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PLANT AND SOIL RELATIONS AT AND BELOW THE WILTING PERCENTAGE

By O. C. MAGISTAD and J. F. BREAZEALE

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*In cooperation with United States Department of Agriculture, Bureau of Plant Industry.

†In cooperation with the New Mexico Agricultural Experiment Station and the United States Department of Agriculture, Bureau of Animal Industry.

FOREWORD

This paper is partly a theoretical discussion and partly supported by experiment. The whole subject of water movement in the soil, the relation of plant growth to soil moisture, the relation of soil moisture to wilting, afford almost unlimited opportunity for important research work. We do not know by actual proof that plants are able to remove ions from the soil after the movement of water has ceased but there seems good reason to suppose that if a contact of moisture film is continuous from plant to soil, and there is no proof that there is no such contact, ions might pass along this film from soil to plant. The gradual lowering of soil moisture below the wilting coefficient when other portions of the root system are supplied with available water would indicate that below the wilting point the water itself could be removed slowly.

In this paper the authors have discussed the forces at work and indicated the physical reasons for the relatively definite and uniform wilting point for all plants. They have brought also a new point of view in maintaining that the plant may even at the wilting point continue to draw on the nutrient material in the soil. If this is true, and every effort should be made to demonstrate it by experimental methods, the surface or plow layer of soil is much more important in dry land agriculture than previously supposed. In many cases the dry land crop draws water from this cultivated zone for only a few days after germination and relies entirely on the deeper soil for its continued growth. The surface soil at or generally much below the wilting coefficient, if it gives up any of its nutrients, must do so with no movement of moisture or very little movement and along films of water which are held very firmly to plant tissue and soil particles. It has been generally assumed that soil at this degree of dryness contributed no nutrient salts to the plant since diffusion is at best a slow process and when the film of water is reduced to a thickness of one hundred molecules movement has been assumed to be negligible. The rapidity with which water is taken up by drought-enduring or drought-resistant plants would be more easily explained if these plants continually maintained an equilibrium with the soil about their roots. This bulletin is suggestive of important lines, which, if properly investigated, will further elucidate the complicated and imperfectly understood phenomenon of the balance between the water available and the water demand of desert and crop plants.

H. L. Shantz

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By
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and
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INTRODUCTION

The terms "gravity water," "capillary water," and "hygroscopic water," are so vague, and are subject to so many different interpretations when applied to the moisture in a soil, that they will not be used generally in this discussion. As the title of the bulletin indicates, only that water which is held by the soil at its wilting percentage and below, and only those features of soil water movement that relate to cultivated plants, will be considered. The work that has been done heretofore, by other investigators, upon the water that is held by a soil above the wilting point will not be discussed in detail. Likewise, the water that goes to supply the physiological demands of organisms other than higher plants, will not be considered.

The chief value of a soil to mankind is that it supports plant life. Therefore, in soil investigation the plant-soil relationship is of primary importance. In this sense, it is often expedient to consider or at least to interpret, many soil phenomena in biological terms.

Water exists in the soil and moves from one place to another in the soil in both the liquid and gaseous phases. No matter what the moisture content of a soil may be, equilibrium, or a condition approaching equilibrium, exists between the plant and the soil through the medium of the soil solution. It is the aim of this bulletin to point out some of the features of this equilibrium and to show that, during its era of development, the plant has adapted itself to certain soil conditions, and that these conditions are now reflected in the habits of growth and nutrition of plants.

THE SOIL SOLUTION

Certain constiuents of all arable soils are soluble or slightly soluble in water, and, when water is brought into contact with a soil there is a constant tendency of the water to come into equilibrium with the soil with respect to its more or less soluble salts. All of the water, together with the dissolved salts and gases, that is included in a soil may be termed the soil solution.

The secret of soil fertility rests in the soil solution. Whatever is taken up by the roots of plants, whether for good or for bad, must first enter into solution.

The soil solutions of alkali soils usually differ from those of soils of the humid areas in salt content only. An alkali soil often contains too much soluble salts for the best growth of plants, and the most valuable plant food, potassium nitrate for example, may actually become an alkali if it occurs in the soil in excessive amounts. Therefore, it is the nature of the soil solution that determines whether a soil is fertile or infertile, and whether it is saline or non-saline.

The soil solution is the connecting link between the soil and the plant. After absorption has been satisfied, and after the finely divided and slightly soluble substances have been brought into equilibrium with the water in the soil, the presence of inert, insoluble materials, or of slightly soluble substances, that may still exist partly in the solid phase, plays no direct part in the nutrition of plants. The plant deals primarily with the soil solution, while the solid phase holds the plant in correct position and furnishes a storehouse of nutrient material.

If a soil upon which a crop is growing is thoroughly saturated with water by rain or irrigation, the soil will become temporarily water-logged, and unsuited to the growth of plants. In a short time, however, under field conditions, depending upon the texture of the soil, the nature of the subsoil and other factors, the excess of water will be carried off by gravity, evaporation, or otherwise, and the soil will reach its field-carrying capacity with respect to water. Crops will now grow in this soil and draw water therefrom until the water content is diminished to a fairly definite percentage. This precentage is called the wilting point, or wilting percentage, and, while it varies widely with different soils for all plants, it is fairly constant for all plants with any particular soil. If the percentage of water falls below and is maintained below this point, nearly all plants will wilt and die at approximately the same percentage in the same soil. The optimum moisture content of a soil is often expressed as the "moisture equivalent" which is an empirical constant, representing the water that is held by a soil against a centrifugal force of 1,000 gravity, exerted for a period of 30 minutes. (18).

The water that is included in the soil, from its field-carrying capacity down to its wilting percentage may be considered the available moisture of the soil. The soil solution, however, includes all the water in the soil, whether available or non-available.

THE SOIL FILM

The solid portion of the soil consists of particles of different material, that range in size from 2 mm. in diameter, such as the coarse sands down to the ultra-microscopic particles that constitute the clays or colloids. These soil particles may lie as close together as the shapes of the bodies will permit, but the bodies are not squares, nor are they even regular, so there are always spaces between the particles that vary in shapes and volumes according to the size and shape of the soil particles.

When a soil is completely saturated the spaces between the soil particles are filled with water. Such a soil is termed "waterlogged." If the soil is gradually dried out a part of the interstitial water will be evaporated, and the soil will reach a moisture content that is ordinarily termed its optimum. At this percentage, the larger interstitial spaces are filled with air, but there is a film of water surrounding each soil grain regardless of its size. This film furnishes the water and all of the mineral nutrient material for plant growth, and at and below the optimum moisture content of the soil, the water is fairly static.

THE SOIL FILM AND ITS RELATION TO THE SHRINKAGE AND EXPANSION OF SOIL

A wet soil on drying, diminishes in volume equal to the volume of water lost (7), (8), and (9). If soil volume is plotted against water content, a soil shrinkage curve is obtained whose initial slope is 1. At a point where air begins to enter the soil there is a sudden break in slope, and from that point to complete dryness, volume of soil plotted against water content gives a straight line of slope less than 1.

Keen (13) and Comber (6), and (7), first developed the idea that each soil particle may be surrounded by a colloidal layer or gel. Haines (9) adopted this hypothesis and concluded that the first shrinkage of the soil upon drying, or the "normal shrinkage," is caused both by a loss of interstitial water, and by the loss of water that is held by the jelly-like colloidal coat surrounding the soil particles.

Shrinkage after air enters, or "residual shrinkage," is probably caused by a diminution in thickness of the gel coat, but the volume loss is not numerically equal to the volume of water lost. At this point the gel becomes more vitreous and rigid, and air takes the place of a portion of the water lost. Kaolin, which has no such colloidal coating, shows no residual shrinkage (9), nor does a mixture of kaolin and silica gel. This refutes the idea that residual shrinkage is caused by a decrease in the thickness of the water film surrounding the soil particles. When silica gel is precipitated upon soil grains, or upon kaolin, residual shrinkage is obtained. This latter observation admirably supports the idea of a colloid-coated soil particle, and differentiates between a colloid-coated particle and a mixture.

A graphic conception of soil particles coated with gel is shown in figure 1.

