NATURAL RESOURCES

CORNELL COOPERATIVE EXTENSION

Water and the Soil

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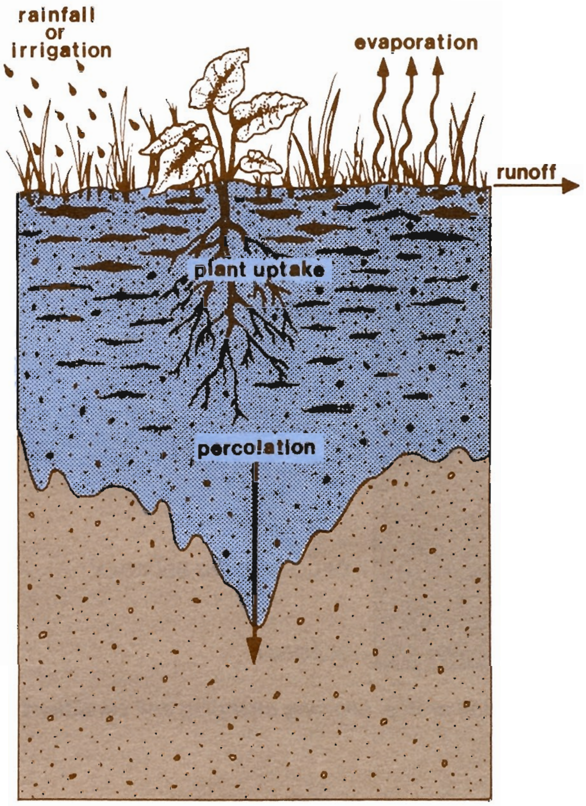

Figure 1. Water cycle in the soil.

Movement of water through soil determines whether a septic system will drain properly, whether a basement will flood, and how successful a farmer's harvest will be. The farmer's dependence on having the right amount of water in the soil becomes obvious when heavy spring rains delay planting or when crops are threatened by summer droughts. Less apparent, but equally important, are the effects of interactions between soil and water on the availability to crops of soil nutrients, fertilizers, and pesticides over the course of the growing season. Movement of water through soil determines how much fertilizer or pesticide remains accessible to crops versus how much is carried downward to the groundwater. Understanding how soil properties determine water movement, therefore, is critical in managing farm irrigation, fertilizer and pesticide applications, and protection of well-water quality.

Water added to the soil by rainfall or irrigation percolates downward to groundwater unless it runs off to surface waters, evaporates, is taken up by plants, or remains within the soil profile (fig. 1). Chemicals such as fertilizers or pesticides can move with the water if they are not first broken down into other chemicals, transformed into gases, retained by chemical interaction with the soil solids, or taken up by plants or soil organisms. Successful crop production depends on careful management of soils, water, and chemicals so that plant needs are met as they occur in the growing season. Meeting these needs efficiently may also help to protect the quality of underlying groundwater by reducing the amount of chemicals being carried downward by recharge waters.

Composition of Soil

The word *soil* generally refers to the layers of materials overlying solid rock, called bedrock. These soil materials consist of four major components: minerals, organic matter, water, and gases (fig. 2). Soils are formed from the decomposition of both bedrock and organic materials. Bedrock decomposes slowly over decades or centuries, gradually weathering into minerals such as quartz, calcite, or dolomite. Soil material in any one location may have been derived from the underlying bedrock or may have been carried there by glaciers, streams, or wind. Whatever their origin, the mineral particles combine with organic matter from decomposition of plant and animal tissues to form soils. Most organic matter is found in the topsoil, with gradually increasing percentages of minerals in the underlying layers of subsoil (fig. 3).

The various combinations of minerals and organic matter produce different soil types, ranging from dense, impermeable clays to loose, gravelly sands. Within a single farm field, some parts of the field may drain immediately after rainfall whereas others remain flooded for weeks at a time. This is because of the varying amounts of organic matter and sizes of mineral particles in the

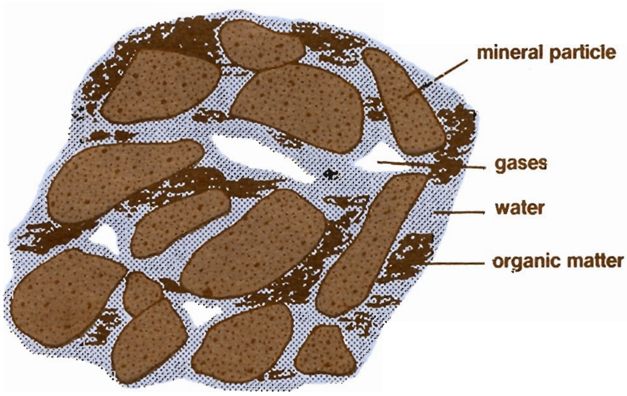

Figure 2. The four major components of soil.

