USE OF TENSIOMETERS IN MEASURING AVAILABILITY OF WATER TO PLANTS

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(WITH ELEVEN FIGURES)

Efforts by several investigators to measure availability of water to plants by vapor pressure (**2, 12**) and other methods (**10, 14**) have indicated that the potential of water at the permanent wilting percentage is approximately 16×10^6 ergs per gram, whereas others (**1, 11**) have obtained results which indicate somewhat lower values. A great many experiments (**3, 4, 5, 6, 13**) have demonstrated that soil moisture seems to be equally available to plants at all times, as measured by the response of plants, as the moisture content is decreased from a high value to about the permanent wilting percentage. This conclusion seems to be general for all plants which have been studied. Evidently plants do not respond markedly enough to show any change in availability of water until the soil moisture is reduced to about the permanent wilting percentage. On the other hand, physical measurements show that the energy required to remove water from the soil, changes materially as the soil-moisture content decreases. It was surprising therefore, when ROGERS (**9**) found, while working with strawberry plants in pots, that the plants wilted severely at a tension of 60 cm. of mercury (potential of 0.8×10^6 ergs per gram). Furthermore, his illustration shows plants wilted slightly at 47 centimeters (0.6×10^6 ergs per gram). The maximum potential measurable by tensiometers is less than 1×10^6 ergs per gram. The work reported herein was undertaken largely in an effort to explain this apparent discrepancy.

Experiments with sunflowers and strawberries

Since much of the work at Davis had been done with sunflowers, the first trial was made with these plants. The plants were grown in a metal container holding approximately 15 kilograms of soil. A tensiometer connected to a mercury manometer was inserted near the center of the container. The plants were allowed to dry the soil to the permanent wilting percentage several times before the experiment was started.

Figure 1 shows the tension as a function of average moisture content of the soil. The permanent wilting percentage and the moisture equivalent are given. The potential at the maximum reading of the gauge (56 centimeters of mercury) is approximately 0.8×10^6 ergs per gram. Figure 2 shows the appearance of the sunflowers when the tension was near the maximum value. Clearly the sunflowers were fully turgid; furthermore, they remained so until the permanent wilting percentage was reached. The gauge did not operate at the lower moisture contents. This disagrees with the results published by ROGERS (**9**). He worked with strawberry plants, however, so it was decided to see if by some chance these plants behaved differently than sunflowers. Strawberries were accordingly planted in double-walled burned clay jars (**7**), the inside wall of which was porous. The arrangement is shown in figure 4. Samples of soil to determine the moisture content in the jar were taken at various times with a cork borer, the holes being refilled with soil at approximately the same moisture content. The top half of the sample was kept separate from the bottom half and the average moisture content of the top half as well as the bottom half of the jar are plotted as a function of time in figure 3. The moisture equivalent and the permanent wilting percentage of the soil are shown. The plant continued to maintain its turgidity until the permanent wilting percentage was reached. Figure 4, A, was taken immediately following an irrigation so that all the

