chapter 4

The Turfgrass Environment

The turfgrass community exists in intimate association with its environment. All components of the natural and artificially induced environment affect the persistence and quality of a turf. The environment consists of a highly integrated and dynamic array of forces that, in the aggregate, determine the adaptation and growth of plant species. For academic treatment, it is useful to consider the environment in three distinct, but interacting, dimensions: the atmosphere above and immediately surrounding the turfgrass aerial shoots; the edaphic environment (thatch–soil), including roots and other belowground plant organs; and the biotic component of the environment, encompassing cultural practices, pest organisms, and use of the turf by people. The turfgrass community and its environment form the turfgrass ecosystem.

ATMOSPHERIC ENVIRONMENT

The atmospheric conditions affecting turf result from seasonal and daily fluctuations in the weather. These conditions are measurable as temperature, moisture, light, and wind. Each results from the influence of the sun on the earth's atmosphere. The sun provides light to brighten an otherwise dark universe. Temperature is a reflection of the sun's warming effects on the earth's surface and, subsequently, the atmosphere above it. Moisture conditions result from evaporation of water from oceans, lakes, and other bodies and the subsequent influences of pressure systems, temperature, geographic features, and winds. Finally, wind occurs as result of differential heating of the earth's surface, rotation of the earth about its axis, and the formation and movement of pressure systems.

The orientation of the equator relative to incoming solar radiation (insolation) changes as the earth revolves about the sun. This accounts for seasonal changes in weather (Figure 4.1). In spring and fall, insolation is most direct at the equator; during winter in the northern hemisphere, insolation is most direct below the equator; during summer, the opposite is true. Thus, in the northern hemisphere, winters

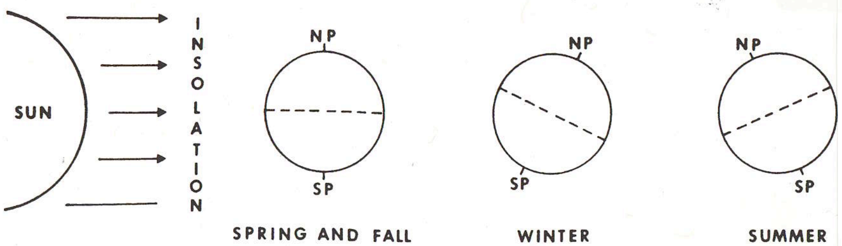

Figure 4.1. Revolution of the earth about the sun and the resultant shift in the equator's position relative to insolation account for seasonal changes in weather.

tend to be more severe and summers milder as one proceeds poleward; summer heat tends toward higher intensity and winters are milder as one moves closer to the equator. These trends are substantially modified by variations in topographical relief and the proximity of large bodies of water. As pointed out in Chapter 3, sites at high elevations in the tropics may be quite suitable for the growth of cool-season turfgrasses, since average temperatures decrease appreciably with relatively small increases in altitude. Because water bodies tend to modify diurnal and seasonal temperature fluctuations, oceanic sites are milder in summer and winter compared to continental areas at the same latitude.

Light

Turfgrasses absorb and convert to chemical energy, through photosynthesis, only about 1 to 2 percent of the incident radiation. Most of the absorbed energy is reradiated at longer wavelengths with the release of heat that significantly affects atmospheric temperature. At the turfgrass leaf surfaces, solar radiation may also be reflected or transmitted through the leaf for possible absorption by other leaves (Figure 4.2). The amount of reflected radiation varies among plants and is affected significantly by moisture conditions. Glossy or wet leaf surfaces are more reflective than dry, dull leaves. The amount of radiation absorbed by the leaves varies from about 50 to nearly 80 percent of insolation, depending on leaf orientation; the more horizontally oriented leaves are more efficient absorbers of solar radiation (Figure 4.3).

The amount of light received by turfgrasses is influenced by many factors in the environment. Clouds, buildings, trees, and other features can reduce light intensity through shading. Turfgrass response to variations in the intensity of light ranges from a relatively horizontal orientation of the leaf blades at high intensities to a failure of the turf to persist under extremely low light. With moderate shading, turfgrass leaf blades typically assume a more upright orientation

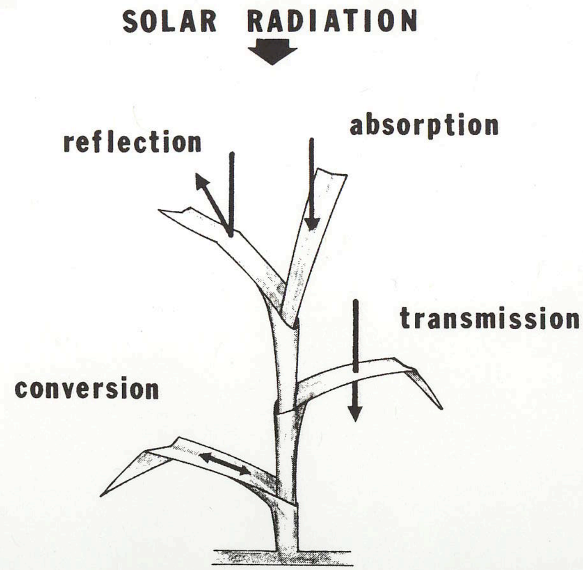

Figure 4.2. Solar radiation may be absorbed, transmitted, or reflected by turfgrass leaves. A small amount of absorbed solar energy is converted to chemical energy by photosynthesis.

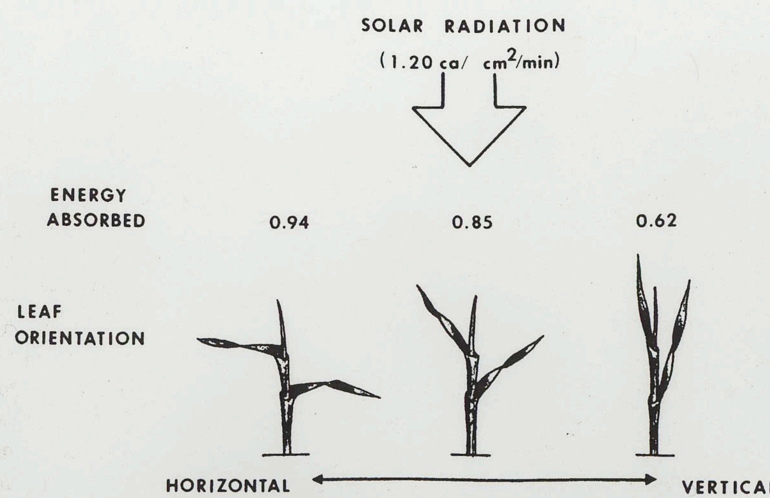

Figure 4.3. Effect of leaf orientation on the efficiency with which solar radiation is absorbed by turfgrasses.

as if they were "reaching up" for more light (Figure 4.4). Additional effects of reduced light include thinner, longer leaves; reduced density

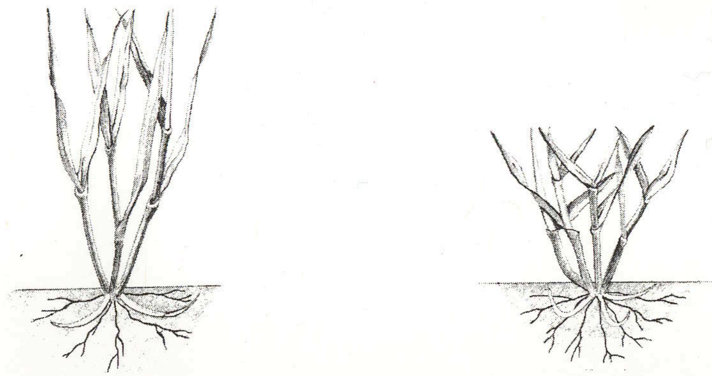

Figure 4.4. Comparison of turfgrass leaf orientations under low- and high-light intensities.

and tillering; shallower rooting; thinner cuticles; and lower reserve carbohydrates within the plants. A "shade" turf is thus more delicate and less tolerant of wear, disease, and environmental stresses.

Sufficient light is necessary for sustaining a level of photosynthetic activity that is adequate for the plant's respiratory requirement and for new growth. Since older plant tissues eventually die, growth must proceed at a rate sufficient to at least replace those tissues lost to senescence. In a heavily trafficked turf, the loss of plant tissue to mechanical damage necessitates an additional increment of growth to sustain turfgrass quality. Thus, several dimensions of essential photosynthetic activity are recognized in turfgrasses: an adequate level to reach the *compensation point* at which photosynthesis equals respiration; an additional increment to sustain the plant's respiratory requirement during dark hours when no photosynthesis is taking place; and extra carbohydrate production to promote a growth rate sufficient to offset the losses of plant tissues from natural senescence and mechanical damage. If the level of photosynthetic activity is inadequate to provide for the necessary rate of growth, then deterioration of the turf is inevitable unless some adjustments can be made. Some possible courses of action include increasing light penetration by pruning or removing interfering plants, reducing traffic intensity to minimize mechanical damage, or establishing shade-adapted plant species or cultivars in place of the existing turfgrass community.

Some adjustments in the turfgrass cultural program can improve the appearance and persistence of a shaded turf. Raising the mowing height can partially compensate for the more upright leaf orientation

that results from reduced light. The rate of nitrogen fertilization should be reduced from that of turf in full sun to reduce the potential for carbohydrate depletion. Trees should be fertilized separately by employing deep-root feeding devices or applying fertilizer to holes produced on 2-foot centers. Irrigation should be conducted infrequently but with sufficient intensity to encourage deep rooting of the turf and to provide for the moisture requirements of the trees. Finally, fungicides may be used to control disease-causing organisms that impose an additional stress on shaded turf.

The ultimate shading problem is called *light exclusion*. This results where heavy clippings from mowing or other obstacles to light penetration occur directly on the turf. Injury from light exclusion can take place within hours if temperatures are high. Objects that exclude light should not be allowed to remain on the turf for any longer than absolutely necessary, and heavy clippings should be broken up or raked.

Where trees are responsible for a shading condition, other factors further complicate the problem. Trees may severely compete with turfgrasses for available moisture and nutrients in the soil, and the roots of some trees exude chemicals that may be toxic to turfgrasses. Tree leaves not only intercept light and thus reduce the amount of light energy available for the underlying turf, but may also deplete light of its photosynthetically active wavelengths. Therefore, the light penetrating to the turfgrass surface may be of little value in sustaining the turf. Finally, the accumulation of tree leaves on turf can result in injury from light exclusion. Thus, in tree-shaded sites, special measures may be necessary to ensure the survival and desired quality of the turf. These measures include root pruning of trees to reduce root competition, trimming lower tree limbs and pruning the tree's crown to allow better light penetration, and immediate removal of fallen leaves.

The effects of shading on the turfgrass microenvironment include moderation of diurnal and seasonal temperature fluctuations, restricted air movement, and increased relative humidity. Depending on the intensity of these factors, the results may be beneficial or highly detrimental to the turf. Partially shaded turfs often appear healthier than nonshaded turfs during summer stress periods because of the apparent differences in heat and drouth stresses. Where air movement is severely restricted and high relative humidities occur, however, the turf may be much more susceptible to disease. This is especially evident on low, poorly drained sites.

One final aspect of light that is important in turf is photoperiod, or day length. At intermediate latitudes, short photoperiods occur in the early and late portions of the growing season, and long photoperiods occur during mid-season. In equatorial regions, photoperiods are relatively constant during the year, while in arctic regions continuous light or dark periods may persist for months. Photoperiodic conditions influence flowering (Chapter 2) and vegetative growth and development of turfgrasses. Turfgrasses growing under short day lengths typically exhibit increased density and tillering, shorter leaves, smaller shoots (including rhizomes and stolons), and a more prostrate growth habit compared to plants under long day lengths (Figure 4.5).

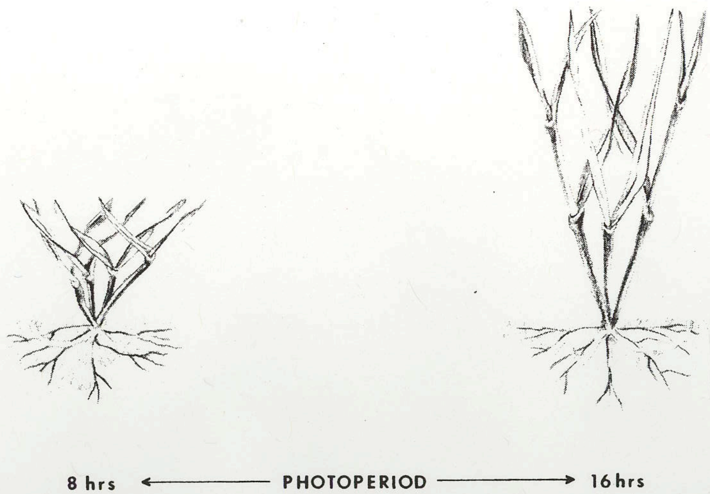

Figure 4.5. Comparison of cool-season turfgrass plants under short versus long photoperiods.

Temperature

Temperature is the most important environmental factor affecting the adaptation of turfgrasses to a particular geographic region. It is a measurable expression of heat energy from solar radiation. Many factors affect the net accumulation of heat energy by specific objects in the landscape. Much of the absorbed heat energy can be transferred from one environmental feature to another by various processes, including evaporation, radiation, conduction, convection, and advection.

Evaporation is the process by which water is changed from a liquid to a gaseous state with the concurrent conversion of sensible heat to latent heat. The sensible heat of an object or of the atmosphere is measurable as temperature; latent heat is absorbed by water, causing a change from the liquid to the gaseous state with no temperature change. Thus, water acts as an energy sink to effectively moderate temperature fluctuations through changes in its physical state (Figure

4.6). Transpiration by plants is essentially an evaporative process by which internal plant moisture (liquid) is converted to water vapor (gas) and released to the atmosphere through the stomates. This conversion requires 570 calories per gram of water, and the plant is therefore cooled through transpiration.

Much of the solar radiation absorbed by plants is *reradiated* at longer (infrared) wavelengths to the atmosphere. This process transfers heat from the plant to the ambient air with a resultant increase in air temperature.

Heat energy can also be transferred through *conduction* by objects or molecules that are in contact with each other. Heat is transferred by adjacent soil particles from the surface downward. Air molecules in contact with a warmed object can conduct some heat to the surrounding air; however, air is a relatively poor conductor, and conduction probably contributes little to the cooling of plants.

