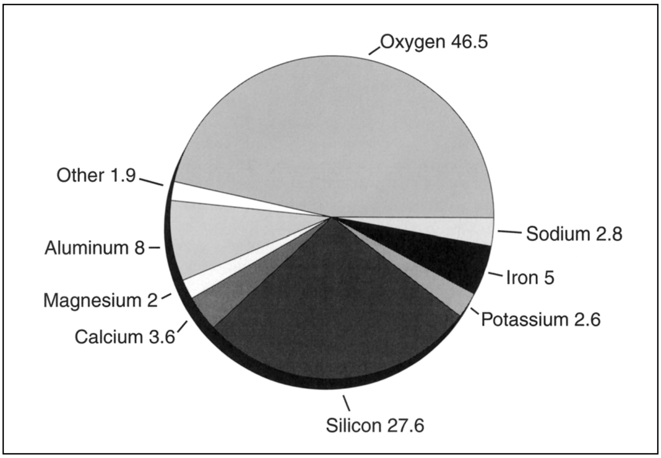

FIGURE 1-7 Mineral Components. Eight elements comprise 98% of soil mineral.

eral component of soil, however, are oxygen, silicon, aluminum, calcium, sodium, iron, potassium, and magnesium (see Figure 1-7). The oxygen that exists in soil minerals is part of the chemical structure and is not in a gaseous state. Many elements exist in a naturally formed molecule with oxygen.

All of these weathering forces, both physical and chemical, combine to form soil particles from rock that are better known as *sand*, *silt*, and *clay*. These particles are defined by size, as shown in Table 1-1. Most soils have a combination of all three sizes of particles and are classified depending on the percentage of each (see Chapter 4, under "Texture Analysis").

TABLE 1-1
USDA Soil Particle Classification

Clay	≤ 0.002 mm
Silt	> 0.002 mm ≤ 0.05 mm
Sand	< 0.05 mm ≤ 2.0 mm
Gravel	> 2.0 mm

The concept of weathering isn't difficult to grasp and seems to give a clear picture of how soil is formed, but the result is not soil yet—just dirt. Weathering simply provides a picture of how soil texture is formed.

BIOLOGICAL CONTRIBUTION

Dirt needs something else before it can become soil, and that is life—and also death. Life and death in the soil are vital phenomena of an ecosystem that perpetually generates energy for the biosphere. Here is where the soil and its system of cycles become more complex. Magdoff and van Es (2000) classify the organic fraction of the soil into three categories: the living, the dead, and the very dead. The soil's living component includes the biomass—that group of organisms from the single-celled bacillus to macro-organisms such as earthworms, arthropods, and mammals that live in the soil. But all organisms, including plants and humans, are connected to the soil in many ways. They are affected by and have effects on the soil. So all terrestrial life should be included in this category.

Leaves that fall from trees, grass clippings, animals that burrow into or just trespass on the soil leave residues that contribute to the system of cycles (see Figure 1-8). Most of these residues fall into the dead category. They not only provide energy and sustenance for numerous organisms but also contribute to the development of humus—the very dead.

HUMUS

Humus is a byproduct and end product manufactured by organisms during decay processes. Humus is a dark, inconsistently shaped substance that is biologically resistant to decay and makes up the major portion of organic matter in most soils. A vital component of soil, humus provides a cornucopia of benefits.

Humus may be crucial to the existence of every living thing on earth, but it is not a sexy topic of discussion. It constantly contributes to the mechanisms of life but can't carry on an engaging conversation or take out the garbage (but it has some friends that can break down food waste into a soil-like substance). It can't keep you warm at night unless you belong to a family of thermophilic or mesophilic bacteria, and, although all material wealth in the world is linked either directly or indirectly to humus, it can't buy

FIGURE 1-8 Organic residues in different stages of decay.

FIGURE 1-9 Even when mature, compost is still undergoing physical, chemical, and biological changes. It cannot be considered stable humus.

you a new car or anything else. It is important, however, to understand the role humus plays in the soil ecosystem. So put the kids to bed, grab a cup of strong coffee, and turn off the TV. This section may be as boring as the Department of Motor Vehicles driver education booklet, but you needed to get your driver's license and you need to know this too. This information is, without a doubt, more interesting than the stuff one has to read to get (and keep) a pesticide applicator's license.

The following discussion covers two distinct forms of humus. The first is young or *labile* humus, and the second is *stable* humus. Labile humus is like compost; it has a wealth of resources available for soil organisms but is fragile and relatively ephemeral (see Figure 1-9). Labile humus is still undergoing humification, and very little of it may ever become stable humus; its future depends on the chemical structures of its organic contents and environmental conditions. Stable humus, compared with labile humus, has fewer available resources for soil organisms but makes greater contributions to soil structure and cation exchange capacity (CEC). Both types contribute to the soil's capacity to hold water and air—two essential constituents for most soil organisms (including turf plants). Both can increase a soil's resistance to compaction. In fact, humus is an amazing soil conditioner—a mere 3 to 5 percent humus can transform almost lifeless sand into a relatively rich soil. Humus can both bind sand and flocculate clay. Plants tend to produce more microscopic root hairs when growing in a soil environment that contains adequate amounts of humus. These tiny root hairs have significantly more surface area than the coarse roots that typically grow in sandy soils and can absorb more water and nutrients than an equal mass of larger roots.

In sandy soils—those often prescribed for sports field construction—plant and microbial mucilage from humus can reduce the size of the pore space between sand particles, increasing the moisture-holding capacity of the soil and reducing the leaching of soil solution with all the dissolved nutrients it carries. As moisture-holding capacity increases, more plants and soil organisms can inhabit the environment. This, eventually, creates more humus. Under ideal conditions, the advancement of humus in sand can develop the preferred type of soil for plant production. Many sports field designers and builders, however, will tell you that the accumulation of organic matter is one of the last things a manager wants. A common belief is that, left unchecked, organic matter will accumulate to monstrous levels that arrest drainage and weaken turf. In a biologically impoverished environment where only undecomposed organic residues can accumulate, this may very well happen, but in a biologically active environment where residues are constantly being consumed by soil organisms, it rarely does.