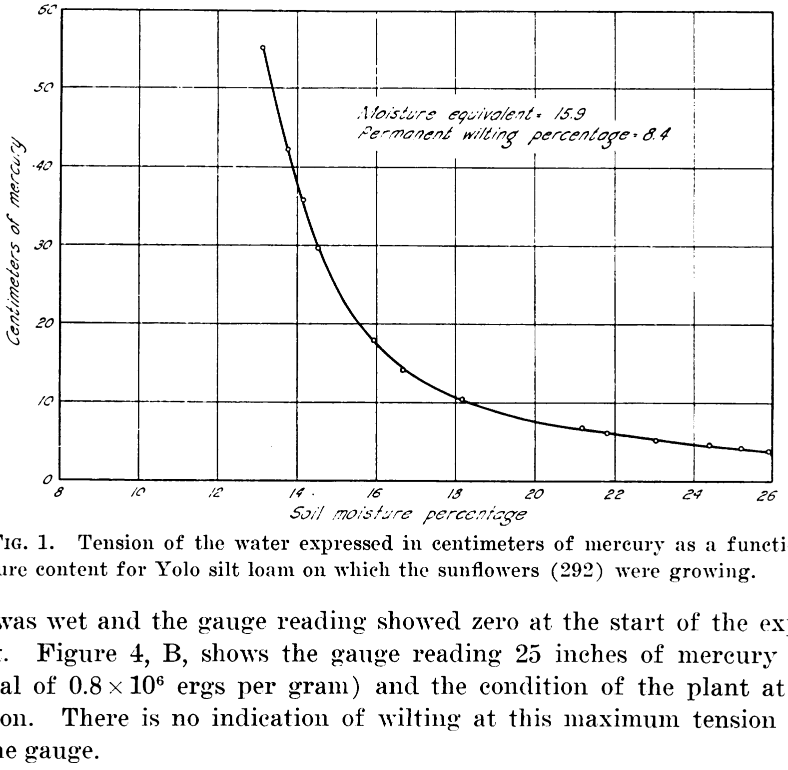

FIG. 1. Tension of the water expressed in centimeters of mercury as a function of moisture content for Yolo silt loam on which the sunflowers (292) were growing.

soil was wet and the gauge reading showed zero at the start of the experiment. Figure 4, B, shows the gauge reading 25 inches of mercury (potential of 0.8×10^6 ergs per gram) and the condition of the plant at this tension. There is no indication of wilting at this maximum tension read on the gauge.

As shown in figure 3, there was some difference in moisture content between the top half of the jar and the bottom half even though lead foil was used to cover the surface of the soil to retard evaporation. While there were variations in moisture contents in different portions of the soil, that at the center of the pot was not consistently higher or lower than at the edge. To test the distribution of tension within the jar a small porous cup was placed approximately in the center of the soil mass and connected to a gauge as shown in figure 5. The pot was then irrigated and the plants were allowed to reduce the moisture until the tension of 25 inches of mercury was reached. No corrections have been made for the difference in elevation of the gauges above the center of the porous vessel containing the water, but it is clear that the readings on the two gauges are approximately the same; that is, the tension at the outside wall is practically the same as in the center. This was to be expected from our measurements on the horizontal distribution of moisture within the pot as reported above. Our results indicate that strawberries are no different from other plants studied in their ability to use soil moisture from soil permeated by their roots. Our results, never-

FIG. 2. Sunflowers (292) near the maximum obtainable tension of the water in the tensiometer. They appear to be the same as the sunflowers (209) growing on soil above field capacity.

theless, differ markedly from those of ROGERS (9). A possible explanation is that since ROGERS grew his plants in single-walled porous flower pots, evaporation from the wall had dried the outer part of the soil mass to a greater extent than the center of the pot where the porous cup used to measure the tension was located.

A further study was made of the use of the tensiometer with strawberries under field conditions. The porous cup was connected to a tension gauge and placed with its center about 18 inches below the surface of the soil in a

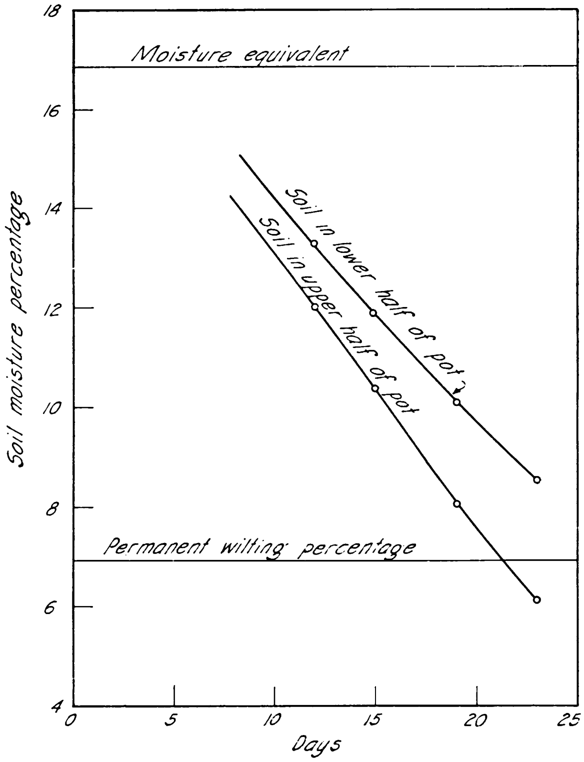

FIG. 3. Soil-moisture in the top half and bottom half of the double-walled pot shown in figure 4 containing Madera silt loam.