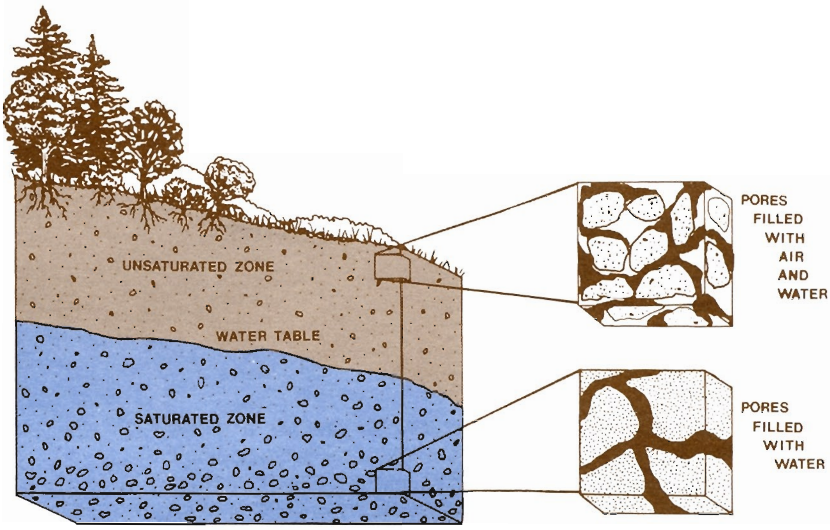

Figure 5. Composition of soil pores above and below the water table.

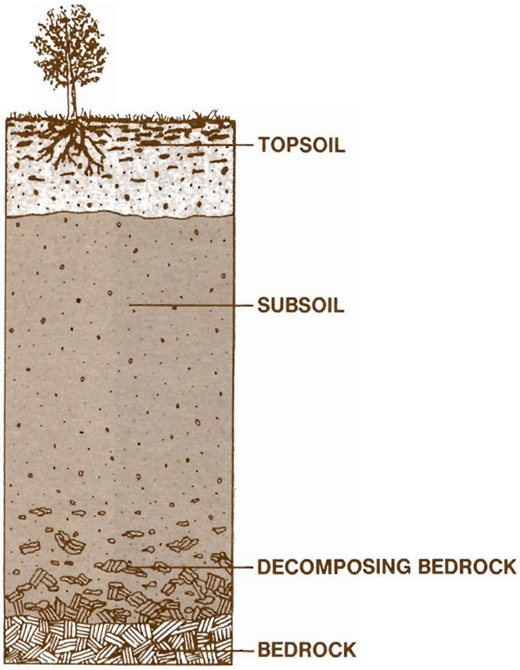

Figure 3. Soil profile, showing changing soil conditions with depth.

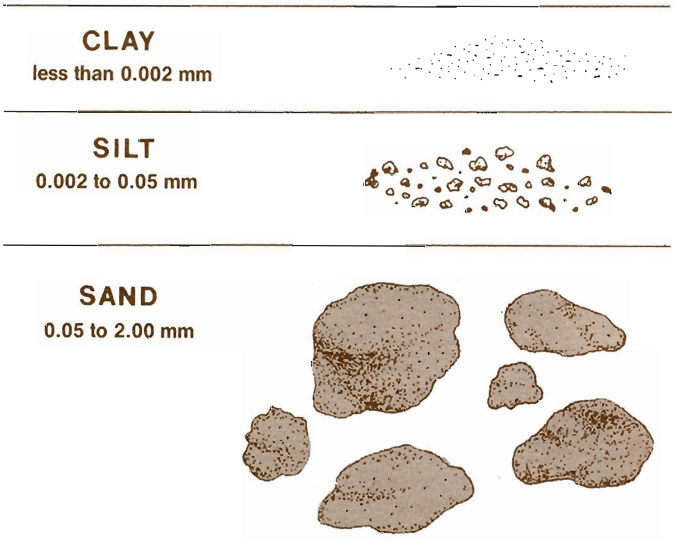

Figure 4. Soil designations based on sizes of mineral particles.