Conditions for the development of humus in sand, however, are seldom ideal. In tropical and subtropical environments, for example, where moisture, temperature, and the duration of the warm season are optimum for populations of bacteria, fungi, and other saprophytic (decay) organisms, organic matter is quickly assimilated back into the biomass. This rapid assimilation, coupled with the abundance of oxygen in porous sand, makes it extremely difficult, if not impossible, for humus to accumulate to an adequate, let alone an extreme level. Unlike a rain forest, a playing field situated in a tropical or subtropical environment has little chance of maintaining adequate levels of humus mainly because little organic debris is contributed to the soil. The types of debris that contribute to thatch are not at issue here. These tough, fibrous residues may eventually contribute to the formation of humus, but they must be balanced with residues containing sugars, starches, and proteins such as clippings, organic fertilizers, and mature compost. Without this balance, not only is there little chance of soil improvement from humus accumulation but also less carbon dioxide can be recycled back to the grass plants for the production of photosynthesized materials (see Chapter 2, under "Carbon"). Many sports field architects recommend sand-based fields for their water-draining characteristics; however, this near obsession with drainage obscures the view of other necessary components of the plant-growing system. This approach is a little like washing and waxing a car twice a week but never changing the oil.

In clay soil, humus forms an alliance with clay particles because both humus and clay particles are colloidal, possessing an electronegative charge capable of attracting and holding cation nutrients. These complexes not only increase the soil's overall cation exchange capacity (CEC—a good thing; see following paragraph) but also lessen the cohesive nature of clay by causing granulation; they also increase the decay resistance of humus, giving it a longer life span. Clay is considered an even more taboo soil component than organic matter. An abundance of clay is, without argument, a less than ideal medium on the field, but does that mean there should be no clay in the soil? We know arsenic can be lethal, but we also know that a little is essential to human health. The common assumption among most turf managers is that clay is not added to soil mixes because of compaction and drainage problems. The real reason clay is not commonly used anymore is cost. The addition of clay to soil mixes results in superb physical properties.

The term *colloidal* refers to the attraction certain soil particles have for ions of mineral nutrients. Whether organic (humus) or mineral (clay), the colloid is a tiny soil particle, often referred to as a *micelle* (meaning "microcell"), and it carries a negative electromagnetic charge that can hold positively charged ion nutrients (cations), such as calcium, magnesium, ammonium, and potassium, in a manner that allows plant roots access to them. This phenomenon is called *cation exchange*. The quantity of clay and humus in a given soil is usually relative to the amount of cations the soil can retain, but the type of clay and the age of the humus are also factors. Different types of clay have varying abilities to hold cation nutrients, as does humus at different stages of its development. The combined competence of clay and humus quantitatively determine the soil's capacity to hold cations, which is measured as CEC. Clay is not a material often used in sports field construction; however, many experiments have shown that small additions of clay materials like bentonite, montmorillonite, and zeolite significantly benefit the dynamics of a soil ecosystem. Not only do they increase CEC but also they can improve plant performance.

Humus accumulates more easily in a soil containing some clay than in sand because the clay soil's environmental conditions tend not to support decay bacteria. Pore space in clay soils can often reach the point where the oxygen needed by aerobic life is restricted. Soil water can also act as a buffer for temperature changes, which often suppresses the warmth needed for biological activity. In addition, the evaporation of moisture from the surface has a cooling effect on the soil (just as the evaporation of perspiration from the skin cools the body). Clay can also assist in the stabilization of humus. The clay-humus complexes formed in the soil can further inhibit rampant bacterial decomposition and can increase the life span of humus to over a thousand years. Soil scientists calculate that in Allophanic soil (a type of volcanic clay soil) the residence time of humus can range from 2,000 to 5,000 years. This clay-humus complex may form in old fields built with native soils but is rare in a field constructed predominantly with sand.

The formation of humus begins when residues from plants and animals come in contact with decay organisms (saprophytes) in an average soil. Many of the carbon compounds contained in those residues are proteins, carbohydrates, and other organic materials that supply energy to soil bacteria, fungi, actinomycetes, nematodes, earthworms, protozoa, and other organisms involved directly or indirectly in the decay process. Aerobic saprophytes are the most adept at decomposing organic matter. To live and be active, they need an environment containing an adequate amount of free oxygen. The degree to which free oxygen exists in the soil plays a major role in regulating the conditions under which humus is formed. The same is true for the amount of moisture, the soil temperature, and the carbon-to-nitrogen ratio of the residues being decomposed (see Chapter 3, under "Compost Production"). Where little or no free oxygen exists (for example, in stagnant water), anaerobic organisms contribute most to the decomposition of organic matter. The process is slower than that conducted by aerobic organisms but can, in the long run, produce a greater amount of humus (as muck, or organic soil).

OK! Turf is not an aquatic plant, but it's important to understand the whole picture, so hang in there. Many fields are constructed from native muck soil. Humus formed under water is slightly different than its aerobic counterpart, due as much to the nature of the residues from the two environments as to the process of aerobic versus anaerobic humification (see Figure 1-10). Most of the contributions of organic matter to organic soils are from water-dwelling insects and other organisms, which have a higher percentage of protein than do the plant residues commonly found in soil. Other components come from organic residues transported by wind and water currents to a location where they accumulate and settle. In fact, some of this translocated material may already be humus. Higher percentages of humus are found in soils formed anaerobically because conditions are both more favorable for humus accumulation and less favorable for its destruction.

At the other extreme is an environment containing too much oxygen. If moisture and soil temperature are at optimum levels, organic residues can be decomposed so quickly that little or no humus accumulates. We see this in tropical and subtropical environments, where high temperatures and moisture levels occur in predominantly sandy soils that naturally contain an abundance of air. Conditions such as these also

FIGURE 1-10 Humus formed under water is different than its aerobic cousin but is the basis for many organic soils.

occur on many sports fields, even in the more temperate regions of the world. If the soil is composed mainly of sand, the turf is mowed too low to protect the soil from the sun's heat, and irrigation provides precipitation like that of a tropical rain forest, then soil organic matter (humus) may never accumulate.