Convection occurs when plumes of heated air rise from plant surfaces. This process is important in the transfer of heat from plants and other warmed objects to the atmosphere. A similar process associated with air movement is *advection*. Air passing slowly over a warmed surface picks up heat that is transferred to an adjacent site

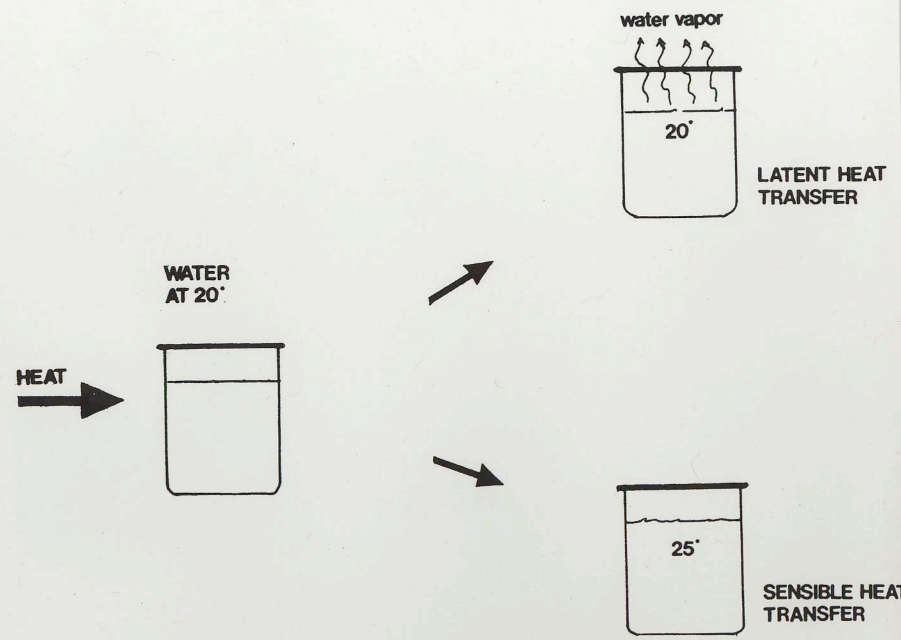

Figure 4.6. Comparison of latent and sensible heat transfer processes.

located downwind. Small strips of turfs located close to efficient, energy-absorbing surfaces (paved surfaces, gravel beds, and the like) encounter greater heat stress in summer than do large turfgrass sites. Similarly, advective cooling can occur on turfs located near large bodies of water when the air above the cooler water moves inland.

Acting together, energy transfer processes can sustain turfgrass temperatures near those of the ambient air. A ranking of these processes in the order of their relative importance would be radiation > convection > transpiration > wind. In turfgrass culture, the only processes over which there is usually some control are transpiration and wind. Adequate transpirational cooling can be promoted by ensuring an adequate supply of plant-available moisture through irrigation and other cultural practices. Air movement across some turfgrass sites can be improved by removing trees and other obstacles. Such measures could be decisive in promoting a desired level of turfgrass quality.

TURFGRASS ADAPTATION TO TEMPERATURE CONDITIONS

The growth of each turfgrass species and cultivar is characterized by three cardinal temperatures that establish the temperature range within which growth takes place: maximum effective temperature, minimum effective temperature, and the temperature at which

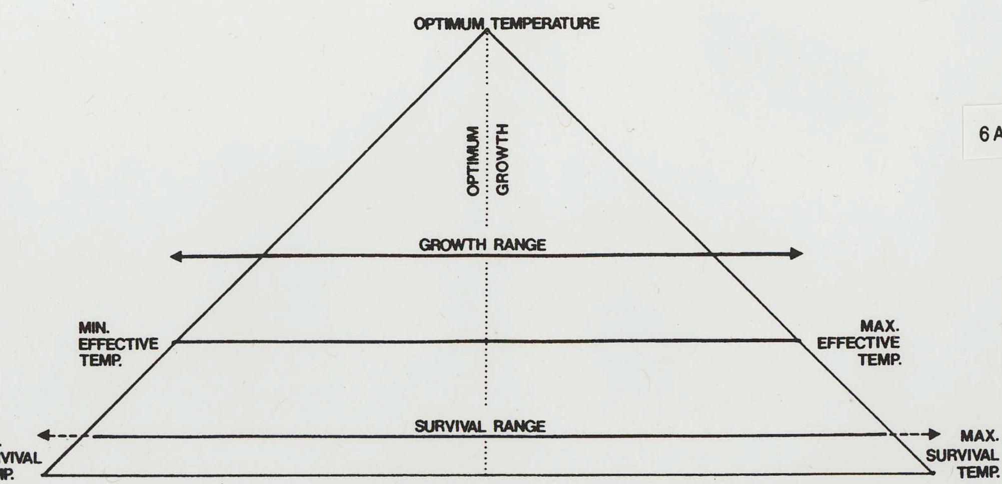

Figure 4.7. Cardinal temperatures influencing turfgrass growth and survival.

optimum growth occurs (Figure 4.7). In addition, two other cardinal temperatures (maximum survival and minimum survival) establish the temperature extremes beyond which the turfgrass cannot survive. The position of these latter temperature points varies depending on the exposure period. Turfgrasses may survive at very high or very low temperatures if the period of exposure is short; however, death may occur durng a period of prolonged exposure to those same temperatures.

In the natural environment, temperature is continually changing. The highest temperature typically occurs at midday, while temperatures are usually lowest just prior to sunrise. Furthermore, the temperature of the soil surface (bare soil) generally fluctuates more widely than that of the air 5 feet above ground—the height at which temperatures are measured by weather-reporting services (Figure 4.8). This occurs because the temperature of a surface (soil, turf, and the like) results from the net accumulation of heat energy from solar radiation. The temperature of the atmosphere, however, is the result of the transfer of heat from an absorbing surface to the air above it. Since these processes occur in sequence and usually at different rates, soil surface

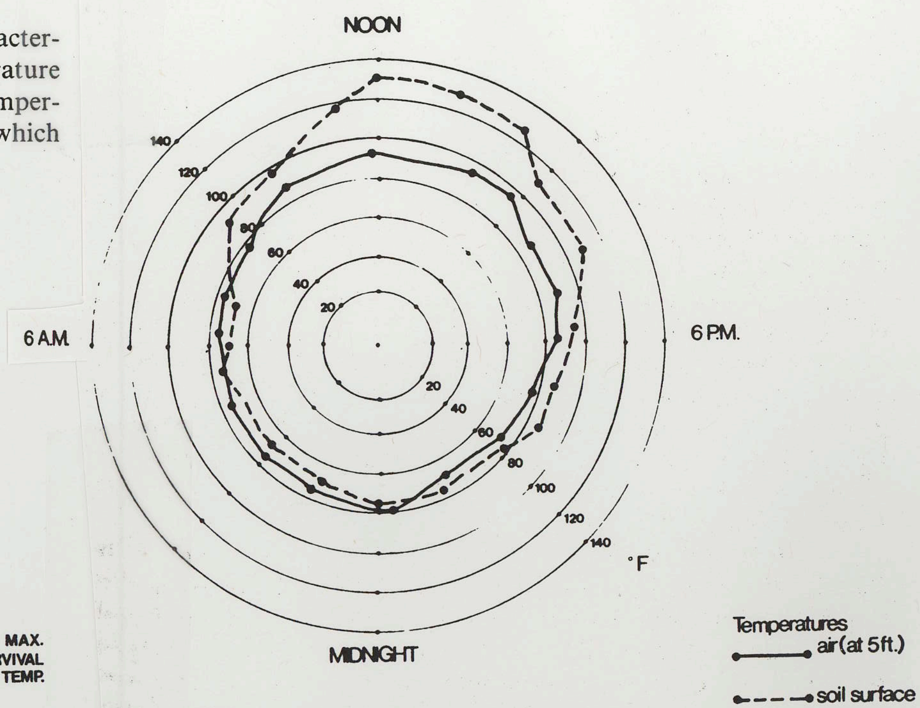

Figure 4.8. Diurnal temperature fluctuations of the soil surface.

temperature tends to be higher than that of the atmosphere during the day and slightly lower at night when no solar radiation is being received. Turfed surfaces do not accumulate heat as rapidly as most nonturfed surfaces because of transpirational cooling and other differences in their energy transfer characteristics; thus, the temperature of a turf and the air above it are generally cooler than that of many other terrestrial features. This is most evident on athletic fields constructed with artificial surfacing materials or around residences where large expanses of gravel or other materials have been substituted for lawn turf. The temperatures above these surfaces can be appreciably higher than those occurring above turfgrass plantings.

Growth measurements of turfgrasses in controlled-environment chambers set at constant temperatures cannot be directly related to the growth responses of these plants in the field. Experiments with Kentucky bluegrass and bermudagrass at constant and alternating day and night temperatures showed that shoot growth was promoted by fluctuating diurnal temperatures. The response of plants to rhythmic variations in temperature is termed *thermoperiodism.* The presumed basis for the favorable thermoperiodic growth of plants is that optimum rates of photosynthesis and growth occur at different temperatures; photosynthetic production of carbohydrates occurs during daylight hours, while plant growth proceeds at an optimum rate at night when temperatures are cooler.

Seasonal fluctuations in temperature substantially influence the growth of turfgrasses in two important respects: they determine the duration of optimum, or at least favorable, growing conditions, and they establish the limits of adaptation for each turfgrass. Thus, many warm-season species may grow well during the summer months in regions with temperate climates but do not survive the winter. Conversely, cool-season grasses may grow vigorously during late fall to mid-spring in subtropical climatic zones, only to die or be overtaken by warm-season grasses during the summer. Mulching of bermudagrass turf prior to winter may improve its survival in locations where it is marginally adapted. Likewise, carefully controlled irrigation of annual bluegrass turf can aid summer survival. Correct application of cultural practices can thus extend the limits of adaptation of specific grasses to some extent.

Besides diurnal and seasonal fluctuations, temperature varies with latitude, altitude, and topography. Increases in latitude and altitude are generally associated with cooler temperatures. Topographical features, however, exert such substantial influences on the climate of a region that predictions of the adaptation and growth of turfgrasses based strictly on latitude and altitude are unreliable. Important topographical factors that affect the turfgrass environment include the proximity and size of water bodies; the size, shape, and orientation of elevated land relative to prevailing winds; and the size, position, and density of plants and other features in the landscape. Turfgrass sites located near large bodies of water typically have less severe diurnal and seasonal temperature fluctuations than do inland sites at the same latitude. Large mountain ranges, such as the Rocky Mountains in North America and the Andes Mountains in South America, result in relatively humid conditons over vast areas of their windward sides and relatively dry conditions on their leeward sides. Even small variations in relief can substantially affect the temperature and moisture conditions for turfgrasses on different sides of elevated sites. South-facing slopes receive more direct solar radiation than do north-facing slopes in the northern hemisphere, resulting in the greatest heat accumulation at the southern and southwestern exposures. This effect can be so dramatic at some locations that, along highways, the south-facing slopes have predominantly bermudagrass turf, while Kentucky bluegrass or tall fescue thrive on the opposing north-facing slopes. Reflection of heat from the sides of buildings can also significantly affect growing conditions for turfgrasses planted around them. Summer heat is most severe along the south side, while on the north side, where heat stress is minimal, shading may threaten turfgrass survival.

Moisture

Water is the most important requirement for turfgrass growth and survival. Turfgrasses are composed of living containers (cells) of water within which all metabolic processes take place. Since the water content of actively growing turfgrasses approaches 90 percent of total mass, a small reduction in the moisture content of a plant can dramatically reduce growth and appearance, and even cause death.

The various functions of water in the plant include maintaining cell turgidity for structure and growth; transporting nutrients and organic compounds throughout the plant; comprising much of the living protoplasm in the plant cells; constituting a raw material for various chemical processes, including photosynthesis; and, through transpiration, buffering the plant against wide temperature fluctuations. This last function accounts for the greatest utilization of water by plants.

Transpiration involves the absorption, transport, and release of water to the atmosphere by plants. The evaporation of water films surrounding leaf cells requires heat energy (570 calories per gram of water) and, thus, transpiration is an important means of maintaining the plant within a tolerable temperature range. The exit of water vapor from the plant occurs primarily through the stomates, or small openings distributed throughout the leaf epidermis. As it exits the plant, much of the water vapor surrounds the leaf to form a layer of moist air called the *boundary layer.* The thickness of the boundary layer is determined by numerous factors, including transpiration rate, relative humidity of the ambient air, and wind velocity.

With rapid transpiration, high relative humidity, and no wind, the boundary layer may reach up to 1 centimeter in thickness. As wind velocity increases, the moist air surrounding the leaf is mixed with dryer air to reduce the boundary layer to as little as a few millimeters in thickness. When the ambient air is at 40 percent relative humidity (RH) and 86°F, its vapor pressure is 12.74 mm of mercury (Hg), while that of the saturated boundary layer (100 percent RH) is 31.85 mm Hg; thus the large vapor pressure gradient of 19.11 mm Hg (31.85 − 12.74) results in rapid movement of water vapor away from the boundary layer and in the direction of lower vapor pressure. On a very humid day (80 percent RH) with the same air temperature, the vapor pressure of the ambient air would be 25.48 mm Hg and the vapor pressure gradient only 6.37 mm Hg; therefore, the tendency for water vapor to move away from the boundary layer would be considerably reduced. The boundary layer is important in that it reduces the vapor pressure gradient between the intercellular spaces within the leaf and the air immediately outside the leaf. The result is a much reduced rate of transpiration and, thus, a smaller amount of water consumed by the plant.

Under some conditions, plants may lose water faster than it is absorbed by the roots. This creates an internal moisture deficit that may be favorable or highly unfavorable to the plant, depending on the magnitude and duration of the moisture imbalance. Carefully controlled moisture deficits can result in more extensive root growth and other morphological alterations that generally improve the tolerance of the turfgrass to environmental stresses. When severe moisture deficits are allowed to develop, however, the plants wilt and may eventually die or become dormant.

FORMS OF ATMOSPHERIC MOISTURE

The oceans covering approximately three-fourths of the earth's surface are the basic sources of atmospheric moisture. Water evaporates from bodies of water and, as water vapor, becomes a component of the atmosphere. When the air is cooled, water vapor condenses around small particles (condensation nuclei) to form clouds. Precipitation from clouds transfers moisture to terrestrial areas, where it is utilized to support life. Subsequent return of moisture to the atmosphere or bodies of water completes the hydrologic cycle.

