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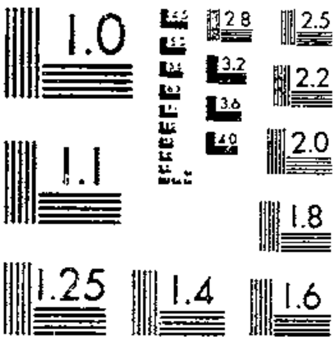

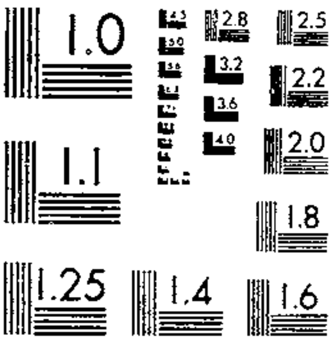

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TECHNICAL BULLETIN No. 640 MAY 1939

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

GROWTH OF LEMON FRUITS IN RELATION TO MOISTURE CONTENT OF THE SOIL[1,2]

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INTRODUCTION

In the south coastal basin of southern California, citrus orchards require irrigation throughout the dry season from about May to November. Winter rainfall is usually sufficient to moisten the entire root zone of citrus trees so that for a period in early spring the trees have a full reservoir of soil moisture. As this supply becomes depleted, irrigation water is applied. The application may be such that the entire root zone is again moistened to field capacity, but more often water is applied to a limited portion of the root zone, in some cases 50 percent or less. The remaining soil then becomes quite dry.

Water for irrigation is usually delivered on a regular schedule established from the experience of the district, but where the supply system is flexible enough it may be obtained on demand. In many orchards the interval between irrigations is of such length that trees may show evidence of water shortage before irrigation. Some growers employ the services of commercial laboratories for taking soil samples

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[1] Received for publication February 7, 1938.

[2] This bulletin is a report of investigations carried on under a cooperative agreement between the Bureau of Plant Industry and the Bureau of Agricultural Engineering. The work of the Bureau of Plant Industry was carried on under the general direction of J. R. Magness, principal pomologist, from 1932 to 1935, and after the spring of 1935 under that of Knowles A. Ryerson, principal horticulturist. The work of the Bureau of Agricultural Engineering was done under the general direction of W. W. McLaughlin, Chief, Division of Irrigation, and H. F. Blaney, irrigation engineer in charge in southern California.

[3] The authors acknowledge indebtedness to the managers of the various irrigation companies and to the orchard owners who have cooperated in this study. Acknowledgment is also made of the assistance in collection of field data rendered by D. W. A. Bloodgood, associate irrigation engineer, Harry G. Nickle, assistant irrigation engineer, and H. W. Kistner, of the Division of Irrigation, Bureau of Agricultural Engineering.

to determine when to irrigate. When this method is used the general procedure has been to recommend irrigation when the moisture content of the soil at selected locations reached the calculated wilting point. The value for the wilting point has been generally calculated from the moisture equivalent by the 1.84 formula of Briggs and Shantz (*5*).[4]

A few growers are convinced that they get as good results from applying water in one or two furrows per row at each irrigation as from making the applications in several furrows; others believe that water should be applied over as much of the soil area as possible, using basins on the flatter lands. Many growers claim that they get most rapid growth of fruit and highest yields with frequent applications and large seasonal use of water; others are convinced that the soil should be dried out between applications of water and that a more sparing use of water yields the best returns. It also has been the experience of some operators that trees are actually injured and yields reduced by overirrigation. In this sense overirrigation is not meant to imply waterlogging of the soil, but simply a failure to allow the soil to dry out between irrigations so that the soil-moisture content tends to remain near field capacity. While these opinions are certainly widely divergent, they are based upon the experience of growers who are producing fruit under a wide diversity of conditions, and doubtless most of these opinions are at least partly justified by the conditions under which they were formed.

These investigations were conducted in order to establish basic information for promoting better methods of applying water in practice and to provide for the most effective utilization of water by orchard trees. The work reported in this bulletin deals primarily with the response of lemon trees to decreasing soil moisture under orchard conditions. Both the effect of irrigating various proportions of the soil in the root zone and that of varying the intervals between irrigations have been investigated.

The reactions in the trees throughout the range of readily available soil moisture and in the range of moisture percentages at which wilting of the trees occurred have been studied in certain detailed tests as a basis for the larger field trials. This phase of the subject will be reviewed first, particularly since the terminology used by various writers in referring to the wilting of plants is confusing in some respects.

WILTING POINTS OF SOILS

The concept of the wilting coefficient as a soil constant was introduced by Briggs and Shantz in 1912 (*5, p. 19, also p. 74*). In definition of this term they state:

> The wilting coefficient of a soil is then defined as the moisture content of the soil (expressed as a percentage of the dry weight) at the time when the leaves of the plant growing in that soil first undergo a permanent reduction in their moisture content as the result of a deficiency in the soil-moisture supply. By a permanent reduction is meant a condition from which the leaves cannot recover in an approximately saturated atmosphere without the addition of water to the soil. In most plants wilting accompanies this reduction of the water content of the leaves and is the criterion used to determine the wilting coefficient of a soil for that plant.

As a result of their work Briggs and Shantz made certain fundamental generalizations as follows (*5, pp. 75–77*):

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[4] Italic numbers in parentheses refer to Literature Cited, p. 71.

> The results obtained show that species differ only slightly as regards the soil-moisture content at which permanent wilting first takes place. * * *
>
> These determinations * * * indicate that the wilting coefficient is not materially influenced by the dryness of the air, by moderate changes in the solar intensity, or by differences in the amount of soil moisture available during the period of growth.
>
> That portion of the soil-moisture content which is available for plant growth is represented by the difference between the actual water content and the wilting coefficient. * * * From this comparison a series of linear relationships has been established, as expressed in the following equations, which thus provide a means of computing the wilting coefficient when direct determinations are not feasible.
>
> $$\text{Wilting coefficient} = \frac{\text{Moisture equivalent.}}{1.84\ (1 \pm 0.007)}$$
>
> * * * * * * *
>
> The moisture-equivalent method, in which the measurements are made with the aid of a centrifugal machine exerting a force 1,000 times that of gravity, is the most accurate and satisfactory of the indirect methods.

Certain of these generalizations have been questioned by later investigators (*6, 12, 16*). One point that is of importance in connection with these criticisms lies in the varied technique that different workers have employed in making the wilting-point determinations. In their direct determinations on 20 soils, Briggs and Shantz found the ratio of the moisture equivalent to the wilting point to range from 1.67 to 2.02, and the average was 1.84.

The term "wilting coefficient" was used by Veihmeyer in 1927 in reporting on irrigation studies in Santa Clara Valley prune orchards (*15*). However, in 1928 Veihmeyer and Hendrickson (*16*) concluded from their experiments that the indirect method of determining the wilting point from the moisture equivalent was not satisfactory because the departures from the 1.84 ratio were too great to warrant the use of this or any other ratio. They report ratios varying from 1.73 to 3.82, with an average of 2.46 for 14 soils. The ratio was less than 1.84 for only one soil, although in later work they show a ratio as low as 1.39. They did not advocate the use of any average ratio and considered it essential that wilting-point determinations be made experimentally by growing plants in the soil under test. It should be noted, however, that Briggs and Shantz did not relate the wilting point to the moisture equivalent by the factor 1.84 in their definition of wilting point. They simply presented certain formulas in their conclusions to provide means of computing the wilting point when direct determinations are not feasible. For the actual residual soil-moisture content at permanent wilting, Veihmeyer and Hendrickson proposed the term "permanent wilting percentage" (*17*) to substitute for the term "wilting coefficient."

While the average ratios cited above may have only limited application, nevertheless they afford a means for comparison of the criterion of wilting used by Briggs and Shantz with that employed by Veihmeyer and Hendrickson. It appears that the higher average ratio found by Veihmeyer and Hendrickson may be the result of using a more advanced stage of wilt, which would result in lower soil-moisture contents at the permanent wilting percentage than Briggs and Shantz found in their direct determinations of the wilting point. Veihmeyer and Hendrickson made the majority of their determinations with well-established sunflower plants. They report that the force holding water in the soil at the permanent wilting percentage is of the order of 16 to 20 atmospheres (*18*), while Shull (*13*) found that the force holding water in the soil at the wilting point as defined by Briggs and Shantz corresponded to about 4 atmospheres. The use of a more advanced stage of wilt yields not only larger ratios but also a greater range in ratios, such as Veihmeyer and Hendrickson report.

The conclusion of Veihmeyer and Hendrickson that wilting-point determinations should be made experimentally by growing plants in the soil under test is well supported. Hence, if it is essential to make wilting-point determinations by growing plants in the soil under test, the establishment of a ratio for the particular soil is secondary and the ratio is limited in application. The implication from the word "coefficient" is for a fixed ratio and in this sense the choice of the term "wilting coefficient" seems unfortunate.

The question of stage of wilt to be used as a criterion is a recurrent one (*5, 14, 16, 19*). Briggs and Shantz considered their wilting point to represent the lower limit of the water available for growth and not, as is sometimes mistakenly stated, the percentage of soil moisture unavailable to plants. This was clearly stated by Briggs and Shantz (*5*), and has been shown also by Alway (*1*), Batchelor and Reed (*2*), Veihmeyer (*14*), and numerous other investigators. Veihmeyer and Hendrickson in their definition (*17*) of permanent wilting percentage state that it is a narrow range in soil-moisture contents in which wilting takes place. Hence their determinations must be made at the end of that range through which the plant wilts.

Taylor, Blaney, and McLaughlin (*14*) found that, during periods of several months without rain, perennial native vegetation would reduce the moisture content of the soil to a value which they termed the ultimate wilting point. Moisture contents in the zones of greatest root concentration came to equilibrium at the ultimate wilting point, and well-established sunflower plants in small metal pots reduced the moisture content to the same value when allowed to reach complete wilt. The ultimate wilting point was found to be a useful base in calculating the total moisture available to well-established native plants. In tests with sunflower plants the range in soil moisture from that at which the basal pair of leaves wilted to the condition of complete wilt of the apical leaves was termed the wilting range.

Breazeale (*4*) has discussed some of the sources of error in wilting-point determinations, and a comparison of the results of independent determinations by different workers is given by Work and Lewis (*19*). Wilting-point determinations were made on samples of soil from the same plot of Medford soil by the Medford branch of the Oregon Agricultural Experiment Station and by the Division of Irrigation of the Bureau of Agricultural Engineering, United States Department of Agriculture, at Pomona, Calif. In their comments on this comparison, Work and Lewis state (*19, p. 361*): "The west-half percentages (determined at Medford) appear to be relatively too low and the east-half percentages (determined at Pomona) appear relatively too high." The determinations made at Medford averaged 17.2 percent, and those made at Pomona averaged 17.7 percent. While the numerical difference between these two values is not large, all determinations made at Pomona were for a complete degree of wilt of well-established sunflower plants described as the ultimate wilting point (*14*). Work and Lewis, on the other hand, refer to their determinations as permanent wilting percentages.

An example of the wilting range for a clay soil of this type is given in figure 1. It is apparent from this chart that progressive stages of wilting for plants on this soil may take place over a range of 4 percent in actual soil-moisture contents, which is nearly 25 percent of the total range of available moisture. If we made use of Briggs and Shantz's definition of wilting coefficient, then the wilting coefficient would be 20.2 percent. This was the percentage at which the basal leaves wilted and marks the upper end of the wilting range. The permanent wilting percentage, as determined by Veihmeyer and Hendrickson, would lie somewhere within the wilting range, and finally the ultimate wilting point would be found at the end of the wilting range with a value of 16.2 percent in the case of sample No. 1156.

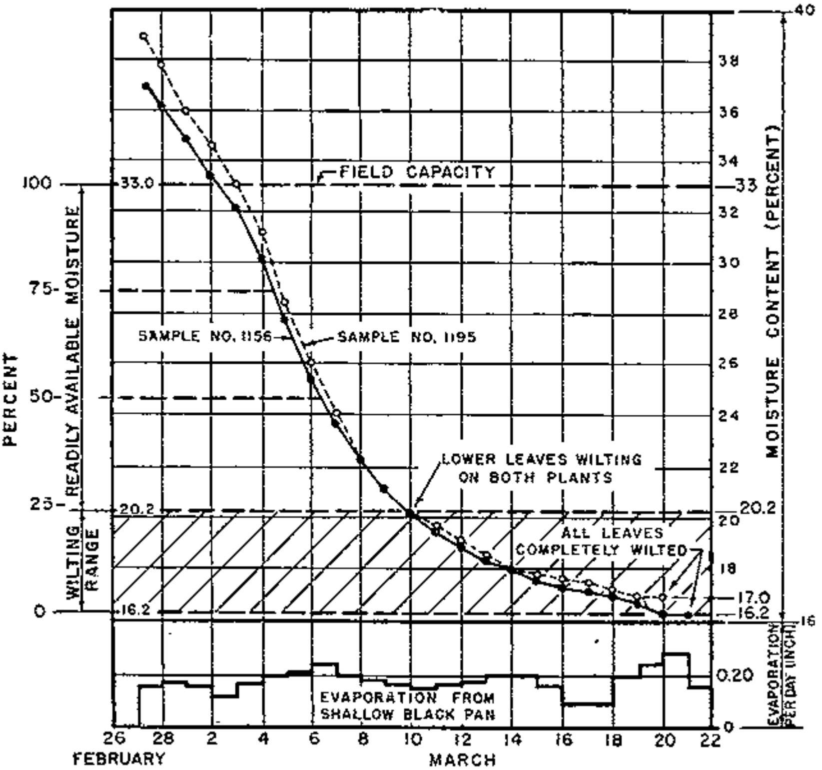

FIGURE 1.—Rates of extraction of soil moisture by sunflower plants from Meyer clay adobe soil in sealed containers from the moisture equivalent down to the point of complete wilting of all leaves on the plants.