Soil temperature is an important controlling factor in the formation of humus. As the temperature of a soil increases, there is a corresponding increase in biological activity. Soils in warmer regions of the earth tend to have lower average levels of humus than soils in colder areas (see Figure 1-11). Figure 1-12 shows that at a soil temperature of 88° F (30° C), with adequate aeration, humus can no longer accumulate. When soil temperatures rise beyond a certain point, not only are the activities of decay organisms stimulated and prolonged but also plants often use more energy than they can create. This phenomenon significantly reduces the amount of plant residues contributed to the soil. If the height of cut (HOC) is unreasonably low, this scenario is likely to occur sooner rather than later on sports fields.

During humification of organic matter, saprophytes use most of the sugars, starches, proteins, cellulose, and other carbon compounds for their own metabolism. The assimilation of nutrients and energy from organic residues is the first stage in the process of creating humus. It is not precisely known to what degree the different residues contribute to the creation of humus. Some of the more easily digested components of the residues end up being used by many organisms and may never actually become humus. However, these components provide energy and protein for organisms involved in synthesizing humus. The components of the residues, which are more decay resistant, are not so much assimilated as they are biologically altered into humic substances. Soil organisms actively involved in the humification process produce substances that can also contribute to the components of humus.

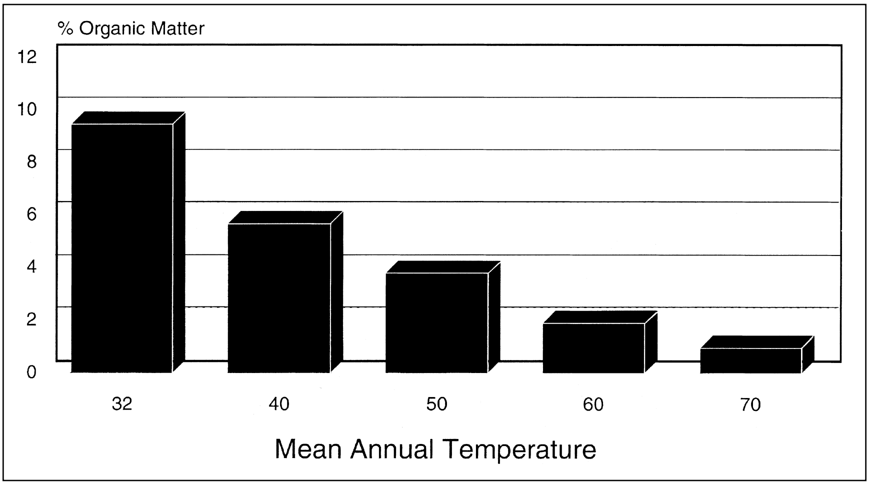

FIGURE 1-11 Influence of temperature on soil organic matter content. Adapted from Jenny, 1941.

The nutrients and energy assimilated into the bodies of soil organisms is normally reused by other organisms that are either predacious or saprophytic. Some is assimilated by the consumer, some is mineralized into plant nutrients, and some is changed into biologically resistant compounds that accumulate as components of humus. The cycles of soil life are implemented as more and more members of the biomass club participate in the festivities of eating, dying, and being eaten—dead or alive. Plants create organic residues that feed soil organisms that then transform the resources from the residues back into plant nutrients, into food for other organisms, and into humus.

Some of the components in organic residues are much more resistant to decay than others. Most carbohydrates, such as sugars and starches, decompose faster than mate-

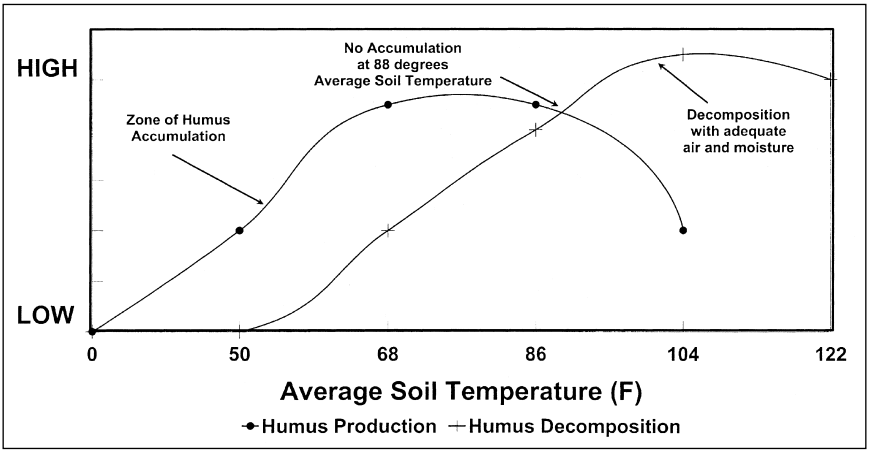

FIGURE 1-12 Influence of soil temperature on humus accumulation. Adapted from Waksman, 1936.

rials such as cellulose. Of all organic components, fats, waxes, and lignin are the most resistant to decay. Proteins vary in decay resistance: they are generally more resistant than sugars and starches but more easily decomposed than many other components.

Although many of these components exist in humus in a biologically altered form (see Figure 1-13), the degree to which they exist in the organic residues plays a role in the accumulation of humus. Materials that contain high percentages of easily decomposed components such as sugars, starches, and some proteins are, for the most part, assimilated back into the living biomass. Although the energy and protein provided by these residues help in the creation of humus, the ratio of their mass to the measure of humus produced is relatively wide (i.e., a small amount of humus is created).