Forms of moisture important in turfgrass culture include precipitation, irrigation, water vapor, and dew. The distribution of precipitation over land masses greatly affects the quantity and type of vegetation that can be sustained. In some areas even the most drouth-hardy turfgrasses may not persist without supplemental irrigation. Under different climatic conditions, turfgrasses may thrive strictly from naturally occurring precipitation. A detailed discussion of turfgrass irrigation is provided in Chapter 5.

Water vapor is a relatively small component of air, but it is an extremely important factor in the turfgrass environment. Precipitation, transpiration, and temperature are influenced by atmospheric water vapor. These, in turn, control the distribution and growth of turfgrasses and other plant species. The water vapor content, or relative humidity, of the air surrounding turfgrass shoots influences the incidence of disease through its effect on the growth and survival of pathogenic organisms (see Chapter 7). The amount of water vapor that can be held by air is directly proportional to the temperature of the air (Figure 4.9). Increasing the air temperature from 62° to 87°F allows for a doubling of the water vapor content of saturated air. Conversely, a substantial drop in the temperature of moist air can

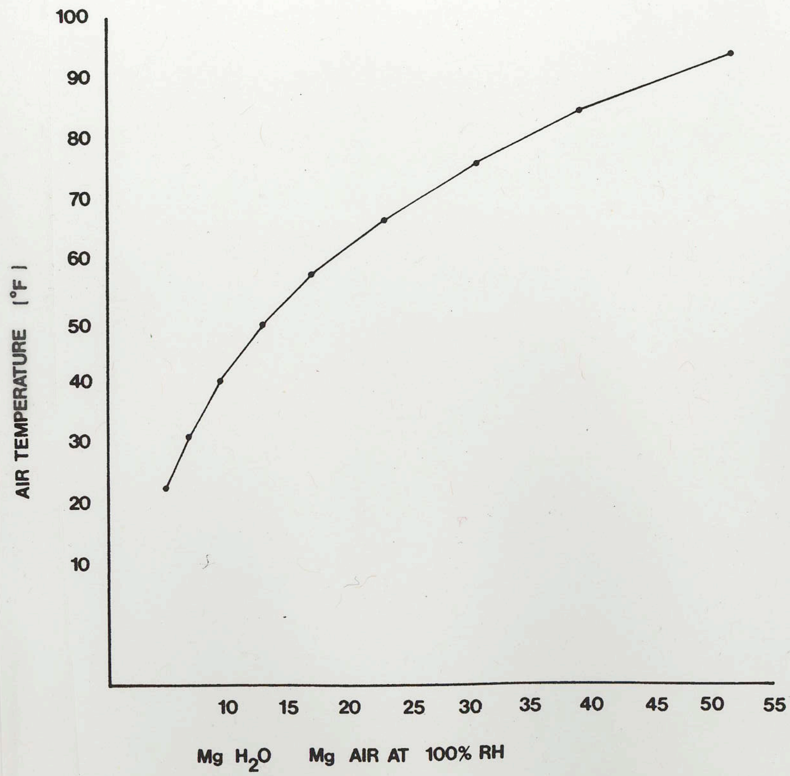

Figure 4.9. Relationship between temperature and the amount of water vapor held by saturated air.

result in condensation of moisture around particles or on plant surfaces.

Dew is the accumulation of visible moisture on plant leaf surfaces observed in the early morning hours. It is the result of several processes occurring independently or together. One process, called *guttation,* involves the exuding of plant moisture from openings (hydathodes) along the leaf margins or from the ends of freshly cut leaves (Figure 4.10). Guttation occurs when water pressure builds up in the roots during periods of minimal transpiration and rapid water absorption. Guttation fluid contains various minerals and simple organic compounds collected from within the plant. As droplets of this fluid form on the leaves, these dissolved materials accumulate on the leaf surfaces and may significantly enhance the growth of fungal pathogens as well as disease incidence. Some burning of the leaf tips may also result as the guttation fluid evaporates and leaves high concentrations of salts on the leaves.

Condensation, another dew-forming process, may occur on leaf surfaces when radiation cooling of the leaves reduces leaf temperature to below that of the surrounding air. The moist air immediately adjacent to the leaf is cooled to its dew-point temperature* and, with further cooling, water vapor condenses on the leaves. Condensation is the opposite of evaporation; latent heat is converted to sensible heat during condensation, and the drop in leaf temperature from radiation cooling is reduced. Dew formation typically occurs during the evening hours, especially on clear nights when radiation cooling is proceeding rapidly. Under favorable conditions, so much dew may form that water drips from the leaves onto the soil. The amount of moisture gained from these processes, however, is usually not very substantial.

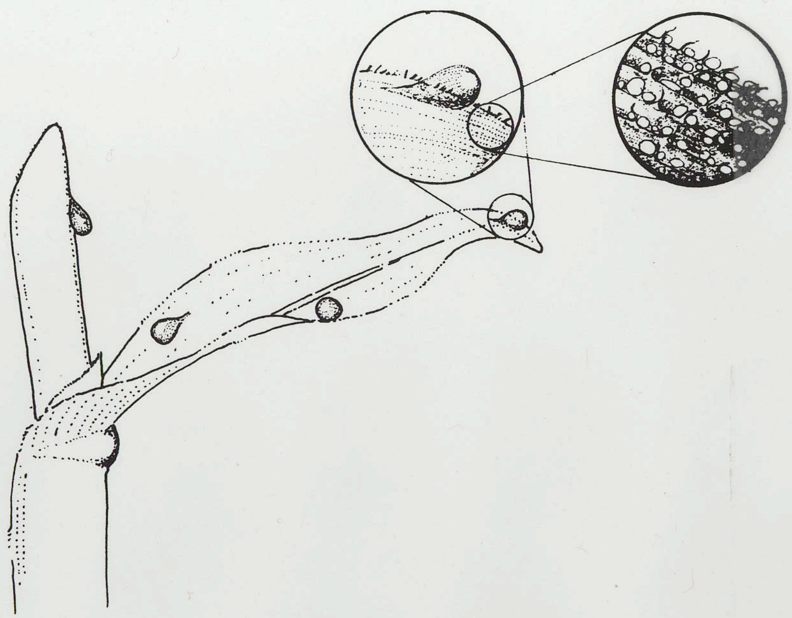

Figure 4.10. Guttation water (large droplets) and condensation water (small droplets on grass leaf surfaces).

During cold seasons when night temperatures drop to below freezing, frost is formed in place of dew. Traffic should be avoided on frosted turfs until the frost has disappeared; otherwise, damage of the leaf tissue may occur and be evident until sufficient new growth has taken place.

Dew may be of some benefit to the turfgrass community. It delays the onset of transpiration during the early morning hours so that soil moisture is conserved. In summer, the rise in leaf temperature is retarded until later in the day when the dew has evaporated. The application of various pesticides is facilitated by the presence of dew. Sprayer operators are less likely to miss strips of turf where dew clearly marks the unsprayed areas.

An undesirable effect of dew is the enhanced disease development that results, especially on greens and some other closely mowed turfs. A traditional disease control practice has been to remove dew by poling, dragging, or syringing with water during the early morning hours.

During winter months, snow and ice may accumulate on turf and remain for extended periods. Snow cover protects the turf from winter desiccation and traffic-induced injury; however, several winter disease problems may be favored in snow-covered turfs and, for this reason, greens are usually treated with preventive fungicides prior to snowfall. Freezing rain may quickly form ice layers over a turf during winter. There is little evidence to suggest that temporary ice cover can directly result in serious injury to turf; however, when the ice thaws on sites with poor surface drainage, submerged turfgrass crowns may absorb enough water to reduce their cold-hardiness. A rapid freeze could then result in some direct low-temperature injury. Partial removal of a thick ice cover may be advisable on greens to reduce the potential for this type of injury.

Wind

Wind is air in motion. Its direction and velocity can have important effects in turf through mixing action and transport of debris.

*Temperature at which air is saturated.

Concentrations of atmospheric gases, water, and other materials in the immediate vicinity of turfgrasses can be dispersed through the mixing action of wind (Figure 4.11). In effect, parcels of "clean" air from above the turf are carried into the shoot zone to displace parcels of "dirty" air. Thus, water vapor and other gases are diluted with air containing lower concentrations of these substances. Likewise, temperature differentials between air from the shoot zone and air from higher altitudes are also reduced. Evapotranspiration from the turf is accelerated by wind, because of the reduced boundary layer surrounding leaf surfaces. Finally, winds carry soil particles and other debris that can cause direct abrasion of the foliage or other effects associated

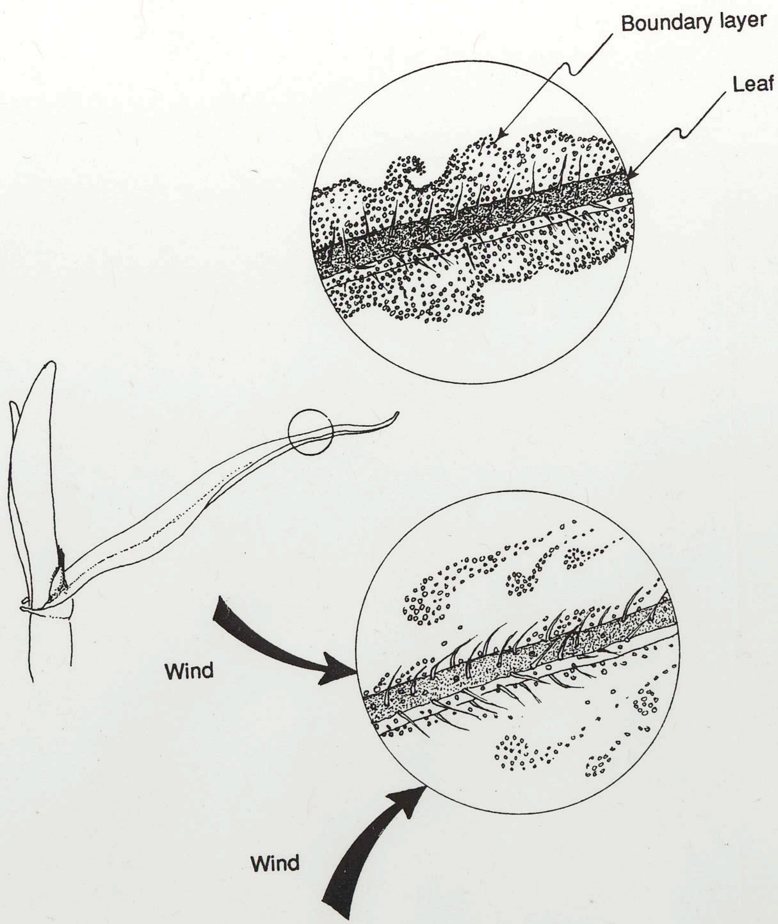

Figure 4.11. Wind-induced dispersal of water molecules constituting the boundary layer surrounding turfgrass leaves.

with deposition of materials onto the turf. Deposition of small amounts of soil is usually not harmful and may actually be beneficial as a topdressing. However, large quantities of deposited soil can completely cover the turf and entirely exclude light from photosynthetically active tissues. Layers of different soil materials in the turf profile resulting from deposition by wind can interfere with soil-water movement. This is of greatest concern where fine-textured material is deposited on top of a relatively coarse textured soil. This type of layering can result in reduced infiltration and poor drainage from the surface layer, as discussed later in this chapter.

WIND PATTERNS

Air circulation around the earth is initiated by differential heating of the earth's surface from solar radiation. Since the most direct solar radiation occurs in the vicinity of the equator, the heated air expands upward and flows toward the poles aloft. Descending air at about 30° latitude and at the poles produces high-pressure systems that migrate over water and land masses. At intermediate latitudes where cold and warm air masses converge, the warmer air is lifted and cooled. If sufficient moisture is present in the air, clouds form and produce frontal weather.

As high-pressure systems move across the ground, air also moves around and away from the centers of high pressure due to the rotation of the earth about its axis (Figure 4.12). The direction of this airflow is clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. Atmospheric pressure is lowest where two high-pressure systems (air masses) meet; this results in the formation of a low-pressure system in which air converges and rises. Air movement around low-pressure systems is counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. In the United States, air masses generally move from west to east. Their moisture and temperature are influenced by the nature of surfaces over which they travel. Canadian highs moving into the U.S. interior have relatively dry, cold air, while air from the Gulf of Mexico carries considerable moisture to states located to the north and east. Pacific highs carry moisture to the western coast and deposit most of it west of the Rocky Mountains. The continental United States is rich in climatic diversity due, in part, to the differential origin and movement of air masses across the continent.

Air movement over a specific turfgrass site is largely due to general weather patterns; however, local topography can have consider-

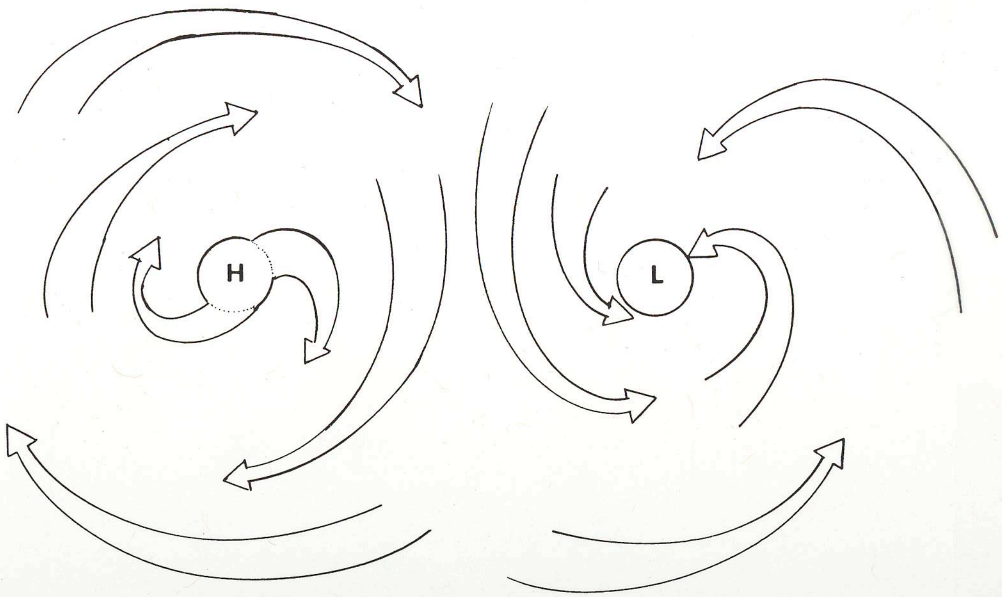

Figure 4.12. Airflow patterns associated with high- and low-pressure systems in the northern hemisphere (airflow patterns are reversed in the southern hemisphere).

able influence on the nature of winds. In coastal areas, sea breezes result from differential warming of land and sea surfaces during the day and the consequent pressure force that accelerates the air from sea to land. At night, when the land is colder than the sea, a gentle flow from land to sea, called a *land breeze,* develops. Mountain and valley winds result where air adjacent to mountain slopes warms faster than the air at some horizontal distance from the slope, causing circulation similar to sea breezes; air flows toward and up the mountain slope during the day and downward at night. Drainage winds occur from gravitation of cold air off high ground in intermountain areas. This air seeps down the slopes and gathers in valleys to produce a gentle or moderate cool or cold breeze. Where mountains are located close to a coast, drainage winds can be severe. An example is the Santa Ana wind, which flows down the Santa Ana Canyon of Southern California and spreads over the lowlands toward the coast. Chinook winds are strong, dry, and warm winds that develop along the lee slope of mountain ranges. In the United States, lowlands just east of the Rocky Mountains are subjected to chinook winds from westerly airflow across the mountains.