In the present work use has been made of the wilting range as determined with sunflower plants in the laboratory, to compare with the findings under orchard conditions, and it is believed that such a conception is essential in interpreting the results of trials with orchard trees. Under field conditions, soil-moisture contents will be found throughout the entire range from field capacity down to values approaching the ultimate wilting point. When the irrigation interval is extended sufficiently, soil-moisture contents will approach the ultimate wilting point. When the soil in most of the root zone is kept relatively moist, water deficit in the plant will not be great, and minimum moisture contents in unirrigated parts of the soil will be higher than the ultimate wilting point, but still may be within the wilting range.

RANGE OF SOIL MOISTURE READILY AVAILABLE TO THE PLANT

While Briggs and Shantz considered that their wilting point practically marked the lower limit of soil moisture available for growth, they made no statement as to its relative availability at different soil-moisture contents above the wilting point. In 1927 Veihmeyer (*15, p. 277*) published information showing that in his experiments—

> The results obtained from the controlled studies made with prune trees in tanks indicate that not only the use of water but the trees themselves were not affected by variations in amount of soil moisture above the wilting coefficient.

Veihmeyer and Hendrickson introduced the term "permanent wilting percentage" in 1929 and added the expression "readily available" moisture to designate the soil moisture above the permanent wilting percentage. As a result of further irrigation experiments with peaches, Hendrickson and Veihmeyer (*9, p. 55*) concluded:

> The data presented in this paper show that the permanent wilting percentage is a critical soil-moisture content, and leads to the conclusion that trees either *have* readily-available moisture or *have not*.

On the other hand, Lewis, Work, and Aldrich (*10, p. 27*) published data showing that in the experiments at Medford, Oreg., whenever the soil moisture in the upper 3-foot average fell much below 70 percent of the available capacity the rate of growth of fruit was reduced. These conclusions represent the most divergent views. Other investigators (*3, 11*) also have reported on the range of readily available soil moisture under orchard conditions. This problem is of vital importance in determining the most effective irrigation practice, and much effort has been directed toward its solution.

As a basis for studies under field conditions, certain experiments with potted plants were made to determine plant reactions to variations in soil-moisture content and to establish certain indices for comparisons between the different plots. The reactions of a potted lemon tree to a gradual reduction in soil moisture are shown in figure 2.

Lemon trees were grown 2 years in sandy loam soil in metal pots. At the end of this period the soil in the pots was thoroughly permeated by roots and each tree had set one or more fruits. Two trees were set up in a room in which the temperature was kept at about 78° F. and the relative humidity at about 48 percent. They were exposed to artificial light 14 hours a day. The pots were sealed with metal covers to prevent water loss except by transpiration. Transpiration was determined by loss of weight of pot and tree. Measurements of fruits and weighings of pots were made at the beginning of the light period each day. The responses of both trees over a period of several months were very similar.

From December 22 to 24 there was a slight increase in volume of the fruit, but from December 24 to 27 the volume was decreasing. The slope of the curve representing weight of pot and tree shows that there was no decrease in transpiration rate from December 24 to 27. On December 27 the moisture content of the soil was raised above field capacity by irrigation, and the fruit swelled rapidly from December 27 to 28. From December 28 to January 7 the fruit continued to gain in volume, but the rate decreased sharply after January 4. During this period the transpiration rate was unaffected by the decreasing soil-moisture content.

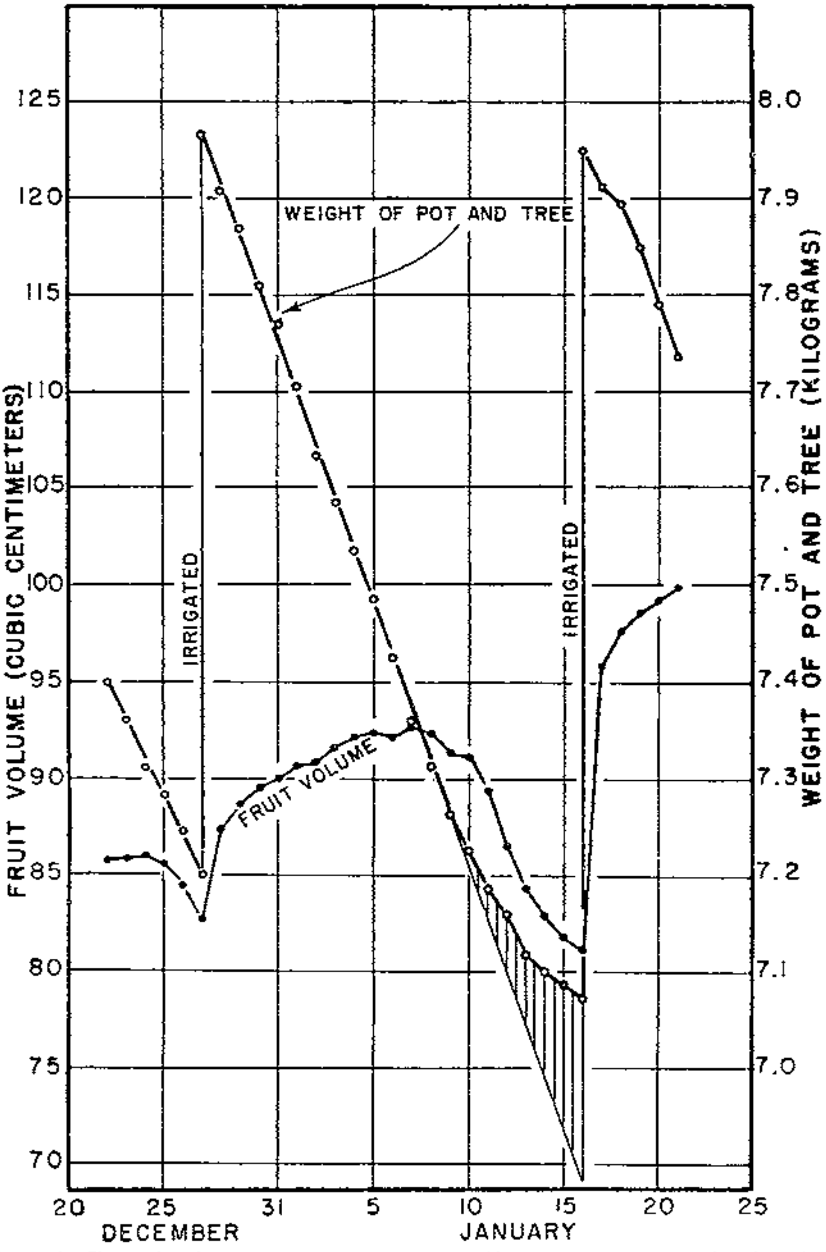

Figure 2.—Changes in volume of a fruit on potted lemon tree No. 7 in response to changes in soil-moisture content.

From January 7 to 16 the volume of the fruit decreased. During the latter part of this period, from January 10 to 16, there was a significant decrease in the rate of transpiration. The departure of the weight-loss curve from an approximately straight line is shown by the shaded area on the graph.

The first visible sign of wilting was the curling of immature leaves on succulent, elongating shoots. In several of the tests with potted trees the curling of young leaves and cessation of shoot elongation occurred 3 days after the fruit began to decrease in volume. By January 16 the young leaves were showing severe distortion in shape and nine old leaves had been abscissed. Although transpiration had been materially reduced by January 16, it was continuing at an appreciable rate—a fact that indicates that the soil-moisture content was within the wilting range but not yet at the ultimate wilting point. Under the particular conditions of this series of tests with potted lemon trees, fruits were shrinking for 3 days before the first stage of wilting of the leaves and the first decrease in transpiration rate occurred.

Following the irrigation on January 16, the fruit swelled much more than it had on December 27. This shows that the water deficit of the tree was greater on January 16 than on December 27. One of the most striking and significant results of this series of tests is the fact that the rate of volume change of fruit was affected over a wide range of soil-moisture contents, whereas the transpiration rate of these potted plants was practically unaffected by decreasing soil moisture until the plants began to wilt. In other words, a gradually decreasing rate of volume gain or actual shrinkage of the fruit is evidence that a gradual increase in the moisture deficit of the tree occurred as the soil-moisture content was reduced. For a while the rate of transpiration was maintained undiminished by the rising suction pressure in the plant. However, by January 9 it appears that the soil-moisture content had become so low as to limit the rate of transpiration, and after this date the transpiration rate gradually decreased. The exact percentages of soil moisture were not determined in this test, since during the wilting process the loss of water from the plant tissue could not be determined. However, the soil used has a field capacity of 12 percent, and fruit measurements gave evidence of a rising water deficit at a soil-moisture content somewhat below 9 percent, while the rate of transpiration was not decreased until the moisture content of the soil was below 6 percent. In other tests on this same soil, when the lower leaves of sunflowers first wilted and failed to recover overnight, the moisture content of the soil was found to be 4.9 percent.

A chart of the extraction of moisture from this soil by a sunflower plant is shown in figure 3. Values for the wilting range and ultimate wilting point are shown, and also, from the test with the potted lemon tree, the range of moisture contents in which evidence of rising water deficit was indicated from fruit measurements. Other points are shown as follows: In tests in which tomato plants were grown with the roots divided in partitioned containers, 5.7 percent was the average minimum percentage of moisture found in the unirrigated one-seventh of the root zone when the remaining portion was kept near field capacity. In a similar test with a sunflower plant, 4.6 percent was the average minimum percentage of moisture found in the unirrigated one-half of the root zone when the remaining one-half was kept near field capacity. In a grass-covered field where the soil used in the above tests was obtained, 3.1 percent was the average moisture content of the soil at a depth of 2 feet in October, 251 days after the last effective rain. The minimum moisture contents obtained in these experiments are thus shown to be related to the degree of water deficit permitted to develop in the plants and to extend from

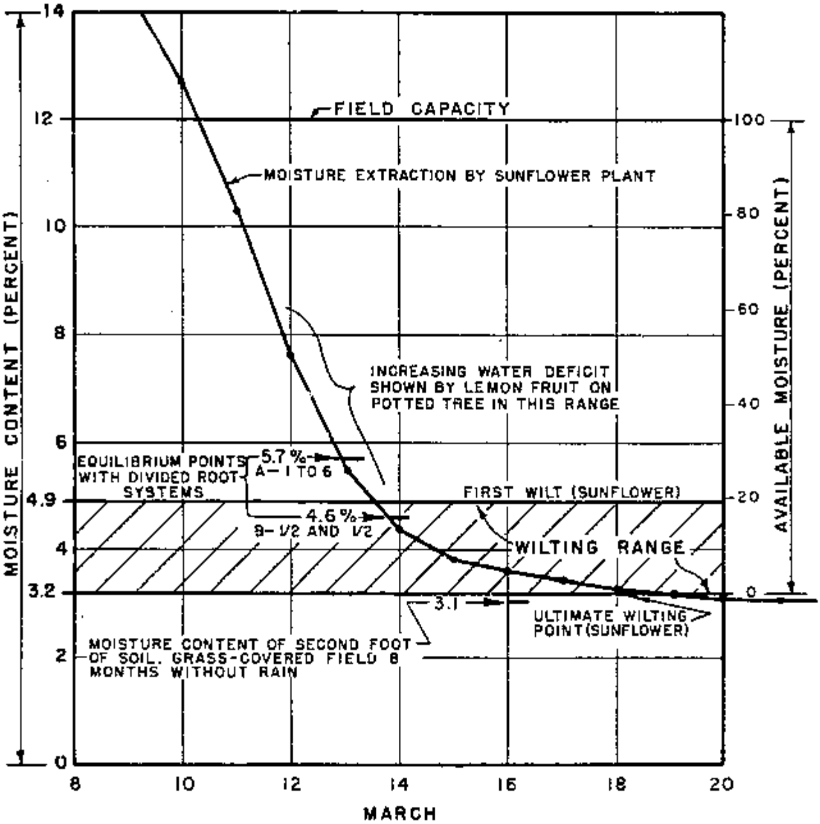

FIGURE 3.—Comparison of moisture extraction from Hanford sandy loam by plants under various degrees of water deficit.

above the wilting range, as determined with sunflower plants, down to the ultimate wilting point.

