4

Soil and Water

INTRODUCTION

Soil is important for plant growth as a source of water and minerals, as the anchorage for plants, and as a medium for development of the root systems essential for absorption and anchorage. It is a complex system, consisting of varying proportions of rock particles and organic matter forming the solid matrix, and soil solution and air occupying the pore space. In addition, soil usually contains an active population of bacteria, fungi, algae, insects, and small animals that directly or indirectly affect soil characteristics and root growth (see Wild, 1988, Chapters 14–17).

IMPORTANT CHARACTERISTICS OF SOILS

Soil characteristics such as texture and structure have important effects on the suitability of soil as a medium for plant growth.

Composition and Texture

Those characteristics of soil most important for plant growth, such as water and mineral storage capacity and suitability for root growth which is related to aeration and resistance to root penetration, depend largely on texture and structure. Soils usually are classified as sands, loams, or clays, depending on the proportions of large (>2.0–0.02 mm), intermediate (0.02–0.002 mm), and fine particles (<0.002 mm) present. By definition, sands contain less than 15% of silt and clay, clay contains over 40% of fine particles, and loam soils contain intermediate proportions of sand and clay. Clay soils are compact and cohesive, often poorly drained and aerated, but because of their large internal surface they usually store large amounts of water and minerals. Sandy soils are loose, noncohesive, well drained, and well aerated, but with a limited storage capacity for water and minerals. Loam soils are intermediate in respect to these characteristics (Fig. 4.1). In general, a high clay content increases the storage capacity of soils for water and minerals (cation-exchange capacity) but decreases the aeration so essential for good root growth and functioning. Thus the clay fraction is very important in determining the suitability of a soil for plant growth (Fig. 4.1).

A large amount of organic matter also increases the water-holding capacity and cation-exchange capacity, but decreases the effectiveness of pesticides and decreases injury by toxic substances. According to Wild (1988, pp. 585–588), the more organic matter soil contains the more herbicide, insecticide, or nematocide must be applied to be effective. Attempts have been made to increase the water storage capacity of soil by adding water-absorbing polyacrylamide polymers to the soil. This would seem to be promising for sandy soils. However, Letey *et al.* (1992) reported that although the water held by the additives is available

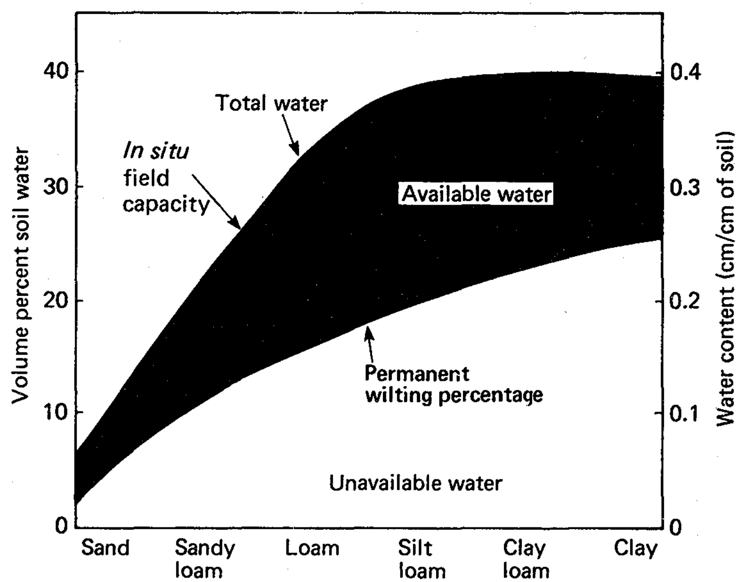

Figure 4.1 Diagram showing the relative amounts of available and unavailable water in soils ranging in texture from sands to clay. Amounts are expressed as percentages of soil volume and centimeters of water per centimeter of soil. After Cassel (1983), from Kramer (1983).

to plants and the interval between irrigations is increased for container-grown plants, little water is conserved over a season.

Numerous attempts have been made to develop systems by which soils with similar properties can be classified together but there is no universally accepted system and readers are referred to Wild (1988, Chapter 24) and to soil textbooks for further information on soil classification.

Structure and Pore Space

Soil structure and amount of pore space depend on particle size and the extent to which the basic particles are assembled into stable crumbs or aggregates. Aggregation of clay particles into stable "crumbs" apparently is aided by the presence of root exudates and organic colloids produced by soil organisms. Maintenance of stable aggregates is particularly important in clay soils because it increases pore space, improving infiltration of water and maintenance of good aeration. The structure of clay soil often is damaged by traffic and cultivation when wet, and occasionally in arid regions by flocculation (precipitation) of the clay, caused by an excess of alkali in irrigation water. According to Richter (private communication), growth of tap roots of pine trees increases the bulk density of the soil surrounding them.

The relative amounts of capillary and noncapillary pore space strongly affect soil drainage and aeration and hence its suitability as a medium for plant growth. Capillary pore space consists of small pores (30 to 60 μm or less) that retain water against gravity. This determines the field capacity or the amount of water retained in a soil after a rain or irrigation. Noncapillary pore space is the fraction of soil volume from which water drains by gravity, providing the air space so important for good aeration of roots. About half the volume of most soils consists of pore space, but the proportions of capillary and noncapillary pore space vary widely in different soils, as shown in Figs. 4.2 and 4.3. The past history or treatment of a soil also has important effects on the proportion of capillary pore space, as shown for a forest soil and an adjacent cultivated field soil in Fig. 4.3. Cultivation often damages soil structure and decreases noncapillary pore space. According to Ravina and Magier (1984) the presence of rock fragments decreases compaction and improves aeration of clay soils, but according to Richter *et al.* (1989) it also decreases the water storage capacity, as would be expected. Nobel *et al.* (1992) found more water beneath flat rocks and around boulders than in soil a few centimeters away and stated that this plays an important role for root proliferation of desert succulents and probably for other plants growing in dry soil.

A decrease in pore space increases the bulk density (weight per unit of volume) and resistance to root penetration as measured by a penetrometer. Those changes are accompanied by a decrease in root growth (Barley, 1962; Taylor and Ratliff, 1969). Bengough and Mullins (1991) suggest that some of the early

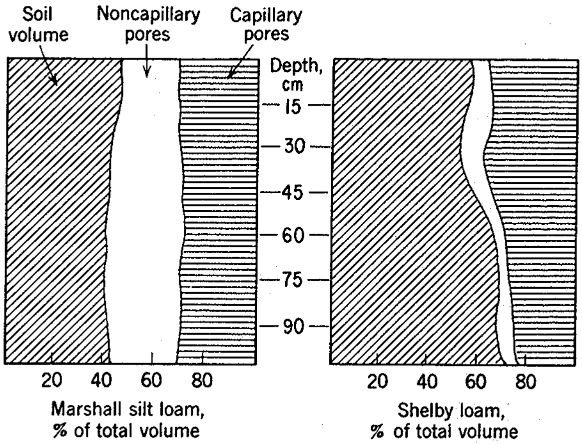

Figure 4.2 Examples of the differences in amount of capillary and noncapillary pore space in two dissimilar soils. A large proportion of noncapillary pore space promotes drainage and improves aeration. After Baver (1948), from Kramer (1983).

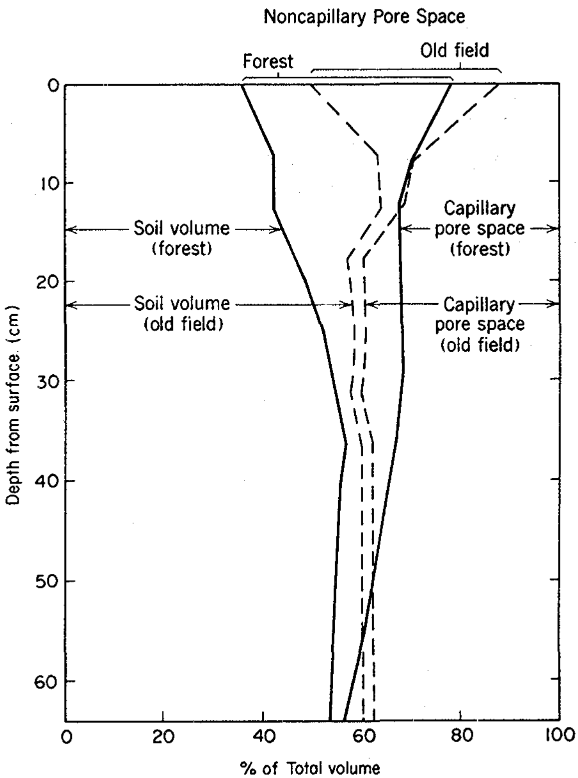

Figure 4.3 Difference between amount of capillary and noncapillary pore space in an old field soil and an adjacent forest soil on the same type of soil. The large volume of noncapillary pore space in the forest soil provides better root aeration and more rapid infiltration of water (Fig. 4.6), reducing surface runoff and erosion during heavy rains. After Hoover (1949), from Kramer (1983).

data on soil resistance and root growth suffer from faulty technology and need to be reinterpreted. However, research indicates that in some instances increasing soil density decreases stomatal conductance, photosynthesis, and shoot growth (Carmi *et al.*, 1983; Masle and Passioura, 1987; Tardieu *et al.*, 1991), but increases water use efficiency, root–shoot ratio, and carbon discrimination in some plants (Masle and Farquhar, 1988). Hamblin (1985) discussed the relationship among soil structure, root growth, water movement through soil, and water absorption in detail.

