SOIL-MOISTURE CONDITIONS IN RELATION TO PLANT GROWTH

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(WITH SIX FIGURES)

Recent investigations at the University of California have yielded much information regarding the relation of soil moisture to the normal growth and behavior of fruit trees, and have indicated serious disagreements with results secured by some previous investigators of the problem of water relations of plants. It is logical to suppose that the moisture conditions of the soil do not exert any direct retarding influence on the plant so long as water is supplied to the absorbing surfaces of the roots and is conducted to the leaves as rapidly as required by the transpiration rate. However, just as soon as the rate of supply falls below this requisite amount, then soil moisture becomes a limiting condition. An inadequate moisture supply may be evidenced by lessening of turgor, cessation of growth, and wilting, and, in more advanced stages, by death of the tissues. Of course, the wilting of a plant does not indicate that water has ceased to move from the soil into the plant, but simply that transpiration has exceeded absorption and conduction. It is obvious, since wilting is progressive, that various stages of wilt might be recognized. Several attempts have been made to fix upon a definite degree of wilting. The "saturation deficit" of RENNER (**6**) and the "incipient drying" of LIVINGSTON and BROWN (**4**) are not definite stages, but represent broad ranges in the progress of wilting, but the "permanent wilting" of BRIGGS and SHANTZ (**1**) represents a fairly definite stage or degree of wilting, which can be readily recognized in experimentation, and this has received much study. However, KOKETSU (**3**) has pointed out that definite stages of wilting may be recognized readily in *Mimosa* because of the movements of its leaves.

BRIGGS and SHANTZ defined their permanent wilting as that stage of wilting when the leaves first undergo a permanent reduction of their moisture content as a result of deficiency in the soil-moisture supply. A permanent reduction is here taken to mean a deficiency in leaf-water content from which the leaves do not recover in an approximately saturated atmosphere, without the addition of water to the soil. LIVINGSTON and KOKETSU (**5**) have further discussed the condition of permanent wilting and have emphasized the dynamic nature of the wilting process.

BRIGGS and SHANTZ (**1**) concluded from their studies that atmospheric environmental conditions have little or no effect upon the residual water content of the soil at the time of the beginning of permanent wilting and that this residual water content, called by them the wilting coefficient, for any given soil is a constant for all species of plants grown on it and for all stages of their development. On the other hand, CALDWELL (2) and SHIVE and LIVINGSTON (8) found, from a study of plants grown in small containers, that the time required for the onset of permanent wilting after watering had been discontinued, and also the residual water content of the soil when permanent wilting began was dependent upon the intensity of the evaporation conditions for the period during which permanent wilting was attained. LIVINGSTON and KOKETSU (5) found that the water-supplying power of the soil was practically constant for all soils when permanent wilting began in their plants, and they predicted that this critical value of the supplying power would be found to depend upon the evaporation conditions.

Observations extending over a number of years in deciduous fruit orchards in California, as well as in experimental plots at Davis, California, at the Branch of the College of Agriculture of the University of California, indicate that the soil-moisture supply may fluctuate between wide limits without measurably affecting the growth of the tree or the yield and quality of the fruit. This range of fluctuations in the moisture of the loam soils on which the experiments were conducted was between the maximum field capacity and the calculated wilting coefficient, a range of 10 per cent. or approximately 9.5 acre-inches of water in six feet of soil. The difficulty of adequately sampling the soil in the orchard plots, in spite of the employment of an unusually large number of samples, and the consequent difficulty of determining with satisfactory certainty the average soil-moisture condition in the root zone, led to a study of trees grown in large containers, and the results from these experiments were substantially the same as those obtained in the orchard plots.