These tests for equilibrium points with divided root systems are representative of conditions in irrigated orchards where various parts of the root zone may be irrigated. The minimum moisture contents to which the unirrigated parts of the root zone are reduced depend on the water deficit developed in the tree. This in turn depends on the water available in the irrigated portion of the root zone. Hence, no exact values can be set for the minimum moisture content at which moisture is considered available for growth of plants in the field.

It is apparent from these experiments that lemon fruits are sensitive indicators of water deficit and that fruit measurements may indicate impending water shortage in advance of actual wilting. However, the degree of water deficit is shown only relatively from fruit measurements, and it should not be inferred that exact predictions of the time of wilting may be made in advance from an inspection of fruit-growth records.

In the orchard, root distribution is usually so variable that the process of wilting is not as abrupt as it is when plants are grown in small containers in which there is uniform root distribution. Orchard conditions are more comparable to the above test with divided root systems. As increasing proportions of the root zone are reduced in moisture content, a gradual rise in water deficit may be noted in the

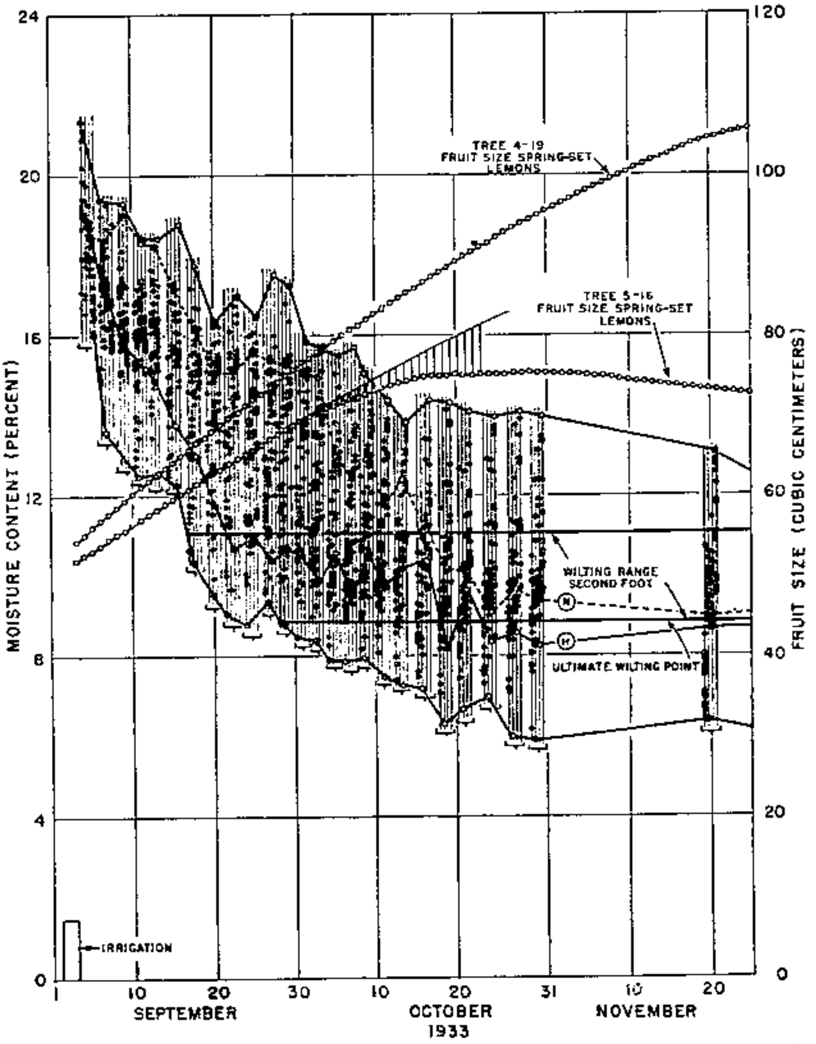

FIGURE 4.—Variation in moisture content of the soil around lemon tree 5–16 as moisture content is reduced following irrigation, and growth of lemons on tree 5–16 in comparison with growth on tree 4–19, which had frequent irrigation. All moisture contents are for tree 5–16. For each date of sampling the moisture content of the top 6 inches is the row of dots to the left, that of the second 6 inches next, then that of the second foot, and finally that of the third foot on the right.

tree. This is illustrated in figure 4. Two trees were used in this test, and both were kept well irrigated during the summer. On September 2 and 3, tree 5–16 was given a final thorough irrigation and none thereafter during the test period. Tree 4–19 was irrigated frequently during the test so that the soil was kept near field capacity. The average size of fruits on each tree is shown in figure 4. Lemons on the control tree 4–19 show the normal trend of seasonal growth. On tree 5–16 the decreased rate of volume gain by fruit after September 30 is evidence that a gradual increase in water deficit occurred as the water supply decreased. The shaded area on the curve indicates the extent of the decrease in rate of fruit-volume gain.

Determinations of over 1,500 soil-moisture contents made on samples from the first, second, and third foot of soil and at different locations around this tree are shown in figure 4. In this case the soil samples were taken starting at the ground surface because of the presence of a cover crop. In all other cases reported in this bulletin the loose, cultivated layer of soil, usually about 4 inches thick, was scraped away and sampling was started from a point below the soil mulch. Variations in moisture contents, such as shown, occur in many orchard situations and make an important difference between soil-moisture conditions in the field and in small containers. The wilting process is less abrupt in the field, and water deficit rises gradually as successive parts of the root zone become depleted of readily available moisture.

The problem then arises as to which part of the root zone serves as the best index of needs of the tree for water. A more or less arbitrary selection must be made, and as an example the moisture content of the second foot of the soil might be chosen. However, the moisture content of the second foot zone varied as much as 5 percent from point to point on each date of sampling. It may be noted that between September 30 and October 15, while the fruit was showing a rising water deficit, the preponderance of soil-moisture contents shifted from above the line representing the first wilt with sunflowers down into the wilting range. Some moisture contents were found in the wilting range as early as September 20 where the cover crop was most dense.

Instead of using the entire group of samples, which were obtained at rather high cost, a selection might be made of a certain depth at a specific location for use as an index of need for irrigation. Records from two such locations are given in figure 4. A solid line connects the points for location H, where a high rate of extraction was found, and a broken line connects the points at location N, where there was a low rate. Moisture contents were in the wilting range at location H on September 22 and at location N on October 16.

Note the somewhat abrupt change in slope for the extraction curve from location H as the moisture content entered the wilting range on September 22. This was at a time when there was still plenty of readily available moisture in other parts of the soil. By October 16, when location N entered the wilting range, the general level of moisture contents was low, and high water deficits had developed in tree and cover crop, so that the slope of the extraction curve for location N does not change abruptly until the ultimate wilting point is approached. After October 16 the moisture content at location H also proceeds to lower levels after having remained in the upper half of the wilting range for nearly 30 days. It is apparent from this that readily available water will be exhausted from zones of high root concentration first, and the end point depends on the magnitude of the suction pressure developed in the plant. Setting some certain value for the lower limit of moisture available for growth seems impracticable, for although a high water deficit had developed during the first half of October the fruit continued to grow. The term "wilting range" is more descriptive of conditions, and transient stages of equilibrium may exist at various points within the range.

The soil at the 12 other locations sampled reached the wilting range at different times between the dates for locations H and N, and it is apparent from this that the selection of a representative location is largely a matter of personal judgment. Consideration should be given to such items as depth of sample, root density within the sample, location with respect to trees and furrows, plow sole, and density of weeds or cover crop. The moisture content of a sample will show the relative need for irrigation of the soil at a specific location, but the chances are somewhat against its being a true index for the tree as a whole in cases similar to that used in this illustration. Its rating as an index for the tree requires either a careful correlation of the moisture-content record with some measure of water deficit within the tree, or proof that the moisture-content record is itself a primary index of the water supply of the tree.

From theoretical considerations the moisture contents of single samples from portions of the root zone with high concentration of rootlets might serve as measures of the relative water deficit within the tree. However, conditions would have to be favorable for exact work. All of the readily available moisture might be extracted from zones of greatest feeder-root concentration, while the tree might still get ample water from other roots. There would be a further extraction of moisture from all portions of the root zone when the water deficit increased within the tree. The moisture contents of zones with high feeder-root concentrations would then drop farther down in the wilting range, and this additional decrease would be evidence of the increased water deficit within the tree. Data bearing on this point will be submitted later in connection with field plot experiments.

The illustration just given for an orchard tree shows how a gradual rise in water deficit develops within the tree as time from irrigation increases. It is important to know how long a water deficit may be permitted to develop before additional water is applied. The field problem then becomes one of determining what degree of water deficit causes measurable reductions in photosynthesis, rate of growth, yield, or other effects, such as abscission of leaves or young fruit. The concurrent soil-moisture problem is that of determining the general level of the soil-moisture reservoir corresponding to different degrees of water deficit in the tree and of determining rates of withdrawal of moisture as well as minimum values reached in various portions of the root zone.

EXPERIMENTAL METHODS

MEASUREMENTS OF TREE RESPONSE

It was expected that soil type and root distribution might have considerable influence on the response of trees to various soil-moisture conditions. It seemed advisable, therefore, to conduct several short-time experiments on different soil types rather than an elaborate long-time experiment under one set of conditions.

When short-time experiments of 1 year, or even several years, are conducted on mature trees, the problem of obtaining a reliable measure of the effect of the treatment on tree response is a difficult one. It was realized that without maintaining uniform treatment on all trees and obtaining records of yield per tree for several years before treatments were given it would be difficult if not impossible to determine whether differences in the yields of different plots were due to the treatments applied or to other causes. It was apparent that in experiments of the sort conducted in this investigation measurement of yields could not be depended upon to show the effects of the different soil-moisture conditions over periods as short as one irrigation interval, and it was doubted that yield records for a complete season would be significant, since yield records prior to treatment were not obtained.

As a measure of the effects of treatments, growth rates of fruits have been used for these experiments, and the average growth per fruit was determined for each plot. Representative samples of 100 to 200 fruits per plot were tagged when the fruits were about 10 to 20 cc in volume. At intervals of several days throughout the season the circumference of each fruit was measured with a steel tape. The volume was then obtained from a conversion table which had been made up from an empirical curve based on determinations of the circumference and volume of a large number of lemons covering the entire range of sizes measured in the field.

The reliability of this method of comparing the effect of soil-moisture conditions on growth is dependent to some extent upon uniformity in number of leaves per fruit on the trees in the plots to be compared. However, above 30 leaves per fruit the influence of number of leaves on growth rate is slight. In experiments in which entire trees, three to each treatment, were thinned to definite leaf-fruit ratios of 10, 20, 30, 60, and 100 leaves per fruit, the differences in growth rate of fruits above 30 leaves per fruit were barely significant. The leaf-fruit ratio of lemon trees is rarely lower than 25 during the irrigation season, so that slight differences in leaf-fruit ratio on different plots would probably have little effect on growth rate. Furthermore, lemon trees, because of their tendency to flower and set fruits rather quickly in response to an increase in number of leaves per fruit, tend to maintain greater uniformity in leaf-fruit ratio than most fruit trees.

In an experiment carried out in an attempt to shift the period of heavy fruit setting from spring to late summer or fall, all spring-set fruit and all flowers were removed on July 15 from alternate trees in a block of 50 trees under uniform cultural and irrigation treatments. The other 25 trees were left untreated as controls. The removal of all fruit except a very light crop that had set the previous fall resulted in a marked stimulation of flowering and set of fruit on the treated trees during August, September, and October. Fruit counts made at monthly intervals showed that by the last of October the number of fruits per tree was nearly the same on the treated and control trees, though most of the fruits on the thinned trees were quite young. Measurements made from August to December on comparable lots of fruit on the thinned and control trees showed that there was little difference in growth rate of fruit.

Apparently, foods were largely utilized in the production of flowers and in setting a heavy crop of young fruit, rather than in increased growth of the older fruit.

In the experiment previously mentioned, in which trees were maintained at a definite leaf-fruit ratio, it was necessary to remove flowers and preset fruit periodically to maintain the higher leaf-fruit ratios, while the trees with low ratios set almost no fruit but pushed new shoots, so that leaves had to be removed to maintain the desired ratio.

Because of this tendency of the lemon to adjust rather quickly the leaf-fruit ratio to about 25 to 35 leaves per fruit, one of the most troublesome variables in fruit-growth studies is minimized to a considerable extent. However, it was found early in the course of the experiments that readjustment of leaf-fruit ratio does not take place for a long time on heavily pruned trees, and that trees from nonuniform buds may show considerable variability in leaf-fruit ratio.

In growth measurements of lemon fruit, diurnal variations in volume must be taken into account. Each day there is a regular cycle of change in volume of a fruit. From sunrise to midday the volume may normally decrease 5 percent as a result of transpiration by the tree exceeding absorption. During late afternoon and night, if there is ample soil moisture, the fruits regain almost full turgor.