Materials that contain a large percentage of lignin, cellulose, or other biologically resistant components have less recyclable nutrients to offer the soil food web but contribute significantly more to the formation of humus. Different plant residues have inherently different ratios of these organic components, but variance also appears in the same plants at different stages of their lives. Green leaves from deciduous trees, for example, contain a different ratio of proteins to other components than do their dry, fallen counterparts. These same differences would appear in grass plants if they were allowed to mature and produce seed. Constant mowing, however, produces a fairly consistent residue (clippings) throughout the growing season. At this young, succulent stage, grass clippings contribute far more recyclable nutrients and less of the substances needed for the accumulation of humus. However, much of the turf root system, which dies off periodically throughout the season, contributes many components needed for the production of humus. Thatch is also made up of components that can contribute to the accumulation of humus—but, for the most part, don't. Unlike roots, thatch has limited contact with the soil and the decay organisms therein. It also cannot sustain moist enough conditions to support abundant soil life. Additionally, thatch residues may lack sufficient sugars, starches, and proteins for relatively rapid decay.

Biological processing structurally and chemically changes decay-resistant components such as lignin, fats, and waxes into other biologically resistant byproducts, and

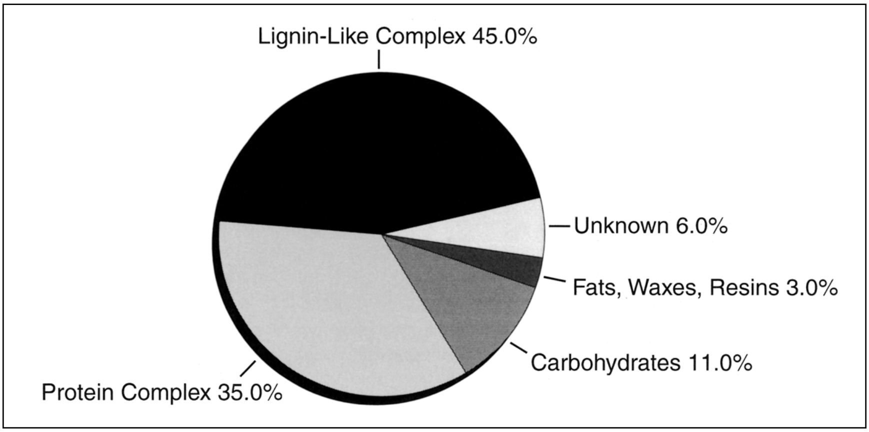

FIGURE 1-13 Humus. Typical consistency in mineral soils. Adapted from Waksman, 1936.

these decay resistant compounds are what make up humus. This is not to say that humus is immune from further decay, but its resistance to decomposition enables it to exist for decades, if not centuries, as a soil conditioner, a habitat for soil life, and a vast reservoir of moisture and dissolved nutrients for plants and many groups of soil organisms. The three main components of humus—fulvic acid, humic acid, and humins—all decay slowly, but at different rates. Fulvic acid is the most ephemeral, lasting only 15 to 20 years. Humic acid compounds can last several hundred years and humins, over 1,000 years.

The digestion of organic matter in the soil is analogous to digestion in mammals. Mammals ingest food and derive nutrients from it. The nutrients are diffused into the body and used for energy to function and to produce new cells. Byproducts, such as urea, water, carbon dioxide, and other simple compounds, are given off. The indigestible portion of the food is excreted as feces.

In the soil, organisms assimilate organic residues, using the nutrients and energy for their own metabolism. Their activities convert some of the organically bound nutrients back to a mineral form, which is usable by plants and other soil organisms. The indigestible portions of the residues accumulate as humus. However, humus is not completely immune to decomposition. Soil organisms eventually recycle all the elements in humus, even if it takes a millennium (or longer).

Humus, plant residues, and other components of soil organic matter are like storage batteries containing energy originally derived from the sun. Researchers in England calculated that an acre of topsoil (6–7 inches deep) with 4 percent organic matter contains as much energy as 20 to 25 tons of anthracite coal. A researcher in Maine equated the energy in the same amount of organic matter to 4,000 gallons of number 2 fuel oil. Most of this organic energy was originally derived from the sun by plants, but only about 1 percent of the sun's energy that reaches plant leaves is used to produce photosynthates. During its life, a plant uses most of the energy it absorbs from the sun for growth, foliage production, flowering, seed production, and other functions. About 10 percent of the absorbed energy is left in the plant tissue for a consumer (e.g., an organism that eats and digests the plant). This leftover energy is called *net primary production*. Like the plant, the herbivore uses most of the energy it consumes for functions such as growth and sustenance, and it offers about 10 percent of the energy it derived from the plant to the next consumer in the food chain.

Subsequent digestions through the food chain continue the rapid depletion of available energy from one link to the next. Often, the final consumers of this energy reside in the soil. In Figure 1-14, an arbitrary quantity of energy is used as an example to show its flow and use. In this case, a figure of 1,000,000 calories of energy offered by the sun is reduced to 1 calorie of available energy by the time it flows through the food chain to soil saprophytes. During the season when plants are active, however, up to half of their photosynthesized nutrients are released through the roots into the soil. Organisms living near, on, or within the root surface then use these compounds for sustenance. One might consider plants rather inefficient organisms for allowing half of their photosynthetic production to leak from their root systems, but nature has a good reason for this design. This phenomenon provides a direct and constant flow of

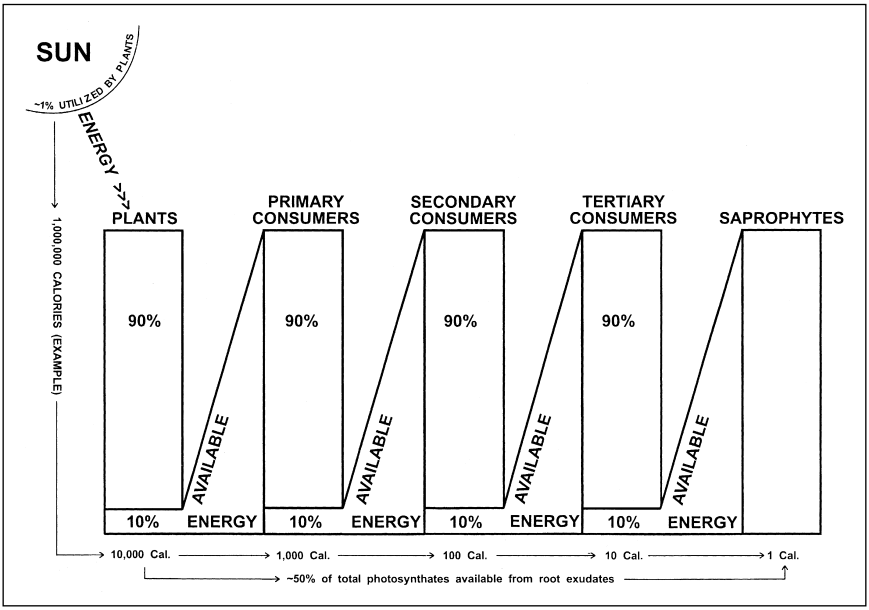

FIGURE 1-14 Energy flow.