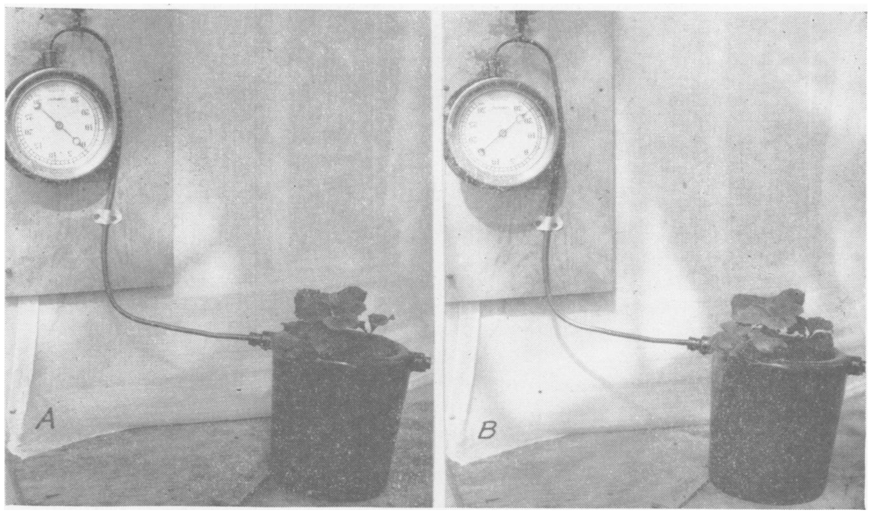

FIG. 4. Strawberry plant in a double-walled porous pot: (A) at the beginning of the experiment when the soil was wet; (B) the same plant when the tension of the water in the tensiometer had been increased to 25 inches of mercury. At this tension, there was no evidence of wilting.

strawberry bed. Moisture samples were taken at 6-inch intervals to a depth of 2 feet. It is commonly thought that strawberries are extremely shallow-rooted plants and, therefore, it was assumed that 2 feet would be ample depth at which to sample. Figure 6 shows four curves, one for each 6-inch depth, giving the moisture content as a function of time. The permanent wilting percentage and moisture equivalent are also given.

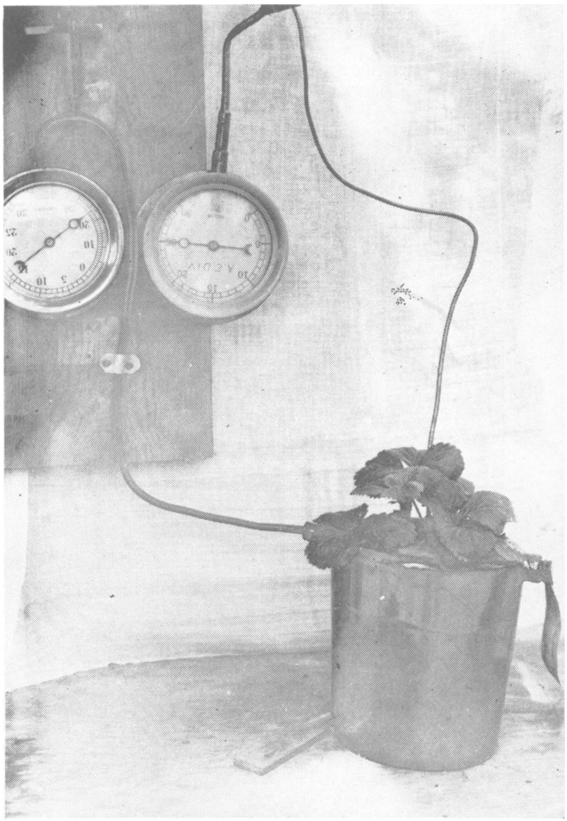

FIG. 5. The readings of two gauges, one of which measures the tension of the water between the two walls of the porous pot; the other is attached to a porous cup placed in the center of the soil mass. This arrangement was employed to determine whether there was an appreciable difference in the tension between the center and the outside of the soil mass. The readings were so close that no differences could be observed.

