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SOIL MOISTURE IN RELATION TO PLANT GROWTH

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SOIL AND ITS PHYSICAL CHARACTERISTICS

Some knowledge of the principles governing the distribution and availability of soil moisture is essential to a proper understanding of plant-water relations. Soil, considered in relation to plant growth, is not a mere mass of "dirt", but a complex system consisting of varying proportions of four principal components: mineral materials, organic matter, water and solutes comprising the soil solution, and air. While the amounts of mineral materials and organic matter vary but little in a given soil, the amount of water fluctuates over a considerable range and the amount of air varies approximately inversely with the water content. Furthermore, the proportions of oxygen and carbon dioxide in the soil atmosphere vary with depth, season and other factors (10). In addition to these four components, soil usually contains numerous living organisms, such as bacteria, fungi, algae, protozoa, insects, earthworms and other small animals. These may directly or indirectly affect plant development, and the burrows of earthworms and other small animals provide passageways which facilitate the downward percolation of water through impermeable soil strata.

The characteristics of a soil depend chiefly on the texture or size of mineral particles, the structure or manner in which these particles are arranged, and the amount of organic matter incorporated with the mineral matter. On the basis of texture, soils are usually classified as gravel, sand, loam or clay. The last three classes are most important with reference to plant growth and will be discussed briefly. More detailed discussions can be found in various soils texts (7, 52, 62, 81).

The least complex soil is a sand, which by definition contains less than 20% of silt and clay and is composed largely of simple rock particles of comparatively large size. Such a soil forms a relatively simple capillary system with large pores or air spaces which insure good aeration and free movement of gravitational water. Sandy soils are relatively inert, both chemically and physically, quite loose and non-cohesive, and have a very low water-holding capacity.

Clay soils are at the other extreme with reference to size of particles, consisting of 30% or more of clay particles, most of them of colloidal or near colloidal dimensions. These particles are usually aggregated together in complex granules which swell and become sticky when wetted. Because of the large proportion of particles of colloidal size in clay, water and minerals are held in much larger quantities and in a more complex manner than in sand. Most soils owe many of their chemical and physical properties to the clay fraction which they contain. The clay particles, because they are flat and plate-like, possess not only the maximum external surface, but also very high cohesive forces. They are usually negatively charged and carry a shell of cations and associated water molecules. The surface possessed by even a small volume of such particles is tremendous. A cubical sand grain one millimeter on the edge has a surface of only six square millimeters, but if divided into cubes of colloidal size, 0.1 micron on the edge, the total surface resulting would be 60,000 square millimeters. Because of their plate-like shape clay particles have even greater surfaces than cubes or spheres of similar volume. Their extensive surfaces enable clay soils to hold much more water than sandy soils, but since the pores are much smaller gravitational water drains off more slowly and they are sometimes poorly aerated.

Loam soils contain more or less equal proportions of clay and sand and therefore have properties which are intermediate between those of clay and sand. They are most favorable for plant growth because they hold more available water than sand, and are better aerated and easier to work than clay.

Soil structure, or the arrangement of soil particles, is important because of its relation to pore size. Soil porosity refers to the portion of the soil volume not occupied by solid particles, but by air and water. It usually amounts to about half of the volume, generally comprising somewhat less than 50% of the total volume in sand and somewhat more than 50% in clay, though exceptions to this exist (94). The total pore space is not so important as the size of the pores. That portion of the pore space composed of large pores from which water usually drains by gravity and which is therefore normally filled with air is termed the non-capillary porosity to distinguish it from that part of the pore space which is normally filled with capillary water. The large pores and large non-capillary porosity of sandy soils result in better drainage and aeration, but also result in a lower water-holding capacity than in clay soils which have a large proportion of smaller capillary pores. An ideal soil is said to be one which has the pore space about equally divided between large and small or non-capillary and capillary pores (7). Such a soil has enough large pores to permit adequate drainage and aeration and enough small pores to give adequate water-holding capacity. In clay, treatments tending to promote granulation produce larger pores, resulting in a more favorable medium for root growth. The dense mat of roots produced by grass sod seems to promote granulation and good soil structure, while cultivation generally produces the opposite effect (7, 11). The direct effects of root penetration through the soil, followed by their death and decay, is to open up numerous channels and thus to materially increase soil porosity and penetration by air and water. Earthworm activity probably has similar effects.

Soil structure is also affected by the kinds of cations present. According to a summary prepared by Veihmeyer (95), there is evidence from laboratory experiments that various properties, including moisture equivalent, permeability, hardness of crumbs and cohesiveness, are increased by substitution of sodium or potassium ions in the exchange complex and decreased by substitution of calcium or hydrogen ions. Most investigators seem to think these results also apply to field conditions, though few data are available from field tests. Eaton and Horton (30) reported that the wilting coefficient and moisture equivalent of soils partially saturated with sodium were higher than those of the same soils treated with calcium, if most of the soluble electrolytes was first removed. They state that it has been frequently observed that permeability of soil is reduced by irrigation of land with water containing a higher proportion of sodium than of other bases. This is important in semi-arid regions where rainfall is too light to remove the salts concentrated in the surface layer by evaporation of irrigation water.

Appreciation of the importance of soil structure has raised questions concerning the propriety of determining such soil properties as water-holding capacity, moisture equivalent and permanent wilting percentage on disturbed soil, as is usually done. Soil samples are usually dried, pulverized and passed through a sieve, thoroughly destroying the original structure, before they are subjected to various tests. In recent years a number of methods have been described for obtaining soil samples without disturbing their structure. One type of sampler (21) provides undisturbed soil masses for volume weight and water-holding capacity determinations and for permanent wilting percentage determinations.

The organic matter or humus in soil represents that portion of plant remains, chiefly lignified material, which is most resistant to decay. It resembles clay in some respects, being colloidal with negatively charged micelles surrounded by shells of cations, and shows even more chemical and physical activity than does clay. Because of its very great surface it holds much water, and addition of organic matter to sandy soils increases their water-holding capacity. Its addition to clay may improve the latter's structure and workability, but usually has much less effect on available water content than is commonly supposed because the water-holding capacity of clay is already comparatively high and the unavailable water content of organic matter is very high. A mixture of one-half clay and one-half peat moss by volume held only about 25% more available water than pure clay, while a mixture of one-half quartz sand and one-half peat moss held about 800% more water than pure sand (34). Apparently it is difficult to make any important changes in the available water content of soils under field conditions. In California (96) it was found that addition of as much as 200 tons per acre of manure did not appreciably increase the content of water available to plants in sand, loam or clay soils. In New York (40) additions of 8 and 16 tons per acre of manure for 27 years did not significantly increase the available water-holding capacity of Chenango loam, but did significantly increase the available water-holding capacity of Chenango fine sandy loam.