plant-synthesized energy for many groups of beneficial soil organisms. The substrate exuded from the plant roots provides sustenance for huge populations of organisms that, among other jobs, make mineral nutrients available to the plants, protect the plants from pathogens and other pest organisms, and produce carbon dioxide that plants need to conduct more photosynthesis.

The amount of available energy in plant residues, in the remains of herbivores, and what is left over from carnivores is significantly different. The various energy levels of these different residues can stimulate different populations of soil organisms that can perform different functions in the soil. These populations are often controlled by the amount and type of residues introduced into the soil, which, in turn, controls the quantity and characteristics of humus.

THE CARBON CYCLE

Throughout this process of digestion and assimilation, from the first consumption of the sun's energy to the decomposition of all residues in the soil, carbon is released back into the atmosphere as carbon dioxide through a process called *respiration*. The evolution of carbon dioxide from the decay of organic residues is an integral part of the life cycle. Figure 1-15 shows how carbon from the atmosphere cycles through the food chain and back into the atmosphere. Plants need atmospheric carbon dioxide to live. If carbon dioxide were not evolved, it would not be available to plants, and the accumulation of humus and other organic materials would bury the planet. Life, as we know it, could not exist.

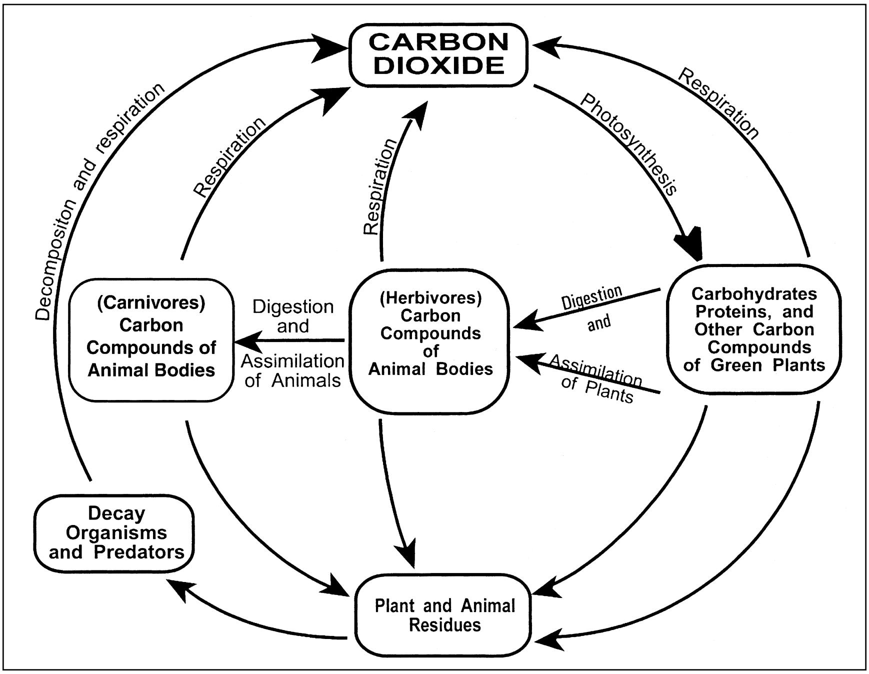

FIGURE 1-15 Carbon cycle.

Over a one-year period and under average conditions, about 60 to 70 percent of the carbon in fresh organic residues is recycled back to the atmosphere as carbon dioxide. Five to 10 percent is assimilated into the biomass, and the rest resides in labile humus. Labile humus is not stable humus, however. It can take decades for humus to develop the biological resistances necessary to be considered stable.

We can see from the carbon cycle that it is necessary for humus to not only accumulate but to be destroyed as well, so carbon dioxide can be returned to the atmosphere where plants can access it. In an uncultivated, natural environment, humus accumulates in accordance with the favorable and unfavorable conditions of the region. Unless global or regional conditions change, the level of humus accumulation reaches equilibrium with the factors that destroy it. The level of humus then becomes a relatively fixed component of that environment so long as the quantity and source of the organic residues being contributed to the soil remain relatively constant.

In cultivated environments, both labile and stable humus are important assets that, like most assets, are easier to maintain than replace. Unfortunately, the value of humus is too often overlooked until it is severely depleted and its benefits are no longer available. Even then, deficient levels of organic matter are rarely recognized as a possible cause of problems that inevitably arise. The importance of soil organic matter and the populations of organisms that it supports should rank very high on the manager's priority list. The first step toward preserving and maintaining this resource is to understand its value.

Old, stable humus is biologically resistant. Depending on the environmental conditions under which it exists, humus can sit in the soil for centuries, even millennia, with a minimal amount of decomposition. But however slight, decay still occurs, and even old humus eventually cycles back from where it came. The formation of new humus, which requires a constant source of organic residues, is critical to maintaining a stable presence of this asset.

Figure 1-16 shows the typical fate of organic matter introduced into the soil. It is important to note that even under the best conditions, a relatively small amount of humus is created in comparison to the level of organic residues initially introduced. If conditions exist that further accelerate the decomposition of organic matter, even less humus may eventually be created. In extremes, such as tropical or subtropical environments where moisture, heat, and soil oxygen are abundant, a great amount of carbon dioxide may be evolved but little humus is produced.