Experimental results based on the idea that water applied at any point in the soil would be quickly and uniformly distributed throughout the surrounding soil have led, in the opinion of the writers, to many erroneous conclusions. This thought has also recently been put forth by others, notably SHANTZ (7), who stated upon theoretical considerations that "Because of these peculiarities in the distribution of moisture in soils much of the work . . . is entirely unreliable and will have to be repeated when the conditions are known or better understood." The writers have been unable to maintain any soil-moisture content lower than that which the soil would hold against the force of gravity—the maximum field capacity. What takes place when water is applied to the surface of nearly dry soil is illustrated by the results of a test, the results of which are shown in figure 1. A rain of 2.15 inches on the surface of a loam soil resulted in wetting the soil to a uniform depth of about 14 inches, but no farther, samples being taken 48

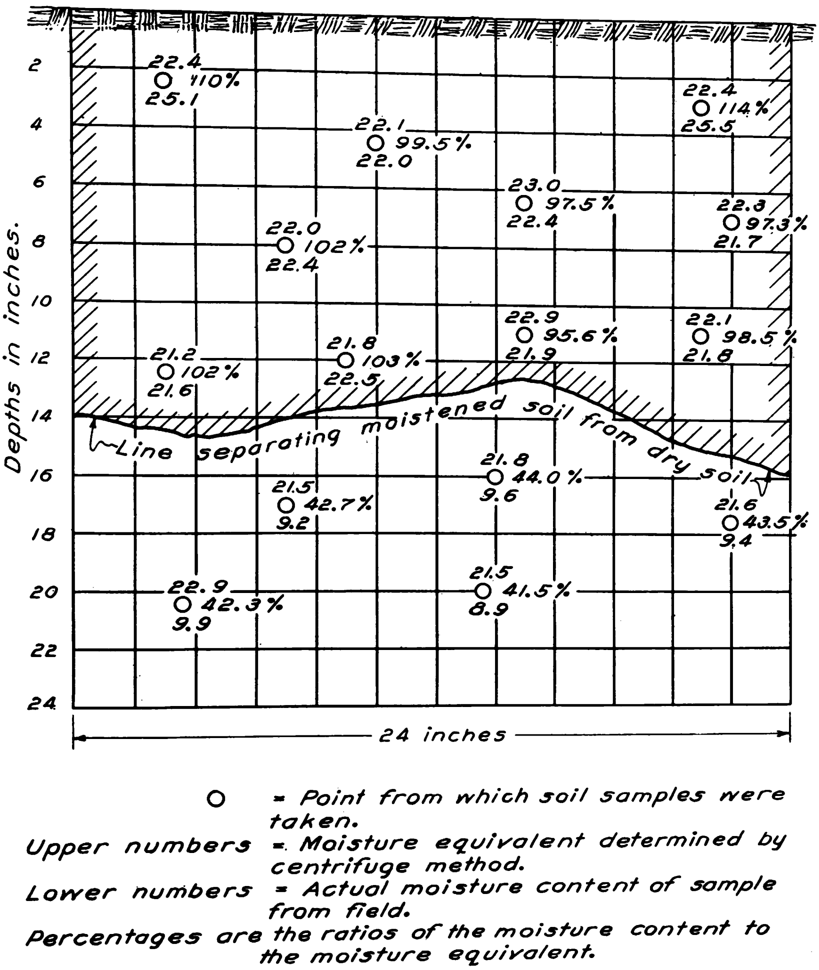

FIG. 1. Vertical distribution of water in a loam soil 48 hours after a rainfall of 2.15 inches. The upper margin of the diagram represents the soil surfaces.

hours after the rain ceased. As the figure shows, the soil throughout the wetted region was raised to a moisture content closely approximating its moisture equivalent made by the method suggested by VEIHMEYER, ISRAELSON and CONRAD (9). In general, an application of a definite amount of water on the soil surface results in the wetting of the loam soils used in these experiments always just to a definite depth, this depth depending upon the water-holding capacity of the soil and its initial moisture content. This was observed many times in our work, both in field plots and in large con-