There is also a cycle of change in water content that extends over each irrigation interval. For some days after the adjustment following an irrigation the fruits regain approximately full turgor during each night, but as time after irrigation increases and the amount of water in the soil decreases, the water deficit of the tree at sunrise gradually increases. The rate of change in volume from day to day, determined by measurements of fruits made early in the morning before transpiration has become appreciable, provides a relative day-to-day measure of the changes in turgor of the fruit. The results of the following experiment make clear the relation of volume change to moisture content of fruit, specific gravity of fruit, and average dry weight per fruit, and show how the volume changes of fruit indicate the moisture conditions in the tree.

Eureka lemon trees, growing on stony, sandy-loam soil where the irrigation interval was sufficiently extended for relatively high water deficits to develop before each irrigation, were used in this experiment. Figure 5 shows graphically an analysis of the relationship of changes in the moisture content of fruit, specific gravity, fresh weight per fruit, and dry weight per fruit through one irrigation interval.

The average volume per fruit was determined from measurements made on 10 tagged fruits on each tree at each sampling date. Determinations of fresh weight, dry weight, and specific gravity were made from samples of fruit carefully selected on each sampling date to match the tagged fruit. From the average specific gravity, the average volume, and the percentage of dry weight it was possible to calculate approximately the fresh weight and dry weight of the tagged fruit that remained on the trees throughout the test. Measurements of fruit and samplings were made at about sunrise on each date. Measurements were made and samples of fruit were taken just before the irrigation water was applied on July 8 and 27.

The curves of average volume per fruit for trees 4 and 6 rose abruptly following irrigation on July 8, but from July 11 until July 24 the rate of volume gain decreased, and from July 24 to July 27 the fruit on

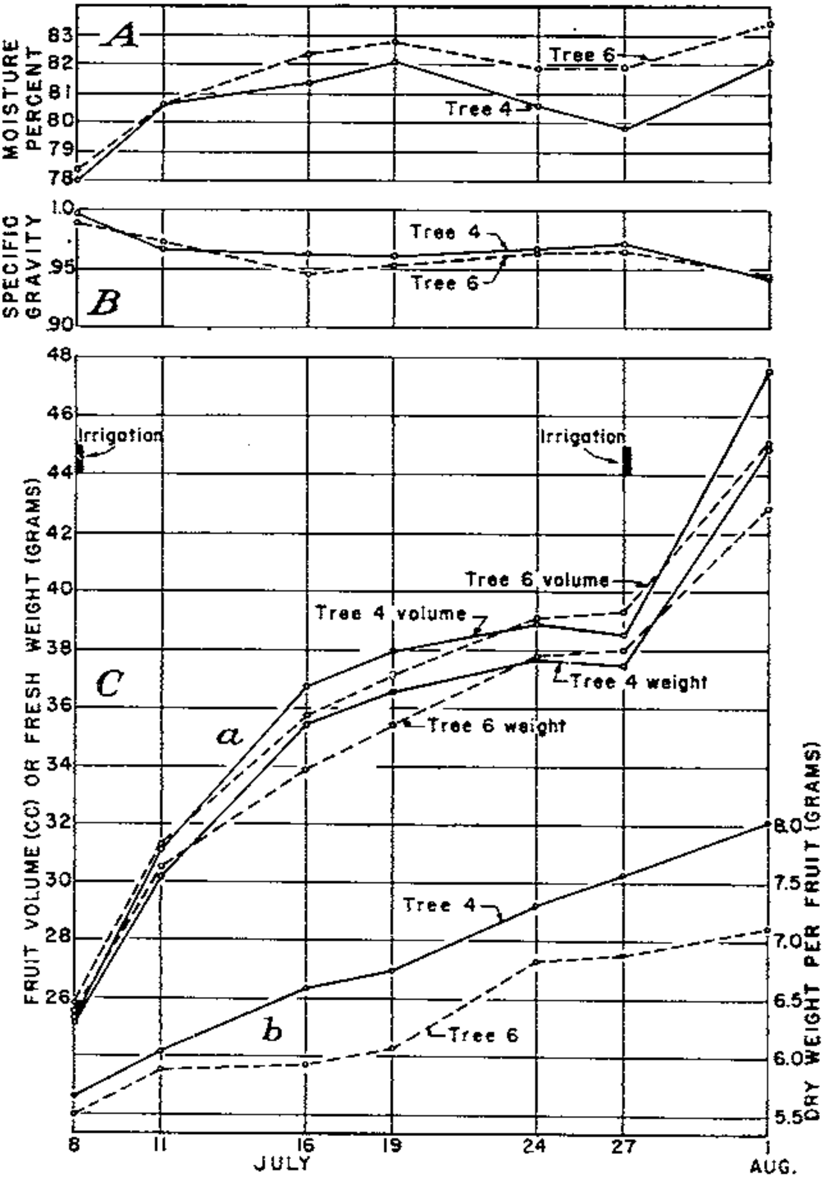

FIGURE 5.—Changes in percentage of moisture on a fresh-weight basis (*A*), average specific gravity (*B*), average volume and fresh weight (*C*, *a*), and average dry weight per fruit (*C*, *b*) in relation to changes in volume of fruits.

tree 4 decreased in volume and the fruit on tree 6 gained very little. The curves for fresh weight per fruit are seen to parallel closely those for average volume per fruit. The curves for dry weight per fruit do not show changes corresponding to the changes in fruit volume. It is obvious that the experimental error may be rather high for the determinations of dry weight per fruit, but it is practically certain that there is neither a sudden large change in dry weight per fruit during the periods just following irrigation nor a gradual decrease in dry-weight gain for some time prior to the irrigation on July 27.

In short, it appears that the marked changes in the rate of apparent fruit growth shown in the volume curve from July 8 to August 1 can be attributed largely to changes in percentage of moisture and that the fairly regular increase in dry weight per fruit may have been unaffected by the changes in the percentage of moisture in the fruit.

The curves for percentage of moisture in the fruit show a continuous rise, though at diminishing rates, until July 19. From July 19 until the trees were irrigated on July 27 the percentage of moisture decreased. From July 27 to August 1 it increased sharply in response to the irrigation. Although, as has been shown by Caldwell (7), there is a seasonal increase in the percentage of moisture of citrus fruits accompanied by chemical changes, and although it would actually be possible for both the turgor deficit and the percentage of moisture of fruits to increase at the same time, the relative changes in the percentage of moisture of fruit are very closely related to the changes in volume.

The curves showing the changes in the specific gravity of these fruits are almost exactly the reverse of the percentage-of-moisture curves. However, the changes in specific gravity cannot be due entirely to changes in the ratio of water and solids. Calculations based on the assumption that the solids have a specific gravity of 1.5 suggest that roughly 40 percent of the change in specific gravity is due to change in intercellular space in the fruit.

The curves for percentage of moisture, specific gravity, average volume per fruit, and average fresh weight per fruit show that moisture content, turgor of cells, and volume and mass of the fruit are undergoing continuous change from one irrigation date to the next. This is typical of fruit on trees that are subjected to considerable water shortage before each irrigation.

It is clear from these experiments that the changes in the volume of fruit over short periods of time provide an excellent index of the relative moisture deficit of the tree, but that true growth may not be measured accurately for periods shorter than an irrigation interval. The gain in volume from one period of full turgor to the next or for an entire season should provide a reliable measure of the true growth rate of fruit. Rates of change in fruit volume over periods of time shorter than one complete irrigation interval are termed apparent growth rates, since the influence of water content of fruit may obscure the true growth over shorter intervals.

SOIL-MOISTURE DETERMINATIONS

One of the first tasks in the soil-moisture work was to study the variability in root distribution and its effect on rates of extraction of soil moisture. Trenching showed great variation in density of roots, and it was desired to learn something of the corresponding variation in extraction of moisture. For this purpose, unit areas equivalent to one tree space were used and 10 points for sampling located within this unit area, as indicated in figure 6. Rates of extraction of soil moisture were determined separately for each foot in depth at each of the 10 locations. On these plots and on all those following in this bulletin, the loose mulch or the top 4 inches of soil was removed and sampling started from below the soil mulch, so that the top foot of soil represents the first foot of the root zone of the trees.

Rates of extraction of soil moisture were determined graphically from plotted records of soil-moisture contents as illustrated in figure 7. The slope of the mean line through the plotted points of moisture percentages was used as a measure of the average rate of extraction of moisture. This might also be calculated from the difference in moisture contents on successive dates of sampling. However, when it is considered that each new sample is at least 6 inches distant from previous samples, a mean line is preferred as representative of the average extraction of moisture from the soil mass immediately surrounding the point of reference.

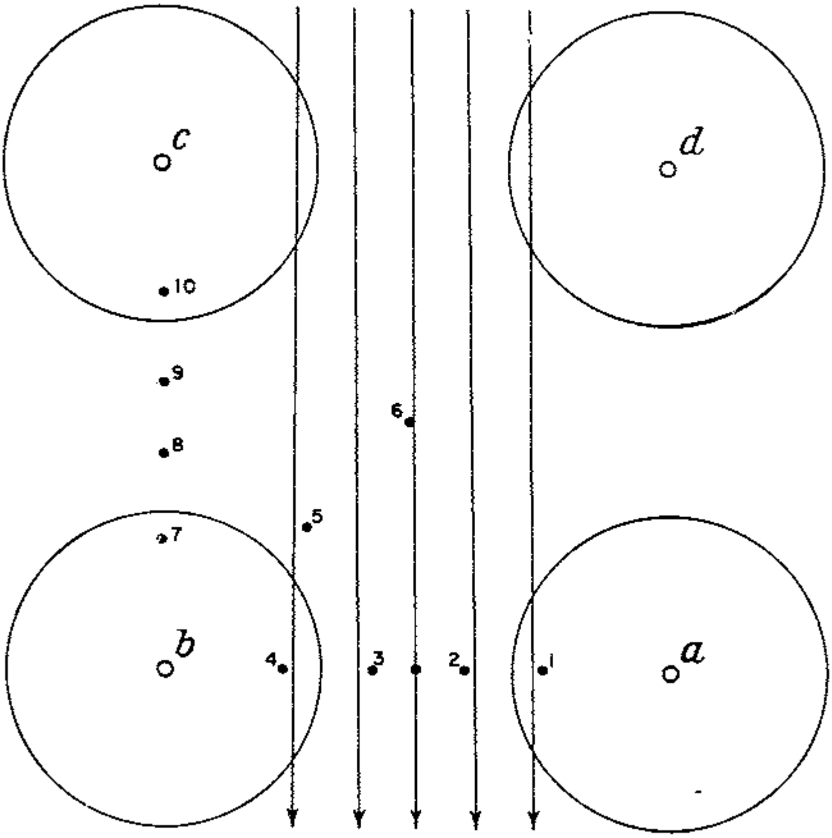

FIGURE 6.—Soil-sampling plan, season of 1932. Nos. 1 to 10 indicate sample locations in relation to trees, indicated by letters *a* to *d*. Circles indicate spread of branches. Perpendicular lines indicate irrigation ditches.

Within the wide range in moisture contents from field capacity down to the wilting range there was no apparent restriction to the rate of withdrawal of moisture around sampling locations with relatively high root concentrations. Rates of extraction were as great when the moisture content of the soil approached the wilting range as when the soil was near field capacity. A straight-line relationship from field capacity down to the wilting range might be taken as evidence that the soil moisture is just as readily available near the wilting range as when at field capacity. On the other hand, as the moisture content of the soil decreases there may be a gradual rise in water deficit and a corresponding rise in suction pressure within the plant. The increase in the suction pressure of plant tissue may be just sufficient to overcome the increasing resistance to absorption of moisture from the soil as the soil-moisture content decreases from field capacity to the wilting range.

Where there were unirrigated strips of soil along the tree lines, the samples were used to determine the lower limits of readily available moisture. Values obtained in this manner were checked against laboratory determinations of wilting with sunflower plants. The manner in which field wilting points were determined will be understood from the following illustration. By referring to figure 4 it may be seen from the extraction curve for location H that there is a more or less abrupt change in the rate of loss of moisture at 11 percent in moisture content. This point represents the field wilting point. Records like this are often obtained in zones of high root concentration, especially along dry tree lines when the major part of the root zone is irrigated and has ample water. The break in the curve for location H corresponds fairly well with the upper end of the wilting range as determined with sunflower plants. In those cases in which large numbers of samples had been taken, so that the curves were well defined, the field wilting points were determined graphically. A straight line was drawn from a point representing field capacity down through points on the soil-moisture-time scale. Another straight line was drawn through the points lying within the wilting range and was extended back to the left until it crossed the first line. The point at which the two lines cross was considered as an approximation of the field wilting point. This results in a value of 11 percent for location II, figure 4.