SOIL MINERALS

Organisms that create humus and that prosper in soil enriched with organic matter also contribute to the phenomenon of soil formation and the availability of plant nutrients. Populations of soil organisms facilitate chemical weathering by creating organic acids—corrosive materials formed in nature by plants, animals, and soil organisms. These include citric, acetic, amino, lactic, salicylic, tannic, nucleic, and humic acid, to name only a few. All of these acids have varying abilities to react with rock surfaces and liberate minerals from parent material.

Soil organisms dissolve minerals from rock through three basic functions: *assimilation*, the creation of *organic acids*, and the creation of *inorganic acids*.

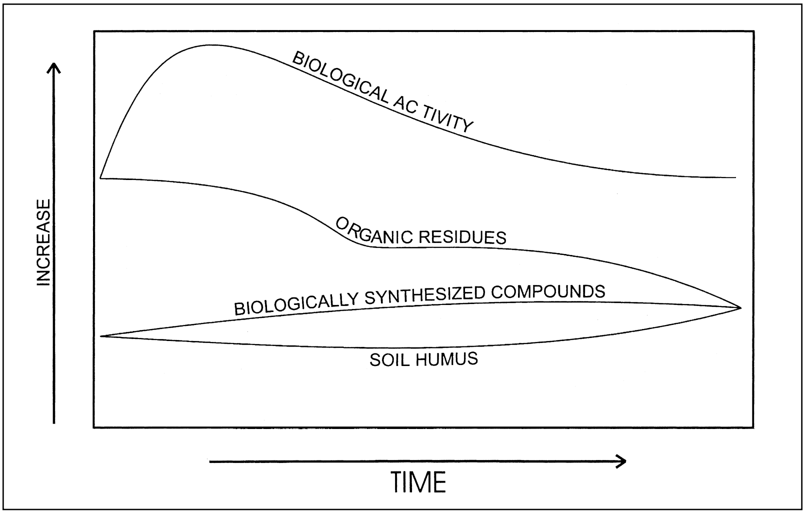

FIGURE 1-16 Humification.

Assimilation is the direct absorption of nutrients by organisms. Most soil organisms work to free nutrients from organic and inorganic matter for their own metabolism. Saprophytes primarily feed on dead residues of plants and animals but also can absorb essential minerals from inorganic sources in the soil. Predators feed on saprophytes and other organisms (including other predators), and much of what becomes available to plants is released during predation. Some organisms work together symbiotically to secure their nutrition. Lichens, for example, are symbiotic combinations of fungi and algae that attach themselves to various surfaces (often rocks) and dislocate minerals for their own nutrition. The hyphae (microscopic tubing) of the fungal component can penetrate the finest hairline cracks in rock, releasing enzymes and acids powerful enough to liberate mineral ions from surrounding surfaces. Eventually, the minerals assimilated by the lichen are recycled through the agency of other organisms that either feed on lichen or decompose their remains after death. After mineral nutrients are incorporated into the body of an organism, however, the nutrients are bound in organic compounds, which are easier for nature to process. Unless these elements are removed from a given area (by cropping, erosion, or other means), they tend to accumulate over time and increase fertility for both plants and other indigenous organisms.

Most organisms create enzymes and organic acids during assimilation, or the acids are byproducts of their metabolism. Regardless of their origin, these acids and enzymes contribute to the formation of soil and to the availability of many essential plant nutrients. Figure 1-17 shows the influence of azotobacter bacteria's organic acids on the mineral content in soil solutions. These beneficial organisms also fix nitrogen from the atmosphere.

Inorganic acids, such as sulfuric and nitric acid, are formed in the soil as an indirect result of biological activity. Specific organisms such as sulfur bacteria and nitrify-

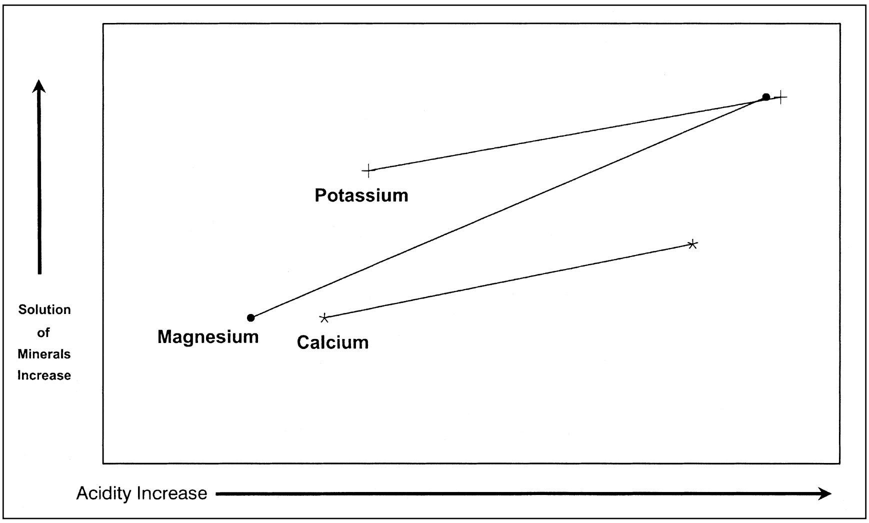

FIGURE 1-17 Influence of acidity created by azatobacter on solutions of Ca, Mg, and K in the soil.

ing bacteria oxidize (combine with oxygen) sulfur and nitrogen respectively and can then combine with soil hydrogen to form strong inorganic acids. The chemical reaction between rock surfaces and strong acids changes both substances. Part of the rock dissolves, and the acid can then become a mineral salt, which is more soluble and, once dissolved, more easily assimilated by plants and other soil organisms.

Mycorrhiza is a family of fungi that can dissolve mineral nutrients from rock surfaces. These organisms work under the soil's surface in a symbiotic relationship with perennial plant roots. The fungi attach themselves to roots and, in exchange for a small amount of carbohydrate supplied by the plant, provide water and mineral nutrients to the plant. They retrieve and transport the water and mineral nutrients via their hyphae from regions of the soil beyond the reach of the plant roots.