In figure 7 are shown photographs of the strawberries at the three different times indicated in figure 6 by the three vertical lines. The picture marked A was taken immediately following an irrigation. The photograph marked B shows the strawberries when they had dried the soil sufficiently so that the gauge, which had been installed following irrigation, had reached approximately 25 inches of mercury (potential of 0.8×10^6 ergs per gram), no correction being made for the water column from the center of the cup to the center of the gauge. As the plants continued to use water, air gradually leaked in so that the reading dropped to zero by the time the picture marked C was taken; at this time some of the plants were just beginning to show some wilting, although the maximum reading on the tensiometer had been reached 27 days previously. In fact, the plants continued to remain turgid after all the readily available water had been used out of the top 2 feet of soil. This was surprising in view of the fact that it is usually assumed that strawberries are shallow-rooted plants.

In an attempt to find out what the approximate root zone of the strawberry plant was, the bed was irrigated again and samples were taken at

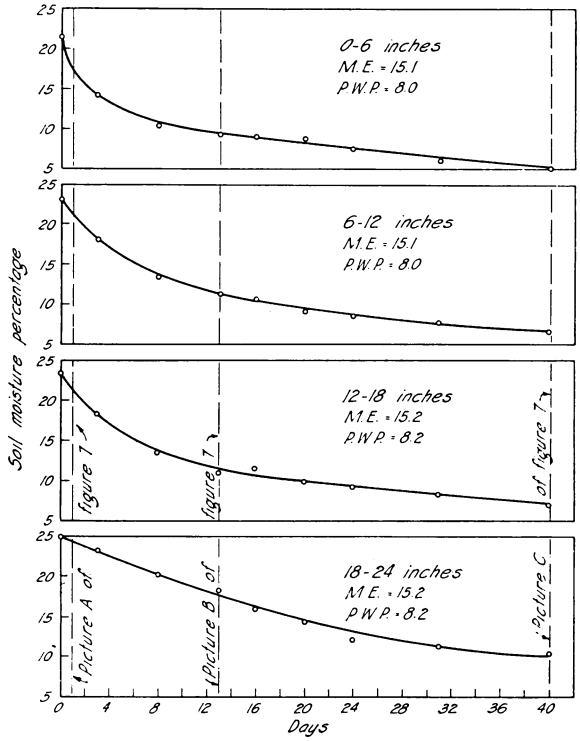

FIG. 6. Moisture content as a function of time for each 6-inch layer to a depth of 2 feet in the strawberry field shown in figure 7 on Yolo fine sandy loam. The three vertical lines show the times at which the photographs, figure 7, were taken.

1-foot intervals to a depth of 4 feet. The curves in figure 8 show the moisture content as a function of time for each foot section down to 4 feet. Apparently, some water was extracted below 3 feet. The conditions of the plants at various times are shown in figure 9. The picture marked A was taken immediately following an irrigation. The picture marked B was taken when practically all the available water was used from the top 2-foot section, whereas the picture marked C was taken at the end of the experiment. As can be seen, the plants show little need of water even at the end of the experiment. An appreciable amount of water was used from the 4th foot.

Replicability of tensiometer readings

Further studies on the use of tensiometers under field conditions were made on a Sudan grass plot. The tensiometers used here were constructed under the direction of Dr. L. A. RICHARDS (**8**), and, through his kindness, loaned to us for the experiment. Tensiometers were placed in the center of