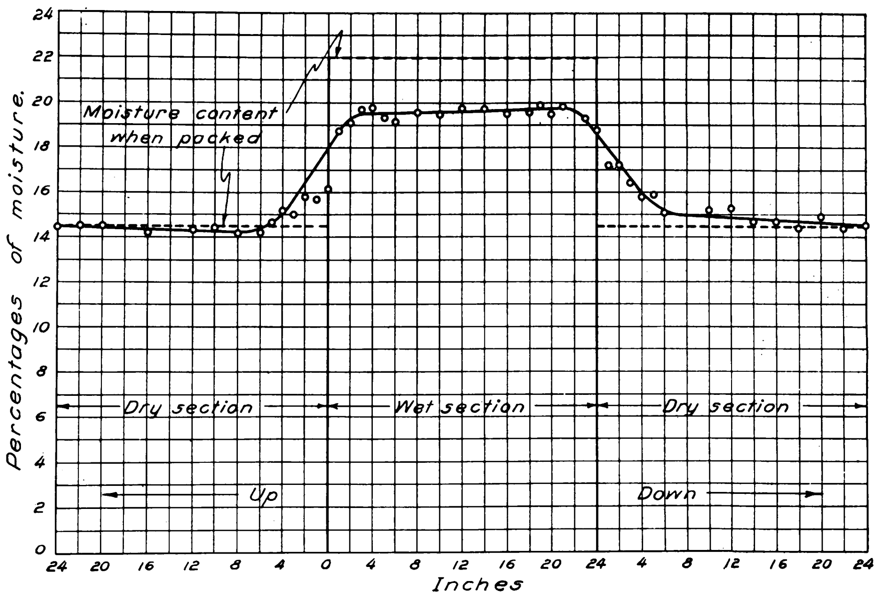

FIG. 2. The movement of moisture upward and downward (left and right in diagram) from soil mass initially containing 22 per cent. of moisture to soils containing 14.5 per cent. of moisture. Column was started September 2, 1922; samples were taken January 18, 1923. The place of sampling in the column and the amount of moisture found are indicated by the circles. Depth is shown by numerals along the base of diagram.

tainers. There is no evidence in such tests of the deeper soil being wetted at all by the surface application.

The results obtained in these experiments are contrary to a long accepted belief that water moves by capillarity with considerable speed from moist to drier soils. Such movement as occurs has been found in our tests to be extremely slow in rate and slight in both amount and extent. The data presented in figure 2 show the movement of moisture upward and downward within a period of 139 days, from a soil mass initially containing 22 per cent. of moisture, calculated on a dry weight basis, to soil masses above and below containing 14.5 per cent. of moisture. The column of loam soil had a cross-sectional area of 36 square inches. The central wet section was initially packed with soil containing water to the extent of its maximum field capacity (22 per cent.) and the upper and lower end sections were packed with the same soil but with moisture content somewhat above the calculated wilting coefficient. The extent of movement in either the upward or the downward direction was approximately 8 inches in the period of 139 days.

Like results were obtained in many similar trials, with soils of different initial moisture contents.

In the experiments with trees in containers, at each application of water the soil mass was raised to its maximum field capacity throughout. The trees were then allowed to deplete the average soil moisture to different extents and then water was again applied. The range of moisture fluctuations was slight, in some cases, while in others it was as much as from the maximum field capacity to the calculated wilting coefficient. These experiments continued through the growing season. The use of water by young French prune trees grown under these conditions of fluctuating soil moisture supply is shown by the data in table I.

TABLE I

AMOUNT OF WATER USED BY YOUNG FRENCH PRUNE TREES, AS RELATED TO LEAF AREA AND TO LENGTH GROWTH

NUMBER OF TREE	LENGTH GROWTH	NUMBER OF LEAVES	LEAF AREA	WATER USED MARCH 1 TO SEPTEMBER 25	RATIO OF WATER USE TO LEAF AREA (LOSS PER SQUARE INCH OF AREA)	RATIO OF LENGTH GROWTH TO WATER USE (INCHES OF GROWTH PER POUND OF WATER USED)
	inches		sq. in.	pounds	pounds	pounds
5	348.0	394	2098	499	0.237	0.698
12	214.0	239	1244	316	0.254	0.678
20	697.5	828	4305	1020	0.237	0.683
21	351.0	398	2070	508	0.245	0.690