SOIL MOISTURE CLASSIFICATION

The classification of soil moisture most familiar to plant scientists is the simple system of Briggs (12) with the addition of water vapor as suggested by Lebedeff (57). This system divides soil moisture into four classes:

a) gravitational water, which occupies the larger pores of the soil and drains away under the influence of gravity; it is often injurious to plants if drainage is too slow;

b) capillary water, which is held by surface forces as films around the particles, in angles between them and in capillary pores; capillary water moves slowly in the form of liquid from thicker to thinner films, and is the only important source of water for most plants;

c) hygroscopic water, which is held on the particles by surface forces and moves in the form of vapor; the moisture remaining in air-dry soil is usually regarded as hygroscopic water and is generally unavailable to plants;

d) water vapor, which occurs in the soil atmosphere and moves along vapor pressure gradients; it is probably not used directly by plants.

Such a classification must be regarded as somewhat arbitrary in the light of present-day theories of soil moisture because there really is no sharp boundary between these different classes of soil moisture (97). Under certain conditions capillary water may become gravitational water and hygroscopic water may merge into capillary water. This classification seems sufficiently useful, however, especially to plant scientists, to retain it in spite of its arbitrary nature. A brief discussion of the various types of water follows.

Gravitational water. For a short time following a heavy rain or irrigation the soil may be completely saturated with water, the air in it having been displaced from the non-capillary pore spaces between the particles. Under the influence of gravity most of this free water soon percolates downward through the soil toward the water table, unless prevented by some barrier such as a hardpan layer. Within two or three days after a rain all the gravitational water usually drains out of at least the upper horizons of the soil, and the pore spaces become refilled with air. If the soil remains saturated with gravitational water for several days serious injury to root systems may result from lack of oxygen and accumulation of excess carbon dioxide. Obviously gravitational water is therefore of little direct value to most plants and even may be detrimental.

Capillary water. After the gravitational water has drained away a soil is said to be at its "field capacity". The water remaining exists as films around the particles, in the angles between the particles, and in the smaller capillary pores. Much of this water is held rather loosely and is readily available to plants. Some of it, often termed "inner capillary water", is held by the colloidal material and in the smallest pores and is relatively unavailable to plants. As previously stated, the finer the texture of the soil the more surface is exposed and the more capillary water it will hold. Since capillary water moves slowly it is relatively unavailable unless the roots actually come into contact with it. Puri (74) claims that the lower limit of water available to plants is determined principally by the number of pores too small to be penetrated by root hairs. In general, movement of capillary water from moist to dry soil is quite slow, and the significance of this with respect to absorption will be discussed later.

Hygroscopic water. The water remaining in a soil in equilibrium with a partly saturated atmosphere is usually termed "hygroscopic water". It is held in a very thin film perhaps 15 to 20 molecules in thickness. The upper limit of hygroscopic moisture is generally supposed to be the moisture content of soil in equilibrium with saturated air, but soil kept in contact with moist air over a long period may accumulate so much water that it actually becomes saturated (52). This illustrates the difficulty of sharply distinguishing between these two classes of soil moisture. Hygroscopic water, if the term is used to refer to the water in approximately air-dry soil, is obviously unavailable to plants.

SOIL MOISTURE TERMINOLOGY

The literature dealing with soil moisture contains numerous special terms. Many are of interest only to soils men or engineers, but a number of them are frequently used in discussions of plant and soil moisture relations. Among the terms frequently encountered in discussions of plant and soil water relations are "capillary potential, pF value, capillary capacity, maximum water-holding capacity, field capacity, hygroscopic coefficient, wilting coefficient, wilting point, permanent wilting percentage, wilting range, moisture equivalent, readily available water, relative wetness, water-supplying power".

The "capillary potential" or "pressure potential" of a soil, often designated by the Greek letter psi (ψ), is a measure of the attractive forces with which water is held by the soil, or an expression of the work done in moving water against the capillary forces of the soil. Buckingham (17), who originally proposed the term, expressed it as the height in centimeters of a water column which would exert sufficient pressure to move water in a soil at a given moisture content. It may also be expressed in gram centimeters per gram or ergs per gram. The potential of free water, which is the base or reference value from which the potential of soil moisture is measured, is regarded as zero. Since the potential of water in unsaturated soil is lower than that of free water, the potential of soil water must be regarded as having a negative value. The capillary potential increases negatively with decreasing moisture because more energy is required to move water in dry soil than in moist soil. Since it is negative the potential is sometimes expressed as a tension in terms of the height of the water column required to produce it, as for example 250 or 500 centimeters of water, or the corresponding height of a mercury column.

Recently use of the thermodynamic function of "free energy" has been proposed to deal with soil moisture problems (31, 32, 83). It is a more generalized quantity which includes the capillary potential as a special case. The latter deals only with the energy relations resulting from the tension or pressure existing in soil moisture, and excludes the effects of dissolved salts and the possible adsorption of water molecules around soil particles. These are included by the quantity "free energy". The capillary potential is approximately equal to the free energy value when the concentration of solutes is negligible. The free energy and the capillary potential can be measured or calculated from measurements made in various ways, such as by determining the vapor pressure or the freezing point, and by use of the centrifuge, dilatometer, osmotic membranes, tensiometers and pressure devices. Tensiometers (77) are essentially porous clay cups, similar to autoirrigators, connected to a mercury manometer or vacuum gauge which indicates the negative pressure or tension when the water in the cup is in equilibrium with the soil moisture. The capillary potential at various moisture contents is sometimes measured in the laboratory by placing the soil in contact with a porous plate attached to a vacuum line. The soil is subjected to any desired suction and the moisture content is then determined. Unfortunately these methods operate only to a potential equal to one atmosphere or less, so the higher potentials existing in drier soils are usually calculated from their vapor pressures. Richards (76) has recently developed a method of applying pressure which gives potentials under pressures up to 16 atmospheres or more.

The energy concept of soil moisture is becoming more popular because it indicates the condition of the soil moisture independently of texture, structure or composition. The moisture relations of very diverse soils can therefore logically be compared because, for example, the capillary potential, pF, or free energy of the soil water at the permanent wilting point is approximately the same in all soils.

"Soil pF". Schofield (85) proposed the use of the logarithm of the capillary potential expressed in centimeters of water. He termed this the pF scale by analogy with the pH scale, "p" referring to its logarithmic character and "F" indicating that it refers to the logarithm of the free energy difference. The chief advantage of this scale is that it permits the entire range of soil moisture tension to be shown on one compact scale, although the equivalent water column is almost 10 kilometers (1,000,000 cm.) at equilibrium with 50% relative humidity (pF 6) and about ten times greater at oven-dryness (pF 7). The moisture equivalent is at a pF of about 2.7, the wilting percentage at about 4.2. Water may be regarded as moving along a pF gradient from regions of low pF to regions of higher pF. The pF can be directly determined down to about pF 3 by applying suction to a thin layer of soil, and values for drier soils have been calculated from vapor pressure and freezing point depression data or more recently by application of direct pressures up to 16 atmospheres (76).

The "hygroscopic coefficient" is the moisture content of the soil in equilibrium with an atmosphere of known relative humidity—usually a nearly saturated atmosphere. According to Keen (52) and others, the experimental difficulties inherent in making such determinations render them of very doubtful value, although at relative humidities below saturation reproducible results can be obtained. This value generally is of minor interest to plant scientists.