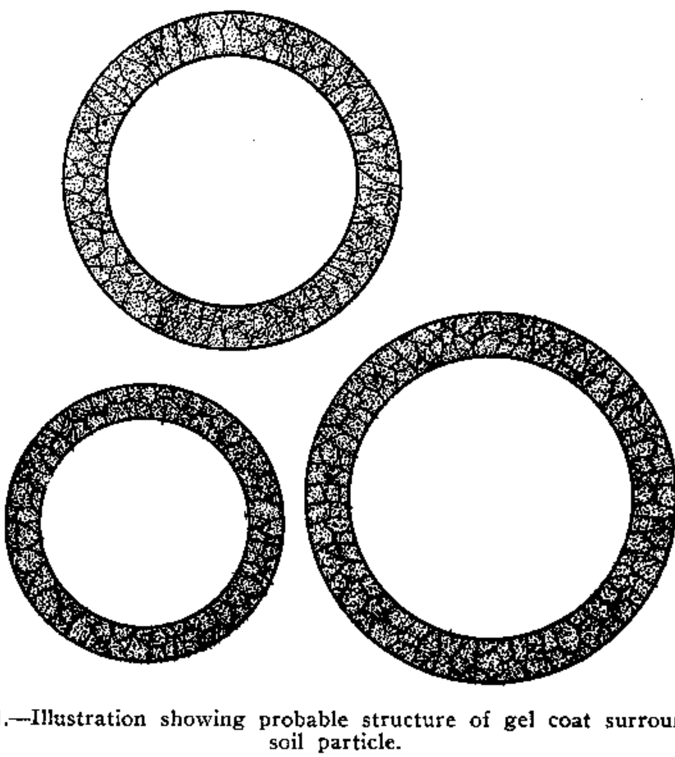

Fig. 1.—Illustration showing probable structure of gel coat surrounding soil particle.

EFFECT OF ABSORBED GASES UPON SHRINKAGE AND EXPANSION

When soils are desiccated completely, their minimum volumes are obtained. When such soils are again brought into contact with water, they apparently increase in volume, that is they swell, and, if allowed to come to equilibrium, will occupy the same space that they occupied before desiccation. The swelling, however, may not be as uniform or as rapid as the shrinkage, due to the fact that in the process of desiccation, the film gels are dehydrated and become vitreous, and thereafter absorb water slowly. This is the conception of Thomas (17).

In the study of the physical properties of solids, we know that most solid particles possess the power of condensing gases upon their surfaces. This property is very pronounced with certain solids. Palladium, for example, will absorb 900 times its own volume of hydrogen and the absorption may be so rapid as to produce enough heat to cause a wire to glow, and to set fire to hydrogen. Carbon will absorb 100 times its own volume of ammonia gas, and it will absorb other gases in varying proportions. The explosions of coal dust in mines are sometimes attributed to a rapid absorption of gas.

Meehan (14) has shown that, when carbon-dioxide is absorbed by carbon black, an expansion of the carbon black takes place, that may be expressed by a definite equation. This action is reversible.

As the absorption of gas is largely a function of the size of the solid particle, a soil colloid should absorb gases also. In fact, clay soil or dust is used for many purposes on account of this property. If a sample of dry, finely divided carbon back is subjected to a pressure of 2,500 pounds per square inch, a briquette may be formed, and if water is then added to the briquette a rapid evolution of gas takes place. This indicates that the dry carbon black had a certain amount of gas absorbed upon its surface that was not removed by pressure but which was liberated by water. Absorption of gas by solids is much less when water is present than when the solid is perfectly dry.

As a soil is being desiccated the soil film becomes thinner and thinner, and more and more of the gases present are condensed upon the surface of the solid particles. A swelling determination is made upon the dry soil. As soon as water comes in contact with the particles that are covered with condensed gas, the attraction of the particle for the gas will be relieved to a certain degree, and the molecules of gas will tend to assume their original position with respect to each other. The gas will either escape or be absorbed by the water, or it may be trapped in the small cavities. If trapped, the expansion of the gas will push the soil particles apart and allow water to come between them. This will cause an apparent swelling of the soil.

At any definite moisture content of the soil there must be an equilibrium between the absorbed gases and absorbed water around the soil grains. The expansion force of the gas must equal the attraction of the solid for water. This fact has apparently been overlooked in all methods for the determination of the swelling coefficient of soils.

Catlin and Vinson* found that soils would often swell when a certain liquid was added to them yet they would not swell when another liquid of like nature was added. Acetone and alcohol will cause soils to swell, while gasolene, chloroform, or pyridine do not swell soils. Apparently a soil particle must be wetted by the liquid before any swelling takes place, that is, the attraction of the soil for the liquid must be great enough to form a film of the liquid. The penetration of water, the movement of soil moisture and the nutrition of plants are influenced greatly by the swelling and shrinkage of soils.

ATTRACTIVE FORCES IN THE SOIL

Water in a soil is acted upon by three forces, adhesion, cohesion, and gravitation. Adhesion is the force of attraction between unlike substances, such as the soil material and water molecules. If we conceive the soil particles to be encircled by concentric shells of water, each shell being one molecule in thickness, then the force of adhesion acting upon water in the shell immediately adjacent to the soil particle is very great. The attraction for water in each succeeding shell decreases in geometric ratio as the distance from the particle increases.

Cohesion is the attraction which water molecules have for each other. Within the water, this force is equal in all directions but on water surfaces it is unequal, the force resultant is exerted inward, and causes surface tension.

*Unpublished work.

The force of gravitation is equal to 981 dynes per gram, or about 0.001 atmosphere, and does not change as the thickness of the water film changes. In thick water films the major forces acting upon water molecules in the outer layer are cohesion and gravitation, while in the inner or thin water films the major force is ahesion. The magnitude of the force holding the water film to the soil particles is of great importance, for, as will be shown later, this very probably determines the availability of this film water to plants.

Briggs and McLane (4), who are to be commended for their pioneer work in the soil-water-force field, investigated the effect of various centrifugal speeds and believed they found a linear relationship between the water content and the reciprocal of the centrifugal force.

The relationship was expressed by the equation $m = m_o + a/f$ In this equation "a" is the slope of the line and has a value of about 6,100, m is the moisture content and m_0 is the point of interception of the Y axis. The curves for various soils do not pass through the origin, but intercept the Y axis at a point below the wilting percentage for light soils, and above this point for heavy soils. That this assumed relationship is an erroneous one, may be shown in three ways.

First, many seeds have a pull of about 1,000 atmospheres, or approximately a million times gravity (15). Shull found that air-dry seeds in contact with air-dry soils, will neither give off nor absorb appreciable quantities of water. According to the graphs of Briggs and McLane, an application of an infinite force could not reduce the moisture content of a soil much below the wilting coefficient, and most certainly could not cause it to approach an air-dry condition.

Second, because the curves for all soils have practically the same slope, Briggs and McLane draw the conclusion that "when a soil is in equilibrium with a force f_1, the amount of moisture which is liberated when the centrifugal force is increased from f_1 to f_2 is

$$m_1 - m_2 = a\left(\frac{1}{f_1} - \frac{1}{f_2}\right)$$

or the moisture set free is proportional to the difference of the reciprocals of the two centrifugal forces. and *is independent of* *the initial moisture content*." Reasoning on the capillary basis will show that this is erroneous. If two soils of different initial moisture contents are centrifuged at speed f_1, each will have a different definite water content which equals the content of water in capillaries up to a definite size, for example those of a 20 milli-microns radius. At speed f_2, the water content of each will again be the sum of the capillary volumes up to a lower but definite capillary size, for example those of a 10-milli-microns radius. Now the soil with the greater initial water content, containing the most colloid, will have more capillaries between the radii of 10 and 20 milli-microns than the lighter soil. Consequently this soil should lose more water between forces f_1 and f_2 than the lighter soil of lower initial water content.

The data of Briggs and McLane, though meager, tend to show that their conclusion is wrong. Omitting an extreme case, the New Mexico dune sand, a portion of these data are given in Table I.

TABLE 1.—EFFECT OF CENTRIFUGAL SPEED IN REMOVING MOISTURE FROM SOILS.

Soil Type	Revolutions per minute 2,700	5,500	Loss
	pct. water	pct. water	pct. water
Sassafrass loam, good	18.60	12.55	6.15
Leonardtown loam, good	18.05	12.10	5.95
Leonardtown loam, poor	12.00	6.30	5.70

The data in Table I show that with these very similar soils, the loss in moisture is not the same with each soil between speeds of 2,700 and 5,500 revolutions per minute. The loss in this interval is greater for the soil with the greatest initial water content.