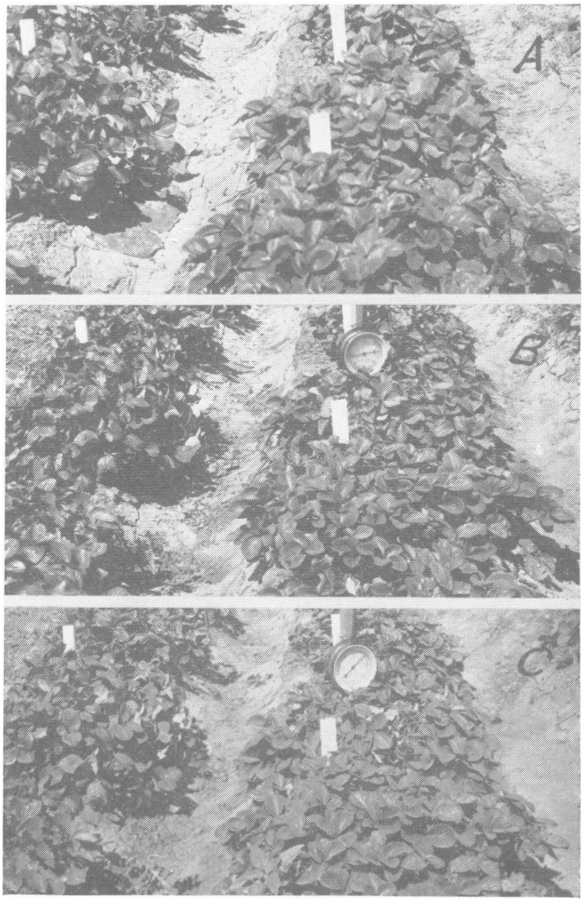

FIG. 7. (A) Strawberry plants immediately following an irrigation; (B) when the tension of the water in the porous cup attached to the gauge had reached approximately 25 inches of mercury; (C) when practically all of the readily available water had been used from the top 2 feet of soil. The tensiometer reading was approximately at its maximum value at the time B was taken. Air had leaked in and the gauge had dropped to zero by the time C was taken.

the first-, second-, third-, and fifth-foot depths. Variations of moisture content and tension with time for each depth are shown in figure 10, the tension being plotted to a logarithmic scale. The moisture equivalent and permanent wilting percentage are given for each depth.

At no time during the season did the Sudan grass show any indication of need for water. When irrigation was applied, it was done not because the grass showed need for water, but in an effort to start the field from a wet condition again so that a check on the replicability of the tensiometer could be made. It should be mentioned that enough water was applied to this field to wet the soil to the water table 10 feet below the ground surface, and hence the soil below the top foot remained well above the moisture equivalent for a long period after the second irrigation. To test the replicability of the tensiometer readings for different "cycles,"[1] the curves of figure 11 were derived from data taken from the curves of figure 10. They show the tension as a function of moisture for each of the foot sections studied.

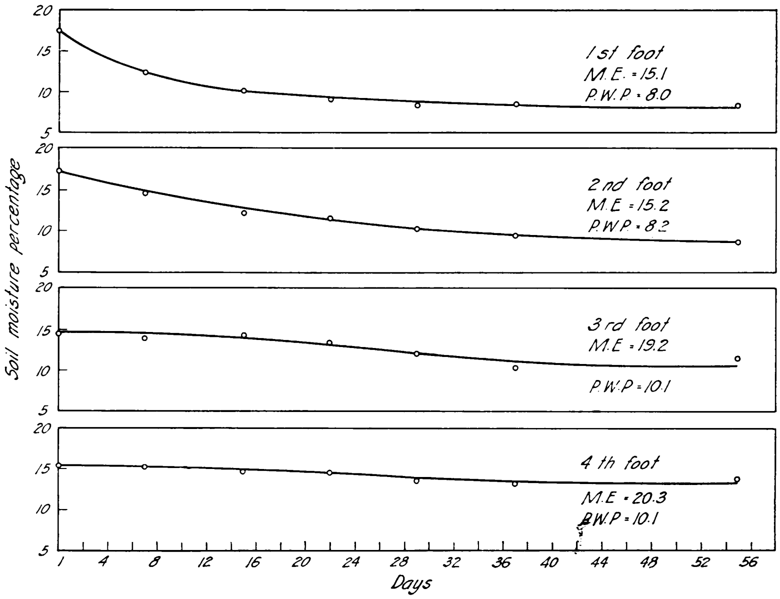

FIG. 8. The soil-moisture content of the top 4 feet of soil in the strawberry field shown in figure 9. This is the same field shown in figure 7.