field's soils. Mineral particles can be classified into ranges of sizes shown in figure 4. These particles can be composed of a variety of minerals, depending on the rock types from which they were formed. For each soil type, the amount of organic matter and the mixture of sand, silt, and clay particles determine the behavior of the soil's two remaining components: water and gases.

The water and gases in soils reside in the pores, or "empty spaces" within the solid framework of organic matter and mineral particles. The *water table* is the dividing line in the soil profile separating the *unsaturated zone*, in which pore spaces are filled by a combination of water and gases, from the *saturated zone*, in which essentially all pores are filled with groundwater (fig. 5).

Water in the soil originates from precipitation, irrigation, or upward flow from groundwater in areas with a shallow water table. It can contain dissolved minerals derived from the soil or atmosphere, as well as soluble pesticides, fertilizers, and other chemical compounds used or disposed of at the land surface. When soils are not saturated with water, then the pores also contain a mixture of gases, including nitrogen, oxygen, and carbon dioxide (as in normal air) and more exotic types such as methane and hydrogen sulfide. Soil gases are produced and assimilated by soil organisms, plant roots, and decay processes, and they are exchanged with gases from the atmosphere. Without adequate exchange of gases in soil pores, crop growth cannot occur because the oxygen needed by the plant roots would rapidly become depleted. Most water management in soil is aimed at providing sufficient water for plants without producing conditions of excess water that prevent proper gas exchange.

Water in the Soil

When rainfall or irrigation soaks into the soil, a certain amount is temporarily retained in the soil pores, and the remainder gradually percolates downward to the water table. The amount held in the upper soil depends on the amount of organic matter and the size, shape, and arrangement of mineral particles. In general, the more organic matter the soil contains, the more water it will be able to absorb. Mineral particles affect water retention by determining the size and number of pores where water can be held. In soils with large, irregularly shaped sand particles, for example, large pores remain between the sand grains (fig. 6). Clay particles, by contrast, fit together more compactly, so that the pores are smaller but more numerous (fig. 7). The *porosity* of a soil is defined to be the volume of the pores as a percentage of the total volume of soil. Sandy soils have porosities ranging from 30 to 40 percent, compared with 40 to 60 percent for clays. Porosity provides a measure of the amount of water that each soil can retain in the root zone where it is available to plants.

Only a small fraction of water entering the soil remains in the root zone for a prolonged time period. If not taken up by plants, the remainder gradually percolates downward to become groundwater. The rate at which this percolation occurs is defined by another soil characteristic, the *permeability*, also called *hydraulic conductivity*, defined to be the ease with which the soil transmits water. Although clay soils have higher porosity and can hold more water than sandy soils, permeability is lower because smaller pores conduct water at lower flow rates. Drainage of fields with clay soils, therefore, is slow compared with drainage in sandier locations. Movement of groundwater to a well also is much slower through a clay than a sand because of tighter retention of water in smaller pores. Most soils are a combination of sand, silt, and clay, and the percentages of these various particle sizes determine the amount of water held in soil pores and the amount and rate of percolation to greater depths. A clay soil may be unsuitable for crops because drainage is too slow, whereas a sandy soil may require frequent irrigation because the water percolates quickly and does not remain in the root zone where it is available to plants.

Water Movement through Soil

Soil water generally flows downward to deeper depths and from wetter areas to drier ones. This movement of water through soil occurs in response to two types of forces: (1) the downward pull of gravity and (2) the forces of attraction between water molecules and soil particles. Just as gravity pulls all objects toward the center of the earth, it pulls water molecules downward through the soil profile. In sandy soils this is the primary cause of water draining downward through soil to groundwater. In clay soils forces of attraction between soil and water molecules also play a key role in determining movement of soil water.