Third, the same plant growing on various soils will wilt at a definite moisture content for each. Briggs' and McLane's curves, extrapolated to the Y axis, intersect it below the wilting point for light soils and considerably above for heavy soils. Here then, an infinite force does not have the same action on several soils which a definite and constant plant force does. The errors were all caused by the fact that Briggs and McLane were limited by their apparatus to relatively small forces, and extrapolation of curves in regions of greater forces was necessary. Such extrapolations have been shown to be unwarranted.

Reduced to ordinary terms, Briggs and McLane tried to show by means of an equation that, between two definite forces such as represented by the moisture equivalent and wilting percentage, all soils will give off the same amount of water. Their assumption is obviously wrong.

The intimate relation between the water content of a soil, that is, the thickness of the soil water films, and the forces involved is admirably treated in a paper by Shull (15). Unfortunately this paper has escaped the attention of many soil scientists. Shull shows, by means of vapor pressure determinations, that the force with which water is held by a soil varies from 1 atmosphere at the moisture equivalent to about 1,000 atmospheres in the air-dry condition. The magnitude of force at water contents below air-dry were not measured. Shull found that the force-water-content curve was decidedly hyperbolic in shape, the break occurring at moisture contents slightly below the wilting point. Thus at moisture contents above the wilting point, a large change in water content causes but a slight change in the magnitude of force with which that water is held.

At water contents below the wilting point a small decrease in moisture content increases tremendously the force with which the remaining water is held. A curve similar to that of Shull's for a silty clay loam is given in figure 2.

More recent work by Thomas (17) along these lines brings out this same relationship. Thomas plotted percent vapor pressure against water content, and obtained a curve having a steep slope from the origin to a point corresponding to 85-90 percent vapor pressure. From this point to 98 percent vapor pressure the slope decreases, rapidly at first and then very slowly. If the percent-vapor-pressure figures of Thomas are converted into atmospheres of force, which can be calculated by the equation given by Shull, or by other equations, a relationship between force and water content similar to that of Shull's is obtained.

In view of these curves it is easy to see that Briggs and McLane, who were using forces up to 5,500 gravity, or roughly 5 atmospheres, were dealing only with the flat portion of the hyperbolic curve having moisture contents above the wilting point. This probably explains why they believed they had obtained a straight line relationship between centrifugal force and water content.

The relatively flat portion of the force-water-content curve extends from saturation to a point agreeing rather closely with the wilting percentage. This portion of the curve varies slightly

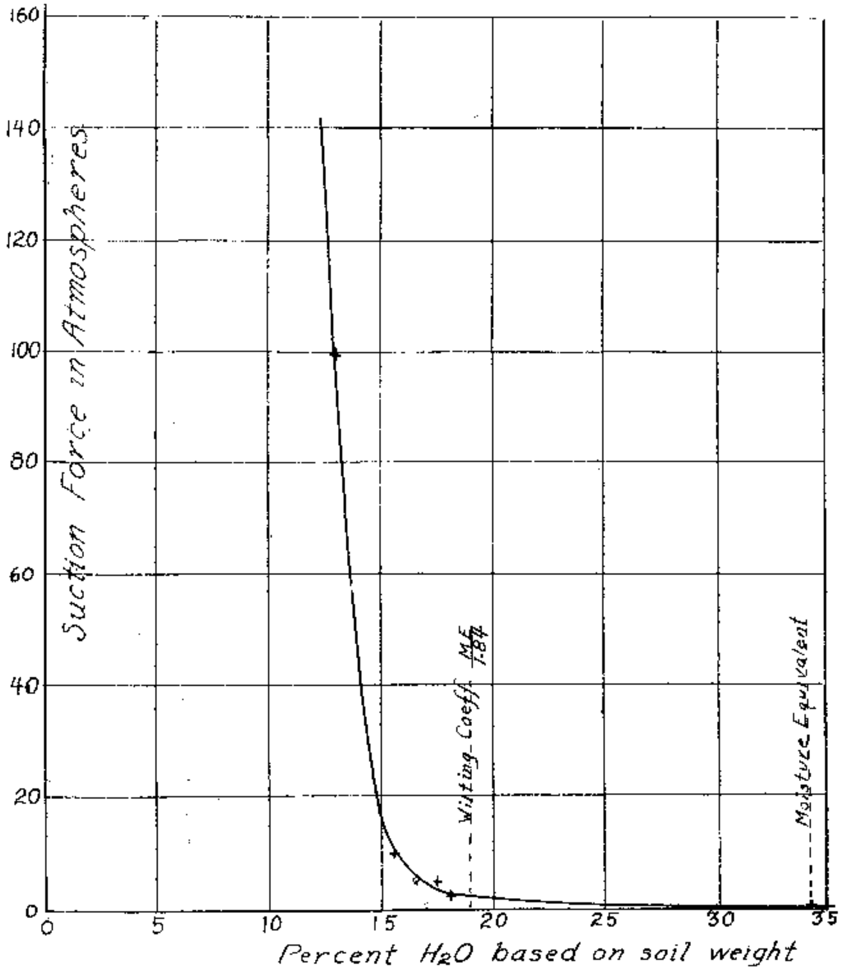

Fig. 2.—Graph showing force with which water is held in a silty clay loam at varying moisture contents.

in slope depending on the soil. We can look upon the moisture equivalent as the X coordinate of a point on the force-water-content curve at which the value equals 1 atmosphere. Similarly we can look upon the true wilting percentage as the X coordinate of a point on the curve whose Y value equals 4 atmospheres (for example). With this picture in mind it is clear that dividing the moisture equivalent by 1.84 may give the true wilting percentage for one soil. For another soil, whose force-water-content curve has a slightly different slope between these two points, wilting percentage cannot be obtained by dividing moisture equivalent by 1.84 but by some other number.

Viehmeyer and Hendrickson (19) have shown that with the soils they used, the ratio, moisture equivalent/wilting percentage, gave values ranging from 1.73 to 3.82. The average value, as found by Briggs and Shantz, is 1.84.

Plants grow in soils when the moisture content lies between the moisture equivalent and wilting percentage. At these moisture contents water is present in the smaller capillaries, or wedges between soil aggregates, and also in the colloidal coat surrounding these aggregates. In these gel-like layers, water is held upon the walls of the compartments, or vesicles, of the gel. When these compartments are full, the soil is very probably above the moisture equivalent. In the end it matters little, if we look upon soil water at the wilting percentage as being present as a film on these gel walls, or as a film surrounding particles of colloidal dimensions.

The thickness of the water film surrounding the small colloidal soil particles varies inversely with the moisture content. Calculations made on Thomas (17) data for three heavy clays give the following results:

TABLE II.—THICKNESS OF WATER FILM IN HEAVY CLAYS AT VARIOUS WATER CONTENTS.

Percent water	Soil condition	Thickness of film Cm.	Thickness of film Molecules of water
1.0	Very dry	2.0×10^{-7}	5
3.8	Air dry	6.0×10^{-7}	16
20.0	Wilting percentage	40.0×10^{-7}	100

These calculations were made on the assumption that the density of the water film is 1, and that the diameter of a water molecule is 3.8×10^{-10} cm. Briggs (3) determined the thickness of the water film on quartz grains of various degrees of fineness. In an atmosphere within 1 percent of saturation, which corresponds roughly to the wilting percentage, he found the thickness to be 2.66^{-6} cm. This is in fine agreement with the above data.

We know from the data on compressibility of water (12) that the decrease in volume with great pressures is small. Thus water at 0° and 10,000 atmospheres pressure has a volume of 0.8030 compared to a volume of 1 at 0° and 1 atmosphere. Its density is, therefore, about 1.2. But soil water films held with a force as great as 10,000 atmospheres are exceedingly thin, the soil water content is very small, and the correction for the thickness of the film due to increased water density is negligible. With thicker water films, such as occur at the wilting point, the average force holding the water is much smaller and the correction for compression is again negligible. Such corrections would probably amount to 5 percent for an air-dry soil and 1 to 2 percent for a soil at the wilting percentage.