Soil Profiles

Although alluvial and loess soils often are uniform in texture and structure to considerable depths, most soils show changes with depth that affect their suitability as a medium for root growth and their capacity as a reservoir for water and minerals. Figure 4.3 shows the differences in capillary and noncapillary pore space at various depths in a forest soil and in an adjacent cultivated field on the same soil type, and Fig. 4.4 shows the horizons that might occur in a well-developed forest soil profile.

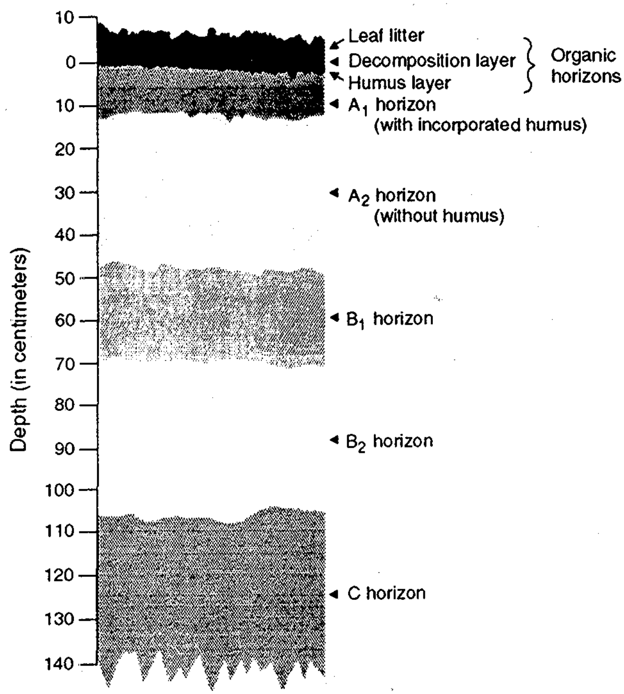

Figure 4.4 A soil profile under an old shortleaf pine stand in North Carolina. Modified from Billings (1978), from Kozlowski *et al.* (1991).

Soil profiles often are interrupted by rock or hard pan layers of natural occurrence (fragipans) or resulting from the passage of heavy machinery (tillage pans) that restrict root growth. Sometimes layers of rock or chemical barriers such as low pH and high concentrations of toxic elements such as aluminum or magnesium in the subsoil, or a high water table, limit root penetration and reduce the volume of soil available to plants as a reservoir for water and minerals. In regions with limited rainfall, a layer of carbonate often accumulates at the deepest point wetted by rain, forming a hardpan or caliche which hinders root penetration. Cassel (in Raper and Kramer, 1983) discussed chemical and physical barriers to root penetration in more detail and it is discussed further in Chapter 5. Perhaps more effort should be made to find genotypes of plants with roots able to penetrate dense soils and to tolerate high acidity and high concentrations of aluminum and other toxic elements. According to O'Toole and Bland (1987) there are extensive genotypic variations in root systems of various crop plants, providing opportunities for selection of root systems with desirable characteristics in special environments.

The effects of restricted root penetration caused by a shallow soil are particularly noticeable during droughts when plants on shallow soils suffer injury sooner than those on deeper soil. Coile (1937) found that height growth of loblolly and shortleaf pine in the Carolina Piedmont was correlated with depth of the A horizon and the characteristics of the B horizon that govern its suitability for root growth. Martin *et al.* (1979) found that subsoiling to break a tillage pan at 25 cm had unidentified beneficial effects on soybean yield in addition to increased availability of water.

SOIL WATER TERMINOLOGY

The water content of soil usually is expressed as a percentage of oven dry weight, or of soil volume. The percentage of soil volume probably is most informative concerning the amount of water available for plants but it is difficult to determine in undisturbed soil. Unfortunately, water content on a percentage basis tells little about the amount of water available to plants because a sand may be saturated at a water content that is near the wilting point for a loam soil, as shown in Table 4.1.

Water Potential

The meaning of water potential and its importance with respect to cell and tissue water relations were discussed in Chapters 2 and 3. The soil water potential depends on four components of varying importance:

$$\Psi_{soil} = \Psi_m + \Psi_s + \Psi_g + \Psi_p. \qquad (4.1)$$

Table 4.1 Water Content of Soils of Various Textures at Matric Potentials of −0.03 and −1.5 MPa and at First Permanent Wilting

	Water content as percentage of dry weight	
Name of soil	−0.03 MPa	−1.5 MPa
Hanford sand	4.5	2.2
Indio loam	4.6	1.6
Yolo loam	12.6	7.1
Yolo fine sandy loam	12.6	5.5
Chino loam	19.7	8.0
Chino silty clay	40.8	21.9
Chino silty clay loam	48.9	15.0
Yolo clay	45.1	26.2

Note. From Kramer (1983), based on data of Furr and Reeve (1945) and Richards and Weaver (1944).

In this equation, Ψ_m represents the matric potential produced by capillary and surface-binding forces, Ψ_s represents the osmotic potential produced by solutes in the soil water, and Ψ_g represents the gravitational forces operating on soil water. Ψ_p refers to external pressure and can often be disregarded because the pressure is near atmospheric in the root zone. The exact significance of the various terms, especially the matric term, are discussed in Appendix 2.3 and by Passioura (1980b).

It sometimes is stated that water always moves toward regions of lower total water potential, but this is not always true (Corey and Klute, 1985). The various forces affecting the free energy status of soil water [Eq. (4.1)] are not equally important under all conditions with respect to water movement. For example, although the osmotic potential is an important part of the total water potential with respect to plants growing in saline soils, it has little effect on water movement within the soil. However, it has an important effect on the movement of water from soil to roots because the soil solution is separated from the plant solution by differentially permeable membranes.

Generally, the major forces affecting water movement in soil are matric and gravitational. After the soil is saturated, a fraction of the water moves downward because gravity causes water to drain out of the larger pores. After equilibrium is attained against gravity the soil can be regarded as at field capacity. However, local dehydration by capillary flow, caused by surface evaporation or root absorption, reduces the water potential and causes internal movement. In order to absorb water, roots must generate water potentials low enough to overcome the matric potential plus any osmotic potential of the soil solution. It also should be noted that liquid water and water vapor can move independently of one another in soils (Gurr *et al.*, 1952; Kramer, 1969, p. 69).

Field Capacity

The *in situ* field capacity of a soil refers to the water content after downward drainage has become negligible and water content has become relatively stable. This situation usually is attained several days after a soil has been thoroughly wetted by rain or irrigation, but may require a month or more (Fig. 4.5). Sandy soils usually attain equilibrium much sooner than clay soils, but the presence of a shallow water table or an impermeable layer will slow the process in any type of soil. Also, the water content or apparent field capacity of a soil allowed to drain in the field may be different from that of a column or pot of the same soil allowed to drain over sand in the greenhouse because of the shorter capillary column in the pot than in the field. The problems peculiar to soil in containers were discussed briefly by Hershey (1990) and by White and Mastalerz (1966). The latter termed the upper limit of water content of soil in containers the "con-

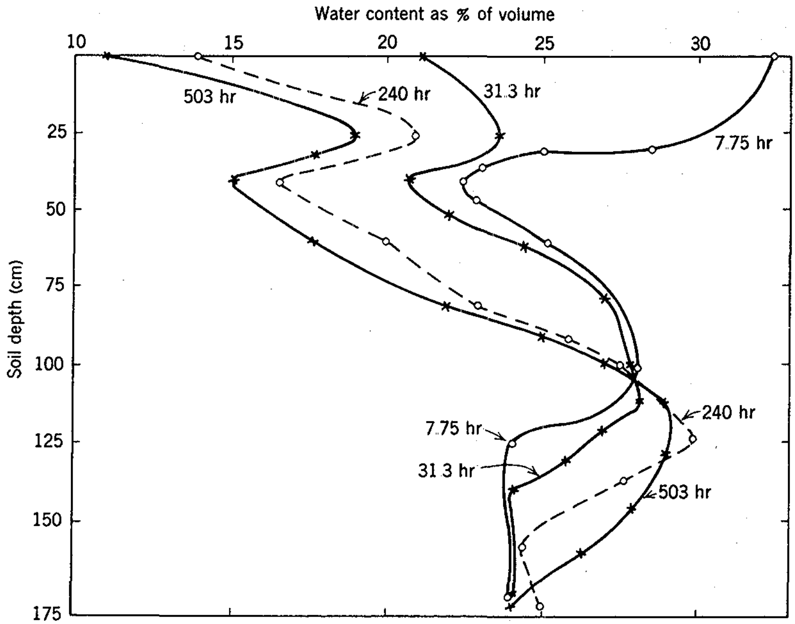

Figure 4.5 Profiles of water content of a nonuniform soil at various times after irrigation. The surface horizon is a sandy loam, changing to a fine sandy loam at about 25 cm, and at 75–100 cm to a clay which holds much more water. The original water content at 125 to 175 cm was about 24%. Over a period of 21 days (503 hr) there was a decrease in water content near the surface and an increase at 100 to 150 cm below the surface. From Kramer (1983) after Rose *et al.* (1965).

tainer capacity" to distinguish it from the field capacity of natural soils. Sometimes laboratory measurements of field capacity are made by subjecting the soil to a pressure of 0.03 MPa in a pressure chamber or an equivalent tension on a tension table. Hillel (1980b, Chapter 3) discussed in detail the problem of measuring field capacity. As it is not really a soil constant, but depends on the conditions under which it is measured, some soil scientists have recommended that it be abandoned. However, it has considerable practical utility if users are aware of its limitations.

