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PERTINENT FACTORS GOVERNING THE AVAILABILITY OF SOIL MOISTURE TO PLANTS

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The soil and plant factors that govern moisture supply and availability to crops are of primary importance in crop production, and since the development of agricultural sciences began they have attracted the interest of both soil and plant scientists. The work reported is too voluminous to allow a comprehensive review here. Moreover, the subject has been thoroughly discussed by Kramer (45, pp. 18-72), Kelley (43), and Richards and Wadleigh (64, pp. 73-251). The present paper refers not only to these reviews but also to some very recent work and to selected published information that illustrate the points discussed.

Although soil and plant scientists for many years attributed the supply and availability of soil moisture to plants almost exclusively to soil properties, we now know that numerous plant and climatic factors are also involved. In a broader sense, the supply of available moisture to plants in a soil is the total quantity that can be extracted from the profile in the plant growth and maturing processes. The plant factors that affect the available moisture supply are (a) plant conditions (including nutrients present, stage of growth, degree of turgor), (b) rooting habit (including depth of rooting, degree of ramification, and absorptive activity), and (c) plant resistance to drought. Climatic factors are air temperature and air humidity (including the effect of fogs and wind). Soil factors are (a) moisture tension relations, (b) soil solution osmotic pressure effects, (c) kinds of ions present in the soil solution, (d) soil moisture conductivity, (e) soil depth, (f) soil stratification, including the

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effect of hardpans and textural layering, and (g) soil temperature and temperature gradients. In this paper, the plant and climatic factors are discussed very briefly, and the soil factors that affect available moisture storage capacity and efficiency are given some attention.

Plant Factors That Affect Available Moisture Supply

The maximum available moisture content of any soil with unrestricted drainage is usually considered that held between its so called field capacity and its permanent wilting percentage. The field capacity is taken as a point or narrow range on the time drainage curve of a soil where the changes in moisture percentage occurring after thorough wetting with irrigation or rainwater become very slow. The so-called gravitational water that drains away rapidly after a well-drained soil is thoroughly wetted is usually considered of little consequence to plant growth. The permanent wilting percentage of a soil is taken as that moisture content at which plants first wilt without recovery in a humid atmosphere, unless water is added to the soil (76). The upper and lower limits of the available moisture percentage range are generally considered as soil characteristics. It should be emphasized that the quantity of available water that can be supplied depends also on several plant and climatic factors. Even though most plants wilt or stop growing at about the same moisture content of any one kind of soil in which they are rooted, the drought resistance of plants (43) varies widely. Guayule will withstand long periods of drought and renew growth when moisture is again available. Likewise, sorghum can be subjected to considerable moisture stress and will renew growth. On the other hand, such crops as celery, potatoes, and lettuce are very sensitive to drought. Plants probably vary over a range of several atmospheres in the suction force exerted through the roots on the moisture in the soil at the permanent wilting percentage. Furr and Reeve (23) found differences of 9 to 22 atmospheres osmotic pressure in the extracted sap of wilted plants. Since the turgor pressure of the plant cells is probably near zero at wilting, one may take the variation given as an indication of a wide range in soil moisture stress at wilting for the plant studied. Richards, Campbell, and Healton (63) found the soil moisture stress for sunflower and cotton at permanent wilting on 16 soils to range from 7 to 43 atmospheres. The wide change in moisture stress due to moisture tension alone for most soils near the wilting percentage is discussed in a later section.

Plants vary considerably in rooting habit, with regard to both depth and ramification (3, 6, 16, 24, 30, 32, 38, 43, 45, 50, 56, 57, 80). The quantities of water that different crop plants will extract from the same soil profile will vary widely with stage of growth (65) and kind of plant. Although the root extraction pattern of maturing plants depends largely on the kind of plant (30, 33, 45, 56) it can be modified by such variables as thickness of stand, soil aeration, soil fertility, dense soil layers, and a high water table (16, 19, 29, 43, 48, 49, 51, 56, 57, 68, 78, 80). Any factor that will affect the vigor or condition of a plant may be expected to influence the extraction of moisture from the soil. Kramer (46) found that wilting of sunflower plants reduced the rate of intake when water was again made available. Injury to plant roots through flooding may reduce absorption of water through plugging of conductive tissue (47) or reduction of absorptive surfaces. Crop management practices will affect soil moisture availability to the crop to be harvested. Rock and Lowe (67), found that available water stored during the summer for fall-planted wheat may be conserved for the production of grain by judicious winter pasturing.