The chemical weathering effect of roots comes from several sources. Carbon dioxide given off by root hairs can combine with water to form carbonic acid. Research has shown significant mineral release from carbon dioxide when dissolved in water. This process is known as *carbonation* and involves the attachment of mineral ions, such as potassium, magnesium, or calcium, to a carbonate ion, thus forming other mineral salts. Plant roots indirectly participate in the formation of organic acids through their relationship with soil organisms. The population of organisms within the rhizosphere (the soil region immediately surrounding the root hair) is always significantly higher than in other parts of the soil. The production of organic acids and enzymes that are destructive to rock is directly proportional to the level of biological activity. Up to 50 percent of the carbon that plants fix from atmospheric carbon dioxide is released through their roots as carbohydrates, most of which are consumed by soil organisms that constantly produce organic acids.

PLANTS

Plants are the link between the atmosphere (heaven) and the pedosphere (earth). Their remains make rich soil from weathered rock particles, and they provide nutrients and energy for most other living things on the planet. They complete the cycles of water, nutrients, and energy. Plants are producers; they combine energy from the sun, carbon dioxide in the atmosphere, and mineral nutrients in the soil to synthesize sustenance, directly or indirectly, for almost every other living thing on earth. Almost all of the protein, energy, and carbohydrates that humans need comes from plants or from animals raised on plants.

Plant life slowly began to appear as prehistoric soils evolved. The meager amount of available nutrients, coupled with what was probably a harsh environment, at first permitted only small, perhaps microscopic, plants to grow. As time went on, the accumulation of organic residues from the remains of countless generations of microplant life slowly enriched the soil, creating an environment that could support a larger and more diverse population of soil organisms. The cycle snowballed for a time, creating a richer soil with each successive increase in vegetative establishment, until an ecological equilibrium was reached—that is, the production of organic matter by plants was roughly equal to the environmental factors that destroyed it.

Plants stabilized much of the volatility in the ecosystem. In a sense, plants bottled the energy of the sun and made it available to other living things. The evolution of plants and other photosynthetic organisms changed the ecosystem of the planet dramatically. Prior to autotrophs (photosynthesizing organisms), life existed on available energy. When the energy was depleted, the organisms often became extinct, and new organisms evolved to recycle the energy left behind by their predecessors. The renewability of energy on earth enabled many species of consumers (heterotrophs, such as mammals) to exist for many generations without depleting their food supply. This phenomenon allowed for the systematic evolution of different species into present-day life forms.

Most plants are composed of two fundamentally different parts: the root system, which anchors the plant and absorbs water and mineral nutrients; and the shoot system, which consists of the plant's trunk, branches, shoots, stems, and leaves. Those parts of the plant that connect the roots to the leaves provide structural support as well as transport passageways for water and nutrients. Leaf surfaces contain pores, called *stomata* or *stomates*, that function as gas exchangers and as part of the plant's ventilation system.

The plant's link to the atmosphere is through its use of carbon dioxide gas, with which it creates almost all the organic carbon compounds that exist on earth. Without carbon dioxide, plants could not live, and neither could any of the organisms that depend on the nutrients plants provide. The balance of carbon dioxide with other gases in the atmosphere depends largely on plants—or, more accurately, on the use of energy stored in plants. Whenever energy is extracted from plant tissue (or animal tissue), whether by animals, insects, or soil organisms, carbon dioxide is given off. Plants capture some carbon dioxide as it wafts from the soil's surface into the atmosphere and transform it into plant tissue. The more carbon dioxide generated by organisms under the plant, the more likely it is that adequate amounts are captured by plant stomates located on the underside of the leaves.

Plant roots make the organic-inorganic connection in the soil. The fine root hairs combine so well with the earth that it is difficult to tell exactly where the soil ends and the root begins. Not only are many root segments microscopic, but they are also so numerous that a single mature grass plant can produce almost 400 miles of roots. In fact, a square foot of thick turf can be connected to over 325,000 miles of roots (13½ times around the world). The roots of plants depend on the shoot system for nourishment. Throughout the plant's life, carbohydrates and other organic nutrients flow to the root system from the leaves, where energy from the sun, carbon dioxide from the atmosphere, and minerals drawn from the soil combine in a complex process called *photosynthesis*.

The root system and plant tops act like different organisms living together symbiotically. The leaves are autotrophic, using carbon dioxide from the atmosphere to manufacture organic carbon compounds and giving off oxygen as a waste product. The root system acts like a heterotrophic organism, dependent on the sugars and other compounds produced in the leaves and using oxygen from the soil while giving off carbon dioxide.

The roots of plants are more than just anchors and siphon tubes extracting water and nutrients from the soil. The rhizosphere is teeming with life in the form of billions of microorganisms. Up to half of the nutrients photosynthesized in plant leaves is released from the roots into the rhizosphere, supplying nourishment for most of these organisms, whose activities help the plant in numerous ways. They can mineralize organic nutrients, compete antagonistically with pathogens, weather parent material, regulate nutrient availability, decay plant residues, return carbon dioxide to the atmosphere, and mobilize water and nutrients (e.g., via mycorrhizae). Some organisms in the rhizosphere can also fix nitrogen from the atmosphere, solubilize phosphorus, and produce growth hormones that increase the plant's resistance to environmental and other types of stress.

Plants also affect soil factors that in turn influence plant growth. Environments like prairies and forests are formed initially by factors such as climate, parent material, and topography, but the establishment of certain types of plants soon becomes another factor acting on the environment. The plant factor can influence the establishment of soil organisms, change the effects of topography, and even create subtle differences in the atmosphere that may affect climate. Turf affects its environment too. Turf plants complete the cycles of nutrients, water, and soil life, providing environmental stability. Most environments are still evolving, but plants act like a sea anchor, stabilizing and often removing much of the volatility from the evolutionary process.