The "maximum water-holding capacity" is the water held by a thin layer of saturated soil. The soil is placed in a shallow metal container with perforated bottom and allowed to stand in water until saturated. This gives measures of pore space, specific gravity and expansion on wetting, and Keen (52) recommends it as a measurement useful to the soil scientist. The method of draining surplus water will affect the results obtained, and the results may also vary depending on whether the measurement is made on pulverized soil or a soil mass with undisturbed structure.

The "maximum capillary capacity" of a soil is the maximum moisture content held against gravity and is therefore essentially similar to the field capacity.

The "field capacity" of a soil is the moisture content after the gravitational water has drained away (101), and it is therefore essentially equal to the capillary capacity. Most soils are at their field capacity within two or three days after a rain or irrigation (103). Soil samples in short columns allowed to drain over sand probably reach approximately their field capacity within a few hours. This is not a true equilibrium value, but only a condition of such slow water movement that the moisture content does not change appreciably between applications of water. While most soils reach their field capacity very quickly, the presence of a water table near the surface will greatly prolong the time required for drainage, and if the soil is saturated to a depth of many feet, drainage of the surface layer to field capacity will be much slower than if only the top few feet are wetted. A fine-textured soil overlying a coarse-textured soil will also have a higher field capacity than a uniformly fine-textured soil (103).

The term "moisture equivalent" was introduced by Briggs and McLane (13) to denote the water content of soil which has been subjected to a centrifugal force of one thousand times gravity in a soil centrifuge. The precautions necessary to insure accurate results have been discussed (*e.g.*, 105). The moisture equivalent has been found to be closely related to the field capacity of fine-textured soils but not of sands (101). Work and Lewis (108) found that the moisture equivalent of certain Oregon soils was not equal to the field capacity, and such a relation should not be assumed without actual determinations. The ratio of field capacity to moisture equivalent of certain West Virginia soils is unity in the vicinity of a moisture equivalent of 21% more than unity for soils with moisture equivalents below 21% and less than unity for those with moisture equivalents above 21% (16). Although the equipment is expensive, determinations are so easily made that the moisture equivalent is one of the most frequently determined soil constants.

"Permanent wilting percentage". The moisture content of the soil at the time when the leaves of plants growing in that soil first become permanently wilted has been variously designated as the "wilting point", "wilting coefficient", "wilting percentage", and "permanent wilting percentage". It will be designated as the "permanent wilting percentage" in this paper. Briggs and Shantz (14) first emphasized the importance of this soil moisture content with respect to plant growth and termed it the "wilting coefficient". Their procedure was to grow seedlings in glass tumblers of soil sealed with a mixture of paraffin and vaseline. When the leaves wilted and did not recover over night in a moist chamber the moisture content of the soil was determined by oven-drying a sample at 105° C. and calculating the moisture content as a percentage of the dry weight. Briggs and Shantz stated that this marked the lower limit of soil moisture available for growth, but not the lower limit of soil moisture available for the plants. Although absorption is too slow for growth at moisture contents below the wilting point, plants are able to absorb water from the soil until it is approximately air-dry or until they have died of desiccation. Permanent wilting, according to Briggs and Shantz, does not mark any definite limit in the movement of water from soil to plant, but simply marks the moisture content at which absorption becomes too slow to replace the water lost by transpiration, resulting in wilting. Shull (91) came to similar conclusions regarding the cause of wilting, and these views have been substantiated by more recent investigations and are generally accepted at the present time.

The moisture content of the soil at the time of permanent wilting might conceivably be affected by the species and condition of the plants used in its determination and by the environmental conditions under which it is determined, as well as by the soil texture. Briggs and Shantz (14) concluded, however, that soil texture is the only factor materially affecting the moisture content at permanent wilting. Age of their plants did not materially affect the values, as the same results were obtained with seedlings and well grown grass plants. Plants grown with different amounts of soil moisture wilted at the same moisture content, indicating that drought resistance had not been increased by growing the plants in dry soil. Contrary to previously accepted views, they found no important differences between different species of plants in regard to their ability to reduce the moisture content of the soil before wilting. The differences observed between various species of crop plants were too small to explain differences in drought resistance, and even these small differences were believed to result from differences in root distribution rather than from differences in forces bringing about water absorption. Similar results have been obtained with a number of crop plants (20). The results and conclusions of Briggs and Shantz have been criticized for various reasons (15, 19, 24, 72, 90), but they are substantiated by more recent investigations. Briggs and Shantz found that while all species wilted at approximately the same moisture content in a given soil there were considerable differences between species in ability to survive in soil below the wilting point. Some species died soon after wilting, while others survived for long periods in a partially wilted condition. Some of the criticisms of Briggs and Shantz' work probably result from failure to differentiate between the early stage of wilting used by them as an end point and later stages approaching the ultimate wilting point of Taylor, Blaney and McLaughlin (92) and Furr and Reeve (37).

The type of plant used in determining the wilting percentage does have some bearing on the reliability of the results. The first requirement is a well-developed fibrous root system which so completely permeates the soil that the moisture content is evenly reduced throughout the soil mass. The leaves must be of a type which show wilting clearly, and plants with heavily cutinized leaves, such as pine needles, are therefore unsatisfactory. The writer found that the wilting point of a sandy loam determined simultaneously with sunflower, black locust and pine seedlings appeared to be highest with sunflower, and lowest with pine seedlings. This probably does not represent any difference between these species in ability to reduce the moisture content, but resulted from the greater difficulty in determining when the pine seedlings had begun to wilt. Moinat (68) suggested that determination of the wilting point may be in error because of the leaves removing water from the stem or other parts of the plant after the soil is really at the wilting point. This would be a negligible factor when oats or other grasses are used as indicators. It probably is also a minor factor if the wilting process is terminated when the first pair or two of leaves have wilted.

A lively controversy arose concerning the influence of atmospheric factors on determination of the wilting percentage. Briggs and Shantz (14) made most of their determinations in a greenhouse where transpiration was very moderate but considered that the values were not materially affected by atmospheric conditions such as humidity or by moderate changes in light intensity. Two other investigators (15, 19) found that plants growing in the open wilted at a higher soil moisture content than plants growing in shade with a lower rate of transpiration. One of these (19) concluded that "for a series of plants grown in any one soil and wilted under a number of aerial conditions, as many different soil-moisture contents are obtained as there are sets of conditions". In another experiment (90) in which several species were wilted under various degrees of shading, it was found that the moisture content of the soil at permanent wilting was lowest in the shade and highest in full sun. Veihmeyer and Hendrickson (102) found the wilting percentage of a particular soil to be remarkably constant, regardless of size of container, species of plant, season of the year, or degree of exposure. Sunflower plants were wilted in the spring and during the hot dry weather of late summer. Some seedlings were allowed to wilt in a moist chamber in a greenhouse, others in a whitewashed greenhouse and still others in the open. The average wilting percentage was the same in all instances, although the rate of evaporation was several times as high when some plants wilted as when others wilted. Furr and Reeve (37) obtained similar results. Discrepancies between the conclusions of various investigators may have been caused in part by differences in opinion as to what constitutes the onset of permanent wilting.