WIND EFFECTS ON TURF

Disruption by winds of the boundary layer surrounding turfgrass leaves and wind-induced soil deposition have already been discussed. Wind can be very beneficial to turfgrasses or highly detrimental, depending on its intensity. Air flowing at a few miles per hour can accelerate heat transfer to substantially cool a turf during hot weather. The importance of wind in drying turfgrass foliage and, thus, reducing disease incidence is most evident on sites where dense trees and shrubs obstruct air movement; the incidence of brown patch, *Pythium,* and *Helminthosporium* diseases is usually much higher on these sites. Exposed sites at relatively high elevations, however, may be subjected to severe winds that promote rapid drying of the turf. Such sites may require more irrigation during the summer. In winter, severe winds across turfgrass sites without snow cover can cause substantial desiccation and loss of turf. Protective windbreaks, including trees, mounds, and other landscape features, can effectively reduce the potential for desiccation injury to turf.

Wind is also important in disseminating weed seeds and vegetative propagules, fungal spores, salt sprays, and nearly all other foreign substances and organisms that can adversely affect turf. Atmospheric pollutants from industrial and other sources are also carried by wind. Sulfur dioxide, fluorides, ozone, and some nitrogen-containing gases can be transported in sufficient concentrations to directly injure turfgrasses or to weaken them so that they are less resistant to other environmental stresses.

EDAPHIC ENVIRONMENT

The science that deals with the influence of soil and other media on the growth of plants is called *edaphology*. The edaphic environment of a turfgrass community may be composed of synthetic materials, native soil, organic residues, or any combination thereof. Where combined, these media may form a uniform mixture or occur as distinct layers within the turf soil profile. Naturally occurring soil profiles have more or less distinct layers, or horizons, resulting from various activities termed soil-forming processes (Figure 4.13). The surface soil (A horizon) is a zone that has received leachates from organic materials situated at its surface and from which various substances have been leached by percolating water. It is typically higher in organic matter and more favorably structured than the lower soil horizons. Below is the subsoil, or B horizon, where accumulation of leachates has occurred. Subsoil is a far less suitable medium for supporting plant growth than is soil from the A horizon. The C horizon is a zone of partially weathered parent material resulting from the deposition of transported materials* or from decomposition of underlying bedrock. Thousands of years of weathering, leaching, and organic matter accumulation are necessary to transform parent materials into soil.

On turfgrass sites, the zonation of the soil profile may be obscured by mixing or transfer of materials from different horizons, especially where deep excavations of soil were made during construction operations. Also, the incorporation of various amendments may have substantially altered the characteristics of a naturally formed soil. Because soil formation requires many thousands of years, productive soils must be regarded as limited environmental resources requiring careful and intelligent management.

Soil is important as a plant growth medium in terms of its fertility, water relations, gas exchange, and physical support of plant roots. For turfgrass plantings, the soil and plant community should also provide a firm, but resilient, surface that resists compaction from traffic and use.

If a block of turf, including soil several inches deep, were examined, three distinct phases of physical composition would be evident. Soil, organic matter in different stages of decomposition, and roots and lateral shoots form a solid phase.

Organic matter may occur as indistinguishable additions to the soil mineral matter or as organic strands positioned within or above the surface soil. The undecomposed or partially decomposed layer of organic matter situated above the soil surface is called *thatch.* When integrated with the surface soil, it is a thatchlike derivative called *mat.* A specific block of turf may contain one or more of these edaphic features (thatch, mat, and soil), depending on naturally occurring phenomena, cultural practices, and turfgrass genotype (Figure 4.14). Thatch and mat formation will be discussed further in a later section of this chapter.

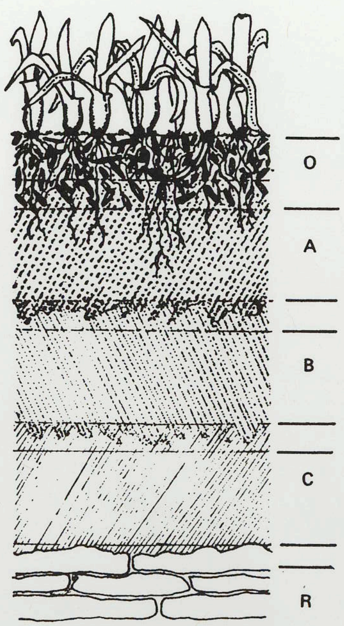

Figure 4.13. Undisturbed soil profile under turf showing surface organic residues (O), topsoil (A), subsoil (B), substratum (C), and bedrock, if present (R).

*These are loess deposits, glacial sediment, and other materials that have been moved into place by water, wind, ice, and gravity.

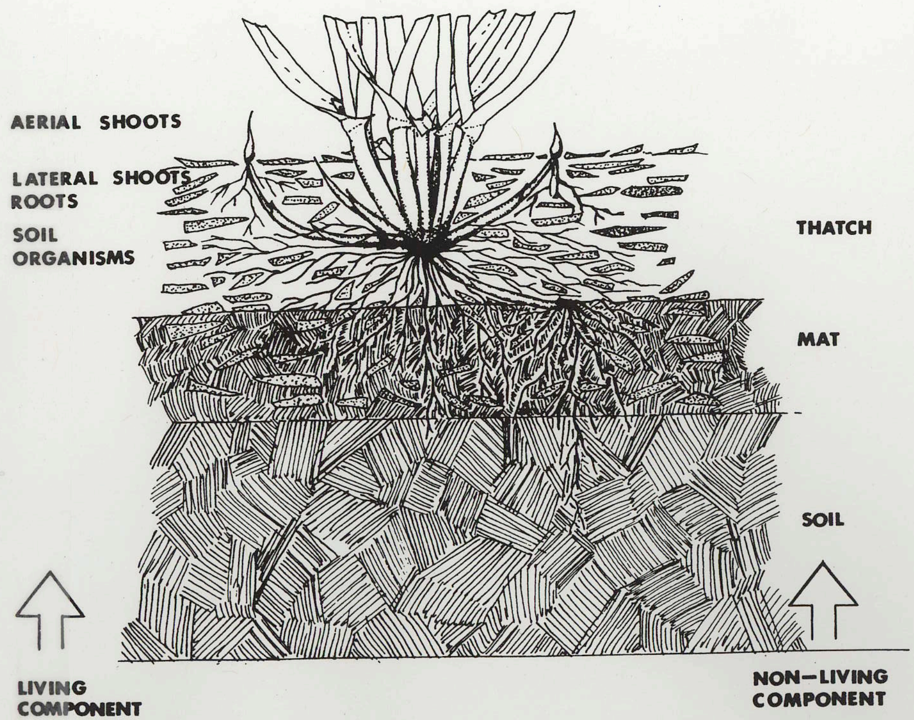

Figure 4.14. A block of turf with thatch, mat, and soil layers in the profile.

Pore spaces of varying size and shape permeate the soil and organic materials. If the turf block were completely saturated, all pores would be filled with water and dissolved substances. If it were allowed to dry, all but the smallest pores would be filled with air.

Thus, the three phases of physical composition are solid (mineral and organic material), liquid (water and dissolved substances), and air (various atmospheric gases). The relative proportions of these phases within the total volume of the block largely determine the suitability of the soil as a growth medium for turfgrasses. Generally, a composition of one-half solids, one-fourth liquid, and one-fourth air is considered an optimum proportion for a plant growth medium. The capacity of a growth medium to sustain this proportion is a function of numerous physical, chemical, and biological factors within the edaphic environment. Thus, turfgrass edaphology involves the physics, chemistry, and biology of soil media.

Soil Physics

The physical properties of a soil, including texture and structure, directly affect its aeration, moisture, and temperature and indirectly affect fertility and the activity of soil organisms.

SOIL TEXTURE

Soil texture is determined by the size of soil particles and their relative proportion. Soil particles range in size from less than 1 micrometer (μm) to 2 millimeters (2 mm or 2000 μm) in diameter. Larger particles may occur in soil, but these are considered separately as gravel or rocks. Depending on their size, soil particles are grouped into various soil separates, including clay, silt, and sand. Further divisions are recognized to separate sand into five textural groups. Thus, there are a total of seven soil separates according to the USDA system of classification (Table 4.1). The proportion of sand, silt, and clay

Table 4.1. Textural Classification of Soil Particles (USDA)

SEPARATE	DIAMETER SIZE (mm)
Very coarse sand	2.00—1.00
Coarse sand	1.00—0.50
Medium sand	0.50—0.25
Fine sand	0.25—0.10
Very fine sand	0.10—0.05
Silt	0.05—0.002
Clay	<0.002

determines the textural class. There are 12 textural classes, as illustrated in the textural triangle (Figure 4.15).

Associated with texture is the amount of surface area that exists within a given weight of soil. One gram of very coarse sand has approximately 11 cm^2 of surface, while the same weight of clay may have a total surface area of 8 million cm^2. Clay is important in chemical reactions involving the adsorption and exchange of plant nutrients. The pore sizes within a predominantly clay soil are so small, however, that much of the water contained in them is generally unavailable to plants. Silt pores are larger and retain higher amounts of plant-available moisture, while sand pores are so large that they contribute little

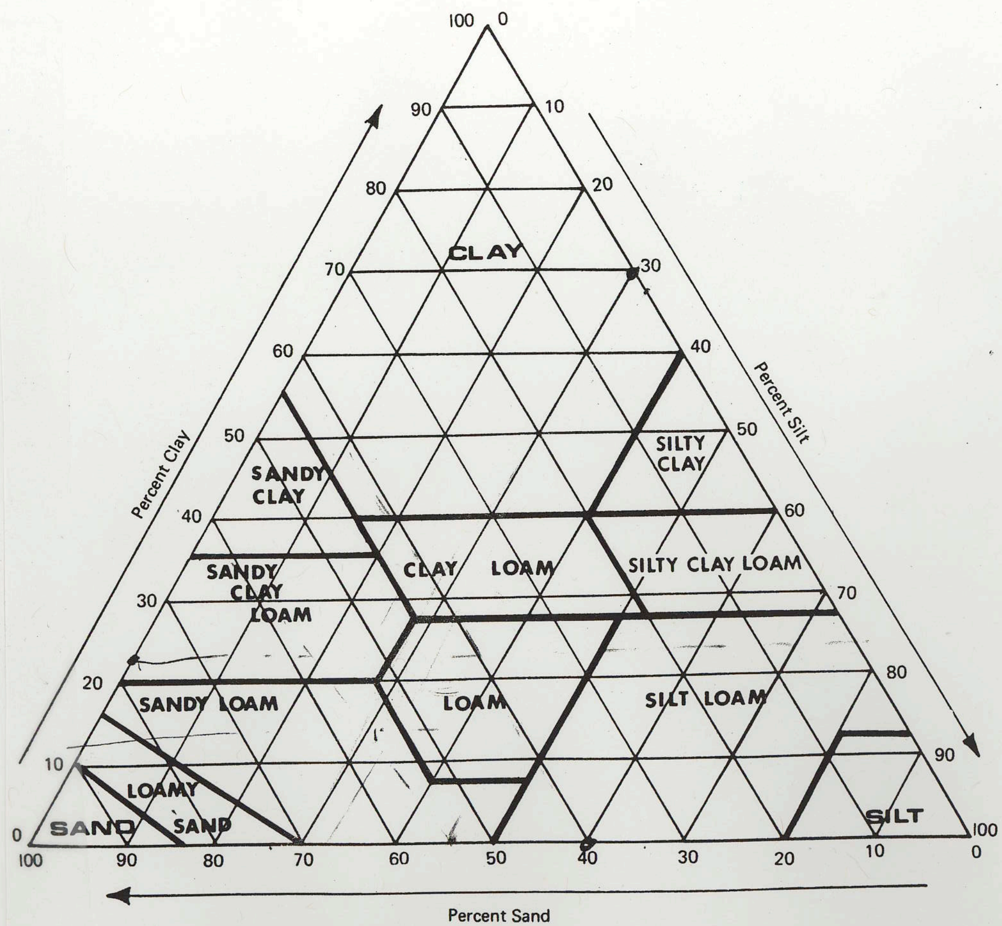

Figure 4.15. Textural triangle with soil textural classes reflecting the relative percentages of sand, silt, and clay.

to water retention. Sand is important, however, in promoting soil aeration and drainage.

SOIL STRUCTURE

Soil structure refers to the arrangement of soil particles. Clay forms aggregates in which individual particles are held together in various configurations. An individual aggregate may be as large as, or larger than, a sand particle. Thus, aggregation provides a medium in which pore sizes covering a broad range exist. If soil aggregates are sufficiently stable, a well-aggregated clay soil can serve as an excellent medium for plant growth. However, aggregates differ in their structural stability, depending on the specific clay minerals present and the strength of the binding agents holding particles together. Also, traffic, splashing rain or irrigation, and cultivation tend to destroy soil structure. Usually, the best soils for plant growth are those that contain a reasonable proportion of various soil separates and that possess a favorable soil structure that has been promoted and sustained through proper cultural practices.