Climatic Factors That Influence Moisture Supply

Ordinarily, loss of moisture from the soil surface is considered small in comparison with that transpiring from plants (12, 22). With sparse plant cover and over long periods (36, 37) loss by evaporation may be considerable. Soil evaporation losses may be increased by soil-air temperature differences. On cold nights moisture vapor will move from warm moist subsoil layers and condense in the colder soil surface, where much of it may be lost by evaporation during the day, especially if the air is warm and dry and being changed by movement over the soil surface. Likewise, on warm days moisture vapor will move from the surface, where it would be available to shallow-rooted plants, and condense in the cooler subsoil. Gains or losses of available moisture due to evaporation and condensation are considered important under certain climatic conditions (7, 27). Under conditions of high humidity or fog, plants may absorb considerable moisture through leaf surfaces (8, 10) and continue to grow though the available moisture supply of the soil is limited. On the other hand, Henrici (35) has cited cases where plants wilted on hot, dry, windy days, even though the soil moisture supply was adequate. Likewise, plants often wilt during freezing weather. This has been attributed by Kramer (45, pp. 18-72) to damage to plant tissues and by Bethlahmy (4) to high moisture stress due to freezing of soil. The effect of climate on soil moisture supply is further indicated by the fact that the moisture storage needed to produce a good wheat crop increases with increasing average daily summer temperature as one moves from north to south over the wheat belt. Because of increase in transpiration rate of plants with increase in air temperature, and hence lowered relative humidity, the water requirement of plants increases. In general, the same moisture supply in North Dakota and Texas will produce more plant dry matter in North Dakota. Some soil moisture tension and conductivity factors modify this effect.

Soil Factors That Affect Moisture Availability

As water is withdrawn from the soil and the moisture content progressively decreases from field capacity to the permanent wilting percentage, there is a progressive increase in the forces resisting withdrawal, referred to as soil moisture stress (64, 77). Soil moisture stress has two components, soil moisture tension and osmotic pressure in the soil solution. The moisture tension component varies with the effective curvature of air-water surfaces in the soil. For most soils the approximate tension at field capacity varies between 0.2 and 0.5 atmosphere, depending on soil texture, compaction, stratification, depth of wetting, and other factors (14, 20, 31, 37, 43, 55, 61, 66, 69). For most soils of low salt content the moisture tension near the permanent wilting percentage is approximately 15 atmospheres (58), though wide variations with different soil-plant couples are evident (63). To understand some of the reasons for variations with tension for both the field capacity and the permanent wilting percentage, one should consider some moisture tension relationships for soils of different textures.

Figure 1 shows moisture release curves for four different soil samples, Lakeland sand, Hiwassee sandy loam, Commerce silt loam, and Sharkey clay. Generally, more water is withdrawn with tension increase at low tensions near field capacity than as the wilting range is approached. This is especially true for coarse textured sandy soils. The sandy soils lose most of their available moisture below 1 atmosphere tension, and silt loam and clay, below about 4 atmospheres.

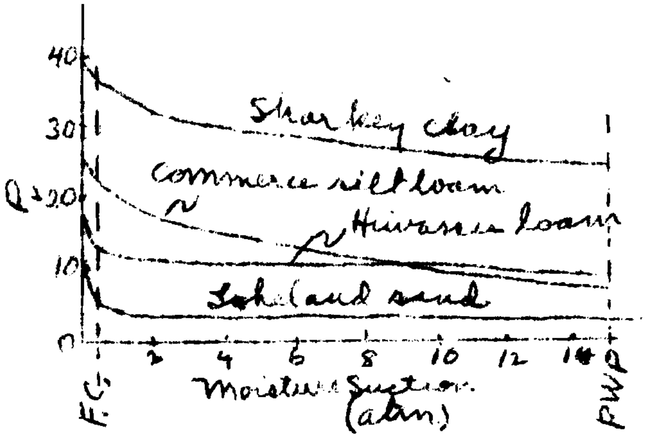

Fig. 1. Volume Percentage Moisture for Several Soils Over the Available Moisture Range from Field Capacity to Permanent Wilting Percentage

P_V, volume percentage moisture; F. C., field capacity, taken as 1/3 atmosphere; P. W. P., permanent wilting percentage, taken as 15 atmospheres

There is no evidence of sharp breaks or discontinuities near the approximate field capacity or the permanent wilting percentage. The tension can change several atmospheres in the wilting range with little change in moisture content.