Sachs (84) seems to have been the first to study the effect of soil texture on the availability of water to plants. He found that when tobacco wilted in sand, loam and a mixture of humus and sand, the moisture contents at the time of wilting were 1.5%, 8.0% and 12.3%, respectively. Apparently little attention was paid to this situation until publication of the very extensive work of Briggs and Shantz (14). They found the moisture content at permanent wilting to vary from 1% in sand to 25% in clay and even higher in soils containing much organic matter.

In addition to actually determining the wilting point, Briggs and Shantz attempted to calculate it from the moisture equivalent. They found that for their soils,

$$\text{Wilting coefficient} = \frac{\text{moisture equivalent}}{1.84 \pm 0.013}.$$

This value has frequently been used, but subsequent work by several investigators show that such a relation does not always exist. In an investigation of 60 California soils (101) the ratio was found to range from 1.4 to 3.8. The ratio of moisture equivalent to wilting percentage in three soils on the Duke Forest ranged from 1.57 to 5.65, varying with soil type and horizon (29). Briggs and Shantz also attempted to relate the wilting coefficient to the hygroscopic coefficient, the moisture-holding capacity and the mechanical analysis. The usefulness of any such cross-relating of values is obviously very doubtful, since the relations are not the same in all soils. The moisture content at permanent wilting appears, however, to be logically and consistently related to certain other values. The permanent wilting percentage of most or possibly all soils falls at about pF 4.2 and at the moisture content existing after application of a pressure of 15 atmospheres. The moisture content of a soil at permanent wilting can be determined most reliably by direct observation. Since the term "wilting coefficient" has often been applied to indirect determinations, it would seem preferable to use the term "permanent wilting percentage" to indicate determinations made by the direct method (100).

Wilting, of course, does not begin at a specific moisture content, but it does begin within a very narrow range of soil moisture for which the value given as the permanent wilting percentage is the average. The more care taken in making the determinations, especially in bringing all plants to the same stage of wilting, the more consistent the results. Since the permanent wilting percentage is so stable for a given soil and since it accurately indicates the lower limit of soil moisture available for plant growth, it is perhaps the most important of all soil constants for the plant scientist. Detailed descriptions of the methods used in precise research have been given by several experimenters (14, 37, 108). The writer has obtained satisfactory results with less elaborate methods, merely growing oat or sunflower seedlings in heavily paraffined pint ice cream containers until they are three or four inches high, sealing the soil surface with paraffin and allowing the containers to stand on a partly shaded greenhouse bench until the lower leaves remain visibly wilted over night.

"Wilting range of a soil" is a term applied to the range of soil moisture from the first permanent wilting of the basal leaves of sunflowers to complete permanent wilting of the entire plant (92). Furr and Taylor (38) and Furr and Reeve (37) have presented data on this range, and Furr and Reeve give detailed instructions for its determination. They use the terms "first permanent wilting point" and "ultimate wilting point" to designate the upper and lower limits of the wilting range and like Briggs and Shantz regard the first permanent wilting point as the lower limit of soil moisture available for growth. The moisture in the wilting range, while unavailable for growth, is available for survival, and the proportion of the total available soil moisture which is within this range is great enough to be of considerable significance in plant water relations. In about 80 soils which were studied (37), a minimum of 11% and a maximum of 30% of the moisture content between the moisture equivalent and the ultimate wilting point was in the wilting range.

The "readily available moisture" in a soil is that which can be used by plants in growth and is therefore the moisture above the permanent wilting percentage. While gravitational water is readily available to plants, it usually drains off too soon to be of much importance. The readily available water is therefore usually considered to be that included in the range from field capacity or moisture equivalent down to the permanent wilting percentage. In sandy soils this range is quite narrow, in clay it is quite wide. The advantages of a wide range of available water in carrying plants through droughts or in obviating the need for frequent irrigation is too obvious to need discussion. The relative availability of water in the upper and lower part of this range will be discussed later. As previously stated, plants can absorb water from soils drier than the permanent wilting percentage, but absorption is too slow for growth.

"Relative wetness" is a term applied to the ratio of moisture content to moisture equivalent (23). Dividing the moisture content by the moisture equivalent enables comparisons to be made between soils or soil horizons which differ in texture. This is particularly useful in following moisture changes at various depths or in various parts of an orchard or field where the soil is not uniform in texture.

The "water-supplying power" of the soil refers to the rate at which water moves from soil to an absorbing surface, such as a root. This term is generally used to refer to measurements made with the "soil point cones" of Livingston and Koketsu (59*a*).

MOVEMENT OF SOIL MOISTURE

Movement of soil moisture is relatively complex because of the various directions and states in which it moves and the various forces operating to cause its movement. Downward movement occurs when the soil is being wetted by rain or irrigation, some upward movement occurs when the surface is drying by evaporation, and lateral movement also occurs. Water moves as liquid in capillary films and in the larger or non-capillary pores. Appreciable movement also occurs in the form of vapor along vapor pressure gradients and in convection currents of the soil atmosphere. The forces causing movement of liquid water are chiefly gravity, hydrostatic pressure and capillary forces. Because it is often difficult to determine precisely which forces are bringing about water movement, it is considered best to regard water as moving along gradients of decreasing free energy, a statement that is true regardless of the nature of the forces involved.

Infiltration. Infiltration of water into the surface is the first step in wetting a soil, and the rate of infiltration into a given soil is a very important factor in determining how much of a given rainfall will be accumulated in the soil and how much will be lost by run-off. A relatively impermeable surface is developed on a bare soil surface after only a few minutes' exposure to rainfall. This results from the packing of small particles around the larger ones by rain drops and surface flow so that water cannot penetrate freely. Formation of such a layer can be avoided and run-off can be greatly decreased by mulches and incorporation of organic matter into the surface of the soil. According to Duley (28), formation of an impermeable surface layer has more effect on infiltration of water into Nebraska soils than soil type, slope, moisture content or profile. Run-off and accompanying erosion, in his opinion, can be practically eliminated by maintaining a mulch of crop residues on the soil. While infiltration into a bare soil is much more rapid at first if it has been cultivated, the rate decreases very rapidly after the first 15 to 30 minutes, and on both cultivated and uncultivated soils it soon reaches a constant rate which is determined by the rate of downward percolation through the deeper soil horizons.

Movement of gravitational water. This movement after the water has penetrated into the soil is chiefly affected by number, size and continuity of the air spaces or non-capillary pores through which it percolates. It usually moves very freely through the large pores of sandy soils, and such soils are generally quickly drained to field capacity. Movement is less rapid through clay because the pores are much smaller; they are frequently blocked by the swelling of colloidal gels, and air is often trapped in them. Lutz (61) found the permeability of clay to decrease as the hydration of the particles increased. Movement of gravitational water is frequently hindered by impermeable subsoil layers which trap air as well as water. Movement is facilitated by worms and other animal activity and by decay of roots, all of which leave passageways. In general, unless a hardpan interferes or the soil is saturated to a shallow water table, gravitational water can be expected to drain out of the surface layer within two or three days after rain or irrigation.