The first step in aggregate formation is the bringing together of soil particles by various forces, including freezing and thawing, wetting and drying, root growth, and the activities of soil organisms. Once joined, polyvalent cations (Ca^{2+}, Mg^{2+}, Al^{3+}, and others) can bridge adjacent soil particles by forming electrostatic bonds. Various cementing agents resulting from decomposing organic matter or hydroxylation of cations can also bind soil particles together. Without structure, a fine-textured soil would be a dense, plastic mass when wet and bricklike when dry. If crushed, a dry structureless clay will be flourlike in appearance.

SOIL DENSITY

Density is the mass of substance per unit volume, usually expressed as grams per cubic centimeter (g/cc). Water has a density of 1 g/cc (at 4°C and 760 mm Hg). Two density measurements, particle density and bulk density, are commonly used for soils. Particle density (PD) is the density of dry, solid soil particles. It averages 2.65 g/cc. Bulk density (BD) is the dry weight of an undisturbed volume of soil. A well-structured, fine- or medium-textured soil will have an abundance of large and small pores, and its bulk density will be low compared to the same soil in a compacted state. If a soil could be so compacted that virtually all pore spaces were removed, bulk density would equal particle density. Comparisons of the bulk densities of different

soils may not provide reliable indexes for determining their suitability for growing plants. Sands have predominantly large pores; yet their bulk densities are high because of the relatively large mass of solids making up these media. For example, a bulk density of 1.5 g/cc may indicate a rather compacted loam soil with insufficient large pores for drainage. However, in a coarse sand of the same bulk density, aeration would not be a limiting factor in plant growth, but water retention might be. Within soil type, bulk density values are valuable for assessing the physical condition of a soil. Soil porosity can also be determined from bulk density:

$$\text{percent porosity} = 100 - \left(\frac{BD}{PD} \times 100\right)$$

A loam soil with a bulk density of 1.3 would thus have 49 percent pore spaces:

$$100 - \left(\frac{1.30}{2.65^*} \times 100\right) = 49 \text{ percent}$$

The percent pore space is only a measure of total porosity and does not directly indicate the distribution of different-sized pores. Within a particular soil type, however, the percent porosity can provide a reasonable assessment of pore size distribution if a sufficient bank of information exists to compare plant growth response to different soil porosities.

SOIL MOISTURE

The importance of soil structure and density lies in their influence on the number and size of pores and the consequent movement of water and air within the soil. Water drains rapidly from large (aeration) pores due to gravitational force. This is called *gravitational water* (Figure 4.16). The remaining water is retained as thin films on the surfaces of soil particles and as wedges where two or more particles come together. To absorb this water, plants must overcome forces of adhesion and cohesion that hold water in the soil. Adhesion is the attraction between soil surfaces and water; cohesion is the attraction between water molecules. The portion of retained water that plant roots can absorb is called *available water*. When water films are reduced in thickness, the attraction of the soil for water becomes greater, and eventually plants can no longer secure enough water to satisfy their needs. The tightly held water that is essentially unavailable to plants is simply called *unavailable water*.

*PD of soil particles averages 2.65 g/cc.

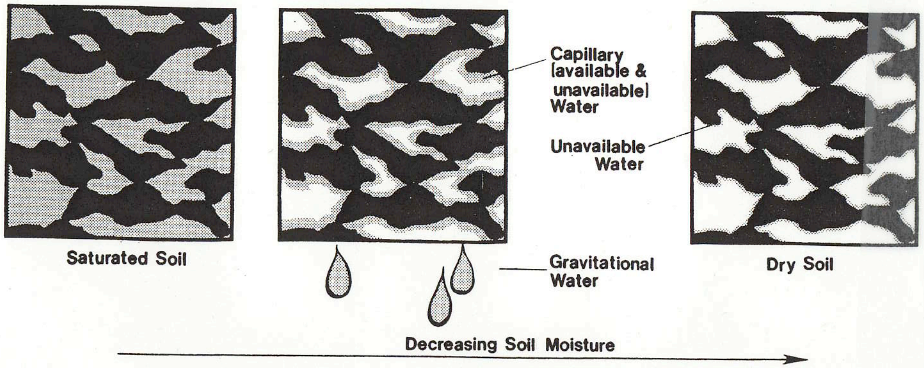

Figure 4.16. Illustration of different types of soil water. Gravitational water drains from the large (aeration) pores, while capillary water is held as films on soil surfaces.

A well-structured soil will release enough water in response to gravity so that aeration porosity is adequate to sustain healthy plants. The water content of the soil following drainage of the aeration pores is called *field capacity,* and the air content is called *aeration capacity.* These are not precise values but are useful as indexes of soil structure for a given soil. In a poorly structured soil, removed water may not be replaced by air because of soil shrinkage. Such soils form massive clods with large cracks instead of friable granules.

The thickness of a water film at which plants can no longer absorb sufficient water to sustain growth is about the same for all soil types. However, the water content, measured in grams of water per gram of dry soil, at which this occurs varies among soils because of large differences in total surface area. When plants growing in a particular soil wilt irreversibly, the soil is said to be at its *permanent wilting point,* and the amount of water remaining in the soil is called the *permanent wilting percentage.* This amount ranges from 1 to 2 percent for sandy soils to 25 to 30 percent for fine-textured (clayey) soils.* Thus, a measure of soil water content cannot serve as a guide to a plant's soil-water requirement, but a good relationship exists between a plant's water needs and the work required to remove a unit of water from the soil. Water potential ($\psi\omega$) is an expression of the energy status of soil water relative to pure, free water. Soil-absorbed water is not capable of doing as much work as pure, free water; thus, its energy, or water potential, is lower. Differences in water potential between two locations in a soil, called the *water potential gradient,* provide a force

*S. A. Taylor and G. L. Ashcroft, *Physical Edaphology,* (San Francisco: W. H. Greeman and Company, 1972), p. 8.

that causes water to flow from locations of higher to lower water potential.

Soil water conductivity is an expression of the ease with which the soil conducts water. In compacted soils, conductivity is low because of high resistance to flow. Well-structured soils conduct water more rapidly. Where a plant is pulling water from the soil immediately surrounding its roots, replenishment of this root-zone soil moisture depends on (1) the water potential gradient between the root-zone soil and a location in the soil where water is available and (2) the conductivity of the soil.

In a saturated soil, water potential near the soil surface approaches zero. As the soil drains, water potential becomes progressively lower (more negative). Water movement in saturated and unsaturated soils should be considered as two distinct processes. Saturated flow occurs when all or most of the pores are filled with water. It takes place through large pores and, thus, is most rapid in coarse-textured soils. The principal force acting on the water is gravity, and the direction of flow is primarily downward. If the number of large pores decreases suddenly at a given soil depth, downward movement is restricted, and water may accumulate above the interface where the two media meet, resulting in a temporary water table. This occurs in sand or thatch overlying loam soil or with a compact subsoil.

Unsaturated water flow occurs in soils in which the large pores are not filled with water. The rate of unsaturated flow depends on the thickness of water films surrounding soil particles; thicker water films allow faster flow rates than thinner films, due to the differences in water potential. Thus, water moves faster in moist soils than in dry soils. Unsaturated flow proceeds in any direction, irrespective of gravitational force. The "wick action" or capillary flow of water from lower to upper soil locations is actually unsaturated flow.

Where the continuity of water films is disrupted, as at the interface between a fine-textured soil and an underlying coarse-textured soil, unsaturated flow is slowed or may stop altogether (Figure 4.17). This can result in an accumulation of water, called a *perched water table,* above the interface. Water will not move across the interface until the water potential in the above soil builds to a level sufficient to overcome the attraction between the water and the fine-textured soil. When sufficient water potential has built up from continued downward flow toward the interface, water will enter the coarse-textured soil and be conducted away.

This principle can be applied to turf soils in which layers exist either by design or by error. Consider a fine-textured soil that has been modified by incorporation of sand or other coarse amendments. If the incorporation is not uniform, but results in subsurface layers of

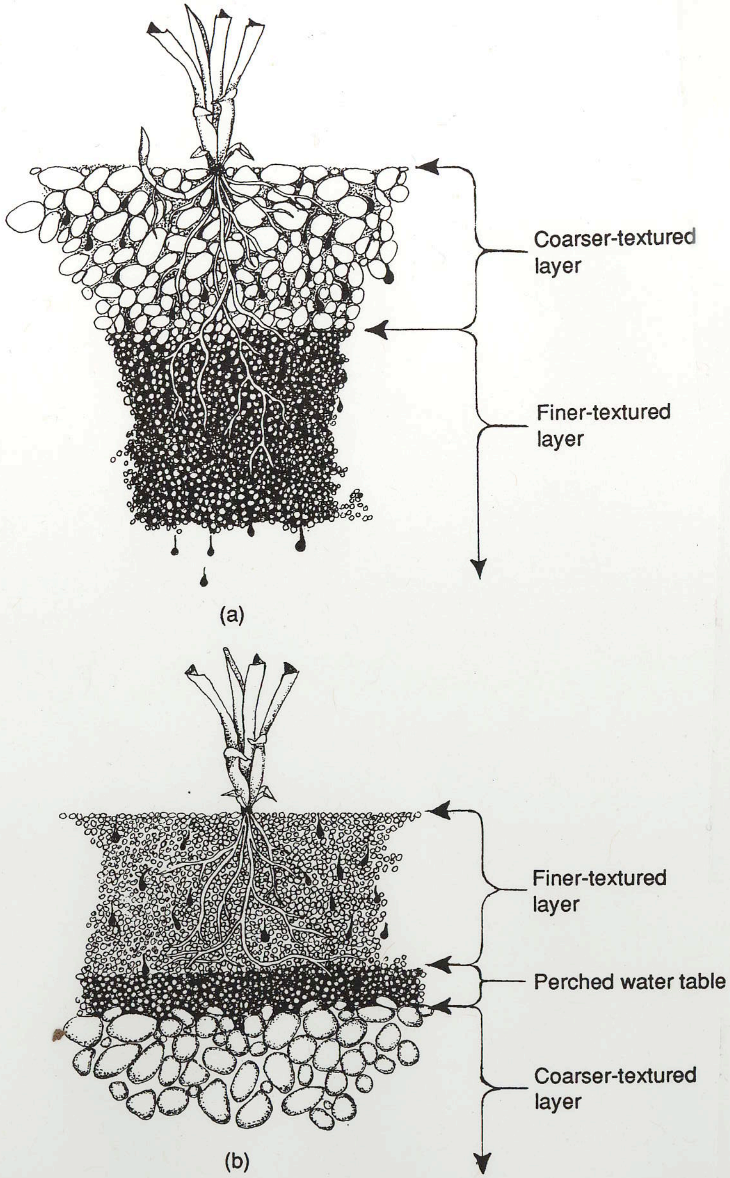

Figure 4.17. Layered turf–soil profiles in which a coarser-textured layer (thatch, sand) overlies a finer-textured soil (a), and in which a finer-textured soil overlies a layer of coarser texture (b), resulting in a perched water table.

coarse material, water flow within the profile can be disrupted. On the other hand, where a layer of coarse sand has been intentionally positioned beneath finer-textured sand with some loam soil and or-

ganic amendments, a perched water table will develop following irrigation or rainfall. In this instance, the perched water table is desired to compensate for the low water retention of the fine sand. A USGA green is constructed in this fashion to combine the advantages of compaction resistance and moisture retention in the root zone. Results are only satisfactory, however, where the design includes a critical depth of the surface medium; a too-shallow surface layer will not drain properly, while a layer that is too deep will be too dry at the surface. This can be illustrated using a rectangular household sponge measuring 5 by 3 by 1 inches (Figure 4.18). When the sponge is saturated and positioned with its 5-inch and 3-inch sides in the horizontal plane, very little water drains out. Turning the sponge 90° to position the 3-inch side vertically results in more drainage. Rotating the sponge so that its 5-inch side is vertical results in still further drainage. This demonstration shows the relationship between height of the water column and water retention within the pore volume of the sponge. Cutting the sponge horizontally into three equal sections while it is still in the 5-inch vertical orientation and squeezing each section to remove internal moisture would reveal that the uppermost section was driest and the lowermost section was wettest. Thus, the distribution of moisture within the sponge is not uniform, but moisture is predominantly within the lower levels.

The sponge analogy facilitates understanding of some soil water phenomena. In a USGA green, the sponge represents the surface soil medium, and the air, or "free space," beneath the sponge represents the coarse sand or gravel layer underlying the surface medium. A workable greens design depends on rather precise application of principles of soil physics. The settled depth (depth after soil settling) of the surface medium must be correct, and the physical composition of the medium must be such that air and moisture within the turfgrass root zone are sufficient to sustain growth. The USGA green and other designs are discussed further in Chapter 9.

SOIL AERATION

The process by which soil air is replaced by atmospheric air is called *soil aeration*. Soil air differs from atmospheric air in that it has higher concentrations of carbon dioxide and water vapor but less oxygen. These differences are due to the consumption of oxygen and production of carbon dioxide by soil organisms. The magnitude of these differences depends on the rate of gaseous exchange between the atmosphere and soil. Aeration is brought about by processes of diffusion and mass flow.