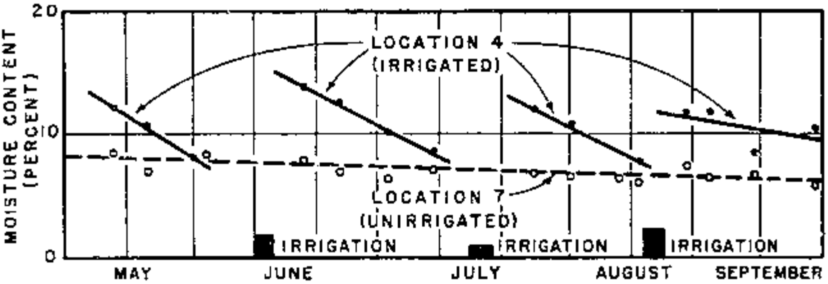

FIGURE 7.—Moisture content of the first foot of soil at two locations (Nos. 4 and 7, fig. 6) on plots M-D, season of 1932. Slopes of mean lines represent average rates of loss of moisture.

Field wilting points represent values to which moisture contents are readily reduced in unirrigated parts of the soil when ample moisture is maintained in the irrigated portions of the root zone. Table 1 gives a comparison of field wilting points, determined as described above, and ultimate wilting points, determined in a greenhouse with sunflower plants. In this table total range in moisture percentage from field capacity down to the ultimate wilting point is given in column 5. Column 6 lists the difference between the field wilting point and the ultimate wilting point, and column 7 is the ratio of this difference to the total available moisture. The average of all values of the ratio is 0.2. Expressed in terms of percentage of total available moisture, the field wilting point in this case represents a moisture content that is 20 percent above the ultimate wilting point as determined with sunflower plants.

TABLE 1.—*Comparison of field capacity, ultimate wilting point, and field wilting point, orchard M, 1932*

Plot	Field capacity	Ultimate wilting point (sunflowers)	Field wilting point	Field capacity less ultimate wilting point	Field wilting point less ultimate wilting point	Ratio (column 6 ÷ column 5)
FIRST FOOT						
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	
A	20.0	6.8	9.4	13.2	2.6	0.20
B	20.2	7.2	9.5	13.0	2.3	.18
C	16.8	5.6	7.6	11.2	2.0	.18
D	15.6	5.2	8.0	10.4	2.8	.27
E	16.4	4.9	7.6	11.5	2.7	.23
F	20.0	7.3	9.7	12.7	2.4	.19
G	20.0	6.8	9.3	13.2	2.5	.19
H	16.8	5.7	8.4	11.1	2.7	.24
I	17.5	5.7	8.8	11.8	3.1	.26
Average						.22
SECOND FOOT						
A	18.7	7.0		11.7		
B	17.6	7.3	8.9	10.3	1.6	0.15
C	17.6	6.5	8.5	11.1	2.0	.18
D	16.8	6.1	8.0	10.7	1.9	.18
E	17.2	6.2	8.4	11.0	2.2	.20
F	18.2	7.9	9.5	10.3	1.6	.16
G	17.6	8.0	10.0	9.6	2.0	.21
H	16.3	6.0	8.0	10.3	2.0	.19
I	14.7	6.3	8.4	8.4	2.1	.25
Average						.19
THIRD FOOT						
A	15.3	6.0		9.3		
B	14.5	6.2	7.6	8.3	1.4	0.17
C	16.1	6.1		10.0		
D	15.4	6.2	8.5	9.2	2.3	.25
E	16.3	6.9	9.5	9.4	2.6	.28
F	18.0	7.9	9.7	10.1	1.8	.18
G	16.6	7.6	10.0	9.0	2.4	.27
H	13.9	5.5		8.4		
I	15.1	6.0	8.0	9.1	2.0	.22
Average						.23
Average of all values (0 to 3 feet)						.21

As long as ample moisture is maintained in the irrigated parts of the soil, moisture contents in the remaining unirrigated part of the root zone do not closely approach the ultimate wilting point. As indicated in figures 1 to 4, it is only when severe water shortage develops in the plant that moisture contents as low as the ultimate wilting point are reached.

During 1932 certain of the orchard plots were maintained with ample moisture in the irrigated part of the root zone. The unirrigated strips along the tree line were sampled in September, 7 months after the soil had been moistened to field capacity by spring rains. The results, listed in table 2, show that moisture contents in the unirrigated strips along the tree lines were not reduced very far into the wilting range in plots where ample moisture was maintained in the irrigated area. High values in the second and third foot indicate sparse root population. In later test plots where the trees were subjected to severe water shortage, moisture contents of the unirrigated tree lines approached the ultimate wilting point in the zones of greatest root density.

TABLE 2.—*Moisture content of soil along unirrigated tree lines in September 1932, in relation to field capacity and ultimate wilting point, orchard M*

FIRST FOOT

Row	Tree	Field capacity	Ultimate wilting point (sunflowers)	Moisture content of field	Field capacity less ultimate wilting point	Moisture content of sample less ultimate wilting point	Ratio (column 7÷column 6)
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	
8	3-4	13.2	3.8	5.2	9.4	1.4	0.15
8	7-8	17.3	5.3	7.8	12.0	2.5	.21
9	3-4	13.3	3.9	5.6	9.4	1.7	.18
9	8-9	19.7	6.0	8.9	13.7	2.9	.21
10	4-5	15.3	4.2	6.5	11.1	2.3	.21
10	7-8	19.7	5.0	7.5	14.1	1.9	.13
Average							.18

SECOND FOOT

Row	Tree	Field capacity	Ultimate wilting point (sunflowers)	Moisture content of field	Field capacity less ultimate wilting point	Moisture content of sample less ultimate wilting point	Ratio (column 7÷column 6)
8	3-4	13.9	4.8	7.2	9.1	2.4	0.26
8	7-8	17.5	6.0	9.9	11.5	3.9	.34
9	3-4	15.2	5.0	8.9	10.2	3.9	.38
9	8-9	18.2	6.2	10.6	12.0	4.4	.37
10	4-5	16.5	5.4	8.6	11.1	3.2	.29
10	7-8	20.4	6.5	9.6	13.9	3.1	.22
Average							.31

THIRD FOOT

Row	Tree	Field capacity	Ultimate wilting point (sunflowers)	Moisture content of field	Field capacity less ultimate wilting point	Moisture content of sample less ultimate wilting point	Ratio (column 7÷column 6)
8	3-4	15.1	6.0	8.8	9.1	2.8	0.31
8	7-8	14.7	5.9	9.3	8.8	3.4	.39
9	3-4	17.3	6.5	10.2	10.8	3.7	.34
9	8-9	14.5	6.1	9.8	8.4	3.7	.44
10	4-5	17.0	6.2	9.9	10.8	3.7	.34
10	7-8	16.1	6.3	10.3	9.8	4.0	.41
Average							.37

In the light of these tests it seems futile to attempt to set a definite percentage above which soil moisture is considered available for growth and below which it is not available for growth. Irrigated orchard trees not only have a variable root distribution but also have variable proportions of their root zones irrigated. The zones of highest feeder-root concentration are reduced in moisture content most rapidly and come to a stage of transitory equilibrium which remains as long as ample moisture can be obtained by the tree from other parts of the root zone. The value for such a stage of equilibrium will depend on the proportion of the root zone with ample available moisture and on the opportunity for transpiration. If an increased moisture deficit is brought about in the tree either by an increase in transpiration or from a restriction in the available supply within the irrigated root zone, then the moisture content of the dry zone will drop to a lower value and come to a new stage of equilibrium. Equilibrium points or field wilting points may be determined in the field for certain sets of conditions, but the values may change when different degrees of water deficit are developed within the trees. A wilting range may be determined within fairly close limits by using sunflower plants under certain prescribed conditions in the greenhouse. For the work with orchard plots it has seemed best to establish the wilting range from tests with well-established sunflower plants under greenhouse conditions, or from dry tree lines when conditions were favorable, and then to make comparisons between the orchard plots on the basis of degree of water deficit developed under different methods of irrigation.

As a result of these tests, the wilting range was determined to be about 20 percent of the total available moisture above the ultimate wilting points, as established by sunflower plants under greenhouse conditions, for the orchard plots used in 1932, 1933, and 1934.

Field capacities were determined in the spring of the year after rains, from soil samples taken at frequent intervals during the period of rapid drainage. Field capacity represents the upper limit of the capacity of the soil to store water in the field, and its value may be influenced by a number of factors. The amount of water applied and its temperature are important. Determinations under orchard conditions are also influenced by the rate of transpiration during the period of rapid drainage. All field-capacity determinations were made in the winter or early spring, in order to obtain values representing the maximum water-holding capacity of the soil.

FRUIT GROWTH IN RELATION TO MOISTURE CONTENT OF THE SOIL

ORCHARD M, SEASON OF 1932

Orchard M is one of the older orchards in the San Dimas area. Many of the trees are lacking in vigor and are in a state of decline so that growth rate of fruit is low and much of the fruit fails to reach picking size before it becomes tree ripe. The owner's practice has been to apply water in five furrows, thereby watering about 60 percent of the area. Since 1925 the furrows have been left open for two irrigations and weed growth has been disked under three times a year. More intensive cultivation of the soil had been practiced prior to that time, and a dense plow sole had been formed below the depth of cultivation.

During the course of the experiments conducted on this orchard various efforts were made to improve the condition of the trees by changes in irrigation practice. Irrigation in alternate middles on successive dates of irrigation was tried in order to dry the soil out as thoroughly as practicable and yet maintain a ready supply of moisture on one side of the trees. The previously unirrigated tree line was watered on another plot, so that 100 percent of the soil was wetted at each irrigation. Other trees were left unirrigated at various seasons until visible signs of water shortage appeared. One block was left uncultivated for 3 years and the cover mowed. At times temporary improvements in appearance of the trees were noted, but none of the treatments had sufficient effect to change the relative ratings of the different plots at the conclusion of the tests.

Red scale was present in the orchard but was controlled satisfactorily by oil spray in 1932 and by fumigation thereafter. There were rather severe infestations of red mite (red spider) each spring, and the trees were dusted with sulphur for control, but the mites caused considerable damage to the foliage.

The experiments carried out on three of the field plots in this orchard were designed to show the effect on fruit growth of wetting different proportions of the soil mass in the principal root zone. Experiments were carried out on two plots to determine the effect of allowing the trees to undergo severe water deficit, followed by application of irrigation water, on the production of flowers and set of fruit during the late summer. This practice is followed occasionally by some growers for the purpose of causing an abnormally heavy bloom and set of fruit in late summer or early fall.

The soil on which the field plots in orchard M were located is classified as Ramona clay loam. This is a secondary soil, moderately weathered, but without sharply defined horizons. The surface soil is brown, moderately friable, puddles when wet, and is approximately 2 feet deep. The surface soil grades gradually into dense reddish-brown subsoil.

The trees are Eureka lemon and in 1932 were about 40 years old. As is to be expected in a grove of this age, the trees are quite variable in size and vigor. The size of the plots was varied so as to include in each at least 10 trees from which records could be taken. All plots were irrigated by the furrow method. One guard row was maintained on each side of each plot.

Treatments were applied to the plots as follows:

Plot A–B.—The entire soil area occupied by the trees was irrigated, but water was applied in alternate middles, designated as plots A and B, on alternate irrigation dates.

Plot C.—At each application of water the entire area occupied by the trees was irrigated.

Plot D.—At each application of water 60 percent of the soil area between each two rows was wetted, and a strip of soil along each row of trees, comprising 40 percent of the area occupied by the trees, was not irrigated at all. It was planned to maintain ample moisture in the irrigated area at all times.

Plot H.—Water was applied in the middles in a strip comprising 60 percent of the area, and the tree row comprising 40 percent of the area remained dry. This plot was dried out severely in August 1932.

Plot I.—The entire area occupied by the trees was irrigated. This plot was dried out severely in July 1932.

Trenches 4 to 5 feet deep were dug at several locations in the plots to determine the distribution of roots. Trenches 10 feet long, at right angles to the tree row and extending from a point on the tree line to near midway between the rows, were dug, and the position of each root on the soil profile exposed was plotted on a chart. All charts of root distribution shown in this bulletin represent the distribution of roots 10 or more feet from the tree trunk.

Figure 8 shows the distribution of roots in typical profiles in orchard M. It is obvious that the distribution is not uniform. Large areas, a foot or more across, on the profile showed no roots. In other areas the roots were found concentrated in "islands." In this soil there seemed to be no difference in texture, color, or other distinguishable characteristics between the soil masses containing a high concentration of roots and those devoid of roots. There were no remains of dead roots in the areas devoid of roots, and, considering the good internal drainage of this soil, it seems unlikely that waterlogging caused the roots in parts of the root zone to be killed some years before the trenches were dug. There appears to be no obvious explanation for the nonuniformity of root distribution in orchard M.