For tree no. 5, the soil-moisture content was kept above 16 per cent. until the middle of August, being then alternately allowed to fall to approximately the wilting coefficient, and irrigated; for tree no. 12, the soil was kept water logged throughout the experiment; for tree no. 20, the soil-moisture content was maintained above 16 per cent.; and for tree no. 21, the soil-moisture content fluctuated between the maximum field capacity and an amount corresponding to the wilting coefficient. The maximum field capacity (or the moisture equivalent) for this soil was approximately 22 per cent. The use of water was nearly proportional to the leaf area and still more nearly proportional to the growth in length. The coefficient of correlation between the use of water and the leaf area for all the trees used (of which those given in table I are a part) is 0.97 ± 0.11, and that between use of water and growth in length is 0.995 ± 0.002. There is apparently no relation between soil-moisture content and either use of water or growth in length as here shown.

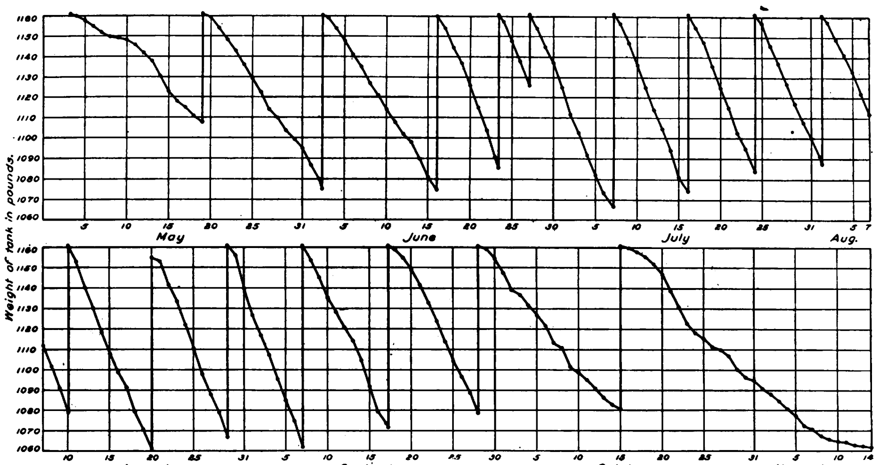

FIG. 3. Use of water by prune tree during the season of 1922, at Mountain View. The weight of the tank with soil containing 22 per cent. of moisture was 1161 pounds and the weight when the soil was at the wilting coefficient (11.9 per cent.) was 1070 pounds.

A further example to show that the rate of use of water by young prune trees in containers was not affected by the amount of water in the soil, provided the moisture content was not below the calculated wilting coefficient, is shown by the graph of figure 3, which presents data which were obtained from a tree on an automatically recording balance. The vertical portions show the applications of water, and the slope of each intervening portion of the graph indicates the rate of use of water, which was clearly no greater with high than with low soil-moisture contents.

When the soil-moisture content was reduced to a percentage corresponding approximately to the calculated wilting coefficient, the trees wilted and did not revive until water was applied to the soil. A remarkable degree of agreement between the observed and the calculated wilting coefficient is shown in table II in a number of cases, which are representative of a much larger number, for two different localities, and at different times during the growing season.

Still further evidence of the importance of the wilting coefficient as a critical point in the process of soil-moisture depletion by plant transpiration was secured from studies on the width of stomatal openings. Apricot, prune and peach trees growing on soil with water content higher than that corresponding to the wilting coefficient showed markedly wider stomatal openings by day than did those grown on soil with water content at or near the wilting coefficient. The average results obtained with prune trees during a 24-hour period beginning at 6 A. M., September 11, 1924, are shown