At soil moisture contents above the wilting percentage the interstitial water bears a fairly large percentage to the total water. This percentage is not definitely known, and for that reason calculations of the thickness of water film above the wilting percentage are very inaccurate. In all likelihood the thickness of the water films under conditions for plant growth varies from about 40.0×10^{-7} to about 70.10^{-7} cm. or from $\frac{40}{10,000,000}$ to about $\frac{70}{10,000,000}$ cm. At the wilting percentage this film will be equally thick in all soils.

MOVEMENT OF WATER IN SOILS AT THE WILTING PERCENTAGE

At the wilting percentage, the force of gravity which is 981 dynes or roughly 0.001 atmosphere, is insignificant in comparison with the forces of adhesion and cohesion which are in the neighborhood of 5 to 10 atmospheres. At these water contents the force of gravity as affecting water movement, may be ignored.

Movement of water in soils in the region of the wilting point can occur in two ways, movement in the liquid phase, and movement in the vapor phase. In either case it is exceedingly slow.

MOVEMENT OF SOIL WATER IN THE LIQUID PHASE

Consider two soil particles, A and B, lying so closely to each other that thin soil water films are in contact. If for any reason the thickness of the film on A is diminished, the water molecules at the point where the two films touch, will be acted on by a stronger force towards A than B. These molecules will move towards A, and the movement will be general until the thickness of the films on both particles is equal. This constitutes the phenomenon of soil water movement in the liquid phase. The movement can be explained by the tendency of soil moisture to establish equilibrium with the forces of adhesion and cohesion as has heretofore been described. The rate of this water movement is not directly proportional to the moisture contents of the two soil particles at A and B, but depends on two factors, the moisture-content-gradient, and the level of this gradient. Thus the rate of water movement in a certain soil from a locality of 4 percent moisture to one of 3 percent, with a gradient of 1, is much lower than in another soil from a locality of 20 percent to one of 19, also having a gradient of 1. In consequence of this the rate of water movement in any soil at the wilting point, or slightly above, is exceedingly slow and entirely insufficient to supply the needs of most plants.

MOVEMENT OF SOIL WATER IN THE VAPOR PHASE

The force with which the water molecules are held to each other, and to the soil particle, prevents their vibratory movement at the surface of the film from being as great as it is in a free water surface, such as the surface of water standing in a dish. Because of this lessened vibratory movement, fewer water molecules get into the air and fewer return to the water film in unit time than on a free water surface. This results in fewer molecules of water being present in the air above the film than over a normal water surface and results in a decreased vapor pressure.

In air-dry soils the forces holding the water molecules to the soil are very great, and few molecules are present in the soil air above the water films. The vapor pressure of the air around the film at this moisture content is only about 35 percent of what it is over a free water surface.

In soils at the wilting percentage the water film is so thick that the outer molecules are attracted to the soil particle with only a relatively small force. As a result the vapor pressure over such films is almost as great as over a free water surface. It will be shown later that the relative vapor pressure over water films in soils at the wilting percentage is about 99.6 percent of that over free water surfaces.

If two soil particles, A and B, lie a few centimeters apart and if for any reason, the films around soil particles at A become thinner than at B, there necessarily will be a lower vapor pressure at A than at B. In soils at the wilting point, the vapor phase above A is very probably connected with that above B. If the vapor pressure above A is 50 percent of that above a free water surface, and that above B is 99 percent, water molecules will distill into the air above B, move as a vapor to A, and will there condense onto the film. It is now believed that water movement in soils at and below the wilting percentage is largely of this type. As far as furnishing water to the growing plant for transpiration purposes, the effect of soil moisture movement as a vapor on most cultivated plants has heretofore been assumed to be negligible. Plants cannot reduce the moisture in a soil very much below the wilting percentage, and below this percentage the movement of water as a vapor in a soil that is free from alkali, is so slow as to be of little value to the plant. However, the effect of such movement in supplying moisture to germinating seeds may be of considerable importance. Seeds germinate slowly, and are able to wait a relatively long time for the water that is required in the germinating process. When seeds are brought into contact with all of the soil, for example, by tumbling the seeds and soil together, in a closed container, they may exert a pull of 1,000 atmospheres upon a soil and reduce the moisture content far below the wilting percentage. Water requirements of growing plants are not the same as those of germinating seeds and the same methods of study cannot be used for both.

EFFECT OF SALTS UPON MOVEMENT OF SOIL MOISTURE

Salts in a water film attract water molecules, and lower the vapor pressure. On account of this, water will distill from one film to another of equal thickness, if the second contains more salts than the first, or in other words, is more concentrated.

In the older methods for determining hygroscopic water a sample of dry soil was suspended in a dish over water in a closed vessel. The salts present in the thin film of water surrounding the soil grains, together with the soil forces, reduced the relative vapor pressure immediately above the soil grains below 100 percent. Water, as vapor, would be transferred from the water to the soil films. Theoretically, because of the salts present in the soil, this movement should never cease and especially when alkali is present, such determinations are of little value. Viehmeyer, in conversation, stated that under conditions of darkness, no temperature variation, and long periods of time, so much water is sometimes distilled from a water surface to peat, that the peat actually floats.

An increase in temperature will cause an increased molecular activity, but not as rapidly as it increases the capacity of the air to hold water in the vapor state. With increasing temperature, therefore, the relative humidity or relative vapor pressure above a film falls, and this causes a transfer of water from the vapor above a cold film to the vapor above a warmer film.

As noted before, the movement of water in the soil as a vapor, is probably of minor importance to ordinary crops that are growing in a soil that is free from alkali. At water percentages slightly above the wilting point, movement of water of any kind is so slow as to be of minor importance to the plant. At low percentages, a plant must either grow to the water or suffer. However, when soluble salts are present in the soil in considerable amounts, the transfer of water as a vapor may be so speeded up as to be of much importance. Many plants, such as citrus, are very susceptible to alkali. Such plants are also usually easily injured by poor drainage, by a sluggish movement of soil water, or by too much water in the root zone. In all probability the presence of salts, especially salts like calcium nitrate, which are prevalent in many sections of Arizona and in southern California, may condense enough water around the roots of such plants as to be injurious. Calcium nitrate alone is one of the least toxic salts.

EFFECT OF RATE OF MOVEMENT OF FILM WATER UPON THE WILTING COEFFICIENT

A growing plant, in a soil above the wilting percentage, removes water from the soil at a certain rate, for example, 2 grams a day. As the wilting percentage is approached, the thickness of the soil water films decrease, and the rate of movement from these films to the plant becomes less. When this rate first becomes insufficient to maintain turgor in the plant, wilting takes place. We must remember that the suction force of a cell is not numerically equal to the osmotic pressure as determined by plasmolysis. Cells having no cell sap can still exert a suction force because the plasma within the cell is not hydrated to its maximum capacity. As a rough approximation, however, we can assume the suction force to equal the osmotic pressure. On this basis using the figures of Shull, root cells at the time of wilting exert an average pull of 8 atmospheres. The suction force of the soil for water at the wilting point is about 4 atmospheres. This leaves a moisture-force gradient of approximately 4 atmospheres in favor of the plant.

In the section on the movement of water in soils at the wilting percentage, it was shown that the rate of water movement in both the vapor and liquid phases decreases rapidly with the decreasing moisture content. As the soil dries out, therefore, the rate with which water moves towards the root steadily decreases. After the wilting percentage is reached water movement still goes on but at a decreased rate. Thus Briggs and Shantz (5) showed that soil No. 26 had a moisture content at the wilting point of Kubanka wheat, of 8.2 percent, while at the death point, the moisture content had decreased to 7.7 percent. Evidently, 0.5 gram of water per 100 grams of soil had entered the plant after wilting occurred, because this water could not have been lost in any other way. The steadily decreasing rate of water intake is very probably caused by a decrease in the moisture gradient between the plant and the soil.

Shull cites some evidence indicating that in a plant-soil system at the wilting percentage, the osmotic pressure of the root sap increases at almost the same rate as the soil-water forces increase. This would maintain a constant gradient in favor of the plant. This is possible, but if so, the force level of this gradient gradually increases. For example, the gradient at the beginning of the wilting period is probably 8 atmospheres minus 4 atmospheres, or 4 atmospheres, while at a later time it may be 16 atmospheres minus 12 atmospheres, or 4 atmospheres. At this force level the rate of water movement is much less than previously, even though the magnitude of the gradient is the same.