Soils are subject to eventual ruination by the same forces that created them. The inherent mineral content of any soil may be vast, but it is also finite and can eventually be depleted by weathering. At some point, perhaps a billion years from the time of a soil's creation, leaching, erosion, or both can fully deplete the mineral resources crucial to the existence of living organisms. As the availability of minerals and organic residues wanes, so does the biomass that sustains the level of native organic matter that structurally protects the soil from erosion and stores much of the moisture and nutrients necessary for biotic development. As depletion continues, only the most weather-resistant particles of quartz and other mineral compounds remain. A rich soil can eventually evolve into a habitat that sustains only the hardiest of organisms.

Erosion, one of the forces that weathers rock and carries particles of parent material to deposits called soil, can also carry soil away. Often, soil is carried all the way to an ocean, where tremendous pressures for long periods can transform the mineral particles back into sedimentary rock. Perhaps, a million years from now, a broad tectonic event will lift the recreated rock into a mountain, and the process can begin all over again. A crucial component of the soil ecosystem that retards weathering and erosion is plant life and the diverse population of soil organisms it supports. Gluelike substances created by many soil organisms, aggregate soil particles and protect them from erosion and other weathering forces.

Plants also protect the soil environment in a number of ways. They provide shade and slow the evaporation of precious moisture needed for their own lives and the lives of other soil organisms. The shade they provide reduces soil temperature, which can increase net primary production (i.e., the production of energy beyond the plant's own needs). The extra energy produced feeds soil organisms that also participate in soil conservation. Plants also control erosion with their root systems and the organic matter they produce. The adhesive qualities of humus hold soil particles together and provide greater absorption of water through an increase in soil porosity. This increase in water absorption provides a relative decrease in surface runoff.

The mechanism by which plants produce the proteins, sugars, starches, fat, and fiber needed by the consuming species of the world is chemically complex. A plant's ability to use the endless energy from the sun and the small percentage of carbon dioxide in the earth's atmosphere to produce all of these organic nutrients is nothing short of a miracle. In simple terms, the stomates on the underside of the plant's leaves allow the transference of gas and moisture into and out of the plant. Plant leaves intercept carbon dioxide, much of it generated by the biological decay of organic residues, as it escapes the soil. Plant cells that contain chlorophyll are excited by the energy of the sun and conduct chemical reactions within the leaves. These reactions combine the carbon and some of the oxygen from carbon dioxide with hydrogen from water, nitrogen, phosphorus, sulfur, and other minerals from the soil to form the complex organic compounds that give life and growth to the plant, to its roots, and to every other organism that depends either directly or indirectly on plants for sustenance. The six elements mentioned above—carbon, oxygen, hydrogen, nitrogen, phosphorus, and sulfur—make up 99 percent of all living matter.

Other nutrients considered essential to plants are calcium, molybdenum, magnesium, boron, copper, iron, zinc, chlorine, potassium, and manganese. It is important to note that elements not considered essential for plant tissue development may be of vital importance to other soil-dwelling organisms, which play their own crucial roles in the dynamics of the plant growing system (see Chapter 2, under "Trace Elements").

All of the carbon plants use is derived from the atmosphere. Oxygen comes to the plant from the atmosphere (as carbon dioxide and free oxygen) and from water (H_2O), which also delivers hydrogen. These three elements—carbon, hydrogen, and oxygen—constitute the basic building blocks of all organic compounds and comprise approximately 95 percent of a plant's diet. The remaining 5 percent is in mineral form and derived from the soil (see Figure 1-18).

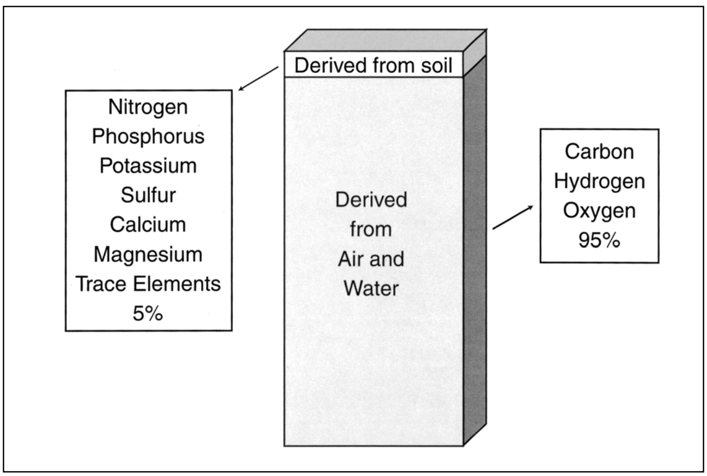

FIGURE 1-18 Plant nutrient needs.

HOLISTIC VIEW

Weathering forces, soil organisms, climate, plants, and animals (including humans) have had, and continue to have, a profound effect, both direct and indirect, on the soil's evolution. The existence of almost all life is both controlled by, and controls, the biological, physical, and chemical diversity in the soil. Managers certainly belongs in this equation, so it is important that they have a basic understanding of the soil ecosystem. The overview presented here is painted with a broad brush. Volumes of information—some of it conflicting—have been published about the soil, and only a brief scan of that material is included in this chapter. But all the currently available information on soil probably represents only a fraction of what has yet to be discovered. The soil is a complex ecosystem whose biological health and vitality appear to be inextricably linked to the vigor and resilience of turf. Recognizing the living component of the soil system as the most ideal barometer of soil health may be the extent of what we need to understand. It's possible that all we have to learn now are the best ways to care for it.

POINTS TO REMEMBER

- Soil was not created overnight. Weathering forces and biological organisms are continually shaping the texture and properties of soil.
- The basal energy that fuels the soil's living component is extracted from organic material.
- Carbon dioxide—a plant nutrient needed in greater quantities than all soil-borne nutrients combined—is generated in the soil by biological respiration.
- Trace minerals in the soil are as essential to plants and soil organisms as water—just in smaller quantities.
- Plants act like two distinctly different organisms—the root systems and the plant tops—living together symbiotically.
- Roots release up to half of the photosynthesized carbohydrates they receive to feed large populations of soil organisms that live in the rhizosphere.
- Plant growth and health are not linked solely to fertilizer, irrigation, and occasional aeration, but also to the physical, chemical, and biological diversity in the soil.