The moisture equivalents for each foot are shown on the graph. It is, of course, impossible to use the data for such a curve at tensions higher than where the tensiometer operates, and hence the moisture content does not decrease to as low a value as it does in the curves of figure 10. The tension increases very rapidly as the moisture content decreases in the neighborhood of the moisture equivalent. This makes it extremely difficult to fix with any degree of exactness the value of the tension at the moisture equivalent. However, as can be seen from the curves of figure 11, a tension of 300 centimeters of water (0.29×10^6 ergs per gram) is approximately the value when these soils are at the moisture equivalent. This is in substantial agreement with RICHARDS (7). It is considerably lower than most

[1] By a cycle we mean the sequence of moisture changes which the soil passes through from one irrigation to another.

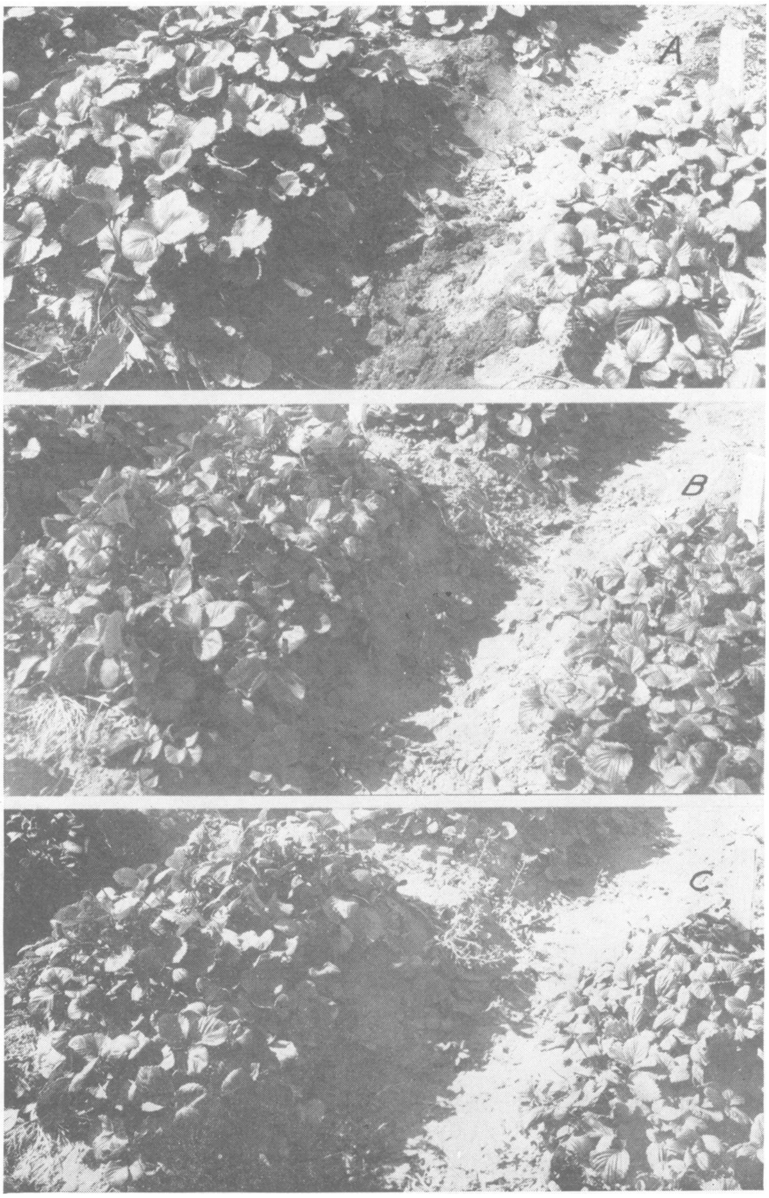

FIG. 9. (A) Strawberry plants immediately following irrigation; (B) 30 days after irrigation, and (C) at the end of the experiment 55 days after irrigation. The plants in B appear to be as turgid as in A.

of the values estimated by SCHOFIELD (10) who concluded from available data, that the pF was between 2.5 and 3.0 (0.31×10^6 to 0.98×10^6 ergs per gram) at the moisture equivalent.