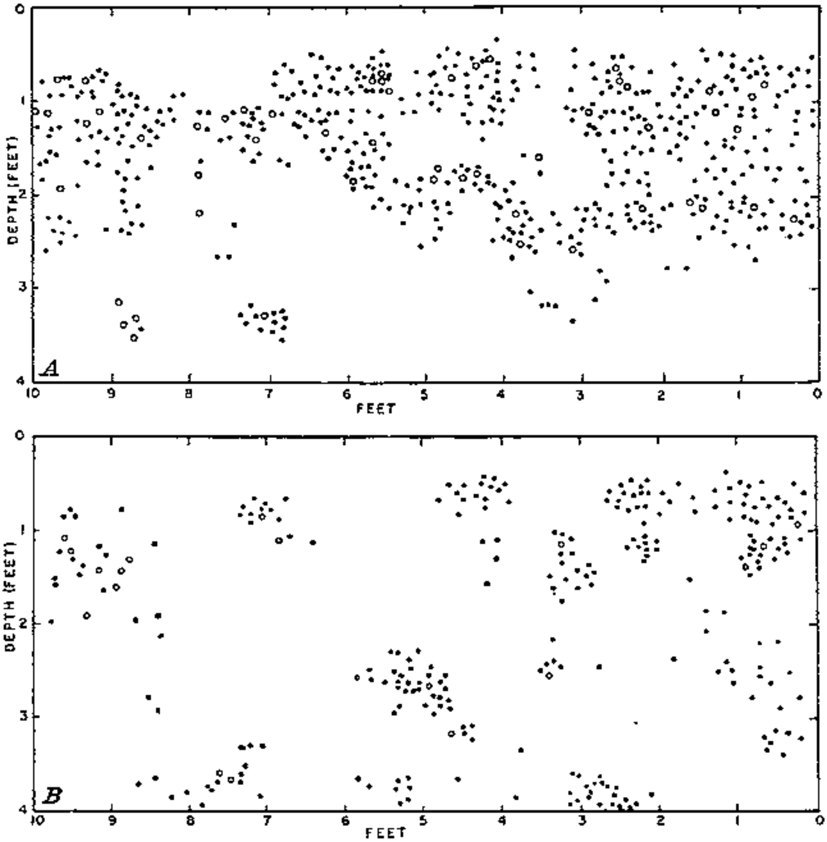

FIGURE 8.—Distribution of lemon tree roots in a soil profile in orchard M, Ramona clay loam. Circles denote lateral roots; dots, feeder roots. *A*, Location 4–3. Density of this soil increases with depth. No sharply defined horizons. Top foot compact, but 1 to 4 feet depth in excellent physical condition. Soil wet in areas devoid of roots. *B*, Location 10–15. Density of this soil increases with depth. Soil denser than at location 4–3. Physical condition good. No sharply defined horizons. Soil wet in areas devoid of roots.

The relationship between apparent fruit growth and soil moisture of plot A–B, which was irrigated in alternate middles, is shown by the line and bar graphs in figure 9. The line graphs represent the average volume per fruit of representative samples of winter-set, spring-set, and summer-set fruits during the irrigation season. The bar graphs show the percentage of soil moisture in the A and B middles (designated plot A and plot B) to a depth of 4 feet.

The four vertical lines at each sampling date represent, respectively, the range in soil-moisture contents of each of the top 4 feet of soil.

The solid dots in each line represent the moisture contents of single samples. Irrigation water was applied at different times on the A and B middles (designated as plots A and B). The dates of irrigation are shown by solid bars. The field capacity and the ultimate wilting

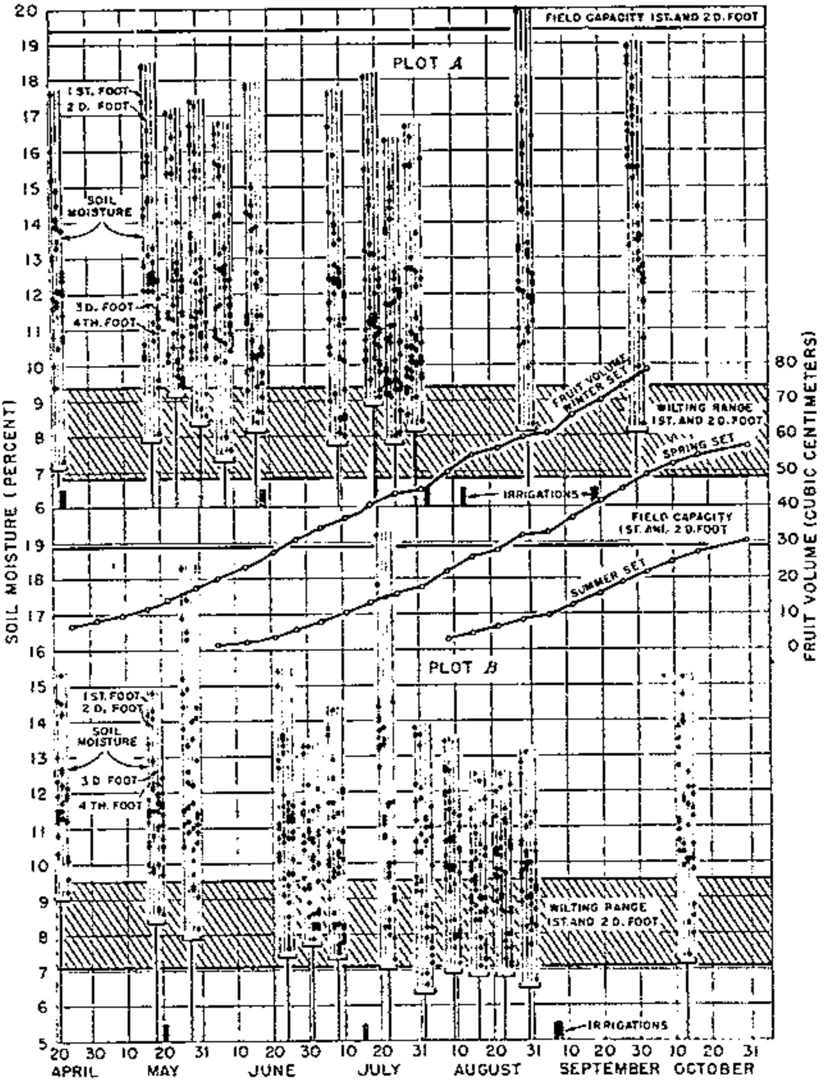

FIGURE 9.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plot A-B, orchard M, 1932.

point, determined directly by growing sunflowers in soil in closed containers, are for the top 2 feet of soil. The wilting range is shown as 20 percent of the total available moisture. Field capacities and wilting ranges vary somewhat with depth, and to avoid confusion on the graphs, values for the lower depths are omitted.

A striking feature of the data shown in figure 9 is the wide variation in moisture content of the different samples from each foot depth throughout the entire season. The apparent growth rate, as indicated by the slope of the fruit-volume curves, was affected only slightly by variations in soil-moisture content until late in July. The fruit volume curves show that the trees were again suffering appreciable water deficits when plot B was irrigated on September 6. After this irrigation the apparent growth rate of fruits indicates no further water deficit until October 10. The decrease in apparent growth rate from October 20 to 31 was caused largely by unusually low humidity and high winds. The apparent growth rate of the fruits on plot A–B shows that, since there was no further rise in the apparent growth rate following the irrigation of plot A on September 17, the trees regained full turgor from the irrigation of plot B on September 6. The soil samples from plot A–B suggest that water was extracted principally from the section with the higher moisture content, and that even after long periods without irrigation the soil in the driest section still had portions with high moisture contents. For example, plot B was not irrigated from May 20 to July 15, a period of 56 days, yet the samples taken on July 8 show that over two-thirds of the soil in the top 2 feet was still above the wilting range. The next irrigation interval, July 15 to September 6, was 53 days. The samples taken on August 30 also show that over two-thirds of the soil in the top 2 feet was above the wilting range. However, by comparing figures 9 and 10 it is apparent that the alternate irrigation system used on plot A–B accomplished the desired effect of allowing a greater proportion of the soil to be dried down into the wilting range.

On plot C the entire soil area from tree line to tree line was irrigated. On plot D the middles, comprising about 60 percent of the area, were irrigated, and a strip along the tree line comprising 40 percent of the area was left unirrigated all season. The fruit-volume and soil-moisture data for plots C and D are shown in the graphs of figure 10.

On plot C the apparent growth rate of fruit was unaffected by variations in soil-moisture content until about July 4. The fruit-volume curves show that there was slight water deficit from July 4 to 15. Water was applied on July 15. The soil samples taken on July 8 indicate that part of the soil in the top foot was in the wilting range. Although the next irrigation interval, July 15 to August 12, was relatively short, the slope of the fruit-volume curve shows that the trees suffered the most severe water deficit of the season from August 1 to 12. The soil samples taken on August 11 indicate that the soil in the top 3 feet was relatively dry on this date. The apparent growth rate again indicates slight water deficit in the trees just before the irrigation of September 17. The soil samples taken on September 9 suggest that only a small proportion of the soil was in the wilting range by September 17. Following the irrigation of September 17 the apparent growth rate of fruit was high and uniform until October 17.

Applications of irrigation water were made on plot D on the same dates as on plot C. The soil-moisture percentages shown in figure 10 are for samples taken from the wetted soil area. With plot D on the same irrigation schedule as plot C, and with only 60 percent of the soil area wetted, it was to be expected that the trees on plot D would show severe water deficits before each irrigation. But it is apparent from the curves representing fruit volume that the trees on plot D suffered somewhat less water deficit than those on plot C. The soil-moisture percentages show that only five soil samples of all those taken during the season were in the wilting range. The trees on plot D were somewhat smaller than those on plots A–B and C and apparently extracted moisture at a lower rate. It is clear that with all of the soil in 60 percent of the root zone maintained above the

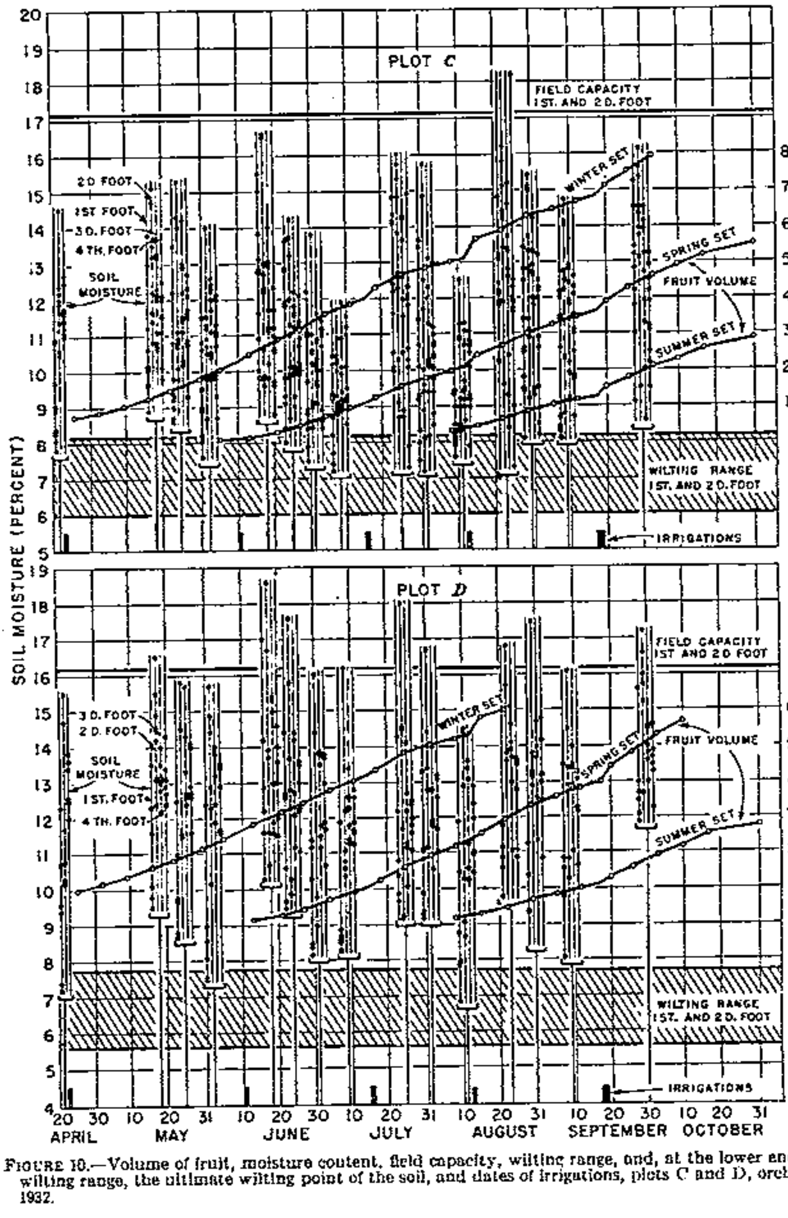

FIGURE 10.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots C and D, orchard M, 1932.

wilting range all season the trees on plot D suffered only slight water deficit.

The total seasonal growth of fruit on plots A–B, C, and D was not significantly different in spite of the differences in method of irrigation or in amount of soil wetted at each irrigation. The results on plots A–B and D indicate that lemon trees may receive an adequate water supply under the environmental conditions of these experiments if the moisture content of the soil in 50 to 60 percent of the area occupied by the root system is maintained at high values so that most of the roots in the wetted zone are always kept in contact with soil above the wilting range.

The treatment of plots H and I was designed to determine the effect of severe drying of the soil and subsequent irrigation in summer on the production of abnormally heavy bloom in late summer or early fall. The fruit-growth and soil-moisture data are presented (fig. 11) to show the relation between the apparent growth rate of fruit and the soil-moisture conditions when the trees were showing severe water deficit.