The intermolecular forces of attraction between soil and water are called *matric or capillary forces*. They are determined by soil properties and moisture content and are most significant in small pores because of the greater surface area for interaction between soil and water molecules. These intermolecular forces usually act in opposition to gravity, producing the net effect of holding water in soil pores. However, these forces also cause water movement from wet soil zones to dry ones in any direction because of the strong attraction between water molecules and dry soil surfaces. When evaporation dries surface soils, for example, water moves upward through the soil profile to rewet the dry pores. Similarly, water moves horizontally to moisten soils along the edges of drainage ditches, furrows, and impoundments.

The forces of attraction between water molecules and soil particles are illustrated in the laboratory by the movement of water upward into glass capillary tubes (fig. 8). The narrower the tube, the higher the water will rise because of the larger surface area relative to water volume. This laboratory example provides a good model of capillary action in soils because the most common molecule in soil minerals is silicate, similar to the silicate molecules in the glass capillary tubes.

Because of these same capillary forces, small pore spaces in soils hold water more tightly than the larger pores, affecting both drainage and plant uptake. Water drains more rapidly from the

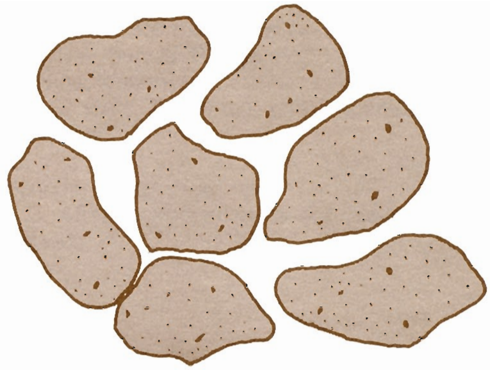

Figure 6. Sandy soils have large pores because the rounded or irregularly shaped particles do not fit together compactly.

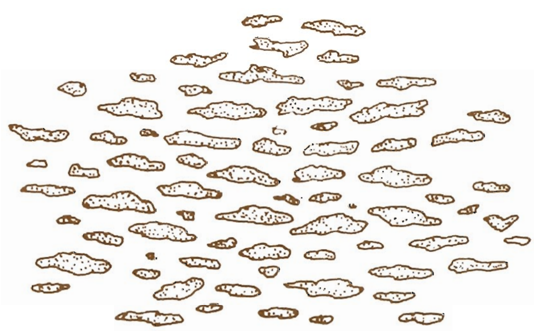

Figure 7. Clay soils have small pores because the particles fit together compactly.

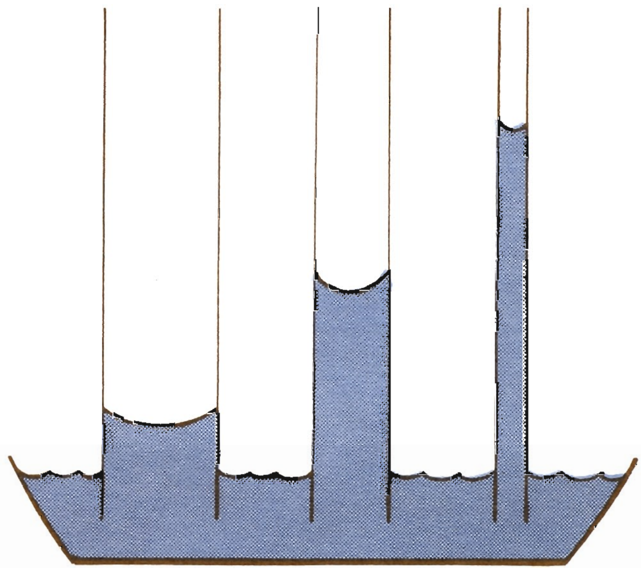

Figure 8. Water rises higher in the narrower capillary tubes than in wider ones because of the greater surface area for attraction between water molecules and the capillary walls (greatly magnified for illustrative purposes).

larger pores, causing them to be mostly air-filled, whereas smaller pores still contain water. The mixture of pore sizes in most soils, therefore, helps to provide plants with both a reservoir of water and areas for gaseous exchange. Plant roots absorb water from soil pores, drawing it first from the larger pores where it is more loosely held. Plants wilt when the demand by the plant cannot overcome the attraction of water molecules to soil surfaces. Although clay soils hold more water than sandy ones, they also hold it more tightly in smaller pores, so that it is less readily taken up by plants. For these reasons, sandy soils require more frequent irrigation of comparatively small amounts of water, whereas clay soils usually are irrigated with larger amounts at longer intervals. Irrigating with regard to the specific soil type can ensure that sufficient water is provided to meet plant needs without excessive leaching of soil nutrients, fertilizers, or pesticides.