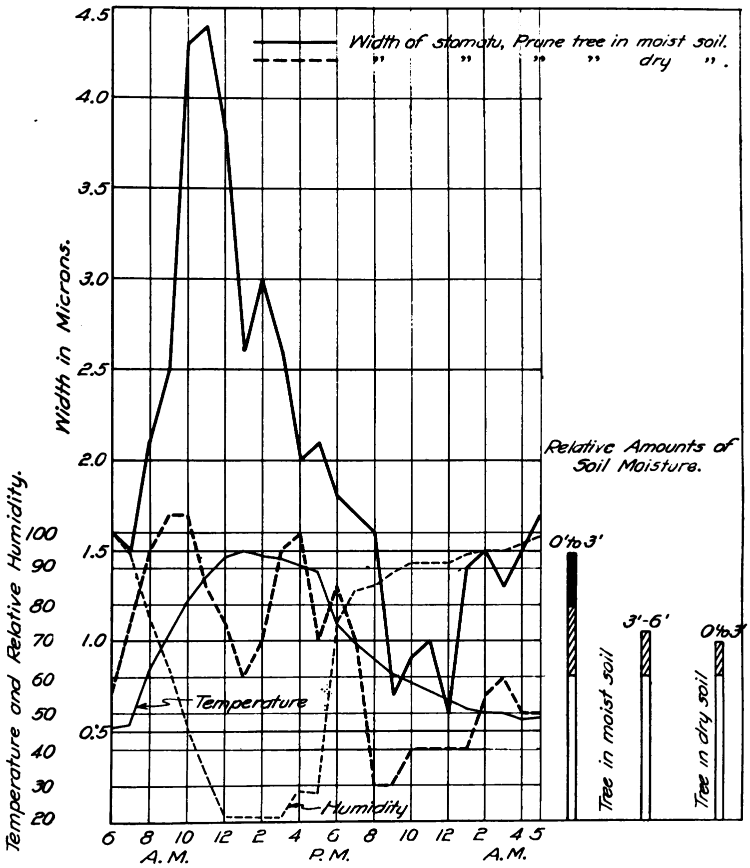

FIG. 4. Width of stomatal opening on prune trees in moist soil and in dry soil at Mountain View, California, September 11, 1924. Temperature and relative humidity are shown by the light lines in the lower left corner. Relative amount of soil moisture above the wilting coefficient is shown by the solid black column; relative amount of soil moisture below the hygroscopic coefficient is shown by the unshaded portion.

graphically in figure 4. The usual diurnal variation in stomatal widths is shown for both moist and dry soils, but the average maximum width for the moist soil is seen to have been about three times as great as for the dry soil. Similar results obtained with peach trees under climatic conditions essentially the same as those to which these prune trees were subjected are shown in figure 5, along with a similar graph for another prune tree on moist soil. However, differences in width of stomatal openings of leaves on any of the trees studied could not be detected when the soil-moisture contents varied but did not fall to the wilting coefficient. The average measurements of