The phenomenon of increase of suction force in root cells with decrease of water content in the soil can be considered as a power of adaptation. Such increases, even though they may be fourfold, do not greatly increase the amount of water available to the plant. From figure 2 it will be seen that if a pull of 4 atmospheres is exerted upon this soil the moisture content will finally be reduced to 17.5 percent. Increasing the pull to 16 atmospheres will reduce the water content to about 15.3 percent. With this soil, therefore, 2.2 percent of water are available between forces of 4 to 16 atmospheres. With more sandy soils the water available between these forces will be considerably less. If the suction force of a plant could be raised to 100 atmospheres very little additional water would become available. This is indicated in figure 2 by the steepness of the force-water-content curve between 16 and 100 atmospheres.*

THE WILTING PERCENTAGE CONSIDERED AS A BIOLOGICAL PHENOMENON

The attractive force of the soil particles for water is a function of the nature and size of the particles, and the thickness of the film. This force is a constant, and all rooted plants have adapted themselves to this constant. The fundamental principles of food and water absorption are practically the same for all rooted plants. This apparently explains why all plants wilt at the same percentage in the same soil, but at different percentages in different soils. Rooted plants of today take up their mineral food as ions, just as did the ferns that formed our coal measures; they draw their moisture from the soil films in the same way, and they wilt at the same percentage in the same soil.

Soil conditions, such as the movement of water and the dissociation of nutrient salts, are controlled by definite chemical and physical laws. These laws have not changed and will never change. Water has always moved in a soil in order to bring about equilibrium between the three forces, cohesion, adhesion, and terrestrial gravitation, and for not other reasons. The plant food

*Since the preparation of this manuscript two papers bearing on this subject have become available to the authors. They are (1) Bachman, F. 1928. Uber die Beziehungen zwischen dem Wassergehalt des Bodens und seinem Wasserdampfdruckle, sowie über diejenigen zwischen der Saugkraft des Bodens und dem Welkens von Pflanzen, Planta Vol. 4., and (2) Gradmann, H. 1928. Untersuchungen über die Wasser Verhaltnisse des Bodens als Grundlage des Pflanzen-Wachstums,—Jahr. Wiss., Botan., Vol. 69. pp. 1-100.

These men, by experimental methods, have corroborated some of the theoretical portions of our paper. Gradmann has accurately determined the force-water-content curve for various soils between 99 and 100 percent relative humidity and finds a sharp break or change in direction at about 99.5 percent relative humidity which corresponds roughly to 7 atmospheres.

in the soil solution has always been partly ionized and always will be.

The soil cannot adapt itself to the plant, so the plant must adapt itself to the soil, if it is to survive. From the beginning of plant life upon earth until the present time, certain relations between rooted plants and the soil have not changed and they are not capable of being changed.

All plant cells that are concerned with the absorption of water, appear to have approximately the same attractive force for the water, regardless of what plant these cells belong to. Thus Hannig (10), by the method of plasmolysis, found that the root cell sap pressure for 64 species of plants varied from about 4 to 14 atmospheres, the average value being equivalent to 7 or 8 atmospheres. These variations may seem large, but the probable error is also large. Variations between plants in the same family are often as great as variations of plants in different ecological groups.

THE PHYSICAL NATURE OF THE SOIL WATER FILM

The force of adhesion between soil material and water is very high, and probably amounts to as much as 25,000 atmospheres. As water is absorbed upon the surface, the force attracting additional water decreases very rapidly. This is clearly shown in figure 2. It is estimated that when the water film is approximately 15 molecules thick, the force with which the outer molecules are held is only of the order of 1,000 atmospheres.

The compressibility of water is measurable; thus, with a force of 10,000 atmospheres, the water is compressed to 0.8 of its volume at 0° and 1 atmosphere. We can, therefore, look upon the first few molecular layers of water nearest the soil material, as being condensed, probably somewhat viscous, and under great force. Each succeeding molecular layer is held with less force till at a distance of 100 molecules or so from the soil grain the water is held with a force of only a few atmospheres. This last layer is similar to ordinary water, in that it has the normal density, and is not appreciably compressed.

Bouyoucos, (2) by means of dilatometer measurements, concludes that a portion of the water in soils will not freeze even at temperatures as low as -78°C. He found too, that the amount of water failing to freeze, called by him "unfree water," varies with the temperature used. Thus, with the same soil, smaller amounts remain unfrozen at -78°C. than at -40°C. The amount of unfree water in soils varies with the soil, being greater for the finer textured soils. In one of his earlier investigations Bouyoucos found that the amount of water failing to freeze at -4.0° or -1.5°C. bore a fairly constant relation to the wilting percentage of these soils. He stated, later, "It was strongly emphasized, however, that this relation should be considered more a remarkable coincidence than as indicating certain absolute values, because the methods in question were empirical." (2).

Water in freezing increases in volume about 11 percent. Water which contains dissolved substances, or which is held to a soil particle by a great force does not freeze at 0°C. The presence of salts and also surface forces causes a lowering of the vapor pressure, as well as a depression of the freezing point. The surface forces of the soil tend to compress the water in the films surrounding the soil particles. The force of freezing tends to increase the volume of water. The force of freezing must, therefore, be acting in the opposite direction from that of adhesion, as far as volume of water per gram is concerned. Under these conditions freezing would stop when its force equals the force of adhesion or absorption.

The freezing point depression of a water solution containing one gram molecule per liter of non-ionized salt is 1.86°C. Soil water freezing at this temperature has a suction force equal in atmospheres to the osmotic pressure of a molar salt solution. In the case of soil water this force may not be caused entirely by dissolved salts, but also, in part, by the attractive forces of the soil particles. In fact, at freezing temperatures several degrees below zero, the force is undoubtedly largely of this type.

A molar solution has an osmotic pressure of about 22.4 atmospheres. Since the freezing point depression is 1.86°, the osmotic pressure corresponding to a freezing point depression of 1.0° equals about 12 atmospheres. Assuming for convenience that this relationship is linear, the suction forces corresponding to various freezing point depressions have been calculated. These values are given in Table III.

TABLE III.—THE FORCE IN ATMOSPHERES, BY WHICH SOIL WATER IS HELD WHEN FREEZING AT VARIOUS TEMPERATURES.

Freezing temperature Degrees centigrade	Suction force in atmospheres
-1.0	11.9
-1.5	17.9
-2.5	29.8
-4.0	47.7
-78.0	937.0

Of course in the measurements of Bouyoucos, a certain amount of water was frozen and removed from action as a solvent in making the determinations. Before freezing, and the removal of this quantity of water as a solvent, the solution was more dilute with respect to salts and was held with a lesser force. At -1.5°C. for instance, a further slight decrease in its temperature will cause a small amount of water, dw, to be removed. This small increment, dw, is held with a force of 17.9 atmospheres.

If the wilting percentage of soils is about 4 atmospheres, it is easy to see that the amount of unfrozen water at -1.5° is less than the wilting percentage, because the force of freezing for the last increment, was 17.9 atmospheres. Figure 2 indicates that in a heavy soil the amount of water held with a force between 4.0 and 17.9 atmospheres is several percent. For such a soil the unfree water at -1.5°C. should be that many percent below the wilting percentage. In the case of lighter soils the amount of water held with forces between 4.0 and 17.9 atmospheres is small, and with these soils, the unfree water at -1.5°C. should approximate closely the wilting percentage.

Bouyoucos and other workers have found that the amount of unfree water at any temperature depends upon the amount of water initially added to the soil. It is very probable that with higher water contents the gel layer surrounding the soil grains is more dispersed and has a greater gel effect than at a lower water content. When water is added to a dry soil, the dried-out vitreous gel covering does not immediately swell to its full capacity. For that reason all soils should be previously in contact with water for a considerable period in order to get concordant results, whenever these results are a function of the gel action.

THE CHEMICAL NATURE OF THE SOIL SOLUTION AT AND BELOW THE WILTING PERCENTAGE

Judging by previous work upon the soil solution, it seems highly probable that certain food elements are concentrated in the inner layers of the soil film, and that the concentration of these elements gradually decreases as more and more layers are built up around the soil particle. It is true also, that the tendency of the plant is to feed in the most concentrated zone of the soil solution accessible, that is, in the zone that is separated from the soil particle by 100 or more molecules. In order to remain alive the absorbing zone of plants must be surrounded always by a film of water, no matter what the moisture content of the soil may be. At and below the wilting point the film becomes so thin, and cohesion becomes so great, that absorption of water is no longer possible. There is, however, at all times and at all percentages, a layer or film of water, between the absorbing area of the root and the soil grains. Unless this is true the plant root will die. We cannot conceive of a live root-tip remaining long in contact with a perfectly dry soil grain or even closer to the grain than the distance of the diameter of about 100 molecules.