Permanent Wilting Percentage

The permanent wilting percentage (PWP) is the soil water content at which plants remain wilted overnight or in a humid chamber unless they are rewatered. Sachs (1882a) observed that plants wilted sooner in sandy than in clay soil, and Briggs and Shantz (1912) developed a standardized method by means of which they found that plants of many species wilted at approximately the same water content in a given soil. They termed this the wilting coefficient, but it is now known as the permanent wilting percentage. Richards and Wadleigh (1952) found that the soil water potential ranged from −1.5 to −2.0 MPa at permanent wilting for many herbaceous plants, with most values near −1.5 MPa, which is now generally used as the approximate soil water potential at permanent wilting. Slatyer (1957) pointed out that this is not a soil constant because wilting really depends on the potential at which leaf cells lose their turgor. However, most crop plants have osmotic potentials in the range of −1.5 to −2.0 MPa so −1.5 is near the point at which wilting can be expected. Although it is convenient to take −1.5 MPa as the soil water potential at permanent wilting, there is no sharply defined lower limit for water availability (Gardner and Nieman, 1964), despite the claim by Veihmeyer and Hendrickson (1950) that soil water is either available or unavailable.

Readily Available Water

Readily available water usually refers to the soil water in the range between field capacity and the PWP. Generally, finer-textured soils contain more readily available water than coarse-textured soils, as shown in Figs. 4.1 and 4.14 and in Table 4.1. Considerable differences occur in the amount of readily available water present at various depths in nonuniform soils, as shown in Fig. 4.5. This suggests that deep rooting can sometimes compensate for a limited supply of available water in the surface soil. An increase in the amount of organic matter, either from root growth or by addition of manure, usually increases the water-holding capacity of coarse-textured soils and improves the aeration of fine-textured soils. The complex role of organic matter in soil is discussed in Chapter 18 of Wild (1988).

Water Demand versus Supply Rate. The definition of available water as that in the range between field capacity and the PWP is too arbitrary and static to describe accurately the actual situation in the field. From the standpoint of plants, soil water availability depends on the rate at which water can be supplied to roots relative to the plant demand for water. Both supply and demand are variable. Plant demand for water depends primarily on the rate of transpiration which varies widely, depending on the kind and size of plants and meteorological conditions (see Chapter 7). Water supply depends on root length density (root length per volume of soil), root efficiency as an absorbing surface, i.e., their hydraulic conductance, and the hydraulic conductance of the soil which varies with soil type and water content. Thus a water content adequate to meet the plant demand in cool, cloudy weather may become quite inadequate in hot, sunny weather when transpiration is rapid, as shown in experiments of Denmead and Shaw (1962). They found that the average soil water potential in the root zone when the actual transpiration rate of corn rose above the potential rate varied from −1.2 MPa when the rate of transpiration was only 1.4 mm per day to −0.03 MPa when the rate was 6 to 7 mm per day. Thus the need for frequent irrigation is much greater during hot, sunny weather than during cool weather. Some of the implications of this dynamic situation are discussed in more detail in Chapter 7 of Stewart and Nielsen (1990).

WATER MOVEMENT WITHIN SOILS

Movement of water within soils controls the rate of infiltration; the flow to springs, streams, and underground aquifers; and the supply to roots of transpiring plants. The bulk soil solution moves downward under the influence of gravity through the noncapillary pore space, and more slowly through capillary pore space and in films on surfaces of soil particles mostly under the influence of surface or matric forces. Pure water also diffuses as vapor through pore space along gradients of water vapor pressure.

Two important types of water movement are its saturated downward flow (infiltration) after rain or irrigation and its unsaturated flow horizontally toward roots and upward toward the evaporating surfaces of the soil. Sometimes both gravitational and matric forces are involved as in water movement down slopes (Beasley, 1976; Hewlett, 1961). When there are large temperature differences between the surface and deeper horizons there also may be considerable movement of water in the form of vapor from warmer to cooler regions.

Infiltration

The rate of infiltration is important in the recharge of soil water by rain and irrigation. If infiltration is slow, surface runoff is likely to cause erosion, as in the clay soils of the Piedmont of the southeastern United States and in some tropical soils. Downward movement is largely by gravity and depends on the rate at which water is supplied to the wetting front rather than to the difference in Ψ_w between wet and dry soil. Water moves rapidly through the moist soil behind the wetting front because of gravity, but very slowly into the dry soil in front of it. This explains the sharp boundary between wet and dry soil after a dry surface soil has been rewetted by a summer shower. It also explains why soil cannot be rewetted part way up to field capacity by addition of a limited amount of water, because part is wetted to field capacity and part is not wetted at all.

Infiltration into some clays (montmorillonites) is hindered because they swell when wetted, reducing the noncapillary pore space. Infiltration into some sands is hindered because the particles are covered with a hydrophobic coating that prevents wetting (Jamison, 1946). This also sometimes occurs in surface soil after fire. Adams *et al.* (1970) reported that annual vegetation sometimes is excluded from beneath desert scrub because the soil is water repellent. Attempts have been made to improve water infiltration on burned slopes and on watersheds by applying wetting agents (Letey *et al.*, 1962; Mustafa and Letey, 1970). McCauley (1993) reported that the addition of a proprietary compound to irrigation waters increased infiltration and soybean yield on a soil subject to surface crusting. The presence of mulch on the soil surface and the moderate incorporation of organic matter into soil also improve infiltration by preventing puddling and closure of pores. However, incorporation of excessive amounts of peat into potting soils makes wetting slow and difficult. Infiltration usually is more rapid into forest soils than into cultivated soil of similar texture, as shown in Fig. 4.6, because forest soils usually contain more noncapillary pore space (Fig. 4.3). Cultivation tends to destroy noncapillary or macropore space. Channels left by decaying roots probably are important pathways for infiltration in forest soils (Gaiser, 1952) and earthworm burrows also increase the infiltration of water (Wild, 1988, pp. 512–513). Wang *et al.* (1986) concluded that channels made in the soil by roots, insects, and worms have important effects on root growth and movement of gas and water. Infiltration is reduced by compaction caused by human and vehicular traffic and becomes a serious problem in parks, on golf courses, and in some cultivated soils. Various authors in Emerson *et al.* (1978) discuss infiltration in more detail. Bouma (1991) suggested that rapid downward flow of water through macropores is undesirable because it can result in pollution of the groundwater.

Horizontal and upward Movement

In nature there are large diurnal and seasonal variations in soil temperature. For instance, during summer the surface soil often is warmer during the day than at night and it cools more rapidly during the autumn and winter, relative

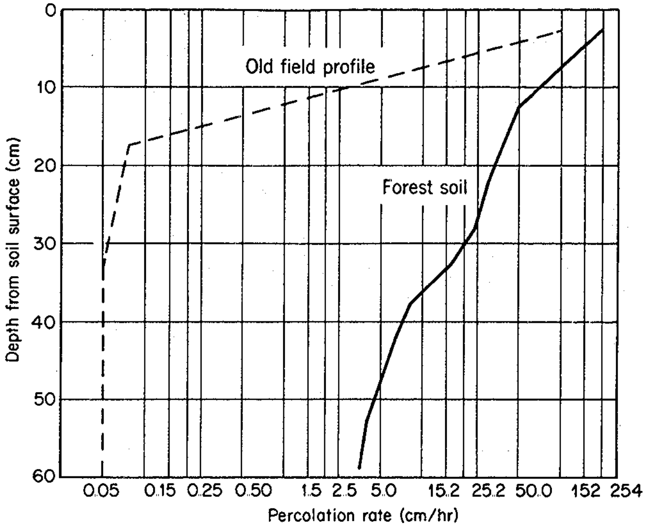

Figure 4.6 Comparison of rates of infiltration into a forest soil and an adjacent old field on the same soil type. Figure 4.3 shows the differences in capillary pore space in the two soils. From Kramer (1983), after Hoover (1949).

to deeper horizons that undergo less change in temperature, causing significant movement of water vapor. This was observed in California by Edlefsen and Bodman (1941), and Lebedeff (1928) reported that in winter in Russia significant amounts of water moved upward from the warm subsoil and condensed in the cooler surface soil. This includes movement both as vapor and as liquid. Movement of water as liquid and vapor was discussed by Slatyer (1967, pp. 109–118), in Gurr *et al.* (1952), and in Hillel (1980b, Chapter 5).