Colman (14) defined field capacity as a point on the soil profile drainage curve where the rate of moisture change is slower than earlier rates. Others have shown it is not an equilibrium condition (20, 37, 54, 55, 66, 76). The rate of movement of moisture in an unsaturated soil depends on two variables, the driving force (the hydraulic gradient) and the unsaturated conductivity at the particular soil moisture contents involved (25, 52, 71). Thus the field capacity condition will depend on the depth of wetting. Somewhat behind a wetting front after irrigation or rain ceases, the flow rate soon becomes slow because the change in tension with distance is small. This change plus the effect of gravity constitutes the driving force. With a great depth of wetting, the field capacity may be relatively high somewhat behind the front because the hydraulic gradient is small. On the other hand, if the amount of rainfall or irrigation is small, the depth wetted will be limited. The moisture soon spreads into the dry soil, and the wetting front "feathers out." Here the slow drainage condition of the field capacity is reached because the moisture conductivity is low at the moisture content in the limited depth zone behind the wetting front. In this case the observed field capacity will be at a relatively low moisture content.

The permanent wilting percentage will decrease with an increase in the salt content of the soil (2, 77, 78). Thus the range of available moisture decreases as the salt content of the soil increases. The range in total moisture stress for numerous soil-plant couples has been found usually to vary between 9 and 22 atmospheres (23), though a considerably wider range was found for 16 soils by Richards and his co-workers (63). In saline soils the salt concentration may increase until plants make little growth or fail to survive at moisture contents near the field capacity. In the humid East, salinity is usually of little consequence. But salt damage due to heavy fertilization or irrigation with water from salty wells has been observed by the author, especially as the other component of moisture stress, the moisture tension, also has been allowed to increase.

Soil moisture flow rate will not only affect field capacity but has some effect on the lower soil moisture limit of extraction by plants. The permanent wilting percentage is not necessarily at a static equilibrium point between plant and soil forces; dynamic forces may also be involved. At moisture contents below the field capacity range, water movement is often very slow (25). Where absorptive roots are not concentrated in a mass of soil, there may be several atmospheres of pressure differential between plant leaves and soil moisture a few centimeters away from absorbing roots at average permanent wilting percentage. That is, one may often expect a moisture content and a moisture potential gradient to exist throughout a soil mass in which the roots of transpiring plants are growing. Breazeale and his co-workers (9) found that tomato plants would extract soil moisture somewhat below the normally observed permanent wilting percentage if air at 90 per cent relative humidity was passed through the soil. It should be noted that the air introduced was drier than the average condition of less mobile air in a soil at the permanent wilting percentage (usually considered to be above 98 per cent relative humidity). The circulating air probably furnished better moisture contact with the roots and eradicated the effect of potential gradients in the soil.

Moisture conductivity in sandy soils is high at low moisutre tensions (15, 25, 54, 64) but very low at intermediate and high tensions.

At high tensions in sandy soils the moisture films are mostly at the points of contact between soil grains, and moisture movement is principally in the vapor state. That is why sandy layers beneath finer textured soil act as moisture barriers. Water will move moderately fast in a medium textured soil at medium tensions, especially if the hydraulic gradient is large. Before water can spread rapidly as liquid into a sandy layer in the soil, it must accumulate in the adjacent soil until the tension is somewhat less than 0.5 atmosphere. Likewise, the conductivity of very loose soil at higher tensions is less than that of moderately compact soil. The popular notion that rapid water movement in soils is through worm holes, cracks, and channels does not hold for normal spreading of moisture in well-drained soils. This may be true for very wet soils with high water tables (15), but in well-drained soils, except for allowing the escape of entrapped air, numerous large channels may retard rather than facilitate the spreading of moisture.