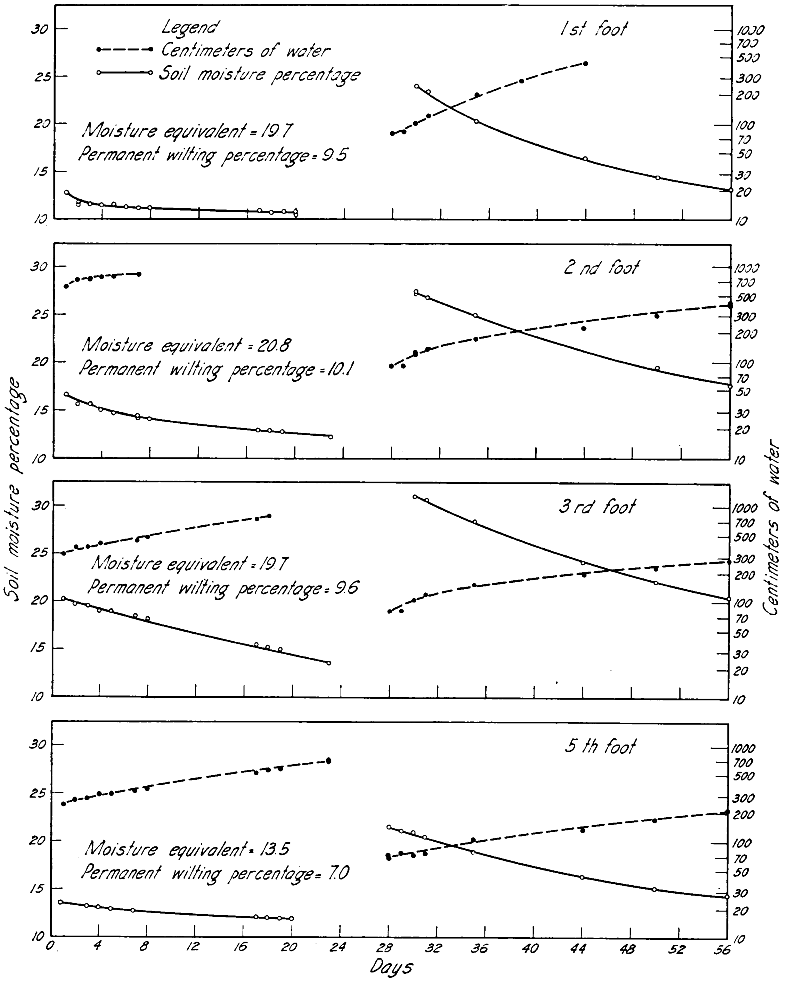

FIG. 10. The tension of the water in the tensiometers expressed in centimeters of water and the moisture content in a Sudan grass plot as a function of time for the first, second, third and fifth-foot depths.

A confusion between numerical and dimensional equality in certain soil-moisture measurements

In this connection, it is worth while calling attention to an error which is frequently made. Since the moisture equivalent is approximately equal to the field capacity (which is usually considered to be the moisture held in the soil against the pull of gravity) of most fine-textured soils but not always sands, and since in the c.g.s. system the pull of gravity on unit mass is *numerically* equal to the pressure of 1 atmosphere, it has been reasoned by some that the potential at the moisture equivalent is equal to a tension of 1 atmosphere, or a pF of 3, or 1.0×10^6 ergs per gram. This is faulty reasoning. The fact that in the c.g.s. system the pull of gravity on unit mass is approximately numerically equal to a pressure of 1 atmosphere is purely coincidental. The pull of gravity on unit mass has the dimensions of force per unit mass, whereas pressure has the dimensions of force per unit area; and potential has the dimensions of energy per unit mass. That pF of 3, or 1.0×10^6 ergs per gram is the value at the moisture equivalent has been