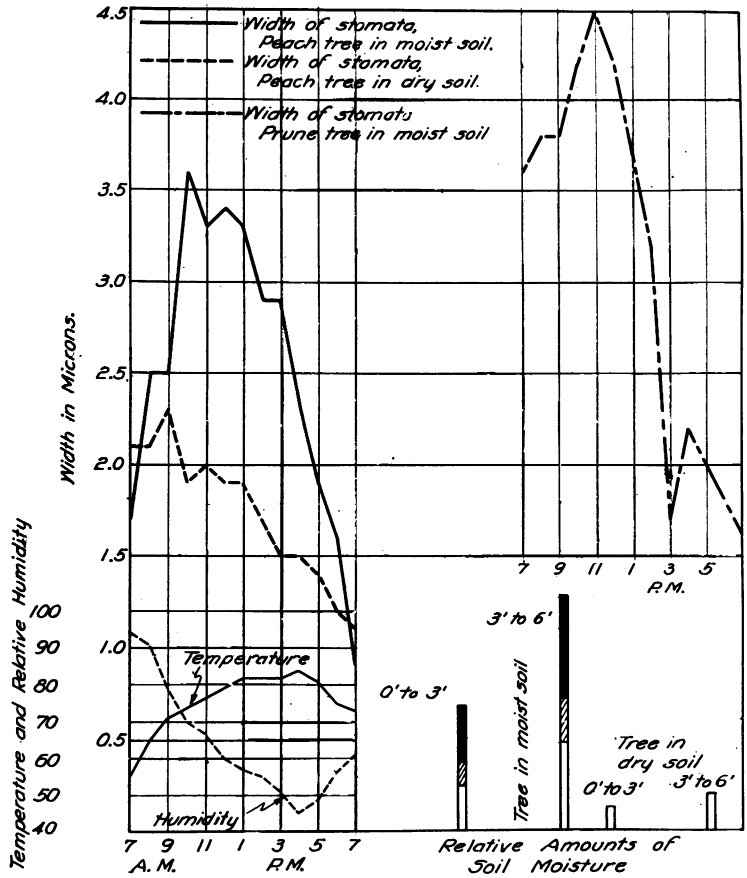

FIG. 5. Width of stomatal opening on peach and prune trees in moist soil and peach tree in dry soil at Delhi, October 1, 1924. Temperature and relative humidity are shown in lower left corner. Relative amount of soil moisture above wilting coefficient is shown by solid black column; relative amount of soil moisture below the hygroscopic coefficient is shown by the unshaded portion.

stomata of leaves on peach trees, one of which was on a soil with high moisture content, and the other on a soil with low moisture content but still above the wilting coefficient are shown graphically in figure 6. The graphs show that no real differences exist in width of stomatal opening. The stomata appear to have behaved as usual as long as the soil-moisture content was higher than the wilting coefficient. These results also substantiate the data given in table I, in that the trees were not affected until the soil moisture was reduced to the wilting coefficient.

TABLE II

RELATION OF THE OBSERVED TO THE CALCULATED WILTING COEFFICIENT FOR YOUNG PRUNE TREES IN CONTAINERS

TREE NUMBER	DATE WILTED	SOIL-MOISTURE CONTENT AT TIME OF WILTING	WILTING COEFFICIENT CALCULATED FROM MOISTURE EQUIVALENT
		per cent.	per cent.
3	May 5, 1922	11.6	11.1
3	August 14, 1922	10.5	11.1
3	September 28, 1922	11.2	11.1
5	August 25, 1922	13.0	12.7
5	October 7, 1922	12.7	12.7
5	May 3, 1923	12.3	12.7
6	August 21, 1922	11.6	11.9
6	September 2, 1922	11.7	11.9
6	April 29, 1922	11.3	11.9
19	June 13, 1924	11.1	11.2
20	June 12, 1924	11.0	11.4
10	July 7, 1924	11.9	11.6

Trials with mature peach and prune trees showed that growth in length of shoots could not be prolonged indefinitely by maintaining high soil-moisture contents throughout the season, and the same result was secured with young trees in containers. If the average percentage of water in leaves and bark and wood of all parts of the tree may be used as a criterion of maturity the results obtained with bearing peach trees indicate that trees growing on wet soils matured at the same time as trees on nearly dry soils for the mean water content of these parts of the tree was approximately the same in the autumn for both soils. Furthermore, young trees on moist soil held in containers dropped their leaves at the same time in the fall as those on drier soils. However, defoliation could be brought about during periods of high evaporating conditions by withholding water until the trees wilted.

The data secured in these studies seem to have an important bearing on a number of questions regarding the relation between irrigation and the hardening or maturing of the wood and buds of fruit trees. An abundant supply of soil moisture throughout the season can not alone account for the immaturity of the current growth of the tree and so-called winter injury that seems to be a result of such immaturity, at least under the conditions of these experiments.