The thickness of the film that lies between the root and the soil particle must be very thin, at or slightly below the wilting point. Under the enormous pressure that the innermost layers are subjected to, the diffusion of salts, ionization and even molecular movement may be interfered with. It is probable that, in the innermost layer, the mineral plant foods are not entirely in true solution as we ordinarily conceive of solution. The ions or molecules under the great pressure may be held tightly against the colloidal soil particles and are not free to move. The mineral molecules may be as much a part of the soil particles as they are of the soil solution.

A plant feeds upon ions, and if the salts in the intermost film layers are ionized, even to a slight degree, to that extent the nutrient elements are probably available. The absorption of water for transpiration purposes and the absorption of nutrient material are separate phenomena. The absorption of nutrients probably takes the form of an interchange of electrical charges, like an ordinary chemical reaction. Neither molecules nor ions can be absorbed from a relatively dilute soil solution, into a relatively concentrated plant sap, by the process of dialysis. Neither can salts be absorbed by osmosis, as omosis concerns movement of solvents only.

Even in the most concentrated zone of the soil film, if any of the nutrient salts are ionized in part, and free ions appear in solution, there is no reason for doubting that the plant can absorb them. The enormous pressure that prevents the absorption of water, should not interfere seriously with the absorption of plant foods. It is highly probable that, while the water in a soil at and below the wilting percentage is not available to plants, the salts that are dissolved in the water are readily available. A surface soil that is maintained at the wilting percentage during a part of the growing season may furnish a feeding ground for plants although it may contain no available moisture.

Such is the assumed nature of the soil film at the wilting percentage of the soil from which the plant must often draw its nutrient material. The chemical nature, however, is largely speculative as no satisfactory method has been yet devised for obtaining the true soil solution, the solution with which the plant root actually comes in contact. Evidence of the nature of the solution,may, however, be obtained from the nutrition of plants, at or near the wilting percentage.

ABSORPTION AS INFLUENCED BY CONCENTRATION

The rapidity of absorption of plant food is largely a function of the concentration of the nutrient solution. It has been shown repeatedly in this laboratory, that the absorption of potassium by plants is increased as the concentration of the nutrient solution is increased until a maximum concentration is reached, when there is a sharp decline. This break occurs at near 100 parts per million. The same phenomenon is true with phosphorus. It is, however, not true with the absorption of nitrogen or nitrates. If a concentration of only a few parts per million of nitrate nitrogen is maintained in the culture solution, seedlings will absorb practically as much as they will from a stronger solution. If the absorption of nutrient ions in milligrams by 100 plants is plotted against the increasing concentration of nutrient solution, the curves for potassium and phosphorus will be regular and very much alike. The absorption of nitrogen will, however, be represented by a fairly straight horizontal line. The absorption of nitrogen is not greatly influenced by the concentration of the solution, by the vigor of the plant as shown by its transpiration, or by the amount of alkali in solution, as is the absorption of potassium and phosphorus.

The reason for this difference is evident. The phosphorus and potassium in the soil solution are derived from slightly soluble soil components, and the concentration of the solution is, therefore, fairly constant for these elements. The soil solution at equilibrium, is saturated with respect to phosphorus and potassium, and if either of these elements is absorbed, more will come into solution and equilibrium will be maintained. It is the tendency of these two elements to remain in the static, or inner-film water. In its era of adaption the plant became accustomed to fairly definite concentrations of these elements.

But this is not true with nitrogen. Nitrates in the soil solution are produced almost wholly by micro-organisms. Under favorable conditions nitrates are produced, but under unfavorable conditions, denitrifying organisms operate and reduce the nitrates that may be already formed. For such reasons, there may be nitrates in the soil solutions at one time, and no nitrates at another, or the concentration of nitrates may vary from nothing up to a high percentage within a relatively short time. Nitrates are mobile and readily soluble, they are not absorbed as potassium and phosphorus are, but move freely with the gravity water. The plant has become adapted to such conditions, and will absorb nitrogen whenever it can get it, and from solutions of all reasonable concentrations. The absorption of nutrient materials is largely a phenomenon of adaptation.

While there may be many objections to this course of reasoning, it appears that the soil solution, to which the plant has become adapted, contains varying amounts of nitrogen, and a fairly constant concentration of phosphorus and potassium.

MAINTENANCE OF EQUILIBRIUM BETWEEN PLANT AND SOIL AT THE WILTING PERCENTAGE

It has been observed many, many times that, although the moisture in the root zone may be reduced to the wilting percentage, the roots of many plants do not die. They may cease elongating, but at the next rain or irrigation, they begin to grow again.

It has been shown in this laboratory that, should the soil in direct contact with the root tip become perfectly dry, the plant root will be desiccated and die. The soil in the immediate vicinity of the absorbing area of the root must be kept at approximately the wilting percentage or above, in order that the root may live. Plants that grow naturally in arid or semi-arid countries have become adapted to such conditions, and have developed different morphological features that have perpetuated their species.

Attention has been called previously to the fact that the force of adhesion between the film of water and the soil particle is inversely proportional to the thickness of the film and that the water is held to the soil grains by a force ranging from that of gravity alone to that of several thousand atmospheres. It has been shown also that the plant as well as the soil, possesses the power of attracting water. When a soil is at its optimum moisture content, the adhesive force of the soil for the outermost layer of water molecules is less than one atmosphere. Since the pull of the plant is much greater, the moisture force gradient is in favor of the plant, and water will move from the soil to the plant. As the thickness of the film is decreased the adhesive force of the soil particles becomes greater and greater, the movement of soil moisture becomes less and less, while the pull of the plant remains fairly constant. The plant, therefore, has more and more difficulty in obtaining its water, until the wilting percentage is reached. Here the pull of the plant is counter-balanced by the pull of the soil, and if transpiration and growth are checked, equilibrium will be maintained, unless some other factor intervenes.

But there are other factors, the principal one being the heat of the sun, that bring about a loss of moisture in the soil. If the soil that is in equilibrium with the plant is thus deprived of some of its moisture, the thickness of the soil film will be reduced further, and the pull of the soil for water will be increased. There will be a gradient established between the soil and the plant in favor of the soil, that is greater than the power of accommodation of the plant, so that water must move from the plant to the soil. If the plant cannot supply water to the root as fast as the water is removed by distillation, the root must eventually be desiccated and die. Many desert plants are apparently able to store up large amounts of water in their tissues, and to use a part of this stored-up water in maintaining equilibrium with the soil during periods of stress.

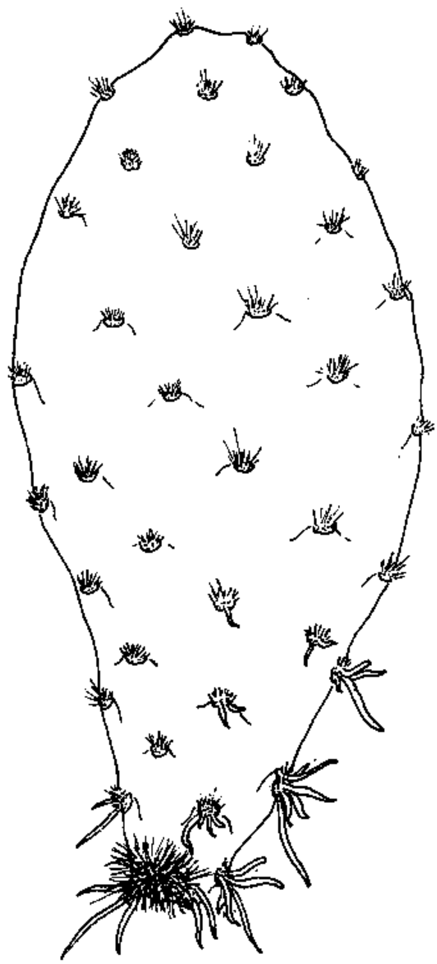

Fig. 3.—Illustration of Optunia joint that was rooted in dry sand.