Diffusion is the movement of gases through air-filled pores from

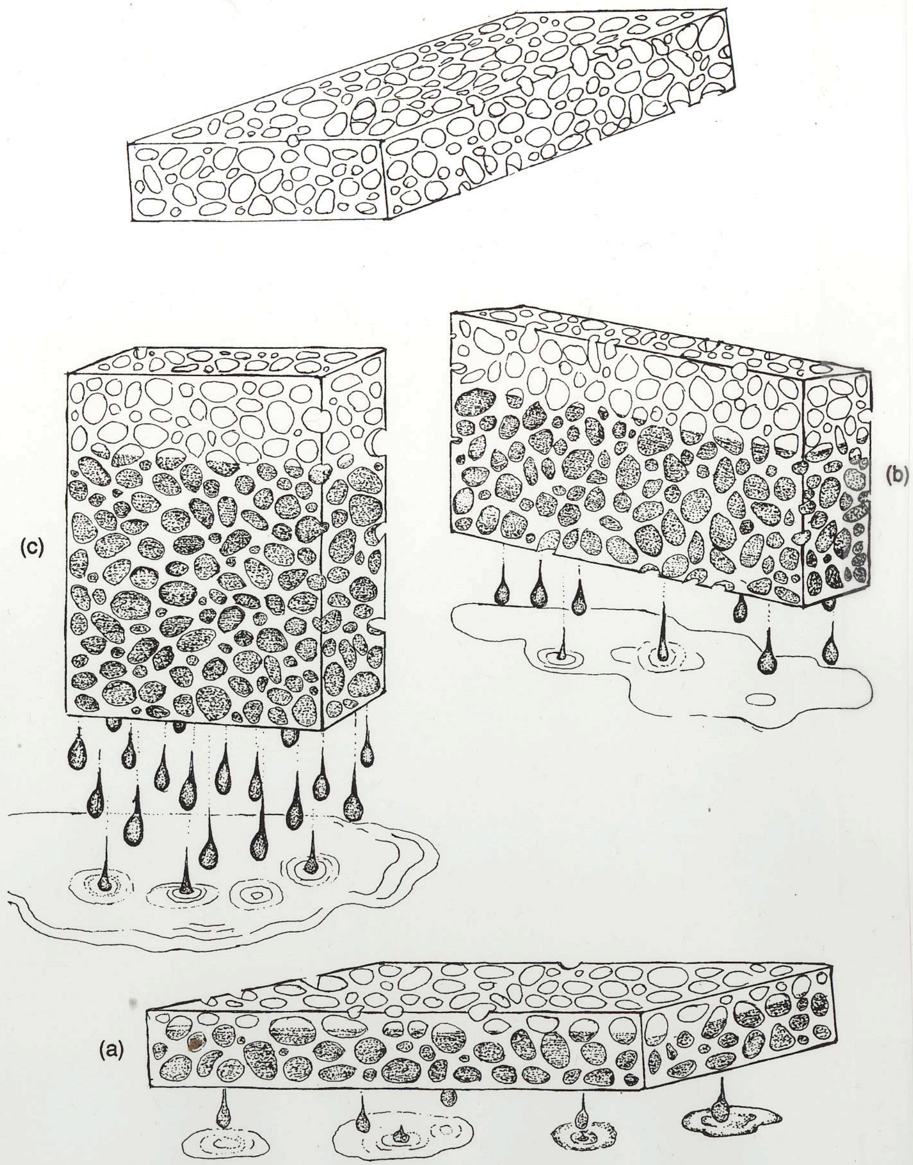

Figure 4.18. Water drainage from a saturated sponge (a) with the thin side oriented vertically, (b) after being rotated 90°, and (c) after its longest side is oriented vertically.

regions of higher to lower concentration of the gas and is proportional to air-filled porosity. Diffusion is low in compacted soils because of reduced pore size and number and the discontinuity of soil pores. Sim-

ilarly, diffusion is low in wet soils because of the absence or reduction of air-filled pores and the extremely low diffusion rate of air in water. Mass flow occurs as a result of:

1. Expansion and contraction of soil gases due to temperature and barometric pressure changes.
2. Soil air removal, through precipitation and irrigation, and replacement, as water is removed by drainage, plant use, and evaporation.
3. Wind action causing air to be forced into the soil at some locations and pulled out at others. Relative to diffusion, mass flow is considered to have a minor influence on soil aeration.

Poorly aerated soils are often deficient in oxygen. Oxygen is utilized by plant roots and soil organisms for respiration, and carbon dioxide is evolved. Without an adequate exchange of gases between the atmosphere and soil, oxygen levels decline and carbon dioxide levels increase in soil air. This can result in reduced absorption of nutrients and water by plant roots, since they must have sufficient oxygen for respiration to generate the energy necessary for these processes. Microbial activity for decomposing organic matter is also inhibited in oxygen-deficient soils, as is the bacterial oxidation of ammonia to nitrate nitrogen. Denitrification, the conversion of nitrate to N_2 and N_2O gases, occurs in persistently wet soils, resulting in a loss of soil nitrogen to the atmosphere.

Turfgrass communities growing in compacted or persistently wet soils are often invaded by various weed species. This reflects, in part, the differential adaptation of plants to poorly aerated soils. Some weed species that typically grow under these conditions may possess the capacity to transmit foliar-absorbed oxygen to their roots to satisfy respiratory requirements. Thus, specific weeds may have a definite advantage over many turfgrasses through their ability to persist under these conditions.

SOIL TEMPERATURE

Many physical, chemical, and biological events that take place in soil are strongly temperature dependent. Soil temperature is, in turn, affected by (1) atmospheric conditions (air temperature, moisture, wind, and solar radiation), (2) thermal absorption and conductivity of the soil, and (3) plant cover. Atmospheric influences on soil temperature have been discussed in an earlier section of this chapter.

Thermal absorption is a function of the color, moisture level, and organic matter content of the soil. Generally, darker soils, high in organic matter, are more efficient in absorbing heat from the atmosphere. Heat absorption occurs faster in drier soils, since the *specific heat* (the amount of energy necessary to raise the temperature of 1 gram of a substance by 1°C) for water, dry mineral soil, and dry humus is 1.0, 0.2, and 0.4, respectively. Therefore, as the water content of a given soil increases, the amount of energy from solar radiation or atmospheric air required to raise its temperature increases proportionately.

Changes in soil temperature are influenced by the air–moisture–solid balance in the soil. Sandy soils warm and cool at a faster rate than clayey soils, due to generally higher aeration porosity and lower retained moisture. Similarly, compacted soils undergo slower warming and cooling than well-structured soils. Temperature fluctuations during the winter months in cooler climates can be beneficial in promoting desirable soil structure. Alternate freezing and thawing of soil and wetting and drying cycles tend to rearrange compacted soil particles in such a way that aeration porosity is increased. Other temperature-dependent processes, including the formation and expansion of ice crystals and the shrinking and swelling of organic matter, also result in improved soil structure.

Most reactions within the soil occur more rapidly at higher temperatures. Microbial activity, which is so important for nitrogen transformations, organic matter decomposition, and other processes, is highly temperature dependent.

Adaptation of turfgrass species is considerably influenced by soil temperature. Root growth of Kentucky bluegrass is slowed at soil temperatures above 75°F, while 95°F is favorable to bermudagrasses.

Soil Chemistry

Soil chemistry deals with the chemical reactions that occur on colloidal surfaces in the soil. A knowledge of soil chemistry is essential for understanding nutrient availability to plants, phytotoxic effects from soil constituents, and the relationship between fertility and soil physical and biological properties.

SOIL COLLOIDS

Soil colloids include small soil particles measuring 0.2 μm or less in diameter. Clay and humus make up the colloidal component of a soil. Most clay colloids are secondary crystalline minerals formed from such primary minerals as quartz, feldspars, micas, hornblende, and augite. Clay colloids are made up of planes of oxygen atoms (O, OH) with silicon (Si^{4+}) and aluminum (Al^{3+}) atoms holding the oxygens together by ionic bonding (Figure 4.19). Several planes of oxygen atoms with intervening silicon and aluminum planes make up each crystal layer within a clay particle, which has many layers stacked like a deck of cards. Silicon and aluminum atoms making up the cationic planes within and the crystal layer may be substituted with cations of lower valence. For example, Al^{3+} may be substituted for Si^{4+}, Mg^{2+}, Fe^{2+}, or Zn^{2+} for Al^{3+}. This is called *isomorphous substitution* and results in unsatisfied negative charges in adjacent oxygen atoms. The net effect is the colloid's negative surface charges and consequent capacity for attracting cations *(cation exchange capacity)*. Other sources of negative charges include unsatisfied edge-of-clay oxygens, ionized hydrogen from hydroxyl groups, and ionized hydrogen from organic materials.

Not all clays are alike. Most have a definite, repeating arrangement of component elements *(crystalline structure)*. Others are not formed from well-oriented crystals and, therefore, are said to have an *amorphous structure*. In temperate climates, the silicate clays are predominant. Sesquioxide clays, which are hydrous oxide clays of iron

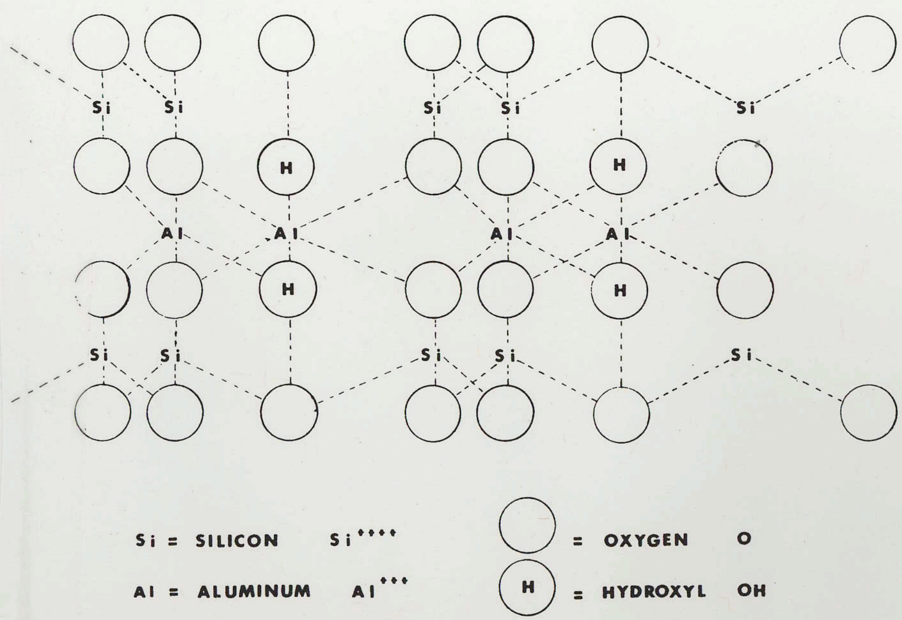

Figure 4.19. Clay particle configuration with many layers, each consisting of several planes of oxygen atoms with intervening silicon and aluminum ions (two-to-one-type clay).

and aluminum (rather than silicon), are found mostly in tropical climates. Within the silicate clays, composition of the crystal layer varies, depending on the number of oxygen and cationic (Si^{4+}, Al^{3+}) planes. A one-to-one-type clay has one plane of silicon and one plane of aluminum cations, along with two outer planes, and a shared inner plane, of oxygens. A two-to-one-type clay has two planes of silicon and one of aluminum with two outer planes, and two shared planes, of oxygens, as in Figure 4.19. Kaolinite is an example of a one-to-one-type silicate clay; it has almost no isomorphous substitution; its cation exchange capacity is low; and because adjacent crystal layers are strongly attracted to each other by hydrogen bonds, water does not penetrate between layers, and almost no swelling of the colloids occurs. Montmorillonite is a two-to-one-type silicate clay; it has a relatively high cation exchange capacity due to considerable isomorphous substitution, and adjacent crystal layers allow water to penetrate between them, causing substantial swelling of the clay particle and shrinking upon drying. Illite is a two-to-one-type silicate clay similar to montmorillonite except that potassium ions hold adjacent crystal layers together, thus limiting swelling.

Sesquioxide clays have a crystal layer composed of a single plane of iron and aluminum cations with planes of hydroxyl ions on either side. These clays do not swell, are not sticky, and behave more like fine sands than silicate clays.

Humus is a semistable end product of decomposing plant and animal residues. Its organic components continue to decompose, but very slowly compared to the original organic material. Humus colloids are amorphous organic particles consisting of proteins, lignins, and complex sugars. On a dry-weight basis, humus has a cation exchange capacity many times greater than that of clay colloids. Negative charges are due to ionization of hydrogen from oxygen-containing groups including:

$$\text{carboxyl groups } (R\overset{O}{\overset{\|}{C}}OH \longrightarrow R\overset{O}{\overset{\|}{C}}O^- + H^+) \text{ in acids}$$

and

$$\text{hydroxyl groups } (ROH \longrightarrow RO^- + H^+) \text{ in alcohols and phenols}$$

CATION EXCHANGE

Positively charged ions (cations) are adsorbed onto colloids at sites with unneutralized negative charges. The adsorbing force is electrostatic attraction between the positively and negatively charged entities (Figure 4.20). The adsorbed cations resist removal by leaching water, but can be replaced by other cations in solution due to mass action and the preferential adsorption of some cations over others. This exchange of one cation for another is called cation exchange. When such cations as NH_4^+ (ammonium), K^+ (potassium), and Ca^{2+} (calcium) are supplied to the soil by fertilizers and lime, these ions replace other cations already adsorbed to exchange sites on the surfaces of soil colloids and plant roots.

The distribution of different cations on exchange sites can dramatically affect soil physical properties. Saturation of the exchange sites by Na^+ (sodium) causes a dispersal of clay particles and a consequent loss of desirable soil structure. Sodium-saturated soils become severely compacted and highly impermeable to water. Replacement of adsorbed sodium cations by calcium can improve flocculation of clay particles, resulting in an overall improvement in soil physical properties.

Cation exchange capacity (CEC) is the amount of exchangeable cations per unit dry weight of soil. It is measured in milliequivalents (mEq) per 100 grams (g) of soil.

The amount of a specific cation in the soil (in pounds per acre) can be calculated from CEC values. First, determine the milliequiva-

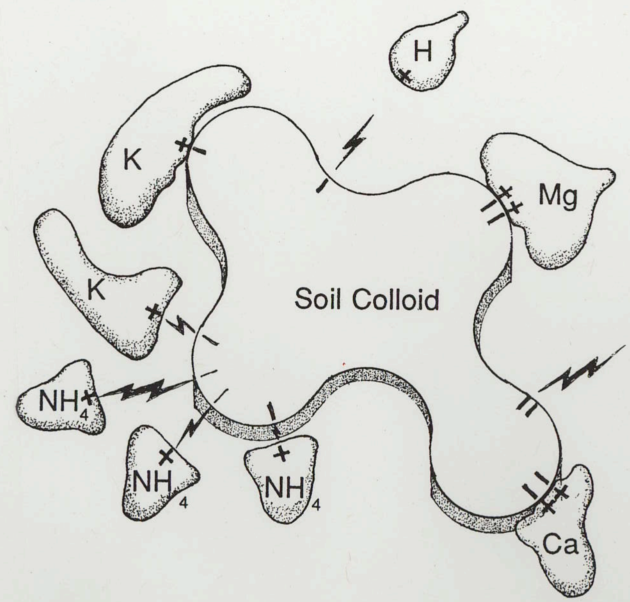

Figure 4.20. Electrostatic attraction between negatively charged soil colloid and positively charged ions.

lent weight of the cation by dividing its molecular weight by its valence. Calcium (Ca^{2+}) has a molecular weight of 40 g/mole and a valence of 2 (two positive charges). Therefore, 40 g/mole ÷ 2 = 20 g/equivalent or 20 mg/mEq. Then, multiply the milliequivalent weight (20 mg/mEq) by the milliequivalent value for calcium given as part of the total cation exchange capacity. If the calcium portion of CEC is determined to be 13 mEq/100 g soil, then 20 mg/mEq × 13 mEq/100 g = 260 mg/100 g or 260 mg/100,000 mg or 2600 ppm (parts per million) calcium. Finally, since the surface 6 2/3 inches of an acre of field soil (acre furrow slice) weighs approximately 2 million pounds, 2600 ppm Ca is equal to 5200 lb Ca/acre.