Movement of capillary water. The earlier discussions of the movement of soil moisture were based on a relatively simple concept of the soil as an aggregate of capillary tubes of various dimensions, and many present-day discussions make use of this capillary theory. According to this theory, as developed by Briggs (12), soil moisture exists principally as continuous thin films around the soil particles and in the smaller spaces and angles between them. These films are under great inward pressure because of the surface tension of the water, and water therefore tends to move from regions with thicker films to regions with thinner films.

While the foregoing assumptions are correct, the capillary theory has been found inadequate to explain certain observed facts and has therefore been sharply criticized. Dissatisfaction with the inadequacy of the capillary theory led to the gradual development of a theory based on the energy relations or work done during the movement of water. Buckingham (17) suggested that movement of water through the soil might be compared to the movement of heat or electricity through a conductor. He considered the driving force to be the difference in attraction for water between two portions of soil having different moisture contents and proposed the term "capillary potential" for the force required to move a unit mass of water from a unit mass of soil. This theory was further developed by various other workers (7, 32, 39, 52, 75, 83) to whom the reader is referred for more detailed discussions of various aspects of the theory.

According to certain writers (7, 97), the most important implication of the potential theory of soil moisture is that there are no such sharp boundaries or differences between various types of soil moisture as are indicated by the terms "gravitational", "capillary" and "hygroscopic water". Various methods of measuring the potential or force with which water is held by soil at various moisture contents agree in indicating that the potential is directly related to the moisture content. When the potential is plotted against decreasing soil moisture it forms a smooth curve, indicating that there is no real change in the state of water as the moisture content decreases from the field capacity past the permanent wilting percentage down to an oven-dry condition, but merely an increase in the energy required to move it. The permanent wilting percentage falls in the region of greatest curvature of the curve for potential over soil moisture, while the field capacity falls in the region where it becomes almost flat.

It has been proposed (31, 32) that the thermodynamic concepts of free energy be applied to discussions of water movement in the soil and through the plant. Such a treatment of soil moisture movement is based on sound principles and is very useful to the soil physicist, but unfortunately many plant scientists are not sufficiently familiar with the mathematical methods used to fully understand such a treatment. It is more intelligible to most workers and for most purposes it is just as satisfactory to discuss the movement of moisture in the more familiar terms of gradients of diffusion pressure, vapor pressure or diffusion pressure deficit (66) which are also based on energy relations. The plant scientist is primarily concerned with understanding the factors which affect the availability of water and its movement from soil to plant roots. Movement of soil moisture can be discussed in conventional terms if we remember that regardless of the terminology its movement is determined by differences in energy or in the forces with which it is held in different regions of the soil. Using this conventional terminology, we may say that water flows under the influence of gravity, moves in capillary films and diffuses as vapor, but it always moves along a gradient of decreasing free energy. Its energy is highest in free water, lower in moist soil and still lower in dry soil. Movement of capillary water is materially affected by soil texture, being most rapid in sandy soils and slowest in clay soils at saturation, but in drier soils the effects of texture are reversed, movement being slowest in sands and most rapid in clay (70). Height of capillary rise also depends on texture, being greatest in clays and least in sands. In no instance, however, has capillary rise been found to be as great as would be expected from calculations based on size of soil particles. Neither has the movement of capillary water proved to be as rapid as it was once supposed to be. Early discussions of this subject gave the impression that as rapidly as water is removed from the soil particles in contact with the roots it is replaced by capillary movement from more distant soil particles. More recent investigations indicate that capillary movement of soil moisture from moist to drier regions is very slow except where the water table is within three or four feet of the surface. Of course, some movement always occurs from regions with thicker films to regions with thinner films, provided continuity of films exists, but such movement is much more rapid in saturated soil than in dry soil. Moore (70) found very little unsaturated flow of moisture in soils at or below the moisture equivalent. Veihmeyer and Hendrickson (99) placed a mass of soil wet to field capacity in a large cylinder with dry soil on each side of it. After 139 days water had moved only eight inches into the dry soil.

Since capillary movement is so slow in soils drier than field capacity it is probable that during periods of rapid transpiration the available water on soil particles in contact with the roots is removed much faster than it can be replaced by capillary movement. Thus each absorbing root may become surrounded by a slender cylinder of soil from which all available water has been removed, although soil a few millimeters away is still at field capacity. Data of Richards (76), however, indicate that water movement possibly may occur fairly rapidly over distances of a few millimeters. He found that a pressure of 16 atmospheres reduced the moisture content of a soil layer five to ten millimeters in thickness from saturation to below the permanent wilting percentage in 24 to 36 hours. In his experiments he displaced water from a moist soil through a collodion membrane, but did not cause it to move from moist soil into dry soil.

Movement of water vapor. As the soil dries out the water films become discontinuous and capillary movement ceases. Any water movement in air-dry soils must be in the form of vapor. According to Lebedeff (57), in soil above its hygroscopic coefficient the atmosphere is normally saturated. Under field conditions, therefore, the soil atmosphere is always saturated, except the surface layer which occasionally becomes air-dry. Movement of water vapor is along vapor pressure gradients; hence it is affected by the relative temperatures and vapor pressures of various horizons of the soil and of the soil and air. Lebedeff states that the movement of water in the form of vapor is of considerable importance, especially in southern Russia and other semi-arid regions where there is no direct connection between the water table and the capillary water in the upper layer. Film movement is exceedingly slow under such conditions, so the effects of movement of water vapor are more noticeable. Lebedeff found that in winter appreciable quantities of water move from warmer, deeper levels to the cooler surface where it condenses, the amount so moving in one winter amounting to 66 mm. During a cool period in summer or autumn when the surface layer is cooled, water moves from the deeper levels to the surface whence it evaporates during warmer periods, thus slowly drying out the deeper layers. Ordinarily the surface layer of the soil is warmest during summer, and presumably some water vapor then diffuses downward where it condenses in the cooler soil, forming liquid water. According to Lebedeff, this is an important source of ground water in southern Russia. During the night the surface layer becomes cooler than the soil a few centimeters below the surface, while the reverse is ordinarily true during the day. These diurnal variations in soil temperature produce variations in vapor pressure which result in diurnal variations in water movement. Lebedeff calculated that in the vicinity of Odessa over 70 mm. of water are condensed in the surface layer of soil annually during periods when it is cooler than the air above it.

Evaporation. The quantity of water lost from soil by evaporation has been the subject of considerable controversy. The amount of water vapor lost depends primarily on the steepness of the vapor pressure gradient from soil to air which in turn depends on both soil and atmospheric factors. The vapor pressure of the atmosphere is affected chiefly by the humidity of the air. Air movement is also important because it changes the air in contact with the soil surface, preventing it from becoming saturated. The principal soil factors affecting evaporation are temperature and moisture content. Differences in evaporation from dark- and light-colored soils and from north- and south-facing slopes result from differences in temperature.