If the distillation of the water from the soil should be too rapid, the plant may be unable to maintain a rate of water movement toward the soil sufficient to keep the soil adjacent to the roots at approximately the wilting percentage. Under such conditions the roots must soon die. This has been found to be true when a cactus root system is placed in oven-dry silt soil. A cactus root will grow into, live, and elongate in a soil that is kept at the wilting percentage, or even in an air-dry soil, but it will be desiccated and killed in a few hours, if placed in an oven-dry soil. Plants in their natural habitat have never come in contact with an oven-dry soil.

A very satisfactory way of rooting cactus joints is to plant them in an air-dry soil or sand, and allow them to stand without water until they establish a root system. A joint thus rooted is shown in figure 3.

Nearly all cacti have very efficient ways that conserve the water that is stored up in their above-ground tissues. They close their stomata, cover their surfaces with a varnish-like coat, and reduce transpiration to a minimum. In all probability, as much water is used by a cactus in maintaining equilibrium with the soil under drought conditions as is used in transpiration. This is illustrated in the following experiment.

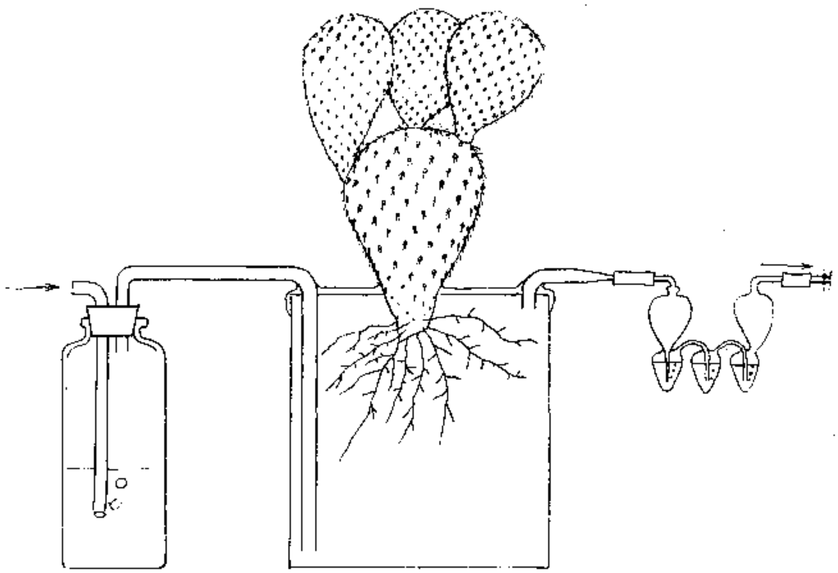

Fig. 4.—Illustration of arrangement of apparatus used in determining amount of water given off by roots of Optunia.

A good-sized cactus plant, *Optunia discata*, with a good root system, was placed in a can, holding 7 kilograms of air-dry soil, in a manner shown in figure 4, and thoroughly sealed in with a mixture of beeswax and paraffin. The part of the joint beneath the soil was covered with wax in order to prevent a loss of water, but the root system was left free, and in contact with the air-dry soil. An inlet and an outlet were arranged, and the system connected in train with a suction pump. Air was drawn through a jar of sulphuric acid or through a tube of phosphorous pentoxide, then through the can of soil and finally through a Geissler bulb of sulphuric acid. A control can with the same amount of soil, but without a plant, was run at the same time.

The plant and can of soil was first weighed, connected in the train, and air drawn through the system for periods of 24 hours. The dry air absorbed a certain amount of water that was given off by the roots of the plant, and this moisture was collected in the Geissler bulbs. The increase in weight of the bulbs, minus the increase in weight of the control, represented the amount of water that was given off by the roots of the cactus. The plant and jar were weighed again, and the loss in weight represented both the transpiration, and the water that was given off by the roots. By subtraction, the amount of water that was transpired, was determined. The data for a typical 7-days run, is shown in Table IV.

TABLE IV.—TRANSPIRATION OF A CACTUS PLANT AND LOSS OF WATER FROM ITS ROOTS.

Total water lost by transpiration and by roots	13.50 grams
Water lost by roots—less control, 2.45 grams	9.08 grams
Water lost by transpiration	4.42 grams

It will be noted, that the loss of water from the roots was greater than the loss by transpiration from the parts above ground. This experiment has been repeated several times, with different species of cactus, and with the same general results. Evidently, the cactus stores up water both for purposes of transpiration and for maintaining equilibrium with the soil layer in contact with its feeding roots.*

*Since the preparation of this article it has come to our attention that Litvinov, from an entirely different mode of approach, has deduced evidence showing that an equilibrium, or condition approaching equilibrium, exists between the soil and plant forces for water in fairly dry soils. A summary of his experiments are:

1. In case the suction power of the plant roots exceeds the soil force for water the roots actively absorb water and exudation (bleeding) of plant sap will occur on cut surfaces of the plant.
2. When the suction power of the plant root is equal to the soil forces, there is no exudation on cut surfaces. This occurs at about 4 atmospheres.
3. When the soil forces exceed the root forces, there is no exudation. If water is placed on the cut surface, however, there will be an intake. This occurs because the soil sucks water from the plant roots.

Litvinov, L. S. 1928. On the development of the phenomenon of the soil drought. Results of Investigations of Perm. Agr. Exp. Sta., Div. of Agr. Chem., No. 2, pp. 55-76. (In Russian).

It was found that great care is necessary, and considerable technique is required in running an experiment of this kind. In experimenting with plants, it is never advisable to subject the plant to a greater stress than it has been subjected to under field conditions. If water is drawn away from the roots too rapidly, that is, if dry air is drawn through the system too rapidly, the roots may lose water faster than the plant can replace it, and the roots will become desiccated and die.

Movement of water from parts above ground to root systems for the purpose of maintaining equilibrium does not seem to be unreasonable in view of the fact that water moves from one part of the above-ground portions to another during periods of water stress. This is especially true of citrus fruits. (1).

THE SOIL SHEATH

It must be remembered that water moves very slowly in a soil at and below the wilting percentage, so it is not necessary for the plant to give up water to the soil, except to a thin layer immediately in contact with the roots. The soil may be dry a few millimeters away from the root, yet the soil layer in contact with the root may be maintained at the wilting percentage for a long period of time.

It has been observed by almost everyone who has had any experience with desert plants, that when a plant is removed from a soil near the wilting percentage, the roots will be found to be covered by a thin layer or "sheath," of soil. This sheath adheres closely to the roots. It has been described by Volkens (20) as characteristic of plants that grow in the Egyptian and Arabian deserts. This soil sheath is moist, and it evidently contains some substance besides water that has slight adhesive properties. In all probability, many plants retain their turgor, even when growing in a soil that is below the wilting percentage, because of this sheath. The moisture content of the sheath is probably maintained at the wilting percentage, by an exudation of water by the root.

The writers have often attempted to transplant desert shrubs and flowering plants, but usually without success. If a healthy and turgid plant is carefully removed from a dry soil, the roots are nearly always covered with a sheath, and the plant will remain turgid as long as the sheath remains moist. In a few moments, however, when exposed to the air, the moisture will be evaporated, and the soil may be shaken from the roots, the roots will be desiccated, and the plant will immediately wilt and die. It is very difficult to transplant many species of desert plants, although one might think that they should lend themselves to transplanting. In theory, if the soil around such plants were first thoroughly saturated with water, and the plant allowed to stand for several hours in the wet soil, the process of transplanting would be more successful.

Many of the phenomena of desert vegetation may be explained upon the theory that a plant can maintain equilibrium with the soil. Many plants, such as the mesquite, will send their roots through several yards of dry soil, and draw moisture from lower levels. It is dfficult to conceive of any root remaining long alive in direct contact with a dry soil. It is probable that the mesquite root pushes a little way into the dry soil, and builds up a moist soil sheath around the newly-formed tip. Further elongation takes place, with the formation of the protective sheath, until many feet of dry soil are penetrated. There may be other ways, however, by which a plant root may penetrate a soil that remains at or below the wilting percentage.

It must be remembered also, that plants only absorb appreciable amounts of water through a very small portion of their root system, that is by their root hairs, and by the area near the growing tip. The greater part of the root system develops an almost impermeable covering, and is, in this way, protected from desiccation. It would, therefore, be necessary for the plant to maintain equilibrium with the soil around only a small part of the root system.