Very fine textured soil, or very compact or frozen soil layers (17), will impede moisture movement and affect the available moisture supply in the soil. One may expect the tension gradient away from absorbing roots to be higher as plants approach wilting in very fine or very coarse textured soils than in soils of intermediate texture and structure. It is noteworthy that Richards (61) found the moisture sorption by a dry soil to be slower than the desorption (or drying) process for the same hydraulic gradient. This, in part, accounts for the high tension gradient at a wetting front.

Rooting depth and moisture storage are often limited by soil depth. Although the layer of rock beneath a shallow soil may be permeable enough to drain away excess water, rooting beyond the soil is limited to cracks and fissures in the rock. Likewise, rooting depth and available moisture supply may be limited when the water table fluctuates periodically between a level of a few feet below the surface and somewhat greater depths. Conditions in the Leon prairie soils of Florida vary seasonally between too wet and too dry for citrus, even though adequate frost protection may be provided by adjacent bodies of water.

The kinds of ions present in the soil solution and absorbed on the soil colloids may be toxic and so limit plant growth. Some may affect moisture movement and tension relationship by causing dispersion and swelling of the soil colloids.

Soil temperature is of consequence because it will affect both the growth vigor of the plant and the soil moisture tension relationships. Richards and Weaver (62) found that as the temperature is lowered, soils generally retain more water both at 1/3 atmosphere and at 15 atmospheres tension. But the difference or approximate available moisture quantity did not consistently increase or decrease with temperature for the soils studied. One would expect moisture conductivity to be increased with temperature and to affect moisture extraction to some degree. Temperature gradients will affect moisture supplies. As noted in the section on climatic factors, moisture will move in the vapor state from warm soil layers and condense in cooler zones (27).

Clearly, available moisture supply is not equally available to plants over the range from field capacity to permanent wilting percentage, though some few scientists persists in holding to this view (34, 76). From tension and conductivity considerations already discussed and from the volume of accumulated evidence (1, 2, 3, 5, 11, 16, 23, 28, 33, 39, 40, 41, 43, 45, 53, 56, 70, 72, 73, 74, 75; 77), it is clear that this view is untenable. As one should expect, moisture availability and plant growth decrease progressively as the wilting range is approached. Available moisture supply is not entirely a soil property. It is not a reservoir that holds just so much and no more. And not all of it is equally available to the plant until it is exhausted. Kelley (43) discussed reasons why some workers have been misled to believe in the equal availability theory. Foremost among the reasons he gave was that coarse textured soils hold most of their available water at tensions below 1 atmosphere. Even for medium textured soil the greater portion of the available moisture supply is exhausted at tensions below 4 atmospheres. Hence, plants growing on such soils will be under stresses above 1 to 4 atmospheres only about 10 to 20 per cent of the time. The effect of tension on availability can be studied better on finer textured soils that hold a fair portion of their available moisture near the wilting percentage.

Although growth response of plants generally decreases as the wilting point is approached, production of fruits, seeds, or other harvested parts may be increased by high rather than low moisture stress. According to Wadleigh and Richards (79), some plants make a physiological growth response to low moisture stress but fail to provide a corresponding economic return. Fruits of better eating or keeping qualities may often be produced at high moisture stress than at low moisture stress. Rubber production by guayule is highest when the soil moisture stress approaches the permanent wilting range, though vegetative growth is greatest when the moisture stress is kept low by frequent irrigations.

Differences in availability of moisture to plants with change in tension have some interesting applications to crop production. Lehane and Staple (50, 70) have compared wheat production on sandy loams and clay loams of about equal available moisture supply. Wheat growing on coarse textured soil will grow rapidly and stool early in its life cycle to exhaust rapidly the moisture supply held at low tension, leaving little for the maturing processes of heading and filling. Wheat grown on finer textured soil will not grow so vigorously at first, but good moisture reserves will be left for the maturing processes. Seed production of some other crops is favored by moisture supplied during the maturing stage at relatively high tension. The type and the quality of plants produced are influenced by soil moisture tension (11), and whether a low or high tension favors seed production will depend on the kind of plant (33).