It is obvious that evaporation from a dry soil surface will be much less than from a moist one because diffusion of water vapor through the soil is very slow. Since when no rainfall occurs the only way the soil surface can be kept moist is by upward capillary movement of water, it has long been assumed that prevention of capillary movement by cultivation will greatly reduce loss by evaporation. Experiments by King (53) showed that less than half as much water was lost from soil covered with a loose dry surface layer two or three inches deep as from an undisturbed surface. King's experiments were with columns of soils in contact with free water. According to Baver (7), Eser had shown in 1884 that evaporation from soil in contact with free water is two to four times as fast as from well drained soils. Unfortunately most people failed to realize that evaporation from soil in contact with a water table occurs much more rapidly than evaporation from soil that does not have a water table near the surface. As a result of this misunderstanding the advantages of a dust mulch in agricultural practice were greatly overemphasized.

More recent experimental work has shown that evaporational losses are less than commonly supposed and that they are not much reduced by cultivation. This is primarily because the water table is so far below the surface in most cultivated land that little upward movement to the surface can occur. Considerable experimental evidence is available which indicates that if the water table is even a few feet below the surface little upward movement of water occurs. Shaw and Smith (89) found considerable water movement to the surface of Yolo sandy loam and Yolo loam with a water table four feet below the surface, but very little when it was ten feet below the surface. They concluded that no appreciable upward movement of water to replace loss by evaporation occurs in these soils when the water table is ten or more feet below the surface. Other investigators have found evidence of slow or negligible capillary rise where the water table is more than a few feet below the surface (18, 52, 80, 96). Where rainfall seldom or never wets the soil to the water table, as in much of the plains area, upward movement is probably negligible. In such soils removal of water by transpiring plants is a much more important factor in drying out the soil than evaporation (22).

Veihmeyer and Hendrickson (102) cite work in Russia and in this country indicating that little water is lost by evaporation from below the first foot. It has been demonstrated (93) that under California conditions most of the water lost by evaporation comes from the upper four inches, much less from the second four inches and very little from below eight inches. By the time the surface soil has dried sufficiently to permit cultivation considerable moisture has already been lost and more is lost from the freshly stirred soil. In general, most soil appears to dry out to about the same extent and the same depth, whether cultivated or not, unless the water table is within a few feet of the surface. Cultivation may reduce loss by evaporation on soils which crack badly, but it is claimed (103) that the cracks in most California soils, including clays, are too shallow to increase water loss seriously. Cultivation of summer-fallowed land may of course be necessary to prevent a crop of weeds from removing the accumulated moisture. This problem is discussed at length by Lyon and Buckman (62, 223–227).

While dust mulches seem to be ineffective, it appears that mulches of straw, grass, leaves, paper and similar materials are usually much more effective in reducing water loss. This is partly because they shade the soil, reducing its surface temperature, and partly because they lengthen the diffusion gradient from soil to air and protect the soil surface from the drying effects of wind. Russel (82) considers mulches to be effective only in preventing drying of the surface layer because he says a layer of dry soil is a better insulator than the average mulch and also more impervious to water vapor.

The relative amounts of water removed from the soil by evaporation and by transpiration are of interest. It is generally accepted that plant transpiration is the chief means by which water is removed from soils and that transpirational losses far exceed losses by evaporation. If evaporation removes water only from the surface foot of soil the remainder of the soil moisture would remain untouched were it not for the roots of plants. Orchard soils in the East are sometimes dried to the wilting percentage to a depth of two or three feet within three weeks (64), and prune trees exhaust the readily available water in the top six feet of soil in about six weeks in midsummer at Davis, California (44). It was found (103) that mature peach trees in the Sacramento and San Joaquin valleys of California absorb the readily available water to a depth of six feet from sandy soil in about three weeks and from clay loam soil in about six weeks. Citrus fruits on sandy loam soils four to six feet deep in San Diego County require irrigation every six weeks during summer, and on more shallow soils irrigation is required more frequently. In such instances loss by transpiration is several times greater than loss by evaporation. In certain experiments (96) a tank with bare soil surface lost 18.9 pounds per square foot of surface in four years, equivalent to a depth of 3⅜ inches of water, or less than one inch per year. A four-year-old prune tree growing in a similar tank lost 1,250 pounds of water by transpiration in one growing season. An acre of deciduous fruit at Davis, California, used eight acre-inches of water in about six weeks in mid-summer, or about one pound per square foot of soil surface per day. It seems clear that plant transpiration is the chief means by which capillary water is lost from the soil, and it therefore appears that maintenance of vegetation cover on watersheds decreases the amount of water stored in the soil. This of course does not reflect on the possible importance of vegetation in reducing erosion and consequently preventing silting up of reservoirs. Kittredge (54) stated that a forest transpires more water than would be lost by evaporation from the same area, hence more water could be obtained from a bare watershed than from a forested one. He recognized the need for plant cover to control erosion and slow down run-off and suggested that species with low transpiration rates be selected, recommending scrub oaks and grasses for California.

AVAILABILITY OF SOIL MOISTURE TO PLANTS

The gravitational water occurring in saturated soils is readily available to plants but is seldom present long enough to contribute much to plant growth. If it does remain more than a day or two its injurious effects overshadow any benefits resulting from its availability. For most plants, then, the water readily available for growth is the capillary water in the range between the field capacity and the permanent wilting percentage. The best moisture supply for growing plants is afforded by soils in which this range of available water is wide. Soils show great variations in this respect, but sandy soils generally have narrow ranges of available water and clay soils wide ranges. Among some soils used by the writer (56) was a pure sand containing only 2%, a sandy loam containing 14% and a clay containing 19% of readily available water. Occasionally soils with high moisture equivalents and field capacities also have very high wilting percentages and contain but little readily available water. For example, in a California study (104), a clay was found to have a moisture equivalent of 31% and a wilting percentage of 25%; it therefore contained only 6% of available water or less than many sandy soils.

Plants growing in soils with a low storage capacity will exhaust the readily available water and suffer from desiccation much sooner than plants growing in soils with a very large storage capacity. Where irrigation is practiced the more frequent applications required result in much greater waste of water by run-off and evaporation than where a few irrigations suffice. This is especially important with shallow-rooted crops, and Veihmeyer and Hendrickson (104) cite several examples of such occurrences.

Much discussion has occurred as to whether water is equally available over the entire range from field capacity to wilting percentage. Veihmeyer and Hendrickson have repeatedly stated that water either is available or is not available to plants, and that it is equally available over the entire range from field capacity down to the wilting point where it becomes unavailable for growth. They have reported results of experiments indicating that the growth and quality of apples and pears (47), grapes (43), peaches (42), prunes (44), walnuts (45) and cotton (1) were not affected by the moisture content of the soil unless it fell to the wilting percentage and remained there for some days. These plants did no better on frequently irrigated plots than on plots where the soil moisture was allowed to fall to the permanent wilting percentage before water was applied. The seeds of many species are reported to germinate equally well over the entire range of moisture content from wilting percentage to field capacity (27). A few, however, germinated better at 1% or 2% above field capacity, and celery seed was found not to germinate at all in the lower range of soil moisture.

The apparent equal availability of water over the entire range is explained on the basis that there is but a small change in the forces with which water is held by the soil over the range from field capacity to permanent wilting percentage. The permanent wilting percentage occurs at the moisture content where these forces begin to increase very rapidly, and a small decrease in soil moisture therefore is accompanied by a very rapid increase in the force required to move water from soil to roots.