The principal cations and their equivalent weights are shown in Table 4.2.

A soil with a cation exchange capacity of 20 mg/100 g may have 65 percent of the exchange sites satisfied with calcium (13 mEq/100 g), 10 percent with magnesium (2 mEq/100 g), 5 percent with potassium (1 mEq/100 g), and the rest with sodium, ammonium, hydrogen, and other miscellaneous cations. The sum of all milliequivalents of all cations adsorbed onto exchange sites in each 100 g of soil is the cation exchange capacity.

The CEC of a soil depends on its texture, type of clay, percent organic matter, and, possibly, pH. Fine-textured soils typically contain more clay and, therefore, have higher CECs than coarse-textured soils. The specific type of clay is important, since montmorillonite ranges from 80 to 150 mEq/100 g, while kaolinite has CECs between 3 and 15 mEq/100 g. Organic matter varies widely in CEC, depending on origin and degree of decomposition; some types contribute significantly to soil CEC due to the multiple adsorptive sites on organic colloids for retaining cations. Since many of these adsorptive sites are the result of ionization of hydrogen, increasing pH usually results in more ionization and, therefore, higher CEC.

Table 4.2. Equivalent Weights of Principal Cations

CATION	MOLECULAR WEIGHT (g/mole)	VALENCE	MILLIEQUIVALENT WEIGHT (mg/mEq)
Calcium (Ca^{2+})	40	2	20
Magnesium (Mg^{2+})	24	2	12
Potassium (K^+)	39	1	39
Sodium (Na^+)	23	1	23
Ammonium (NH_4)	18	1	18
Hydrogen (H^+)	1	1	1

SOIL REACTION

Soil reaction is an indication of the acidity or alkalinity of a soil and is measured in units of pH. Soil pH is actually the negative logarithm of the hydrogen (H^+) ion concentration. The pH scale extends from 0 to 14; each whole-number unit reflects one magnitude of change in the hydrogen (or hydroxide OH^-) ion concentration. At a pH of 7, the H^+ and OH^- concentrations are both 10^{-7} (0.0000001) moles*/liter, and the soil solution is said to be a neutrality. As the pH decreases to 6, the H^+ concentration increases to 10^{-6} (0.000001), and the solution becomes more acidic by a factor of 10 (one magnitude) with each pH unit decrease. At pH units above 7, the OH^- concentration is greater than the H^+ concentration, and the solution is said to be alkaline. The relationship between H^+ and OH^- ions in the soil solution is expressed by the formula

$$\frac{[H^+][OH^-]}{[HOH]} = 10^{-14}$$

which states that the product of the H^+ and OH^- ion concentrations always equals 10^{-14}.

Soil pH can be measured with a pH meter, which actually measures the H^+ concentration in the soil solution. This is called *active* acidity. Because of the exchangeable H^+ and Al^{3+}† on soil colloids, soils also have *potential* acidity. An equilibrium exists between active and potential acidity. If bases are added to neutralize active acidity, potential acidity is released from the exchange sites to maintain equilibrium. Thus, soils containing appreciable amounts of clay and organic matter resist pH change and are said to be buffered due to their relatively high cation exchange capacities and, therefore, high potential acidities.

The normal pH range in soil is 4.0 to 8.0. In areas where sufficient precipitation occurs to leach soluble basic salts, the soil pH tends to decrease. Irrigation may induce a similar effect, except where the irrigation water contains basic salts that accumulate in the soil. In dry regions where evapotranspiration exceeds precipitation, soil pH tends to be alkaline due to the accumulation of basic salts in the surface soil. Sodic soils (high in sodium) may reach pHs of 8.5 to 10.

*A mole equals one molecular weight of ion. Since the molecular weight of H is approximately 1 g/mole, 1 mole = 1 g.

†Hydrolysis of Al^{3+} yields H^+ ions due to this reaction sequence:

$$Al^{3+} \xrightarrow{H_2O} Al(OH)^{2+} + H^+ \xrightarrow{H_2O} Al(OH)_2 + H^+ \xrightarrow{H_2O} Al(OH)_3 + H^+$$

Turfgrass species are adapted to a wide range of soil pHs; however, optimum growing conditions usually exist where the pH is neutral to slightly acid (7.0–6.0). Probably the most important detrimental effect of excessive acidity is the high solubility of aluminum and manganese, which can reach toxic concentrations in acid soils. Soil pH can be adjusted upward through periodic applications of lime, which result in better rooting, increased turfgrass vigor, improved availability of some plant nutrients, reduced availability of toxic elements, and more favorable microbial activity. Liming materials include quicklime [CaO], hydrated lime [$Ca(OH)_2$], calcitic limestone [$CaCO_3$], and dolomitic limestone [$CaCO_3$–$MgCO_3$]. Lime moves through the soil profile very slowly; therefore, applications are especially effective when made prior to establishing a new turf, so that the lime can be tilled in, or possibly in conjunction with core cultivation of established turfs. The amount of lime necessary for neutralizing excessive soil acidity varies with soil texture. Clayey soils may require nearly twice as much lime as sandy soils for comparable pH adjustments. Results from soil-testing laboratories usually include recommendations for lime application where needed. Depending on the type of lime used, the amount applied at any one time should not exceed 25 to 50 lb/1000 ft^2. If hydroxide [$Ca(OH)_2$] or oxide [CaO] forms are used, rates higher than 25 pounds may severely injure the turfgrass, especially when atmospheric temperatures are high.

Excessive soil alkalinity can result in deficiencies of several plant micronutrients. The problem often can be reduced by additions of acidifying fertilizers, such as elemental sulfur and sulfates of ammonium, iron, and aluminum. As with pH adjustments by liming, the amount of sulfur or sulfates required depends on the buffering (cation exchange capacity) inherent in the soil, free $CaCO_3$ in the soil, and dissolved salts in the irrigation water. The maximum rate of finely ground elemental sulfur that should be applied at any one time is 5 lb/1000 ft^2. Due to the high potential for sulfur-induced injury, applications should be confined to periods of moderate to low atmospheric temperature.

SALTED SOILS

Salted soils are classified on the basis of two criteria: soluble salt content and exchangeable sodium percentage. The three types of salted soils are saline, sodic, and saline-sodic.

Soluble salts are inorganic chemicals that have a water solubility greater than 2.4 g/liter (the solubility of gypsum). The amount of total soluble salts in a soil can be estimated by measuring the electrical con-

ductivity (EC) of the soil solution. The procedure involves mixing water with a weighed soil sample to form a saturated paste, removing the water by suction filtration, and measuring the EC of the extract in millisiemens per centimeter (ms/cm). If below 4 ms/cm, the soil is nonsalty. The exchangeable sodium percentage (ESP) is the percentage of total exchangeable cations that are sodium.

Saline soils contain sufficient soluble salts to reduce plant growth. Characteristics of saline soils include EC $>$ 4 ms/cm; ESP $<$ 15 percent of CEC; and pH $<$ 8.5. Saline soils are usually well structured and quite permeable. On the other hand, sodic soils contain sufficient Na^+ to raise the pH to 8.5 or higher; EC is less than 4 ms/cm; and ESP is 15 percent or more of CEC. High concentrations of Na^+ cause dispersion of clay particles, resulting in a structureless, impermeable soil. Saline-sodic soils are high in both sodium (ESP $>$ 15 percent of CEC) and soluble salts (EC $>$ 4 mmhos/cm).

Controlling problems associated with saline soils depends on reducing the concentration of soluble salts. Irrigation must be performed beyond plant moisture requirements in order to leach excess salts from the turfgrass root zone, and it must be frequent enough to prevent drying of the soil so that salts do not move upward in capillary flow. On sites where the intensity and frequency of irrigation cannot be sufficient to adequately reduce salt concentrations in the root zone, or where the irrigation water contains high concentrations of salts, turfgrass species that are tolerant of saline conditions must be used. Warm-season turfgrasses with good salt tolerance include bermudagrass, zoysiagrass, and St. Augustinegrass. The most tolerant of the cool-season turfgrasses is creeping bentgrass, followed by tall fescue and perennial ryegrass. A relative newcomer to this group is alkaligrass *(Puccinellia distans),* which appears to be uniquely adapted to saline conditions.

In sodic soils, exchangeable Na^+ must be replaced by other cations that do not disperse clay particles but, rather, will cause flocculation to occur. The principal cations used for this purpose include Ca^{2+} and H^+ generated from gypsum ($CaSO_4$), sulfur, or other materials. Gypsum usually causes the fastest response due to the direct exchange of Ca^{2+} for Na^+ on colloidal surfaces. This remedy is most effective when the material can be incorporated into the soil as opposed to being surface applied. The gypsum requirement (GR) is the amount of gypsum, in tons per acre, required to reclaim the soil, and is calculated by the formula GR = 1.72 (Na_x), in which Na_x is the milliequivalents of sodium per 100 grams of soil (mEq/100 g) to be replaced. For example, if the exchangeable sodium has been measured to be 10 mEq/100 g (CEC = 28 mEq/100 g; therefore, ESP = 36 percent), and the desired exchangeable sodium is 3 mEq/100 g, then GR = 1.72

(10 − 3) = 12 tons of gypsum per acre or 553 lb gypsum/1000 ft^2.* The efficiency of sulfur in reclaiming sodic soils is approximately 5.6 times that of gypsum; therefore, only 100 lb sulfur/1000 ft^2 (553 ÷ 5.6 = 100) would be required to achieve the same effect. However, since sulfur must first be oxidized microbially to sulfuric acid before it can yield H^+ ions to replace exchangeable Na^+, reaction time would be much slower than with gypsum, which directly supplies Ca^{2+}.

Soil Biomass

Soil biomass consists of the sum total of all living organisms, and their residues, that become part of the soil profile. *Live biomass* is that portion of soil biomass that includes an array of microscopic and macroscopic organisms, plant roots, and subsurface shoots. *Residual biomass,* or dead organic matter, is made up of undecomposed and partially decomposed remnants of plant and animal material occurring within and above the soil. Given the dynamic nature of soil biomass, changes within and above the soil dramatically influence the suitability of the medium for sustaining turfgrasses.

LIVE BIOMASS

The soil is virtually alive with huge populations of microscopic plants called *microflora* (bacteria, fungi, actinomycetes, algae) and microscopic animals called *microfauna* (protozoa, nematodes). Occasionally, we find evidence of larger, soil-inhabiting animals such as earthworms, arthropods (insects, mites, centipedes, millipedes), gastropods (slugs, snails), and even larger burrowing animals including moles, gophers, and mice. These are referred to collectively as *macrofauna.* Live roots and other plant parts constitute the soil *macroflora.*

Soil organisms are largely beneficial in that they decompose organic materials, convert materials into plant-available forms, and improve soil structure. Some, however, are pests that can cause extensive damage to turf.

Of the soil microflora, bacteria are the most numerous. Bacteria occur in two principal categories: *autotrophic* bacteria, which derive their nutritive carbon from CO_2; and *heterotrophic* bacteria, which obtain carbon from organic matter. Autotrophs are very beneficial because of the processes by which they obtain energy. Oxidation of ammonia to nitrites and then to nitrates, as well as oxidation of sulfur,

$$^{*}\ \frac{12 \text{ tons}}{\text{acre}} \times \frac{1 \text{ acre}}{43{,}560 \text{ ft}^2} \times \frac{1000 \text{ ft}^2}{1000 \text{ ft}^2} \times \frac{2000 \text{ lb}}{1 \text{ ton}} = \frac{553 \text{ lb}}{1000 \text{ ft}^2}$$

iron, manganese, and other elements, is an important process for providing plant-available nutrients. Conversion of carbon monoxide (CO) to methane (CH_4), a reduction reaction, or to CO_2, an oxidation reaction, is certainly important in highly populated areas where CO emissions would otherwise accumulate to phytotoxic concentrations in the atmosphere. Some autotrophs engage in less desirable activities such as denitrification, or the reduction of nitrate (NO_3^-) to N_2 or N_2O gases. This may account for substantial losses of fertilizer nitrogen to the atmosphere, especially from persistently wet soils.

Heterotrophs include most of the soil bacteria. They are the principal organisms for decomposing organic matter and, as such, provide for recycling of nutrients contained within plant and animal residues. Were it not for heterotrophic bacteria, turfgrass and other plant communities (indeed, all organisms) would be virtually inundated by their own debris. Some heterotrophs fix atmospheric nitrogen and thus enable plants to obtain nitrogen from the air. Certain nitrogen-fixing heterotrophs attack root hairs of host plants, resulting in the formation of protective nodules. A symbiotic union is thus formed, in which the plant supplies organic substances and minerals to the bacteria, and the bacteria fix and supply nitrogen to their host plant. Fixation actually occurs as the bacteria utilize atmospheric nitrogen for synthesizing body proteins; since the life span of a single bacterium is only a few hours, a portion of the bacterial population is continually dying, decomposing, and releasing ammonium and nitrate ions to host and adjacent plants. The principal turf-type host plants that support nitrogen-fixing bacteria are the clovers.

Fungi occur in three primary categories depending on their nutritive processes: parasitic, saprophytic, and symbiotic fungi. Parasitic fungi that cause plant diseases will be discussed in Chapter 7. Saprophytes are fungi that function as decomposers of residual biomass. Some are especially important for breaking down cellulose and lignin, which are resistant to many other types of biodecomposition. Symbiotic fungi form an intimate association with some plant roots that aids in the absorption of specific nutrients. This association is referred to as *mycorrhizae.*

Actinomycetes are widely known for their production of antibiotics. They are important in turf soils as decomposers of residual biomass, especially cellulose and other resistant forms.

Algae are chlorophyll-containing microflora that serve as a source of organic matter. Some types function in nitrogen fixation. In turf, algal mats sometimes develop following severe disease incidence. Upon drying, they form a hard crust that, unless removed or broken up, makes the surface nearly impervious to water.

The microfauna include protozoa and nematodes. Protozoa are primitive, single-celled animals that feed mainly on bacteria. Nematodes are threadlike worms that are widely distributed in agricultural soils. Predaceous nematodes prey on soil flora and faunae, including other nematodes. Parasitic nematodes are of greatest concern because of their ability to infest plant roots and severely damage turfgrasses. Their entrance into plants facilitates entry by other pathogens. Control of turfgrass-parasitic nematodes will be discussed in Chapter 7.