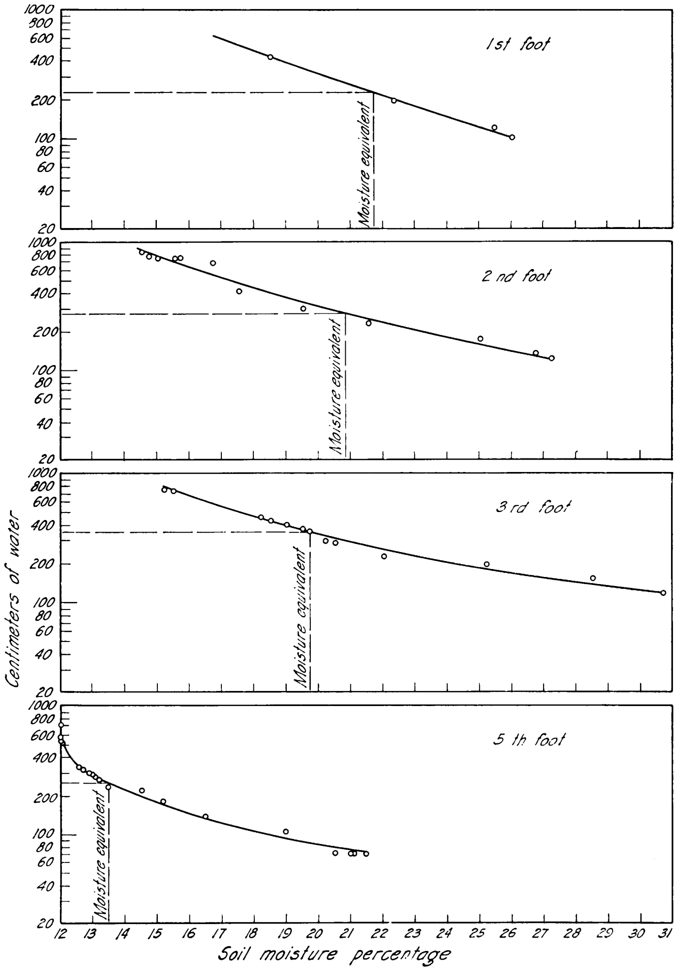

FIG. 11. The tension of the water in the tensiometers expressed as centimeters of water as a function of moisture content for the first, second, third, and fifth-foot depths in the Sudan grass plot, the moisture content of which is shown in figure 10. The tension at the moisture equivalent is indicated.

given added credence because it coincided with the upper range of values for pF at the moisture equivalent as estimated by SCHOFIELD. There is also another reason why a pF of 3 has been associated with the moisture equivalent. By assuming that a potential of zero exists at the outer surface of a soil sample one centimeter thick in a centrifuge being subjected to a centrifugal field of 1000 times gravity, it follows that the potential at the inside surface is 1.0×10^6 ergs per gram or a pF of 3. The average pF for the sample is much less than this.

Summary

Pot and field experiments using sunflowers, strawberries, and Sudan grass indicate that tensiometers are capable of indicating the tensions for moisture contents in the upper one-third to one-half of the range between the moisture equivalent and the permanent wilting percentage.

Strawberry plants in pots remained turgid when the roots were in soil at moisture contents much lower than those which would produce a maximum tension of about 700 centimeters of water. Similarly, the moisture content in the top 3 feet of soil in the strawberry field reached a percentage lower than that which would show a tension of about 700 centimeters of water and yet the plants remained turgid.

All of the soil in the pots and in the top 3 feet of the strawberry field plots was reduced to the permanent wilting percentage before there was any evidence of wilting. At this moisture content there would be an equivalent tension of about 16,000 centimeters of water as estimated by available data on the potential of the water at the permanent wilting percentage.

Tensiometers in the Sudan grass plots showed close replicability for different "cycles." Tensions obtained were about the same even though the soils tested varied in texture as measured by the moisture equivalent.

For the soils tested, the potential at the moisture equivalent, while difficult to evaluate exactly, is in the neighborhood of 0.3×10^6 ergs per gram.

Attention is called to an error in reasoning occurring in the literature in regard to evaluating the pF and the potential of soil moisture at the moisture equivalent.

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