Considerable evidence is available indicating that water is not equally available to plants over the entire range from field capacity down to permanent wilting. The growth rate of apples in Maryland orchards was reduced when the driest part of the root zone approached the permanent wilting percentage, which was long before the entire root zone was dried to that point (64). Stomatal behavior of apples (64) and peaches (50) was also affected by soil moisture, the stomates being open for a shorter period each day in dry than in moist soil. Premature stomatal closure presumably reduces photosynthesis, resulting in a deficiency of carbohydrates. It was found that in very heavy soils in Oregon the rate of growth of pears is closely related to the moisture content of the upper three feet of soil (2, 58). The fruits suffered reduction in size when the soil moisture dropped below about 70% of the readily available moisture. Trees in these soils have very uneven root distribution, and it may be that while the soil in contact with the roots was at the permanent wilting percentage considerable volumes of soil not penetrated by roots were left at field capacity. As a result the average moisture content would appear to be above the wilting percentage, although the moisture content of the soil in which the roots were growing was actually reduced to the wilting percentage. The transpiration rate of loblolly and shortleaf pine seedlings grown in containers decreased with decreasing moisture content before the permanent wilting percentage of the soil was reached (86). This, likewise, might have resulted from uneven absorption of water because of uneven distribution of root systems. Furr and Taylor (38) found that lemons on shallow soil underlain by dense subsoil suffered sufficient water deficit to cause reduction in size of fruit before the moisture content of all the soil in the top foot was reduced to the permanent wilting percentage. They suggested that some discrepancies in conclusions regarding the availability of water result from differences in judgment as to what constitutes permanent wilting. In a heavy clay soil with a field capacity of 33% the basal pair of leaves of well established sunflower plants wilted at 20.2%, but the entire plants did not wilt until the soil moisture was lowered to 16.2%.

The growth rate of sunflower plants was affected by small differences in soil moisture content, even though the moisture content was never allowed to fall to the permanent wilting percentage (65). Growth of young maize plants was also slowed by decreasing soil moisture and ceased before the soil moisture content fell to the permanent wilting percentage. Water appeared to be less available for growth from a moisture content 2% or 3% below capillary capacity, and growth ceased while 3% of available water remained in the soil (25). Growth of *Cyperus rotundus* in pots also appeared to be checked by decreasing availability of water in soil which was always above the wilting percentage (26). Each decrease in the minimum soil moisture percentage reached before rewetting to saturation resulted in a significant decrease in weight of the tops of nut grass. Tuber development was decreased significantly by decreased soil moisture from a moisture content only 2% below the moisture equivalent. The growth and yield of kidney beans were reduced if the soil was allowed to dry part way down to the permanent wilting percentage before watering, even though the moisture content never actually reached the permanent wilting percentage (6).

It was found that a decrease in soil moisture from field capacity to the permanent wilting percentage (first permanent wilting of basal leaves) caused the osmotic pressure of sunflower plants in dry air to increase about five atmospheres and that of plants in moist air to increase about two and one-half atmospheres (37). From these and other data the investigators concluded that plants are subjected to progressively increasing water deficit from a moisture content about half way between the moisture equivalent and the permanent wilting percentage down to the permanent wilting percentage. This is in accord with the observation of the writer (56) that exudation from the stumps of detopped plants ceases while about 45% of the soil moisture available to intact plants is still present. This situation probably results from the fact that the roots alone cannot absorb water against a potential of more than one or two atmospheres, but when attached to a transpiring shoot they can absorb against a potential of several atmospheres. Intact plants can therefore absorb water from much drier soil than can isolated root systems.

The contradictory opinions concerning the availability of water held by various investigators results at least partly from differences in the soil types used, differences in opinion as to what constitutes permanent wilting and differences in interpretation of the data. Where the soil is thoroughly and uniformly permeated by roots it is likely that plants can reduce the average moisture content much nearer the permanent wilting percentage without suffering from a water deficit than in heavy soils where root systems are scanty and unevenly distributed. There is no doubt that more energy is required to move water from soil to roots in a dry soil than in a moist soil. This may not immediately decrease transpiration or growth because as the diffusion pressure deficit of the soil increases, the osmotic pressure and diffusion pressure deficit of the plant may at first increase proportionately. Thus the same gradient from soil to root is maintained, while the increased osmotic pressure of the plant sap does not materially reduce transpiration (36). There is, however, an abundance of data indicating that as the soil moisture decreases to the lower half of the range of readily available water, growth and yield are often decreased before the permanent wilting point is reached.

Concentrataion of soil solution. Another factor affecting the availability of soil moisture is the concentration of the soil solution. It is recognized that high soil concentration may hinder plant growth by toxic effects of the ions as well as by their osmotic effects, but the latter often seem to be quite important. Addition of NaCl producing an osmotic pressure of four atmospheres caused severe wilting of tomato plants (60). In other experiments high solute concentration increased hydrostatic stress and seriously checked growth of tomatoes (41) and kidney beans (6). It was reported from California (63) that normally fertile irrigated soils had a soil solute concentration at the permanent wilting percentage of 1.3 to 1.8 atmospheres. Some soils with osmotic pressures at the permanent wilting percentage of two to four atmospheres produced good crops of alfalfa, cotton and wheat, but those with higher values showed reduced yields, and soils with values of 40 atmospheres or higher were barren.

Soil temperature also affects the availability of water to plants. Many years ago Livingston suggested that temperatures probably markedly influenced the water-supplying power of soils (73). The writer (55) found that the water-supplying power at 0° C. was only about half as great as at 25° C. The decreased rate of movement from soil to absorbing surface results principally from the increased viscosity of water at low temperatures.

MEASUREMENT OF SOIL MOISTURE

Since a review of this subject by another author is expected to appear in this journal the measurement of soil moisture will be discussed very briefly. Two types of methods are used, those giving the actual moisture content and those measuring the forces with which moisture is held or the rate at which it is supplied to an absorbing surface. Livingston and his co-workers (73, 107) have frequently stated that the capacity of the soil to supply water to roots is the essential factor of soil moisture as related to plant growth, and all other factors such as texture, water-holding capacity and permanent wilting percentage are important only as they affect the water-supplying capacity of the soil. This view led to the development of soil point cones to measure the water-supplying power of the soil (59*a*).

The actual moisture content of the soil is usually expressed as a percentage of the oven-dry weight, but it could perhaps be expressed more advantageously on a volume basis. The primary interest is in the volume of water available to the roots occupying a given volume of soil, rather than the weight of water in a given weight of soil (7). Various methods have been developed to determine soil moisture without the delay required by oven-drying and without the disturbance caused by sampling. Attempts have been made to determine soil moisture electrically by measuring the electrical conductivity (9), electrical capacity (4, 5), dielectric constant (35) and heat conductivity (48, 88). Physical methods include use of tensiometers (77, 78, 98), porcelain soil point cones (59*a*), and devices to measure the pressure required to penetrate a soil mass (3). Several of these methods can be used to measure moisture content in the root zone without disturbing the roots, a procedure likely to yield much useful information.