Prominent among macrofauna are the earthworms. Of the 7000 species that have been identified, three are most commonly encountered. These are the garden worm *(Helodrilus calinginosus),* the red worm *(Helodrilus foetidus),* and the night crawler *(Lumbricus terrestris).* Earthworms do not feed on live plants but are extremely effective in reducing accumulations of residual organic materials. The ingested organic material and soil are excreted as small, granular aggregates containing substantial amounts of plant nutrients. The deposited casts are sometimes objectionable in closely mowed turf; however, the beneficial effects of earthworms often outweigh any problems resulting from their activity. In studies conducted in Illinois, control of earthworm populations by pesticides resulted in thatch development in an otherwise thatch-free Kentucky bluegrass turf.* Other effects included higher soil bulk densities, reduced water infiltration and hydraulic conductivity, lower soil organic matter concentrations, shallow rooting, higher wilting proneness, and greater disease severity. Although present throughout the growing season, the earthworms appeared to be more active at the surface during spring and fall.

Occasionally, masses of dead earthworms may be present at the turf surface. This usually occurs when the sun suddenly appears following rainfall. At other times, the surface of the ground may be disrupted from earthworm activity. Under these circumstances, it is tempting to schedule a pesticide application for control. However, we should carefully weigh the long-term advantages and disadvantages before deciding that a chemical control measure will invariably result in better turf!

Several arthropods and gastropods serve as decomposers of organic debris. Others, particularly certain insects, cause serious damage to turf. The appearance of a few of these small animals does not necessarily dictate that some control measure should always be undertaken. Many insects or other small animals occurring in turf do not cause injury, and some of the potentially injurious ones are of no importance unless their populations build up to high levels. Strategies

*A. J. Turgeon, W. N. Bruce, and R. P. Freeborg, "Thatch Development and Other Effects of Preemergence Herbicides in Kentucky Bluegrass Turf," *Agronomy Journal* 67 (1975), 563–565.

for controlling insects and other pests will be discussed further in Chapter 7.

Depending on location, numerous larger animals may occasionally be troublesome because of their burrowing into the turf. As with other macrofauna, their activities may be beneficial. However, when serious damage occurs or is threatened, control measures may be appropriately undertaken (see Chapter 7).

The soil macroflora include turfgrasses and other plants that are anchored to the soil. Root, rhizome, and basal shoot growth are influenced by soil conditions and, in turn, influence the physical, chemical, and biological properties of the soil. Where a fairly contiguous plant community (turfgrass) covers the soil, there is a moderation of soil temperature and moisture extremes. The protective cover provided by turfgrasses reduces soil compaction from traffic, splashing raindrops, and other physical forces. Growth of roots and other belowground plant organs stirs the soil and promotes better structure. Deposition of plant debris within and atop the soil provides residual biomass, which is the carbon and energy source for many beneficial soil organisms. Decomposition of organic residues brings about numerous benefits measurable as improved soil properties and plant growth.

RESIDUAL BIOMASS

Residual biomass includes the undecomposed and partially decomposed organic residues that occur within the soil and above the soil surface. Cultivated mineral soils usually contain 1 to 5 percent organic matter. Turf soils may have somewhat higher percentages, especially near the surface. Three distinct types of residual biomass are common in turf: thatch, mat, and the organic fraction usually associated with cultivated soils.

Thatch is the layer of organic residue located immediately above the soil surface. It may be largely undecomposed, or at an advanced stage of decomposition, especially where it meets the soil. Although considerable attention has been devoted to processes of thatch formation, its development in turf is still not completely understood. A typical explanation is that thatch occurs when plant biomass production exceeds decomposition, resulting in an accumulation of surface debris followed by growth of the turfgrass plants within this debris. Obviously, factors that suppress the decomposition rate or promote excessive production could trigger this imbalance. Another possible explanation is that growth of adventitious roots and stolons above the soil surface provides a medium within which dead or dying plant residues accumulate and decompose more slowly than in soil. Regardless of the mechanism of formation, the living plant community apparently exerts a stabilizing influence on thatch, since it has been shown that death of the turfgrass community is often followed by destruction of the thatch layer. Limited work to characterize thatch as a turfgrass growth medium has shown that it is a well-aerated, compaction-resistant medium with poor nutrient- and water-holding properties. Thus, turfgrasses with most of their roots confined to the thatch layer are more prone to injury from environmental stresses. Diseases and insect injury are generally more severe where thatch is a problem. Measures for controlling thatch will be discussed in Chapter 6.

Mat is a surface layer of organic residue mixed with soil. Often, mat results where soil has been incorporated into a thatch layer. Mechanisms by which this can occur include some naturally occurring phenomena, such as earthworms depositing soil within the thatch or wind deposition of soil onto thatchy turf, and some culturally induced transformations, such as topdressing with soil or reincorporation of soil following core cultivation. Mat is generally considered a desirable feature in turf, especially in those turfs receiving frequent or intensive traffic. A mat layer provides not only better surface resiliency, but seems to stabilize turf against impacting forces encountered in athletic activities. Although a mat layer may not be easily seen in a turf profile, its presence can be qualitatively determined by carefully working a soil core (taken with a soil probe) with the fingers, beginning at the base of the core. At moderate moisture, the soil should be easily separated from the roots until the mat layer is reached; then, the soil resists separation due to the organic material interspersed throughout the surface soil.

Besides thatch and mat, other types of organic residues occur in mineral soils. These result from incorporation of organic amendments during establishment or from the deposition of organic materials during soil formation and under cropping practices. Since the soil organic matter is constantly undergoing change, it must be replenished continuously to maintain soil productivity. The principal replenishing sources are plant roots, residues of other plant parts, and soil microorganisms. Decomposition of organic matter results in the use of some carbon, nitrogen, and other elements by microorganisms; release of carbon compounds, water, and other elements to the soil and to the atmosphere; and the formation of a semistable organic residue called *humus*.

Nitrogen is the nutrient that most often controls the rate of organic matter decomposition because it is used to synthesize proteins in new microbial populations. The ratio of carbon to nitrogen, called the C:N ratio, controls the decomposition rate and largely determines whether nitrogen will be released to the soil or pulled from it by microbial activity. Most organic materials have a carbon content of about 40 percent; however, the nitrogen content is variable. Bacteria have C:N ratios of 4:1 to 5:1, while fungi have a C:N ratio of 9:1. Plant residues having C:N ratios of 20:1 or narrower contain sufficient nitrogen to supply microorganisms and also release nitrogen for plant use. This is because, in the decomposition of organic matter, much carbon is released to the atmosphere as CO_2, while most of the nitrogen is reused repeatedly by microbial populations, thus narrowing the C:N ratio. As the organic matter is used up, microorganisms die, decompose, and release more CO_2, as well as plant-available nitrogen. When organic materials with large C:N ratios, such as sawdust (250:1) and straw (90:1), are added to the soil, nitrogen is pulled from adjacent soil. Since microorganisms can compete more effectively than plant roots for the available nitrogen within the soil, plants may show symptoms of nitrogen deficiency unless additional nitrogen is supplied through fertilization.

The organic matter of greatest importance in soil is that which is undergoing rapid decomposition; this is called the *active organic matter*. The principal benefits derived from active organic matter include soil aggregation and stabilization of soil aggregates by organic gums, which cement clay particles together; mineralization (release) of plant nutrients; and production of humus, which provides additional cation exchange capacity. Decomposition is favored by conditions that favor microbial activity, including adequate aeration and moisture, slightly acid to neutral pH, available nutrients, suitable temperatures (optimum is 95°F), and a favorable C:N ratio.

BIOTIC ENVIRONMENT

The biotic component of the turfgrass environment includes, primarily, the use and culture of the turf by people. Other biota are sometimes included, but, except for humans, most of these have been discussed under Soil Biomass. Human activities frequently constitute the most formidable of adverse influences against turfgrass persistence and quality. Conditions that reflect the type and intensity of these activities are wear and compaction.

Wear is the physical deterioration of a turfgrass community resulting from excessive traffic. What constitutes "excessive" traffic will vary depending on turfgrass genotype, the physiological condition of the plants, and edaphic and climatic conditions. A rough bluegrass turf in a wet, shaded environment will be much more susceptible to wear than a well cared for bermudagrass turf on a sunny, sandy site. However, since bermudagrass would not survive where rough bluegrass is well adapted as a permanent turfgrass, the comparison is somewhat misleading. Additional comparisons of turfgrass species for wear tolerance are given in Chapter 3.

Some general statements about turfgrass wear are appropriate. Direct pressure applied to the turf tends to crush shoots, especially when the plants are stiff with frost or wilted. When the pressure is accompanied by lateral forces, wear is greater. Since wear tolerance varies so much from site to site, and at different times on the same site, a threshold level must be determined for each location and time of year. Then measures can be taken to control traffic intensity so that the wear threshold is not exceeded. In many situations, wear can be minimized by making some simple adjustments. On golf courses, traffic patterns on greens, approaches, exit lanes, and tees can be made less concentrated by coordinating placement of pins and tee markers. Shifting sandtrap positions to provide wider traffic lanes and improving drainage can dramatically reduce wear. On athletic fields used for practice, intensive traffic can be shifted to different field locations to reduce wear and promote recovery of worn turf. Strategic placement of ornamental plantings, sidewalks, fences, and other landscape features is often effective in uniformly distributing, or concentrating, traffic for the purpose of promoting better turf. With a little imagination, small provisions that will result in less wear can be made on almost any site.

In succeeding chapters, cultural practices are discussed in detail; much of this discussion is oriented toward achieving healthy, vigorous turfgrass that is highly tolerant of environmental stresses, including traffic. Some rather baisc cultural considerations for improving wearability include raising the mowing height to provide larger, more vigorous shoots; reducing plant succulence by adjusting fertilization and irrigation practices; and cultivating to promote better shoot and root growth. Some conditions require that traffic be avoided entirely. Frosted leaves, winter-dormant turfgrass, and wet soil conditions predispose the turf to serious injury from even light traffic. Moderately shaded turfgrass may be so weak that it is intolerant of all but minimal traffic.

Compaction is a physical condition of soil resulting from the compression of soil constituents into a relatively dense mass. A moderate amount of compaction may be desirable in turf soils to provide a firm surface and favorable contact between plant roots and soil particles. Severe compaction, however, is usually associated with inadequate soil aeration and poor drainage due to the loss of aeration porosity. Soil compaction can occur in the surface layer or at some depth within the soil profile. Subsurface compaction layers are called *pans;* the two principal types are genetic pans and induced pans. Genetic pans occur naturally due to very high clay content present during soil formation (claypan) or cementation of soil particles by organic matter or inorganic materials (hardpan). Induced pans result from pressure applied by cultivation or tillage operations. In field crop culture, a *plow sole* can develop at plow depth due to the alteration of soil physical structure from horizontal operation of the plow. With core cultivation of turf, induced pans can occur at the maximum depth of penetration of the tines and, possibly, along the sides of the holes resulting from cultivation.

Surface compaction of turf soils occurs primarily in response to traffic. Particles of soil are pressed together with resultant increases in bulk density, soil strength, and water-holding capacity and decreases in aeration porosity, water infiltration, and percolation. Increased bulk density results from the reduction in soil volume following compaction. The change in volume is attributed to a loss in total porosity; some pores are lost or reduced in size as clay particles become flattened in a plane perpendicular to the compacting force. The large (aeration) pores, which are so important in drainage and soil aeration, are most susceptible to loss during compaction. The accompanying shift in pore-size distribution (to generally smaller pores) accounts for the increased moisture retention. Capillary pores assume a higher proportion of total porosity as aeration porosity is reduced. Increased soil strength, measurable as resistance to penetration, partially accounts for the poor root growth commonly observed in compacted soils. Inadequate oxygen concentration and relatively high concentrations of CO_2 and other potentially toxic gases are additional reasons for poor rooting in compacted soils. Low water infiltration and percolation rates typically accompany shifts in pore-size distribution toward smaller pores.

Physiological responses of plants to soil compaction include not only reduced root growth, but reduced shoot growth, reduced water and nutrient uptake, reduced tolerance to heat and drouth stresses, and increased susceptibility to scald and direct low-temperature injury. The generally weakened condition of plants growing in compacted soils coupled with prolonged periods of high humidity in the plant's microenvironment account for higher disease incidence as well.

Ecological responses of turfgrass communities subjected to soil compaction are frequently observed as dramatic shifts to compaction-tolerant weed populations such as knotweed, annual bluegrass, goosegrass, and white clover.

Soil compaction influences turfgrass cultural requirements. More frequent fertilization and irrigation are required to compensate for restricted rooting and generally poor growth. Cultivation practices are necessary to improve infiltration, drainage, and plant growth. Installation of drainage tiles, silt trenches, and catch basins may be essential to dispose of excessive surface moisture. Pesticides are required to control the higher incidence of weeds and diseases that frequently accompany soil compaction. Furthermore, mistakes in the application of pesticides that result in damage to the turf are of greater consequence where, because of compaction, suitable conditions for turfgrass recovery do not exist.

Methods for preventing soil compaction or reducing its effects will be discussed further in Chapters 6 and 8.

QUESTIONS

1. Differentiate among reflection, absorption, transmission and conversion (to chemical energy through photosynthesis) of **light** by a turfgrass plant.
2. How is a turfgrass plant likely to respond to reduced light intensity?
3. How should cultural practices be adjusted to sustain a turfgrass community under low light intensities?
4. Explain the processes by which turfgrasses dissipate **heat** energy.
5. What factors influence turfgrass aerial shoot and root **temperatures?**
6. Explain the significance of **moisture** in turfgrass growth and survival.
7. What influence is **wind** likely to have on turfgrass growth and survival?
8. What is turfgrass **edaphology?**
9. Characterize a block of soil (supporting the growth of turfgrass plants) with respect to the distribution of solids, water, and air.
10. List the different forms of organic residues that are likely to be found in association with turf and explain their significance in turfgrass growth and quality.
11. Differentiate between soil texture and structure.
12. Characterize the different types of soil moisture that occur in a saturated soil and explain their significance with respect to turfgrass growth and quality.
13. What are soil colloids and in what ways are they likely to contribute to turfgrass nutrition?
14. What is meant by soil reaction and what is its significance with respect to turfgrass growth?
15. Characterize the biotic environment influencing a turfgrass community.