The correlation between leaf area and the use of water by trees is illustrated in a concrete way by results obtained in one of the orchards at the Branch of the University of California at Davis. This orchard consisted

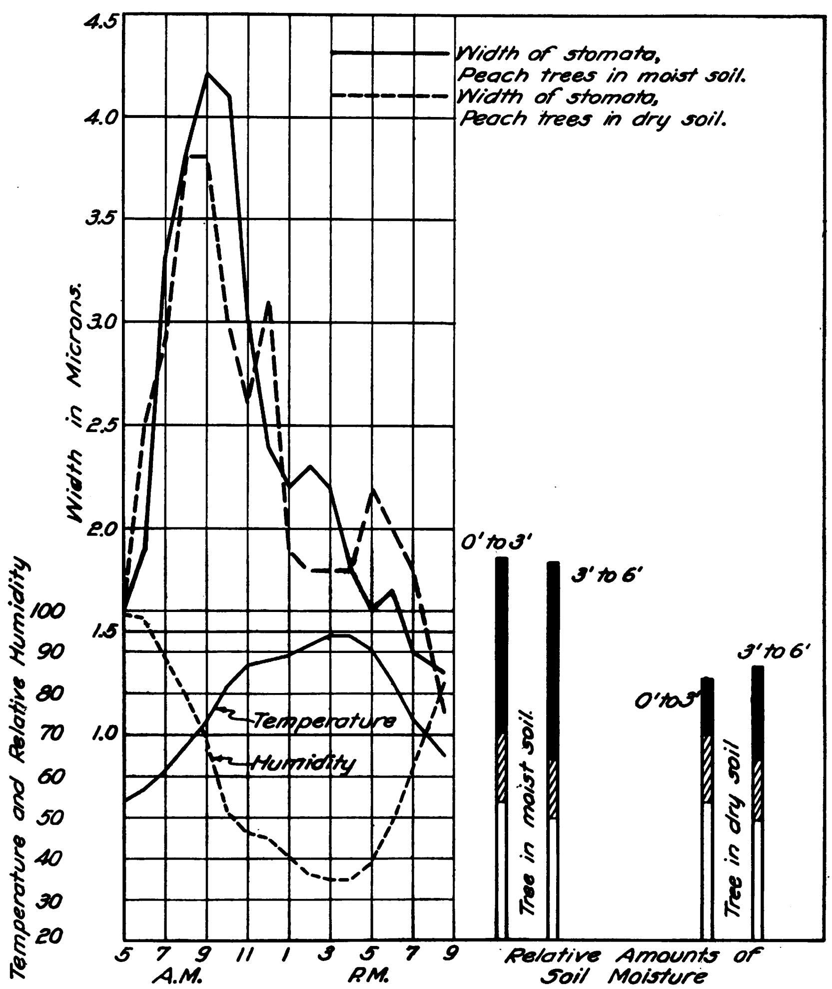

FIG. 6. Width of stomatal opening on peach trees on moist soil and on dry soil at Davis, California, July 9, 1925. Temperature and relative humidity are shown by light lines in lower left-hand corner. Relative amount of soil moisture above the wilting coefficient is shown by solid black column; relative amount of soil moisture below the hygroscopic coefficient is shown by the unshaded portion.

of suitable plots of cherries, plums, prunes, pears, peaches, and apricots, with different spacings. Thus, in the first block the trees were 12 feet apart, in the second, 16 feet apart, and so on until the trees of the last block were 36 feet apart. The trees were planted in 1915 and at the present time only those in the 30-foot and 36-foot blocks are alive. The trees in the 12-foot block showed evidence of drought during the summer of the fourth season. After the fourth or fifth year growth was less and injury (such as sunburn) was greater in the more closely planted blocks than in the others. Those of the 12-foot block showed signs of drought, as evidenced by curling and dropping of the leaves, from two to five or six weeks before those of the 24-foot block showed these symptoms. The greater leaf area, in proportion to the moisture available to the trees, in the closely planted blocks was probably directly concerned with the premature decline of these trees.

The relation of leaf area to use of water by the tree has an important bearing on irrigation practice, especially when alfalfa is grown in the orchard as a continuous cover crop.* The combination of trees and alfalfa requires more water than do trees alone. The writers are of the opinion that any benefits derived by the trees from the growing of alfalfa in this way are probably due to causes other than lessened transpiration, on the part of the tree, though this cause is often given to explain benefit to the trees apparently due to the cover crop.

The writers wish to express their thanks to Dr. B. E. Livingston, of Johns Hopkins University, who kindly read the paper and offered many helpful suggestions.

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