Factors That Affect Available Moisture Storage Capacity

Several plant, climatic, and soil factors that affect the available moisture supply have been discussed. Among these were rooting habits, plant vigor, stages of growth, soil depth, and depth of wetting. Because of misleading statements regarding the benefits of organic matter and soil aggregation to available moisture storage capacity, this subject must be given some attention here. Some of the erroneous ideas regarding available moisture capacity arose from confusion of the early term "water-holding capacity" with "available water capacity." The early method for determining the former consisted in saturating a core and allowing it to drain, then measuring the moisture retained by the sample. Since the sample was no more than 2 or 3 inches high the value obtained came close to the total pore space and included the larger pores that are generally air-filled. Jamison (42) showed that, except for sandy soils, organic matter increases did not increase the capacity of a soil to store available water. Much of the water stored in organic materials is held in the tension range above wilting. Also, the amount held per unit volume is not so great as weight percentage values would indicate. Even the increase in available moisture storage in sandy soils is so small in relation to amount of organic matter increase as to be of no practical value--at least for its effect on this one property. Any small benefit may be more than offset by decreases in wettability.

TABLE I

Availabe moisture storage and air capacities of soils samples varying widely in texture

Soil Type	Available Moisture Capacity*	Air Capacity
	ml./100 ml.	ml./100 ml.
Lakeland sand	3	26
Hiwassee sandy loam	5	18
Commerce silt loam	16	24
Sharkey Clay	14	6
Lloyd clay	15	15

* Based on moisture release between 1/3 and 15 atmosphere tensions.

Materials that bring about structural improvement increase air capacity but seem to have little or no beneficial effect on available moisture storage capacity, as shown by Jamison (42) and Peters, Hagan, and Bodman (59).

Soils of intermediate and fine texture have larger "available moisture storage capacities" than coarse textured soils (fig. 1 and table 1). Dispersed clays or clay loams usually release about as much "available moisture" between the 1/3 and 15 atmosphere tension points as do silt loams, but the latter can be expected to supply moisture to plant roots more readily because of better aeration and moisture conductivity at low moisture tensions. A silty clay loam may store a smaller quantity of available moisture, as based on the accepted tension limits of availability, than will a silt loam, since the voids that would store available water in a silt loam would be partly filled with clay particles in a silty clay loam. Aggregation and structure development in soils will increase the volume of large pores and improve aeration but will reduce the volume of pores that store moisture (42). Because of the improved environment, however, roots may extend into and more completely ramify a larger soil volume, with the result that effective soil improvement may increase the over-all available moisture supply for the crop. Puddling of clay soils will change the moisture tension characteristics (13, 58) and may appear to increase the available moisture storage as measured between 1/3 and 15 atmospheres tension (42). But because of poor aeration in a puddled soil, the roots of most crop plants fail to extend into and withdraw the water from the soil mass even though the moisture tension is low.

Soil compaction will affect available moisture storage capacity. At field capacity very loose soils have high air content but relatively low moisture storage. Moderate compaction will increase available moisture storage capacity as well as unsaturated conductivity in the available moisture range for most soils. Soil disturbance may increase the moisture that a soil will hold between the 1/3 and