Horizontal movement on a macroscopic scale, as from irrigation ditches, and movement toward roots on a microscopic scale are very important. Soil water in the vicinity of roots of rapidly transpiring plants sometimes tends to become depleted during the day because water absorption exceeds the rate of movement of water through the soil toward roots, resulting in a water-depleted zone around them (MacFall *et al.*, 1990, 1991a, Fig. 5.9, and Chapter 6). Fortunately, the soil in this zone usually is rewetted overnight, but the rate at which this occurs depends on the hydraulic conductance of the soil. This decreases rapidly as the soil dries because the larger pores are emptied first, decreasing the cross-sectional area available for water movement (see Fig. 4.7). Also, contact between soil and roots may decrease as soil and roots dehydrate and shrink (Huck *et al.*, 1970; Faiz and Weatherly, 1982). However, Taylor and Willatt (1983) suggest that the importance of root shrinkage may have been overemphasized because shrinking roots seldom completely lose contact with the soil.

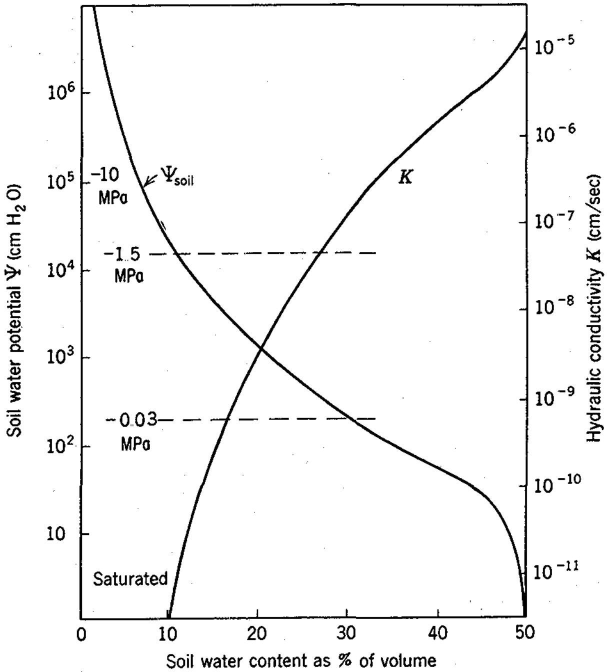

Figure 4.7 Diagram showing approximate decrease in hydraulic conductivity (K) and soil water potential (ψ_w soil) with decreasing soil water content. From Kramer (1983), after Philip (1957).

The movement of water to roots is discussed further in Chapter 6 in connection with water absorption.

Upward movement of water (capillary rise) toward the soil surface is caused chiefly by evaporation from the surface and removal of water by roots of transpiring plants. Upward flow to an evaporating surface from a water table is about twice as rapid in a fine-textured as in a coarse-textured soil (Gardner, 1958). If evaporation is very rapid, loss of water may exceed the rate at which water reaches the evaporating surface which then dries, causing the rate of evaporation to decrease significantly because water movement as vapor in the dry surface soil is much slower than movement as liquid in moist soil. This fact led to emphasis on maintaining a thin surface layer of dry cultivated surface soil as a mulch to reduce the loss of water by evaporation. Gardner and Fireman (1958) reported that lowering the water table from 90 to 180 cm below the soil surface reduced evaporative loss to about 12% of the loss at 90 cm. However, further lowering of the water table to 3 or 4 m had little additional effect on the rate of evaporation. In nature, measurable upward movement sometimes occurs from a depth of several meters (Patric *et al.*, 1965).

There also is evidence that significant amounts of water are transferred from deeper horizons to drier surface soil by roots, where it becomes available to plants (Caldwell and Richards, 1989; Corak *et al.,* 1987; Dawson, 1993, and Chapter 6). In some areas, dew and fog may supply significant amounts of water, and the possible importance of this is discussed in Chapter 6. Vertical movement must be taken into account in estimating the amount of water removed from the root zone. If there is significant upward movement of water and the amount used is calculated from periodic measurements of changes in soil water content in one horizon, water usage will be underestimated unless it is corrected for the amount supplied by upward movement.

In addition to causing loss of water, surface evaporation often results in an undesirable concentration of salt in the surface soil in areas where precipitation is too limited to leach it out. Considerable attention has been given to the reduction of soil surface evaporation by shallow cultivation and by the use of mulches of organic matter and even of pebbles. This is discussed in Hillel (1980a, Chapter 5).

MEASUREMENT OF SOIL WATER

Recognition of the importance of the available water content of soil with respect to plant growth has resulted in development of several methods of measuring soil water content in the field and in the laboratory. Various methods were discussed by Rawlins (in Kozlowski, 1976) and in Stewart and Nielsen (1990, Chapters 6 and 7) and in Pearcy *et al.* (1989, Chapter 3). The variability in soil over area creates serious sampling problems in the field that are discussed in Stewart and Nielsen (1990, Chapter 7).

Soil Water Balance

The chief features of the hydrologic cycle are shown in Fig. 4.8, and a simple equation for the soil water balance can be written as

$$\Delta W = P - (O + U + E_t), \tag{4.2}$$

where ΔW is the change in water content between samplings, P is the precipitation, O is the runoff, U is deep drainage, and E_t is evapotranspiration from soil and plants between samplings. Precipitation is easily measured, but measurement of the other terms is more difficult. Whitehead and Kelliher (1991a,b) discussed the problems involved in estimating the water balance of a Monterey pine stand in New Zealand for a year. Transpiration from the trees accounted for 50% of annual precipitation, evaporation from wet foliage 15%, evaporation from the understory 7%, deep drainage 24%, and increase in water content of soil in the root zone 4%. Of course these values vary with stand, soil, weather conditions, and the time period between measurements.

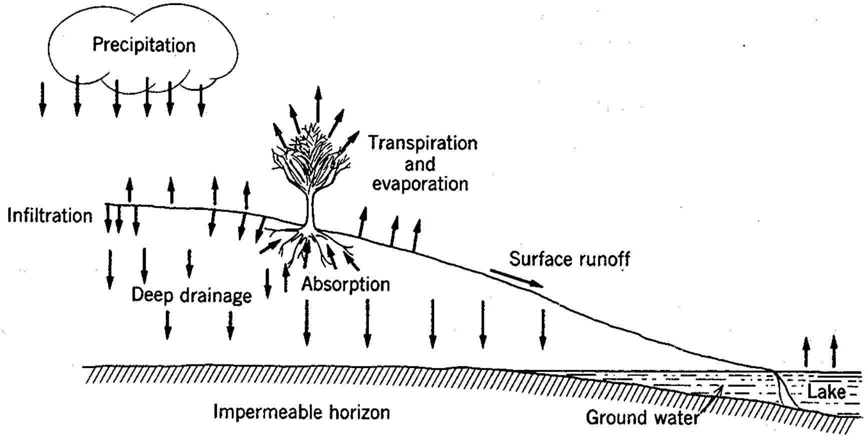

Figure 4.8 The hydrologic cycle, showing disposal of precipitation by surface runoff, infiltration, and deep drainage, and its removal from the soil by evaporation and transpiration. From Kramer (1983).

The most accurate measurements are made with lysimeters. These are large containers filled with soil and equipped with weighing devices which can be buried in a field and planted with whatever crop surrounds them. The use of lysimeters is discussed in Hagan *et al.*, (1967, pp. 536–544) and in Stewart and Nielsen (1990, Chapter 15), and the essential components are shown in Fig. 4.9. Grimmond *et al.* (1992) described a small lysimeter which is said to give as good results as those with a soil area 10 times as great. Good estimates of the soil water balance can also be made from stands of plants growing in small catchment basins where runoff can be measured (Whitehead and Kelliher, 1991b).

Direct Measurement of Soil Water Content

The basic measurement of soil water content is made on samples of known weight or volume dried at 105°C in an oven. Field samples usually are obtained with an auger or sampling tube. Use of a forced draft or microwave oven speeds drying, and other methods requiring less time than oven drying are discussed by Rawlins (in Kozlowski, 1976). Water content as a percentage of dry weight is not very useful unless the permanent wilting percentage and field capacity are known because, as mentioned earlier, a water content representing field capacity in one soil might be below the wilting point in another (Figs. 4.1 and 4.14 and Table 4.1). Sometimes it is useful to convert water per unit of weight into content per unit of volume so the water content can be expressed as millimeters per meter or in inches per foot. Also, additions of water to soil by precipitation are usually given in millimeters or inches. Water content can be converted from