Plot I was not irrigated from May 7 to August 2, a period of 87 days. By June 24 the percentage of moisture of a few samples from the top foot of soil was in the wilting range, and the number of samples in this range gradually increased during July. The sampling of August 1 showed a large part of the top 2 feet of soil in the wilting range.

A comparison of the slope of the spring-set fruit-volume curves for plots H and I shows that the apparent growth rate of the fruit on plot I was appreciably less than that on plot H from July 4 to the time of irrigation of plot I on August 2. Before the application of water on August 2 the trees on plot I were shedding old leaves and showing some rolling of younger leaves during midday, a stage of water deficit in citrus which corresponds to temporary wilting in thin-leaved plants. During August and September the trees suffered only slight water deficit, as indicated both by apparent growth rate of fruit and by the soil-moisture percentages. The fruit-volume curves indicate that plot I suffered considerable water deficit during October.

Plot H was allowed to dry out during August. The fruit-volume curves show that the apparent growth rate of the fruit was reduced from about August 1 to September 6 by moisture deficit in the tree. The percentages of moisture in the soil samples fail to indicate the severe moisture shortage in the trees, since the samples taken on August 31 show only a small proportion with percentages in the wilting range. But as a matter of fact many of the trees were shedding old leaves and all trees on the plot showed rolling of the leaves at midday for several days before water was applied on September 6.

Since appreciable parts of the soil on plots H and I remained moist through these extended periods without irrigation, it may be concluded that the use of cover crops is essential if it is desired to dry the soil out more completely. Summer cover crops are apt to cause acute shortage of water in the trees unless there is enough additional water available to take care of the needs of both trees and cover crop. When additional water is not available, a cover crop may be grown in alternate middles and the remaining middles kept clean cultivated. (The term "middles" is used to designate the spaces between adjacent tree rows.) With a cover crop in alternate middles, all trees in the orchard may have readily available moisture in at least one-half of their root zone while the alternate middles are drying out. The trees may thus be maintained without serious water deficit while half of the soil in the orchard is being thoroughly dried out (*8*). This appears to be the most effective plan for drying out the soil in decadent orchards without causing serious water shortage in the trees and without the need of extra water for growing a cover crop. When alternate middles are being dried out, particular care should be used to keep ample moisture in the soil on the irrigated side of all trees. With the soil on only one side of the tree irrigated, the moisture

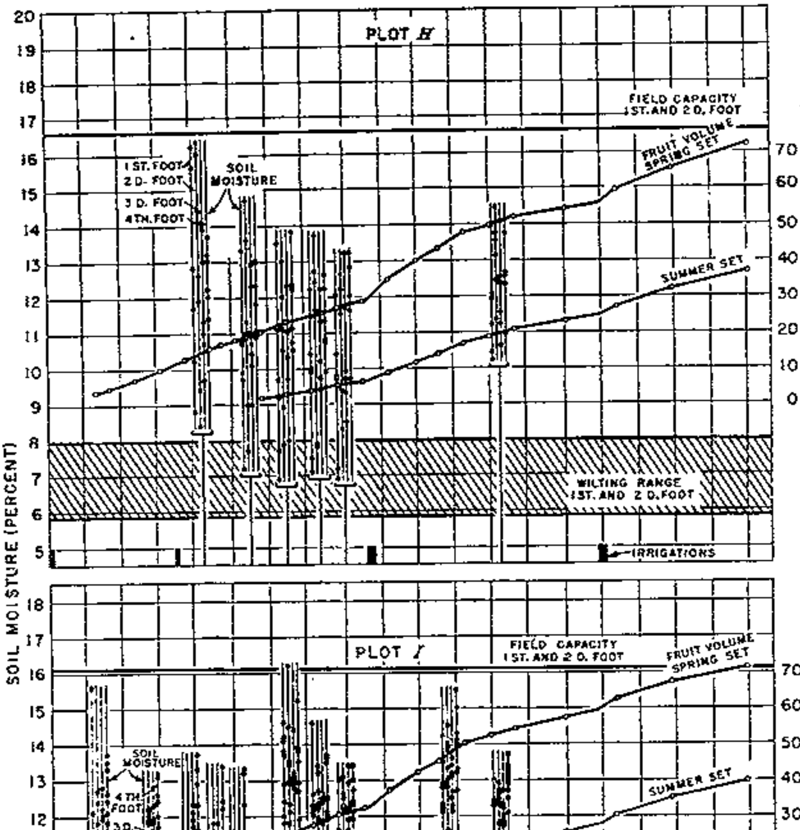

FIGURE 11.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots H and I, orchard M, 1932.

content of the irrigated soil should be maintained at slightly higher values than when all of the soil is wetted at each irrigation.

Orchard M is situated in the intermediate climatic zone of the south coastal basin of California in an area where the average amount of water used is 21 inches a year. Plot A–B, irrigated in alternate middles, received 26.0 inches of water in 1932, and plot C 25.9 inches. Extra water was required for these plots in order to wet all of the soil. Plot D received 20.6 inches of water in 1932 and was irrigated in a manner similar to the usual commercial practice in this area. On plot H one irrigation was eliminated and the seasonal application was 16.2 inches. Plot I had a period of drying out, but water was applied over 100 percent of the plot when it was irrigated, and the total for the season of 1932 was 22.2 inches.

Considering the results from all of the plots on orchard M in 1932, it is obvious that the relation between variations in soil moisture and the apparent fruit growth is not very definite. From an examination of the data on soil moisture alone it would be difficult or impossible to determine when the trees suffered water shortage. The charts illustrating the root distribution in this orchard show why average soil-moisture determinations are inadequate as a means of determining when the trees are suffering water shortage.

If in this orchard applications of irrigation water had not been made until the average moisture content of the top 3 or 4 feet of soil was in the wilting range, it is practically certain that most of the trees would have suffered rather severe water deficit before each irrigation. Though the relation between soil moisture and apparent fruit growth is obscured by the lack of uniformity of root distribution, the soil samples show that the moisture content of a part of the soil in the root zone had been reduced into the wilting range when reduction in apparent growth of fruits, which could be attributed to moisture shortage, occurred.

The average volume gain per fruit for the spring-set and summer-set fruits on the several plots of orchard M is shown in table 3. The differences are of doubtful significance, though possibly the smaller size of the summer-set fruits on plots H and I may have been caused by periods of severe water deficit.

These experiments were repeated in 1933 with substantially the same results. In 1933 the leaf-fruit ratios were determined by counts at monthly intervals of the leaves and fruits on five representative branches per tree. The leaf-fruit ratios were quite high, and there appeared to be little relationship between apparent growth rate and number of leaves per fruit.

TABLE 3.—*Average volume gain per fruit of spring-set fruit for the period June 23 to October 10 and summer-set fruit for the period August 8 to October 31, orchard M, 1932*

Plot	Spring-set	Summer-set	Plot	Spring-set	Summer-set
	Cc	*Cc*		*Cc*	*Cc*
A–B	48.2	27.2	H	45.8	20.9
C	45.7	25.4	I	48.6	24.1
D	53.9	25.7			

ORCHARD P, SEASONS OF 1932-34

Orchard P is located on a soil of the Placentia series. The surface soil is reddish-brown loam, friable when at the proper moisture content for cultivation, but sticky when wet. If cultivated when dry it pulverizes into flourlike dust. The surface soil in this orchard is 1 to 2 feet deep. The subsoil is red and very dense, and upon drying it cracks into columnar blocks.

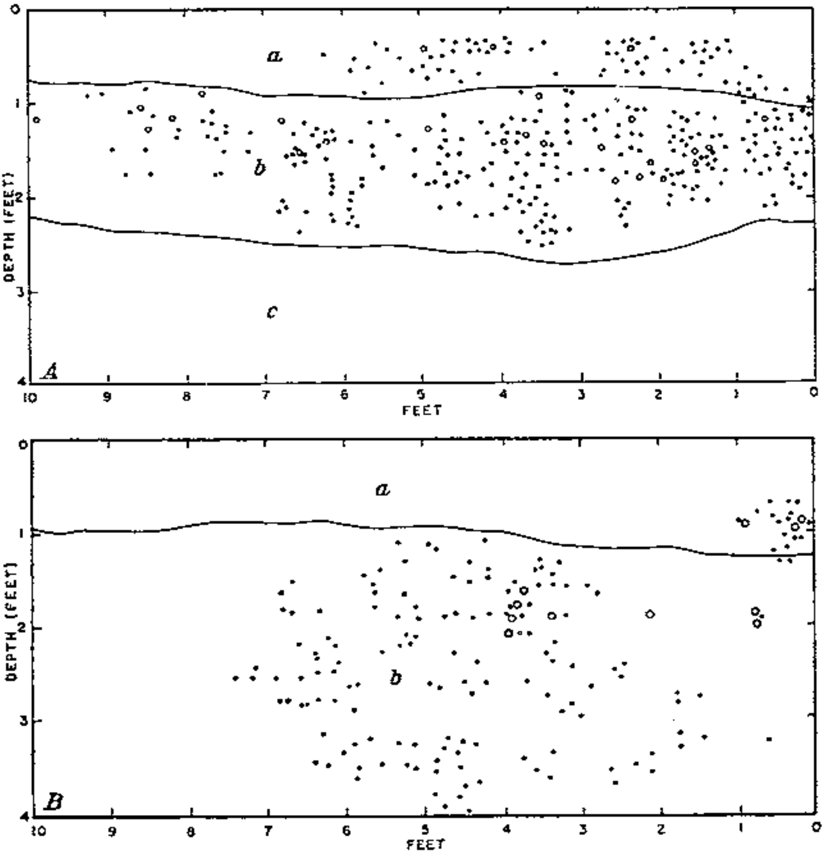

FIGURE 12.—Distribution of lemon tree roots in a soil profile in orchard P, Placentia loam. Circles denote lateral roots; dots, feeder roots. *A*, Location 4–9: *a*, Loam surface soil, darkened by organic matter, friable; *b*, clay loam subsoil, dense but cracked into columnar blocks; *c*, loamy clay, very dense, no cracks. *B*, Location 10–5: *a*, Loam surface soil, friable, deep cultivation probable cause of lack of roots; *b*, clay loam, increasing density from 1- to 4-foot depth, some rotten granite 3- to 4-foot depth.

The trees in this orchard are Eureka lemon, and in 1932 they were 13 years old. The trees were small, but the root systems were found to spread over the entire area between the rows and to extend to a depth of 3 or more feet, though in most of the profile the concentration of roots is very low. Figure 12 shows the root distribution in typical profiles in this orchard. It is clear from this chart that root distribution is quite variable. At location 4–9 (fig. 12, *A*) there are no roots below 2.5 feet, but there is a fair distribution in the upper 2.5 feet. At location 10–5 (fig. 12, *B*) there are few roots in the top foot. Below 1 foot depth the root population is not dense but extends to 4 feet, though there are large areas on the profile devoid of roots. Several other profiles examined in this orchard showed wide variation in root distribution, though in general the highest concentration of roots was found in the top 2 feet of soil.

In orchard P four plots of three or four rows, each plot separated by one border row, were laid out.

The purpose of the experiments on plots A and B of orchard P was to determine the effect of differences in soil-moisture content on the total seasonal growth, the apparent growth, and the yield of fruit.

The treatments on plots C and D were given to determine the effect of severe water deficit followed by an ample water supply on the stimulation of flowering, but the data on fruit-volume increase and soil moisture are presented in this bulletin since they show the response of the trees to severe water shortage.

The treatments applied were as follows:

Plot A.—The entire area except a very narrow strip along the tree line was irrigated by furrows. It was planned to irrigate at such frequent intervals that the trees would show little or no water shortage.

Plot B.—The middles, comprising about 80 percent of the soil area, were irrigated, and the tree lines were unirrigated all season. It was planned to make the intervals between irrigations long enough to cause a measurable water deficit in the tree before each irrigation.

Plots C and D.—Plots C and D were dried out severely in the summer, but except for the one period of severe water deficit, irrigations were sufficient to prevent acute water shortage. On both plots the entire area, except a narrow strip along the tree line, was wetted at each irrigation. Plot C was allowed to dry out in July 1932, plot D in August 1932.

The fruit-volume measurements of the winter-set, spring-set, and summer-set fruits and the percentage of moisture of samples from the top 4 feet of soil from plots A and B are shown in figure 13. It is apparent that the most rapid reduction in soil-moisture content following wetting occurs in the top foot of soil on both plots A and B.

On plot A the apparent growth rate appears to have been unaffected by changes in soil moisture until about the last of June. The sampling of July 2 indicates that most of the soil in the top foot was close to the wilting range. Samples from the 2- to 4-foot zones were all well above the wilting range. The sampling on August 9 showed that the percentage of moisture of most of the samples from the top foot were again close to the wilting range.