Geographic and Seasonal Variations in Soil-Water Movement

The cycle of water to and through the ground varies considerably from humid regions such as the northeastern states to more arid regions such as the southwestern part of the country. Annual average precipitation for the Northeast can be as high as 46 inches, compared with 30 inches for the country as a whole and as low as 9 inches for the southwestern states. All precipitation runs off into surface water bodies, evaporates or is taken up by plants (together called *evapotranspiration*), or infiltrates into the soil. The amounts following these various pathways depend on the local climate, topography, and soil conditions. In general, the northeastern states have far less evapotranspiration and more water percolating to groundwater (called *recharge*) than in more arid regions (fig. 9).

Recharge does not remain constant over the course of the year, especially in the Northeast where soils become frozen in the winter. This results in a periodic rise and fall in the depth to groundwater, as shown in figure 10. Spring and fall generally are the times of greatest recharge and, therefore, also of highest water table elevations. Groundwater levels tend to go down in summer when evaporation and plant uptake are high and in winter when recharge is hampered by frozen soils.

Such fluctuations in recharge quantities can have consequences for recharge quality as well. If spring rains come shortly after

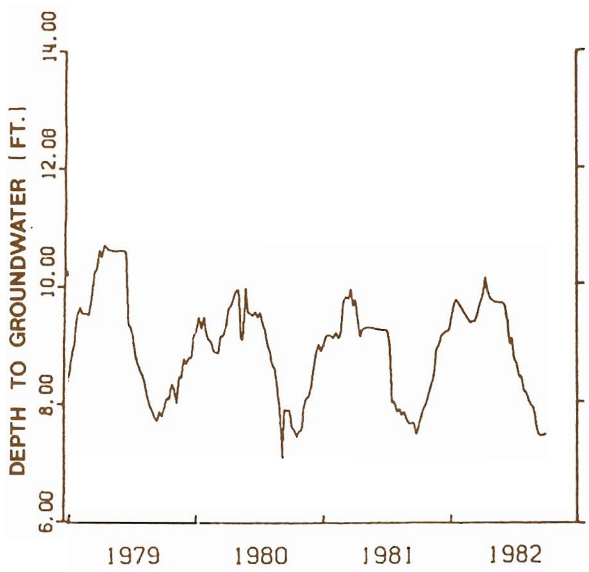

Figure 10. Typical fluctuations in groundwater levels in the northeastern United States.

application of fertilizers or pesticides, for example, large quantities of the chemicals may be transported downward to groundwater because of the minimal root and foliage development early in the growing season. Rising water table elevations may also cause groundwater contamination by intercepting potential contaminant sources such as septic systems or manure storage lagoons.

Biological Influences on Soil Water

Soils are complex ecological communities, teeming with life. Microscopic plants and animals form the basis of the soil food web by breaking down soil organic matter and releasing nutrients in forms that can be taken up by plant roots. Earthworms and hundreds of kinds of insects assist in this continuous decomposition process, turning dead plant and animal materials into rich organic humus. Humus is a vital component of productive agricultural soils,