The ways by which a plant is able to tide over periods of drought are many. Some plants, like the cactus, have the power of storing up large quantities of water in their tissues above the ground to be used whenever necessary during periods of stress. Some plants have large tubers where water is stored; others have tap roots that enable them to draw water from lower levels, which water may be returned in part, to the soil by the feeding roots in order to maintain equilibrium.

NEW INDIRECT METHODS FOR THE DETERMINATION OF THE WILTING PERCENTAGE

The designation of water relationships between plants and soils in atmospheres of force, clearly shows that various soils having different wilting percentages hold the water at this water content with the same force. All soils at the wilting percentage hold the water with an equal force, and theoretically, if such soils were placed together, no movement of water from one to another would occur, either as liquid water or as water vapor. In addition, the manner of expressing the wilting point in terms of atmospheres of force suggests new methods for its indirect determination. As has been shown in the preceding division, a theoretical freezing temperature is possible at which the amount of water remaining unfrozen is exactly equal to the wilting percentage. Although Shull believes that soils at their wilting percentages hold water with a force of about 4 atmospheres, we believe it entirely probable that this may vary within relatively narrow limits, depending on the plant grown.

In the following table freezing temperatures corresponding to various force measurements are given.

TABLE V.—TEMPERATURES AT WHICH SOIL WATER FREEZES WHEN HELD WITH FORCES OF VARIOUS MAGNITUDES.

Atmospheres of force at 25°C.	Freezing point depression Degrees centigrade
4	-0.28
6	-0.43
8	-0.57
10	-0.71
12	-0.81

Since the freezing temperature of the bath can be held practically constant during the short interval required for the determination, the amount of water held with a definite force could be determined very easily and accurately. The dilatometer method of Bouyoucos (2) should lend itself admirably to such determinations.

Another method would be to place the soil over a salt solution having an osmotic pressure of the designated number of atmospheres. If this soil contained water held with a force less than 4 atmospheres, for instance, water would leave the soil and pass to the solution, if the vapor phase, until both were in equilibrium. If the soil water was held with a force greater than 4 atmospheres, for example, water would pass to the soil from the solution till both were in equilibrium. A sugar solution having an osmotic pressure of 4 atmospheres at 25°C. contains about 5.4 grams per 100 grams water. The relative vapor pressure over such a solution at 0°C. is about 99.6 percent and at 25° it would be practically the same. Temperature variations, therefore, have practically no effect on the relative humidity of air above or sulphuric acid solution as long as the air above and the solution have the same temperature.

If, however, the temperature of the soil is lower than the rest of the system, the air immediately above the soil will be cooled and where the relative humidity so closely approaches 100 percent, this slight difference in temperature may cause a condensation of water on the soil. Because of this, the temperature of all parts of the system must be practically equal, and this can be accomplished only under conditions of constant temperature.

The time required to reach equilibrium at an absolutely constant temperature would be great. If the soil did come to equilibrium, weighing the soil plus water, and later dried, would give the amount of water in that soil held with a force of 4 atmospheres. Because of the difficulty of getting equilibrium, this method for determining the wilting percentage of soils should prove unsatisfactory. Thomas (16) has called attention to the defects of the static method of determining the relative vapor pressure of moist soils and advocates the use of the dynamic method. The dynamic method, in which air having a relative vapor pressure of 99.6 percent is passed through a column of soil, might be used for the determination of the wilting percentage of soils, but this, too, is subject to relatively large temperature errors.

SUMMARY

1. This paper is principally a theoretical discussion of the plant and soil moisture relationships in the neighborhood of the wilting percentage.

2. The soil solution includes all of the moisture in a soil whether available or non-available. It is the connecting link between the soil and the plant. There is a tendency for equilibrium between the soil and the soil solution.

3. At all precentages of soil moisture, from optimum to an air-dry condition, there is a film of water surrounding each soil particle regardless of its size.

4. Soils swell or shrink chiefly because of an increase or diminution in the thickness of the gel-like coat which the larger soil grains possess. We can consider the walls of each vesicle in the gel as being covered with a film of water, or the nucleus of each micelle of the gel as being surrounded by a water envelope.

5. The amount of gas absorbed by a soil is a function of the nature of the soil particle, the area of surface, and the water content of the soil. Increasing the water content decreases the amount of gas absorbed with a consequent swelling of the soil if the liberated gas does not all escape.

6. The forces acting upon water in soils are adhesion, cohesion, and gravitation. The last is relatively important at high moisture contents, but the force of adhesion is by far the greatest at low water contents. Water in a soil always arranges itself so as to be in equilibrium with these three forces.

7. Movement of water in soils is an attempt to reach equilibrium with respect to the forces acting upon it. At the wilting percentage or below, movement in the liquid phase is slight. Equilibrium under these conditions is obtained largely by transfer of water in the vapor phase. Salts exert a pull for water, hence movement of water in soils is toward the salt containing areas.

8. In soils above the wilting percentage the rate of water intake by plants is sufficient to maintain turgor. As the soil moisture content decreases, the rate of water movement decreases also and when this rate first becomes insufficient to maintain turgor, wilting takes place in plants not provided with water storage tissues. The decreasing rate of water movement, or water intake, is caused by two factors. First the force gradient becomes less, that is, the soil holds the remaining water with an increasing force, which force gradually approaches the force of the plant for water. Second, the level of this force gradient is gradually increasing, causing a decreasing rate of water movement. As an example of this second factor, the rate of water movement between a soil having a pull of 6 atmospheres to a plant with a pull of 10 atmospheres is much less than the rate of movement between another soil with a pull of 2 atmospheres and a plant with a pull of 6 atmospheres, although the magnitude of the gradient is 4 atmospheres in both cases.

9. Plant adaptations result after changes of environment have taken place. These adaptations enable the plant to live more successfully under the new conditions. Environment is a sum of several factors, some of which, like the chemical and physical nature of the soil material, are relatively fixed and non-changeable. Plant characters enabling a plant to live under these fixed factors of environment are never modified because the environmental factors themselves are constant.

10. The innermost layers of water are held to soil particles with very great force. Each succeeding layer is held with a decreasing force. A measure of the magnitude of the forces can be obtained by freezing-point studies. In such determinations the force of freezing must exceed the force of adhesion in order to produce freezing. From this it follows that very low temperatures are required to freeze the innermost layers of water.

11. In the inner layers of the soil film, nutrient materials are the most concentrated. The enormous attractive force of the soil particle for water at the wilting percentage may prevent the absorption of water by the plant, but it may not interfere with the absorption of nutrient material. A surface soil that is maintained at the wilting percentage during a great part of the growing season may furnish a feeding ground for plants although it may contain no available moisture.

12. The rapidity of absorption of plant food is largely a function of the concentration of the nutrient solution.

13. At the wilting percentage there is an equilibrium between the plant and the soil with respect to moisture. To a certain extent, the plant is probably able to maintain this equilibrium by exuding water from its roots whenever the soil moisture is reduced below the wilting percentage.

14. Much work has been carried on in this laboratory that leads to the belief that there is an equilibrium between the plant and the soil, and that with some plants at least, water moves either from the soil to the plant or from the plant to the soil depending upon the nature of the moisture gradient.

15. Many desert plants are found to have their roots coated with a thin layer of soil or "sheath." This sheath exists as a mechanical result of the exudation of water, and probably of some connecting material. When the plant is subjected to drought conditions the moisture content of the sheath approximates the wilting percentage of the soil. This prevents desiccation of the root and turgor is maintained.

16. We may look upon the wilting percentage of soils as the soil-water-content when the rate of water intake is just sufficient to maintain turgor. At this moisture content the pull of the plant for water slightly exceeds the pull of the soil for water. The water is held by the soil with a pull of from 6 to 10 atmospheres, or thereabouts. The amount of water held by a soil with this

force can be determined by freezing-point methods as well as vapor-pressure methods. These then are new indirect methods for the determination of the wilting percntage in soils. The static method, in which the soil is placed in a container over a solution of the proper relative vapor pressure (approximately 99.6 percent relative vapor pressure) is inaccurate because of the great errors due to slight changes in temperature. The dynamic method in which the soil is brought into equilibrium with air having the proper relative vapor pressure promises to be more accurate than the other vapor-pressure method.

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