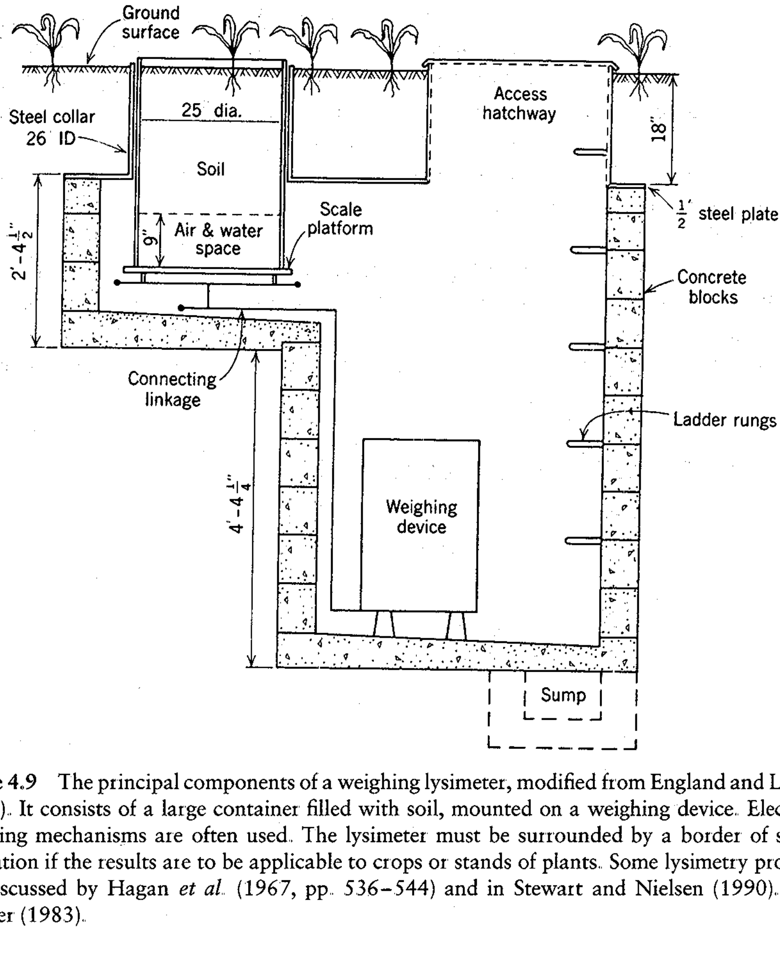

Figure 4.9 The principal components of a weighing lysimeter, modified from England and Lesesne (1962). It consists of a large container filled with soil, mounted on a weighing device. Electronic weighing mechanisms are often used. The lysimeter must be surrounded by a border of similar vegetation if the results are to be applicable to crops or stands of plants. Some lysimetry problems are discussed by Hagan *et al.* (1967, pp. 536–544) and in Stewart and Nielsen (1990). From Kramer (1983).

weight to volume units by multiplying the weight percentage by the bulk density of the soil.

Indirect Measurement of Soil Water

Direct measurement requires many samples obtained at various depths, resulting in considerable disturbance of the soil. It also is very labor intensive. Baarstad *et al.* (1993) describe a method of obtaining soil samples with little disruption of field plots. Most of the measurements are now made by indirect methods which must be related to water content by some kind of calibration procedure.

Neutron Scattering. The neutron probe is used extensively to make repeated measurements of water content at several depths with minimum disturbance. It is based on the fact that hydrogen atoms have a high capacity to slow down and scatter fast neutrons and water is the chief source of hydrogen atoms in most soils. Thus counting slow neutrons in the vicinity of a fast neutron source gives a good measure of the water content of a soil. A neutron probe consists of a source of fast neutrons and a detector for slow neutrons connected to an amplifier and counter (see Fig. 4.10). The probe is lowered in a tube inserted in the soil and measurements are made at various depths. It measures the hydrogen content of a sphere about 20 cm in radius, thus averaging the water content of a fairly large volume of soil. The results can be affected by other sources of hydrogen atoms, such as a high content of organic matter, or by the

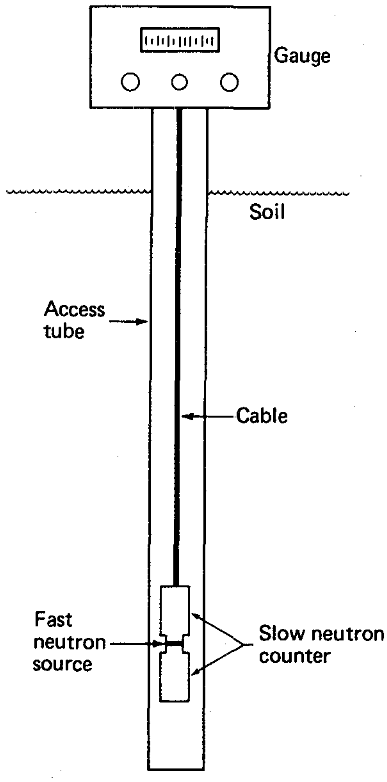

Figure 4.10 The essential features of a neutron meter. A source of fast neutrons and a counter for slow neutrons are lowered to any desired depth in an access tube installed in the soil. The water content of a spherical mass about 20 cm in radius is measured, the size of the mass increasing with decreasing water content. From Kramer (1983).

presence of high concentrations of Cl, Fe, or B. However, some recent models of neutron probes can be corrected and calibrated for most sources of error. The effects of variation in root density on apparent soil water content usually is neglected, but it can be significant if large roots or tubers occur within the soil volume measured by a neutron probe (Faroud *et al.*, 1993). The use of neutron probes was discussed in detail by Hodnett (1986), and Hanson and Dickey (1993) warn of some sources of error.

Gamma Ray Attenuation. The amount of radiation from a standard source of gamma radiation that passes through the soil is decreased in proportion to an increase in water content. Thus if a source of gamma radiation such as cesium is placed on one side of a column of soil and a detector on the other side in a jig to keep them in alignment, changes in the amount of radiation passing through the soil column can be observed. Of course the readings must be calibrated against gravimetric measurements to convert them into water content. The method was discussed by Ferguson and Gardner (1962), Gurr (1962), and Stewart and Nielsen (1990, pp. 130–131).

Other Methods

Attempts have been made to measure changes in soil water content by changes in electrical capacitance and electrical and heat conductance.

Electrical Capacitance. The capacitance method depends on the fact that water has a much higher dielectric constant than air or dry materials (water approximately 80, dry soil 5, air 1), hence changes in water content produce measurable changes in capacitance. The method is used to monitor the water content of grain, flour, dehydrated food, and other materials in which samples of fixed volume are easily prepared. Although theoretically attractive, technical problems make it difficult to use on undisturbed soil. However, development of time domain reflectometry has made the method more useful. Parallel rods or wires are inserted in the soil about 5 cm apart to measure the transit time of pulses of microwave energy. This depends on the dielectric constant of the soil, which varies with the water content. Dasberg and Dalton (1985) and Topp and Davis (1985) reported accurate measurements of soil water content by this method, and the former reported satisfactory measurements of electrical conductivity of soil. The method is rapid, but expensive, and thus far is unsatisfactory in wet, saline, or stratified soil. It is discussed in more detail in Chapter 6 of Stewart and Nielsen (1990), and various versions of the method are discussed by Vegelin *et al.* (1990) and Heimovaara (1993). Richardson *et al.* (1992) found that it is reliable for soil in pots and other small containers. Holbrook *et al.* (1992) used the change in the dielectric constant to measure changes in the water content of palm stems.

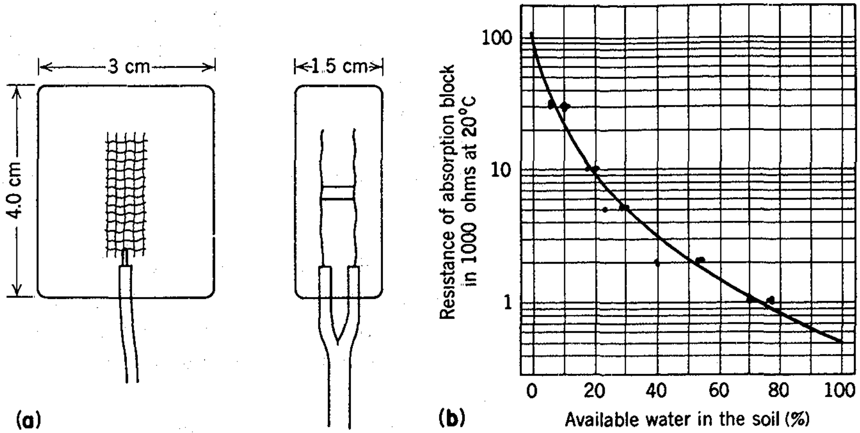

Figure 4.11 Resistance or conductance blocks. (a) Surface and edge diagrams showing location of electrodes in a plaster of paris block. The electrodes are two pieces of stainless-steel screen, separated by a piece of plastic. (b) Resistance in ohms of a plaster of paris resistance block plotted over percentage by weight of available soil water in a silt loam soil in which it was buried. From Kramer, 1983, after Bouyoucos (1954).

Electrical Conductance. Early attempts to measure changes in soil water content based on changes in electrical conductance or resistance were unsuccessful because of poor contact with the soil, variations in salt content, and temperature variations. The salt and contact errors were reduced by enclosing the electrodes in gypsum blocks (Fig. 4.11) or wrapping them in nylon. The latter last longer in the soil, but gypsum blocks are buffered against salt by the dissolved $CaSO_4$ in the blocks. Gypsum conductance blocks function better than tensiometers in dry soil. A vertical array of conductance blocks is effective in observing the progress of wetting and drying fronts in soil. Other developments in measuring electrical conductance of the soil are described by Kano (in Hashimoto *et al.*, 1990) and Seyfried (1993).

Heat Conductance. The heat conductance of soil decreases with decreasing water content, and if a heating element is buried in the soil with a detector nearby, changes in water content can be estimated from the rate of heat conduction to the sensor. Unfortunately, the method is not very sensitive in dry soils.

Measurement of Soil Water Potential

Several methods used to measure soil water content really measure the matric potential or pressure which can then be related to the gravimetric water content.