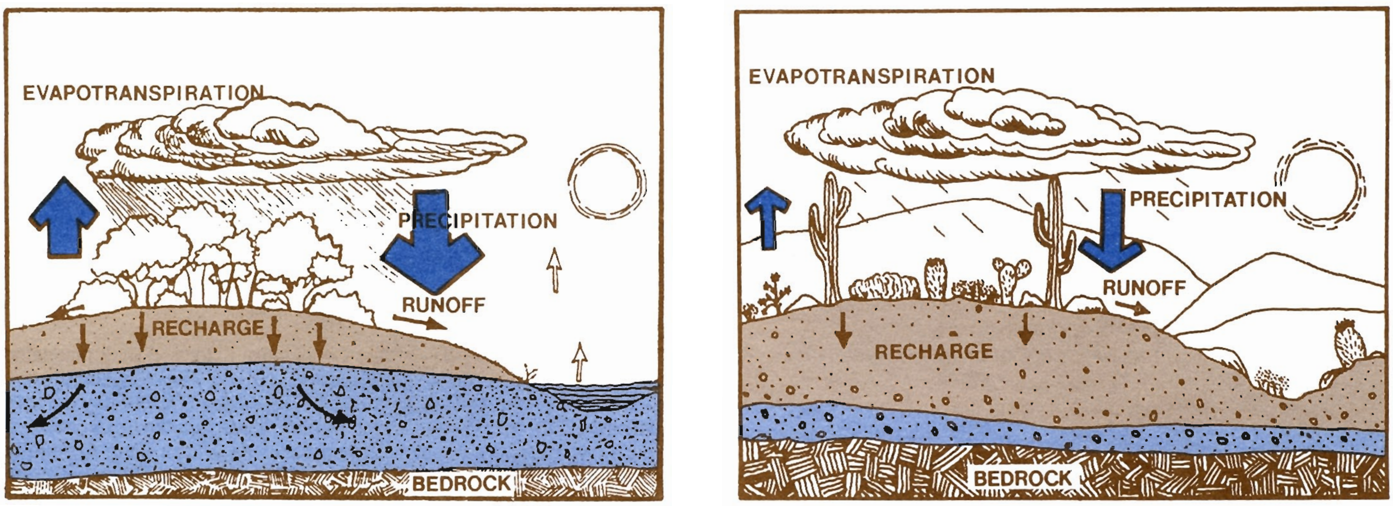

Figure 9. Comparison of water cycle in humid and arid regions.

providing nutrients and helping to retain water, fertilizers, and pesticides in the root zone where they are available to plants. Addition of organic matter makes any soil easier to work and improves its drainage properties. In sandy soils, organic matter retains water, preventing drainage from occurring too rapidly through the large pores. Addition of organic matter to clay soils helps to open up the small pores, making the soil more workable and more permeable to water.

As agriculture has become more intensive, methods that in some cases threaten soil productivity have been adopted. Larger fields, heavier equipment, and greater reliance on chemical fertilizers can lead to higher rates of erosion, compaction, and depletion of soil organic matter. These processes reduce the ability of soil to store water and soluble nutrients until they are needed by plants.

Long-term maintenance of agricultural productivity relies on protection of the complex ecological network of the soil. Planting of a cover crop between growing seasons, for example, helps to maintain or enhance productivity by intercepting runoff, protecting fertile topsoil from erosion, and increasing the amount of water entering the soil. Plowing the cover crop into the soil also helps to protect soil fertility by restoring the supply of organic matter. If topsoils are eroded or organic matter is depleted, fertility will be reduced. Although chemical fertilizers can compensate for lost nutrients, only organic matter can increase the ability of the soil to retain water and soluble fertilizers and pesticides in the root zone. Programs to maintain long-term soil productivity therefore aim to "feed the soil, not the plant," knowing that building a rich organic soil is the best way of providing the water and nutritional needs of crops.

Conclusions

The type of soil in a field determines how much water will percolate through to groundwater and how easily the remaining water can be taken up by plants. Movement of water through soil depends on two factors: the forces acting upon the water molecules and the ease with which they can flow through the soil. These factors vary from one soil to another, depending on the amount of organic matter and the size and arrangement of mineral particles. Although a clay soil can hold more water than a sandy one, it holds it more tightly in smaller pores, making the drainage slower and the water less readily available to plant roots. Movement of groundwater to a well also is much slower through a clay than a sand because of tighter retention of water in the smaller pores.

Many fertilizers, pesticides, and soil nutrients are dissolved in soil water and, therefore, can either leach to groundwater or remain in the root zone available to plants, depending on patterns of water movement through soil. Retention of water and dissolved chemicals in the root zone depends on soil type and is greatest in soils that are high in organic matter. Addition of organic materials to farm fields enhances the water-holding capacity and productivity of the soil and decreases the likelihood of leaching of fertilizers and pesticides to groundwater. Understanding how soils and water work together to control water and chemical movement is critical in managing farm irrigation, fertilizer and pesticide applications, and protection of well-water quality.

For Further Reading

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