EXPERIMENTAL CONTROL OF SOIL MOISTURE

The older literature dealing with soil moisture as a factor in plant growth frequently described experiments in which plants were said to have been grown in containers maintained at certain definite moisture contents, as at 10%, 15%, 20% and 25% of the dry weight of the soil. Other papers have mentioned maintenance of soil moisture at optimum, sub-optimum and supra-optimum contents. Engineers have also described methods of wetting soil to be used in construction to some predetermined moisture content by sprinkling a certain amount of water over the surface.

The impossibility of doing these things should have been realized by all who have observed the distribution of moisture in the soil after a rain. Strange to say, however, it was not until comparatively recently that Shantz (87) and Veihmeyer (93) called attention to the fact that if a small quantity of water is applied to a mass of dry soil the upper layer is wetted to the field capacity and the rest of the soil mass is completely unaffected. Addition of more water results in wetting the soil to a greater depth, but there will always be a sharp line of demarcation between the wetted and unwetted soil. This situation has been observed by everyone who has dug in soil following a summer shower and observed the sharp line of demarcation between the wet soil and the dry soil beneath. Since the field capacity is the amount of moisture held against gravity it is obviously impossible to wet any soil mass to a moisture content less than its field capacity. If a container is filled with dry soil having a field capacity of 30% and enough water is added to wet the whole mass to 15%, one half of the soil will be wetted to field capacity and the other half will remain dry. Obviously the earlier investigators did not really maintain their plants at the specified soil moisture contents, but merely gave them various amounts of water distributed in various proportions of the soil mass. The difficulties of controlling soil mosture have recently been discussed (46).

Numerous investigators have attempted to devise means of controlling the moisture supply and improving its distribution in the soil. Livingston (59) developed the use of porous porcelain cups buried in the soil and connected to a reservoir as a means of controlling the supply of moisture, and this system later became known as the auto-irrigation system. He attempted to limit the water supply by introducing mercury columns of various heights between the irrigator cone and the reservoir, thus increasing the tension necessary to bring about water movement from reservoir to soil. Unfortunately there is a tendency for roots to become massed around the irrigator cones, somewhat nullifying the control, as they absorb directly from the surface of the cones rather than from soil which has come into equilibrium with them. An improvement in moisture distribution is afforded by the use of double-walled pots with a space for water between the glazed outer wall and the porous inner wall (107). The high cost of these containers has prevented their extensive use. Richards and Loomis (79) found double-walled pots maintained a constant soil moisture content for small plants with low tensions (short mercury columns) but not for large plants which removed water rapidly. Even with tensions as low as two to four centimeters of mercury, water was removed faster than it could be supplied. This is because water moves so slowly from wet to dry soil. Numerous tests indicate that many greenhouse plants grow better when supplied with water by some type of auto-irrigator than when watered manually. Use of short pieces of glass rope to supply water to potted plants has recently been described. One end of the rope is pulled through the hole in the bottom of a pot and spread out in contact with the soil mass, while the other end dips into a reservoir. Such devices are particularly useful for house plants which usually are over or under watered. They have also been successfully applied to watering seed flats and greenhouse benches (71).

A number of methods of controlling soil moisture content have been described (8, 33, 49, 67, 69), but none is entirely successful. It seems probable that there is no satisfactory method of constantly or permanently maintaining any soil at a moisture content below its field capacity. Plants growing in the soil may be allowed to reduce the soil moisture to any desired level between field capacity and permanent wilting percentage before applying water, but the moisture content cannot be maintained at any constant level within this range. Most of the proposed control methods simply reduce the amount of water per plant by reducing the soil mass which is wetted, and none of them permanently maintains the entire mass of soil at a uniform moisture content below its field capacity. Discussions of the "optimum" soil moisture content are therefore largely academic and have little relation to actual field conditions. Soil moisture content as related to plant growth can be evaluated only in terms of its relation to the field capacity and the permanent wilting percentage of the soil in which the plants are growing.

SUMMARY

The soil is a complex system consisting of four principal components: mineral materials, organic matter, water and solutes comprising the soil solution, and air. The characteristics of a soil depend chiefly on the texture or size of the mineral particles, ranging in order of decreasing size from sand through loam to clay; on the structure or manner in which these particles are arranged, which determines the number and size of pores; and on the amount of organic matter incorporated with the mineral matter.

Soil moisture is commonly classified as gravitational, capillary and hygroscopic water and as water vapor. Capillary water, which occurs as films around the particles and in angles and the smaller pores between them, usually is the only form of moisture available to plants. There are no definite boundaries between these various types of soil moisture, and they are to be regarded as convenient but wholly artificial categories.

In a soil thoroughly wetted by rain or irrigation the gravitational water usually drains away within one or two days leaving the moisture content at the "field capacity". The field capacity usually approximates the value known as the "moisture equivalent", which is the moisture content of a soil that has been exposed to a centrifugal force of 1000 times gravity. The "permanent wilting percentage" is the moisture content of a soil at which permanent wilting of plants growing therein first becomes apparent, because water no longer moves from soil to roots fast enough to replace the losses by transpiration. That portion of the soil water which is readily available for growth lies between the field capacity and the permanent wilting percentage. The moisture content at the permanent wilting percentage depends on the soil texture, being lowest in sandy soils and highest in clay soils. Obviously the wider the range between the field capacity and the permanent wilting percentage the more water is available for plant growth.

It is sometimes claimed that water is equally available to plants over the entire range from field capacity to permanent wilting percentage, but there is considerable evidence that water becomes progressively less available in the lower part of this range.

Movement of soil water is caused principally by gravity, hydrostatic pressure and capillary forces, the last resulting from differences in curvature and thickness of water films. Since it is often

difficult to distinguish between these forces it is convenient to speak of the movement of water along a gradient of decreasing free energy. The work done in moving water against the attractive forces of the soil increases with decreasing soil moisture. It is often measured in terms of height of an equivalent column of water or mercury and designated as the "capillary potential" or "pressure potential".

Movement of capillary water in a soil mass below the field capacity and lying more than a few feet above a water table is extremely slow. It is therefore likely that relatively little water moves toward the roots and that most soil moisture becomes available only as roots come in contact with it as a result of their elongation through the soil. It has been demonstrated that little or no water is lost by evaporation from below the surface 8 to 12 inches, and dust mulches are therefore relatively ineffective in reducing losses by evaporation.

Soil moisture is usually expressed as a percentage of the oven-dry weight of the soil. It would be more satisfactory if it were expressed as a percentage of its volume, but such determinations are difficult. The moisture content of soil can be measured in place by determinations of electrical conductivity and capacitance, of dielectric constant and of heat conductivity, and indirectly by use of soil point cones and tensiometers.

Numerous attempts have been made to grow plants at various moisture contents between field capacity and permanent wilting percentage. It is impossible to half wet a soil, however, and it appears practically impossible to permanently maintain any intermediate moisture contents. If insufficient water is added to a soil mass to wet it all to the field capacity, a part of it will be wetted to the field capacity and the remainder will remain unaffected.

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