Tensiometers. Direct field measurements of the matric potential often are made with tensiometers, which consist of porous porcelain cups filled with wa-

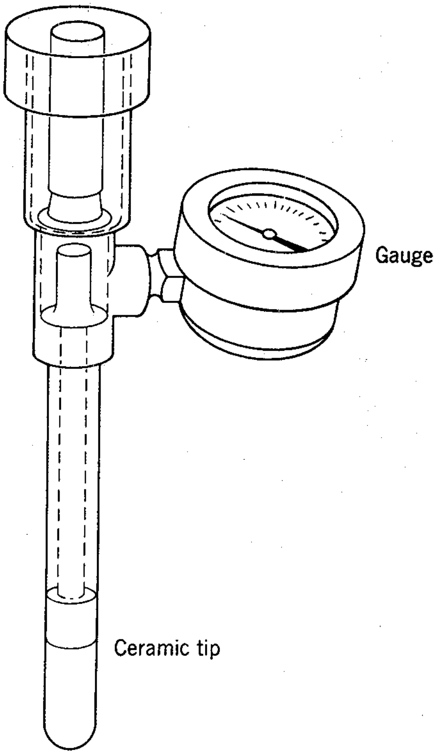

Figure 4.12 Essential features of a tensiometer, consisting of a plastic tube with a porous porcelain cup attached to the lower end, a screw cap at the upper end for refilling, and a vacuum gauge attached at the side. From Kramer (1983).

ter and buried in the soil at various depths and connected by water filled tubes with vacuum gauges, or pressure transducer systems (Fig. 4.12). As the soil water content decreases the pressure in the water in the porcelain cup decreases in proportion and the decrease is shown on the attached pressure gauge. They work well in moist soil, but at soil water potentials below about −0.08 MPa bubbles of air and water vapor form by cavitation and they often become useless. Methods of dealing with air bubbles have been discussed by Miller and Salehzadeh (1993). Tensiometers are discussed by Rawlins (in Kozlowski, 1976, pp. 31–37), Cassel and Klute (1986), in Chapter 6 of Stewart and Nielsen (1990), and in Chapter 3 of Pearcy *et al.* (1989).

Pressure Plates. Laboratory measurements of capillary or matric potential are usually made on the pressure plate apparatus developed by Richards (1949, 1954) and others. An example is shown in Fig. 4.13. Moistened soil samples

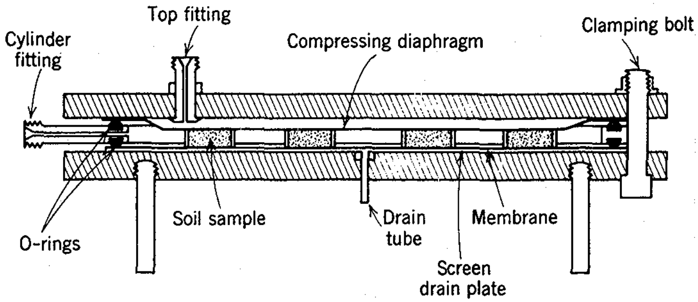

Figure 4.13 A pressure plate apparatus for measuring the matric potential of soil at various water contents. The soil samples are contained in metal rings 5.0 cm in diameter and 1.2 cm deep placed on a cellulose acetate membrane. Compressed air is supplied through the cylinder fitting and air at a slightly higher pressure is supplied through the top fitting to keep the soil samples pressed firmly against the membrane. Sometimes the cellulose acetate membrane is replaced by a porous ceramic plate. The displaced water leaving through the drain tube is collected and measured. Data obtained with this type of equipment are shown in Fig. 4.14. From Kramer (1983).

contained in rings about 5 cm in diameter and 0.5 cm thick are placed on plastic or ceramic membranes permeable to water and solutes and are subjected to a specified pressure until drainage ceases, then removed and the water content determined gravimetrically. By determining the water content at several pressures, instructive water release curves can be constructed such as those shown in Fig. 4.14. The water content of a nonsaline soil at −0.03 MPa is approxi-

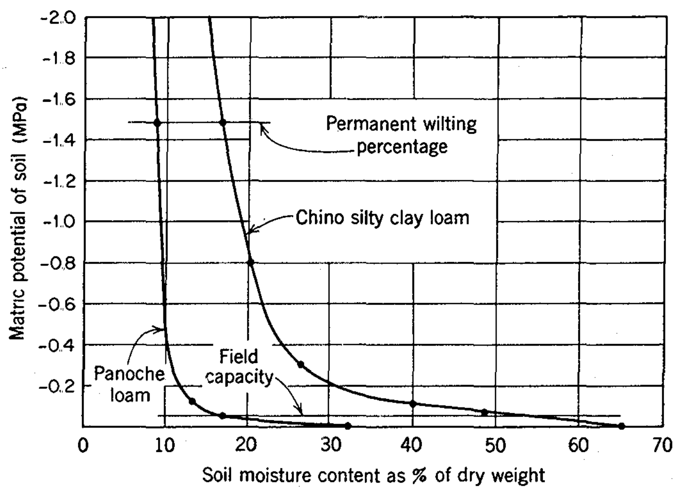

Figure 4.14 Matric potentials of sandy loam and clay loam soils plotted over water content. The curve for the Panoche sandy loam is from Wadleigh *et al.* (1946) and the chino clay loam is from data of Richards and Weaver (1944). From Kramer (1983).

mately the field capacity, whereas that at −1.5 MPa often is taken as the permanent wilting percentage.

Measurement of Osmotic Potential. Measurement of the osmotic or solute potential must be made on samples of soil solution such as those removed in a pressure membrane apparatus or squeezed out of a soil sample in a syringe. The osmotic potential can then be measured in a vapor pressure psychrometer or estimated from its electrical conductivity (Richards, 1954). Sands and Reid (1980) concluded that the most reliable measurements are made on displaced soil solutions.

Measurement of Total Soil Water Potential. The total soil water potential can be measured by burying thermocouple psychrometers protected by enclosure in porous porcelain or stainless-steel screen cylinders at various depths in the soil (Rawlins and Dalton, 1967). Fonteyn *et al.* (1987) used such installations successfully in desert soils. They and others also found that the measurement of predawn plant xylem sap potential usually gives a good indication of soil water potential, although this is questioned by Johnson *et al.* (1991). Measurements also can be made on soil samples removed and placed in thermocouple psychrometers in the laboratory. Boyer (1995) and Brown and Oosterhuis (1992) discussed some of the problems encountered in use of thermocouple psychrometers.

CONTROL OF SOIL WATER

Irrigation

There are two important aspects of soil moisture control, the practical but approximate method used in farming and gardening and the more precise methods used in research. Various aspects of irrigation at the farm and crop level are discussed in Teare and Peet (1983) and Stewart and Nielsen (1990).

Prehistoric farmers evidently realized that rainfall is often inadequate for good crop production because irrigation was being practiced at least 5000 BC in Egypt. It was well developed in Babylonia and China by 2000 BC and in the Americas in pre-Columbian times (Hagan *et al.*, 1967; Masse, 1981 and Chapters 1 and 2). There has been a great increase in the area of land irrigated from about 95 million ha in 1950 to 250 million ha in 1980 (Stewart and Nielsen, 1990, p. 1), but the increase is slowing because of lack of suitable land, competition for other uses of water, and increasing costs. Perhaps the most economical use of water for irrigation is in humid areas as a supplement during droughts (Sneed and Patterson in Raper and Kramer, 1983), where drought often reduces yield (Boyer, 1982). Trends in irrigation practices are discussed in Chapter 3 of Stewart and Nielsen (1990).

Basin and Furrow Irrigation. The earliest method seems to have been basin irrigation where a small area was enclosed in low dikes of earth and the enclosed surface flooded. This method was used widely in orchards until recently. Row crops often are irrigated by running water down furrows between the rows, but this requires careful grading and leveling of the land and considerable labor to control the flow. There often are differences in the amount of water supplied along the rows, and considerable losses by seepage and evaporation occur by both methods.

Sprinkler Irrigation. As sprinklers and power sources have improved, sprinklers have increased in size from those that covered lawns or single trees to systems that cover several acres. In addition to saving water and labor they can be used on sloping land and for the addition of fertilizers (fertigation). Occasionally, sprinkler systems also are used for frost control, especially with citrus (Parsons *et al.,* 1985, 1991). The cooling effect of intermittent sprinkling is beneficial in some situations, especially during hot sunny weather (Bible *et al.,* 1968; Gilbert *et al.,* 1970; Southwick *et al.,* 1991; Unrath, 1972). Several types of sprinkler irrigation are discussed by Sneed and Patterson (in Raper and Kramer, 1983) and in Stewart and Nielsen (1990, Chapter 16). A high salt content in the water used for sprinkler irrigation often results in injury to leaves and reduced crop yields (Maas, 1985; Stewart and Nielsen, 1990, Chapter 36). Prolonged sprinkler irrigation may create conditions favorable for leaf and twig disease, and reducing sprinkling periods to 12 hr significantly reduced the incidence of *Botryosphaeria* blight of pistachio in California (Michailides *et al.,* 1992).