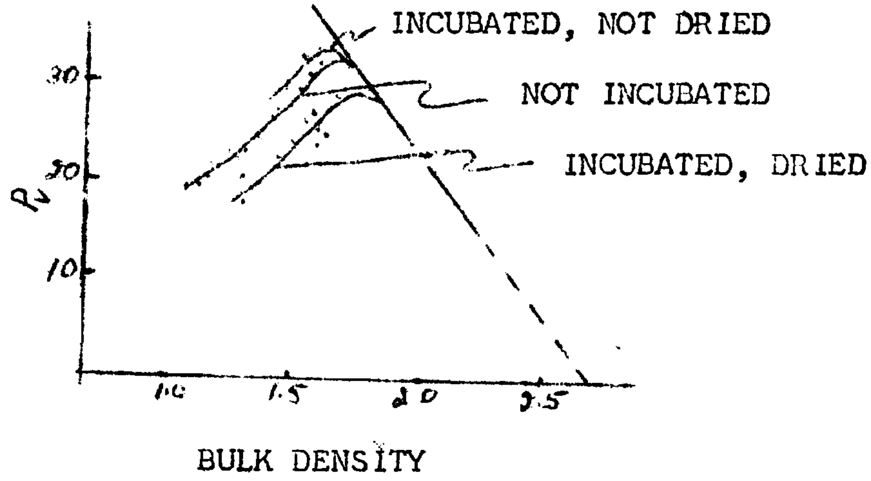

Fig. 2. Volume Percentage Moisture (P_v) At 1/3 Atmosphere Moisture Tension for Briquettes of Commerce Silt Loam Brought to Varying Bulk Densities and Subjected to Various Treatments Including Incubation and Drying.

All samples were soaked 12 hours before subjection to 1/3 atmosphere for 24 hours on a ceramic pressure plate

15 atmosphere points. The author found that soil briquettes allowed to incubate at low tension and room temperature for several weeks and then dried would hold less water at 1/3 atmosphere after being wetted than if undried or freshly compacted to the same bulk density. The effects of compaction, disturbance, and incubation and drying on the 1/3 atmosphere moisture are shown in figure 2. Plowing and tilling the soil may have other benefits than those usually given.

Soils react differently to wetting and to drying, different moisture contents being held at the same tensions for the two processes (64, pp. 73-251). This phenomenon has been referred to as hysteresis. Thus the degree of wetting, as well as the wetting depth, before drying proceeds may affect the moisture stored at field capacity.

Factors That Affect Moisture Storage Efficiency

Storage efficiency, or the proportion of moisture falling on the soil surface that will enter the surface and be stored in the soil, will depend not only on factors that affect available moisture capacity but also on plant interception, soil surface cover, soil surface structural stability, and presence of restricting layers near the surface. Hoover and his co-workers (38) found that in a loblolly pine forest only 86 per cent of the rainfall reached the soil surface and, of this, 20 per cent flowed down tree trunks. The present author believes that the dry soil bodies he observed under citrus tress in sandy soils of Florida were partly due to rainfall interception by the trees. On the other hand, grass sods or mulches generally increase efficiency through decreasing runoff. Kenworthy (44) found that after several years in sod the available moisture supply in the root zone averaged better than in plots that were clean-cultivated. He recommended the use of mulches because the grass would compete with the trees for soil moisture. Goodman (26), Pillsbury and Richards (60), Duley (18), and Fishbach and Duley (21) emphasized the importance of the soil surface to water intake. Fishbach and Duley found that, if a straw mulch protected the soil surface from sealing the claypans in several Nebraska soils did not appreciably retard downward movement of irrigation water. But the presence of very dense, compact or frozen layers near the surface (17) will cause water loss and erosion from melting snow or heavy rainfall. It should be emphasized here that even though treatments that increase air porosity and structural stability fail to benefit the available moisture storage capacity, if applied to the soil surface layers they may be expected to improve water intake and increase storage efficiency.

SUMMARY

Published information is cited to show that available soil moisture supply depends on plant and climatic factors as well as soil factors. Plant factors are drought resistance, rooting depth and ramification, plant vigor, and growth stage. Climatic factors are evaporation and transpiration losses as influenced by air temperature, air humidity, fog, wind, and sunlight. Soil factors that affect available moisture supply are moisture tension relationships and osmotic pressure of the soil solutions (the two combined giving the total soil moisture stress); ions present in the soil solution and absorbed on the colloids; and soil moisture conductivity relationships, including the effect of wetting depth, soil temperature, and temperature gradients. The available moisture storage capacity is usually reduced by structural changes that decrease bulk density, including the effect of organic matter increases (except for sandy soils). Storage capacity of a soil that has remained in an undisturbed state for some time is usually increased by tillage if the soil is repacked to about the same bulk density. Soil briquettes incubated and dried and then rewetted failed to retain as much water at the 1/3 atmosphere tension as did similar samples undried or freshly compacted to the same bulk density. There may be other benefits from plowing and tilling the soil than those usually given. The importance of soil surface condition, including structural stability, in storage efficiency of rainfall and irrigation water is emphasized.

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