Drip and Trickle Irrigation. This type of irrigation has come into favor because it conserves water and the availability of plastic tubing makes installation convenient. Water is distributed in tubing to individual trees and rows of plants and allowed to drip out through calibrated nozzles, improving control of the amount and the precision of placement. In some instances the tubing is placed in the soil, decreasing the losses from evaporation. One difficulty with the underground system is occasional undetected clogging of nozzles. Sometimes trickle and sprinkler irrigation systems are controlled by tensiometers buried in the root zone, as in the experiments of Adamsen (1992), who found that overhead sprinklers and buried trickle systems produced equal increases in corn yield on a loamy sand soil, but trickle irrigation saved water. Unfortunately, trickle systems wet only limited areas of soil and trees do not always grow as well as with more thorough wetting (Zekri and Parsons, 1989). Many aspects of drip and trickle irrigation are discussed by Bresler (1977) and in Chapter 16 of Stewart and Nielsen (1990).

Secondary Uses of Irrigation Equipment. Although the primary use of irrigation equipment is to supply water, sprinkler and trickle systems can be used to supply fertilizer (fertigation), pesticides, herbicides, and even growth regulators, and sprinkler systems are used to reduce frost injury to fruit trees (Parsons *et al.*, 1991). Such specialized uses present special problems and require careful management, description of which is beyond the scope of this book. The use of urban wastewater for irrigation also is being explored (Wood, 1988; Mancino and Pepper, 1992). Readers are referred to Stewart and Nielsen (1990, pp. 958–963 and Chapter 33) for numerous references to such uses on citrus and other fruit crops.

Irrigation in Humid Regions. Although the need for irrigation usually is associated with arid regions, there is increasing evidence that supplementary irrigation is profitable in humid regions to mitigate the effects of droughts. Sneed and Patterson (in Raper and Kramer, 1983) give numerous examples of improvement of crop yield and quality produced by supplemental irrigation, and its potential may be as great in humid as in arid regions because water is required for a shorter time, it is more available, the quality is higher, and there is less likelihood of damage from salt accumulation. However, the timing of irrigation is more difficult in humid regions with erratic rainfall and this hinders its use as a means of supplying fertilizer. There are several papers on irrigation in humid climates in Raper and Kramer (1983), and Fiscus *et al.* (1984, 1991) discuss methods of increasing the efficiency of irrigation.

Irrigation Scheduling

The area of land irrigated has increased greatly in recent years, creating shortages of good quality water and increasing the use of water high in salt. This creates the need for methods that use water as efficiently as possible. Efficient use of water depends on applying enough to prevent serious plant water deficits without creating a surplus that drains below the root zone. If water is scarce and expensive it sometimes is economically preferable to permit a small reduction in yield to increase the area irrigated. For example, the irrigated area in Israel was increased 30% from 1958 to 1969 by increasing the efficiency with which water was used, without any increase in the total water supply (Shmueli, 1971). Some irrigation scheduling problems are discussed in Taylor *et al.* (1983) and in Stewart and Nielsen (1990, Chap. 17).

Methods of timing irrigations include measurement of soil water content, estimation of loss by evapotranspiration, and measurement of plant water status. The availability of programs for personal computers aids farmers and investigators to store and manipulate the soil, plant, and meteorological data needed to maintain cost efficient irrigation programs.

Soil Water Measurements. Traditionally, the farmer or gardener dug into the soil and decided from its appearance and "feel" whether water should be applied. The determination of water content by gravimetric methods is useful only if it can be related to soil water content in different horizons, which vary widely as shown in Fig. 4.5. The successful use of neutron meters, tensiometers, and resistance blocks depends on having them installed in zones of maximum root concentration where changes in soil water occur most rapidly.

Use of Evaporation Data. Because of the difficulty in measuring soil water content over large areas, there is interest in estimating irrigation needs from evaporation losses and the water storage capacity of the soil (Van Bavel and Verlinden, 1956; Blake *et al.*, 1960; Fereres *et al.*, 1981). If the depth of rooting, the water-holding capacity in the root zone, the allowable amount of depletion, and the rate of evaporation are known, the timing of irrigation can be calculated quite accurately. Evaporation data can be obtained from atmometers or evaporation pans or calculated from meteorological data. Tanner (in Hagan *et al.*, 1967) and Hatfield (in Stewart and Nielsen, 1990, Chapter 15) describe several methods of calculating evapotranspiration. Burger *et al.* (1987) discussed irrigation timing for ornamental nurseries based on evapotranspiration from potted plants and from a grass plot. They also calculated crop coefficients based on the ratio of evaporation from various crop plants to that from the grass plot. These varied widely among species, indicating that some kinds of plants use much more water than others.

Use of Plant Water Status. At least in theory, plants are the best indicators of water availability because they automatically integrate the atmospheric and soil factors that affect plant water status. Many plants show temporary midday wilting and partial closure of stomata on sunny days, even when growing in moist soil. However, if they show evidences of stress at dawn, soil water probably is becoming limiting. Other early indicators of plant water deficit are changes in leaf color, leaf angle, and leaf rolling, and some of these have been used successfully as indicators of the need for irrigation (Oosterhuis *et al.*, 1985; O'Toole and Cruz, 1980; Wenkert, 1980). Blum (1979) used infrared photography to monitor changes in leaf color of sorghum as an indicator of plant water stress. Development of a water deficit usually results in daytime leaf temperatures rising above that found in normally transpiring plants, and remote sensing of leaf temperature seems to be a useful method of evaluating the water status over large areas of crop plants. The measurement of leaf temperature was facilitated by the development of portable infrared thermometers. The use of canopy temperature was reviewed by Jackson (1982) and by Idso *et al.* (1986). Plant water status can be used as a guide to the need for irrigation as discussed by Hsiao (pp. 269–274) and others in Stewart and Nielsen (1990).

The use of plants as indicators for irrigation should take into account differences in tolerance of water deficits among crop plants at various stages of development (Salter and Goode, 1967). For example, corn is very susceptible to water deficit injury during silking and pollination, soybeans during pod formation and filling (Sionit and Kramer, 1977), and wheat during early anthesis (Sionit *et al.*, 1980). Radin *et al.* (1992) found that frequent irrigation of cotton during fruiting increased yield significantly. Hiler and his colleagues attempted to use information concerning susceptibility at various stages of development to develop a stress day factor as a guide to more efficient irrigation (Hiler and Clark, 1971). One of the more successful uses of plants to control irrigation was described by Fiscus *et al.* (1984, 1991). They used a computerized system that included a mass flow porometer to monitor plant water stress, as indicated by reduced stomatal conductance, that turned on an irrigation system when a decrease in stomatal conductance indicated that irrigation was needed. This saved water without reducing yield. Bordovsky *et al.* (1974) reported that timing irrigation of cotton based on plant water stress saved a significant amount of water. Irrigation of various crops is discussed further in Chapter 12, in Stewart and Nielsen (1990), and in Teare and Peet (1983).

Deficit Irrigation. Where water supply is limited growers sometimes practice deficit irrigation, applying less water to the soil than is removed by evapotranspiration, resulting in increasing water stress late in the season. This reduces the yield of some, but not all, crops. For example, Miller and Hang (1980) found that irrigation of sugar beets in Washington could be reduced to 35–50% of the loss by evaporation on a loam soil without reducing the sugar yield. This was possible because although the fresh weight of roots was reduced the sugar concentration was increased by moderate water stress. According to Snyder (1992), deficit irrigation in California does not necessarily decrease the yield of cotton, the sugar content of sugar beets, or the soluble solids in processing tomatoes under the conditions of their experiments. However, successful deficit irrigation requires careful monitoring of available soil water and the rate of evapotranspiration, and is most successful if the entire root zone of the soil is at field capacity at the beginning of the growing season. Snyder (1992) described a computer program to calculate the acreage to be planted when water supply is limited.

Irrigation Problems

Unfortunately, while irrigation reduces or eliminates the water stress problem, it often creates other problems. At the crop level these chiefly are associated with waterlogging of the soil and those caused by salt accumulation. At the political and economic level they are related to depletion of aquifers and competition with urban and industrial users for water. Unfortunately, wasteful use of water has been encouraged by government subsidies in some regions and is exhausting aquifers and threatening to limit the water available for irrigation in the future. The complicated history of providing water for irrigation and urban development is told in detail by Reisner in "Cadillac Desert" (1986).

Unexpected side effects sometimes occur. For example, sprinkler irrigation of onions in California, especially after bulb formation begins, is said to increase damage from sour skin disease (Teviotdale *et al.,* 1990), and irrigation may either increase or decrease the incidence of other diseases. Sprinkler irrigation can also cause leaching injury to leaves, or if the water is high in salt it sometimes causes injury such as tipburn and discoloration of leaves (Eaton and Harding, 1959; Harding *et al.,* 1958). Some of the technological and social problems associated with the expanding use of irrigation are discussed in Stewart and Nielsen (1990, Chapter 3 and Section VIII).

Soil Waterlogging. The importance of good soil aeration is mentioned repeatedly in this book (e.g., see Fig. 10.1) and the irrigator must operate between the danger of growth-limiting water deficits and the danger of waterlogging, especially in heavy soils. Basin irrigation is most likely to result in poor aeration, but furrow irrigation also reduces the oxygen supply temporarily. Sometimes poorly drained subsoil becomes saturated because irrigation is based on measurement of the surface soil. Good drainage to remove surplus water is second only to an adequate supply of good quality water in designing irrigation systems. The effects of flooding and deficient soil aeration on plant growth are discussed in Chapter 5, in Kozlowski (1984), and in Iwata *et al.* (1988). Experiments of Sojka and Stolzy (1980) suggest that some forms of irrigation may cause sufficient deficiency in soil oxygen to result in stomatal closure.

Salt Accumulation. Irrigation is most common in arid regions where the water often is high in salt and the evaporation from surface soil is rapid. As a result, salt accumulation in the soil is a major problem in almost all irrigated areas. The productivity of one-fourth to one-third of the irrigated land in the United States is said to have been reduced by salt accumulation and large areas in the Middle East have been rendered unproductive by it. Several writers address these problems in books edited by Hagan *et al.* (1967), Poljakoff-Mayber and Gale (1975), and Stewart and Nielsen (1990).

Experimental Control of Soil Water Content

It often would be useful in research if plants could be grown in soil kept at various levels of soil water potential below field capacity. Unfortunately, one cannot half wet a soil, as should be evident to any one who has dug into a dry soil following a summer shower and observed the sharp demarcation between wet and dry soil. Since field capacity is the water content held against gravity, a soil cannot be wetted to less than field capacity. If a container is filled with dry soil having a field capacity of 30% and enough water is added to wet the soil to 15%, the upper half of the soil will be wetted to 30% and the lower half will remain dry, a fact pointed out long ago by Shantz (1925) and Veihmeyer (1927). Sometimes in the older literature it was stated that plants were grown in soil maintained at an arbitrary water content such as 20 or 30% of dry weight or field capacity. Strictly speaking, this was impossible as part of the soil volume was wetted to field capacity while part remained dry.

This limitation poses a problem to the investigator who wishes to observe the effect on plant growth of soil water contents intermediate between field capacity and permanent wilting. Attempts to accomplish this by growing plants in pots on top of columns of sand of various heights standing in pans of water (Moinat, 1943) or by growing them in autoirrigated pots at various distances above the water supply (Livingston, 1918; Read *et al.*, 1962) have not been successful. Another approach has been to vary the intervals between irrigation so plants are subjected to various degrees of water stress before rewatering (Richards and Marsh, 1961). However, the plants are not really subjected to a constant degree of water deficit. Wadleigh (1946) discussed calculation of what he termed the integrated soil moisture stress for cycles of wetting and drying.

One way to grow plants with a fixed water supply is to grow them in nutrient solution to which additional solute is added to lower the water potential. Inorganic solutes such as NaCl are absorbed by plants (Boyer, 1965; Eaton, 1942) as are some organic solutes. The latter also are often attacked by microorganisms. Polyethylene glycol is often used because it is not attacked by microorganisms, but it can be toxic if absorbed through broken roots (Lawlor, 1970).

Solutes can have direct effects in addition to lowering the water potential and they do not necessarily exactly reproduce the effects of soil water deficits. Zur (1967) and others have eliminated the direct effects of solutes by growing plants in thin layers of soil in containers with side walls made of a differentially permeable membrane such as cellulose acetate (Fig. 4.15). The containers can then be immersed in solutions maintained at any desired water potential. However, plant size is limited because the soil mass can be only a few centimeters thick in order to maintain a uniform water potential in it and the membranes often are attacked by microorganisms.

Another approach is to supply water to only part of the root system, either by dividing the root system between containers holding moist and dry soil (Davies and Zhang, 1991, pp. 58–59; Gowing *et al.*, 1990) or by supplying water to only part of the total soil volume (Boyer and McPherson, 1975; Mc-

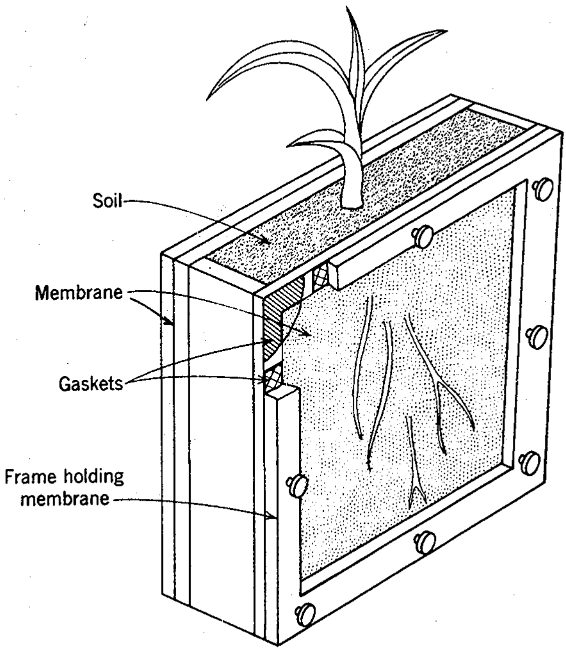

Figure 4.15 A plastic chamber in which plants can be grown in soil maintained at a fixed water potential by immersion in a solution of polyethylene glycol kept at the desired Ψ_w. The soil mass can be only a few centimeters thick because of slow water conduction at low soil water potentials. Designed by Dr. David Lawlor. From Kramer (1983).

Pherson and Boyer, 1977; Westgate and Boyer, 1985a). The limited root surface in moist soil reduces the water supply to the shoots which can be maintained at a reduced water potential for a long period. The roots in the dry soil are kept alive by water transported from the roots in moist soil. Vaclavik (1966) wetted small areas of soil throughout pots by injecting water through a long needle. All of these methods are compromises.

Actually, growing plants with a constant level of water stress is an artificial situation because in nature the soil water content continually changes. In humid climates the soil water content and water potential decrease steadily after a rain until the soil is rewetted by another rain, as shown in Fig. 4.16. In arid regions plants often must survive through the entire growing season on water stored in the soil during the preceding wet season. According to Passioura (1972), under such conditions it may be advantageous to crops such as wheat for roots to have a high hydraulic resistance that conserves water early in the season to be used later during seed filling. However, this is effective only if no other kinds of plants are present to compete for the water.

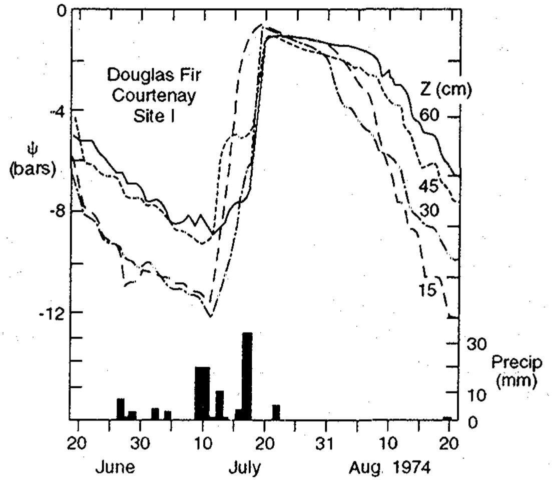

Figure 4.16 Soil water potentials at four depths beneath a Douglas fir forest on Vancouver Island in British Columbia during two drying cycles, before and after midsummer rains. Notice that water was removed most rapidly from the upper soil horizons. From Nnyamah and Black (1977).

SUMMARY

The success of plants is related closely to the properties of the soil in which they grow because it is the source of the water and mineral nutrients essential for growth. It also must constitute a suitable medium for growth of the roots necessary for anchorage and for absorption of water and minerals used in growth. This depends largely on soil texture and structure. Sandy soils are well drained and well aerated and are a favorable medium for root growth, but have limited storage capacity for water and minerals. Clay soils often are poorly drained and aerated and are a less favorable medium for root growth, but because of their large internal surface they store more water and minerals. Loam soils are intermediate in respect to these properties. Occasionally an excess of toxic elements such as aluminum, low pH, excess salinity, or hard pan layers limit root growth.

The amount of soil water available to plants is very important to their success and it varies widely between sands and clays during the growing season. The soil water content can be expressed as a percentage of dry weight of oven-dried samples or measured *in situ* by use of calibrated neutron probes, gamma ray attenuation, or change in electrical resistance. The soil water content is meaningful for plant growth only if it is considered in relation to the field capacity and permanent wilting point of the soil under study. Field capacity is the water content of a soil in which drainage has essentially ceased after thorough wetting (Ψ_w about -0.03 MPa), and the permanent wilting point is the water content at which plants remain wilted overnight unless rewatered (Ψ_w about -1.5 MPa). The water content of a sandy soil at field capacity can be lower than that of a heavy clay soil at the permanent wilting point. The *in situ* water potential of a soil can be measured with tensiometers or psychrometers buried in the root zone.

Control of soil water by irrigation has been practiced since before the beginning of recorded history. There has been a great increase in the area of land irrigated during the 20th century, but the increase is slowing because of lack of suitable land and water and increasing costs. Probably the most economical use of water for irrigation is as a supplement to rainfall during droughts in humid areas. Formerly, irrigation was done chiefly by running water in furrows or basins, but this has become supplanted by sprinklers and trickle systems in which water is supplied directly to plants. Irrigation equipment sometimes is used to supply fertilizer (fertigation), pesticides, and herbicides, and sprinkler systems are used to reduce frost injury to plants. Methods of timing irrigation include measuring the soil water content or rate of evaporation and monitoring the plant water status. Irrigation often creates problems such as waterlogging of the soil and salt accumulation, and good drainage is as important as an adequate water supply for successful irrigation.

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