After the irrigation on July 14 the apparent growth rate was high until July 25. From then until the next application of water on August 11 the apparent growth rate indicated water shortage. The samplings on July 22 and 29 showed that all of the soil was above the wilting range, and on August 9 two samples in the top foot were in the wilting range. By August 29 the apparent growth rate had again declined, and the soil samples taken on this date show that the moisture content of only two samples in the top foot were close to the wilting range.

The apparent growth rate of fruits on plot B indicated that the water deficit of the trees just before the applications of irrigation water was somewhat greater than for plot A, and the moisture contents of more samples were in the wilting range on plot B. The area of soil wetted on plot A was greater than on plot B, and it is possible that this was a factor of some importance in this orchard where a large part of the root activity is in the first foot of soil. For the period of June to September, inclusive, plot A received four applications of water and plot B only three.

Table 4 shows that there was an appreciable difference in total seasonal growth of the fruits on the two plots. The number of trees on plots A and B was so large that, in spite of nonuniformity of trees

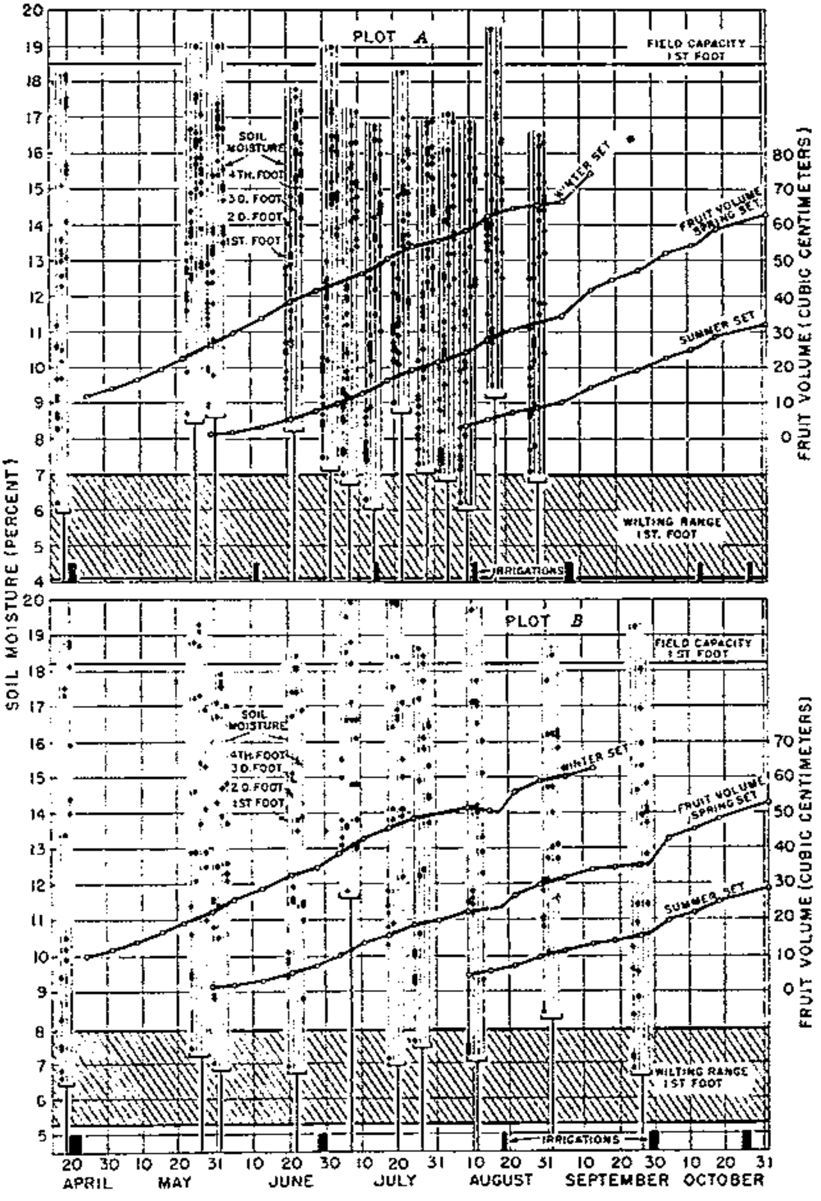

FIGURE 13.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots A and B, orchard P, 1932.

and lack of yield records before the treatments were applied, it seems likely that the differences in yield on these plots for the period covering the harvest of fruits that were affected by the treatments may be significant. There were 36 record trees on plot A and 45 on plot B. The average yield per tree for the period from June 27, 1932, to May 29, 1933, was: Plot A, 111.9±5.3 pounds; plot B, 96.9±4.4 pounds. The increased yield per tree of plot A over that of plot B was roughly 15 percent. The average volume gain per fruit on plot A over that of plot B as indicated by the fruit measurements was roughly 20 percent. The discrepancy between yield and fruit-volume data may possibly be accounted for by the fact that some of the fruits were scarcely affected by the treatments during the early part of the harvest period.

TABLE 4.—*Average total volume gain per fruit of winter-set, spring-set, and summer-set fruits, plots A and B, orchard P, 1932*

Plot	Winter-set, Apr. 25 to Sept. 13	Spring-set, May 30 to Nov. 1	Summer-set, Aug. 9 to Nov. 1
	Cc	*Cc*	*Cc*
A	62.0	61.0	28.0
B	52.5	50.5	24.0

In the fall of 1932 the trees in orchard P were partly defoliated by wind. Almost no fruit was set in the spring of 1933, so that the trees carried only the fruits set in the fall of 1932. The irrigation treatments in 1933 were similar to those of 1932. The most striking result of the 1933 treatments was the effect of the water supply of the trees on the rate at which they recovered a normal leaf surface. The shoot growth and production of leaves on plot A were strikingly superior to those of plot B. In the spring of 1934 the trees were again carrying a normal leaf surface and a normal crop of fruit. Except that plot B was subjected to greater water deficit before application of irrigation water in 1934 than in 1932, the irrigation treatments of plots A and B in 1934 were similar to those in 1932.

The records from the trees on plots A and B in 1934 during the spring months of April, May, and June showed that for a period of 10 to 15 days after the fruits had gained full turgor following irrigation the apparent growth rate was relatively uniform at 0.6 to 0.7 cc per day. After this brief period of rapid volume gain the rate of gain gradually decreased. In plot B this gradual decrease continued for 30 days before water was applied. At the end of this period the rate of gain was 0.3 cc per day. The trees were not wilted, and doubtless the fruits would have continued to increase in size for some time longer without application of irrigation water; but many leaves were showing the change from bright green to a dull yellowish tinge characteristic of lemon trees after prolonged water shortage. It appears that on this soil type the widely dispersed roots in the subsoil continue for a long time to extract sufficient water to prevent wilting and to allow continued growth of fruit at a low rate.

The results obtained on plots C and D, which were subjected to severe water shortage during one irrigation interval, are shown in figure 14.

Plot C was irrigated on April 20, 1932, but received no more water until August 5. The trees were apparently already suffering water shortage when the fruit measurements were begun on June 23. The soil samples taken on July 20 and 27 showed that the moisture content of the top foot was relatively low. For 18 days after the irrigation on August 5 the apparent growth rate showed no decline, but between

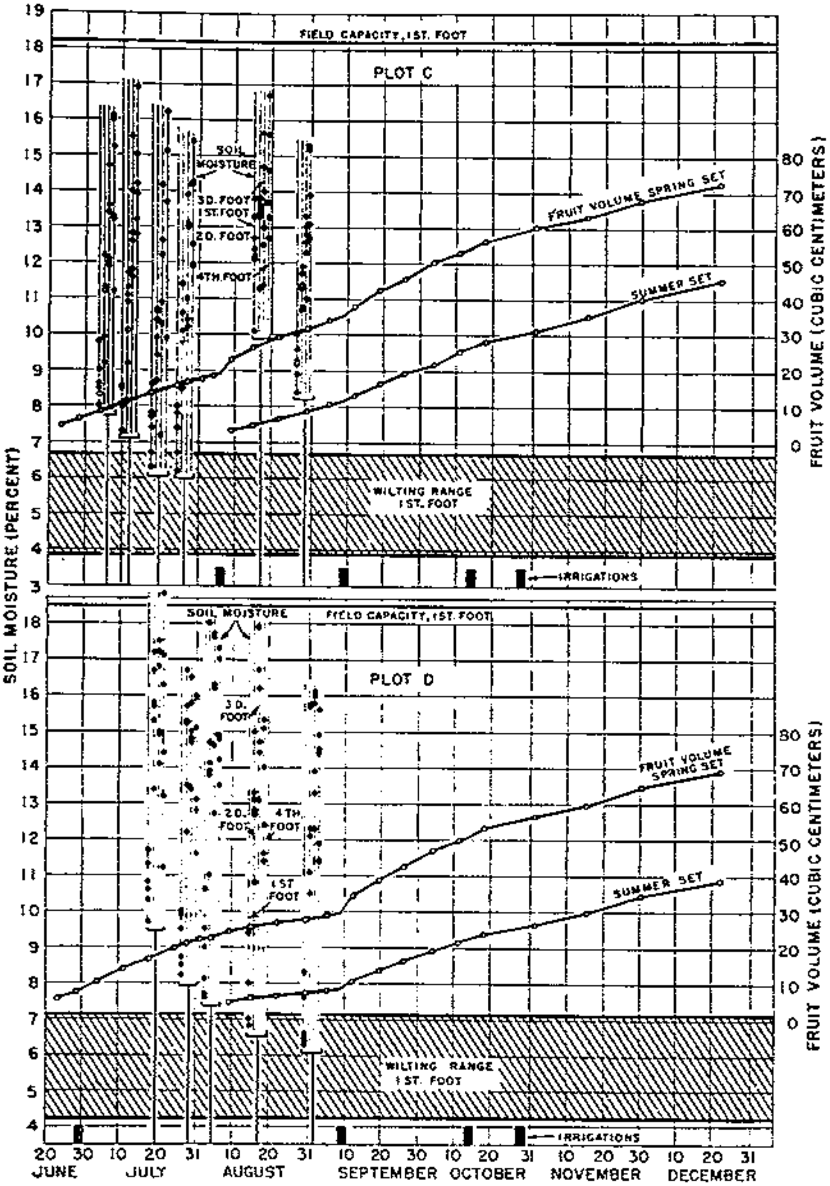

FIGURE 14.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots C and D, orchard P, 1932.

August 22 and 30 the rate of volume gain indicated water deficit. The sampling of August 29 showed that the moisture content of the first foot of soil was low, but all samples were above the wilting range. From September 9 to October 4 no water deficit was indicated by the apparent growth rate. From October 18 to December 22 the apparent growth rate was relatively uniform but was lower than during September. All plots of both orchards M and P showed this drop in apparent growth rate, which was undoubtedly due to unfavorable weather conditions, and in orchard P also to partial defoliation of the trees by wind.

After the application of water on plot D on June 28, the fruit-volume curve shows that the volume increased at a uniform rate until July 28. From then until the application of water on September 8 the apparent growth rate gradually decreased. The moisture content of the first foot of soil decreased rapidly, and that of the second, third, and fourth feet slowly, from July 20 to September 1. On September 1 part of the first foot of soil was in the wilting range.

It is obvious that it would be difficult to tell when to irrigate from the soil-moisture determinations alone. Appreciable water deficits developed in the trees when the general level of soil moisture was relatively high. In both orchards M and P root distribution was irregular and rates of extraction of moisture varied greatly. There were many locations at which no measurable extraction of moisture occurred at depths of 2, 3, and 4 feet. Rates of extraction of soil moisture were made after the manner illustrated in the discussion of figure 7. A summary of all the determinations made during the season of 1932 is given in figure 15. The results are condensed into a frequency distribution showing the number of determinations for each foot in depth that fall in various classes of extraction from 0 to 3.20 acre-inches per acre per 30 days. It is obvious from these frequency curves that the principal root activity is in the first foot of soil in both orchards and that there is great variation in root activity at all depths.

An interesting feature of this comparison is that rates of extraction were highest in the top foot of soil at certain locations in orchard P, although the trees were much smaller than in orchard M. The reason for this appears to be in the difference in soil types. The surface foot of soil in orchard P is a friable loam, but the underlying subsoil is dense and contains a considerable percentage of colloidal clay. Although roots have penetrated the subsoil, movement of moisture in this material is slow, and moisture is extracted much more readily from the looser topsoil. It is apparent from figures 13, 14, and 15 that the top foot of soil is quickly reduced to low values while the moisture contents of lower depths are still high, and it is doubtful if this condition can be changed. Suction pressures high enough to extract an adequate supply of moisture from the denser soil quickly reduce the moisture content in the topsoil so that attempts to dry out the lower soil horizons will certainly cause severe water deficit in the trees. Frequent light applications of water to the topsoil are indicated as desirable for orchards on this soil type.

From the records given for these two orchards it is evident that averages of soil-moisture contents would have little value in interpreting the results. Where root activity is so variable it would be illogical to set up plots where the variations were based on different average minimum soil-moisture percentages. As successive portions of the root zone are dried out the tree must obtain its water supply from the remaining roots, and it is of importance to know how much

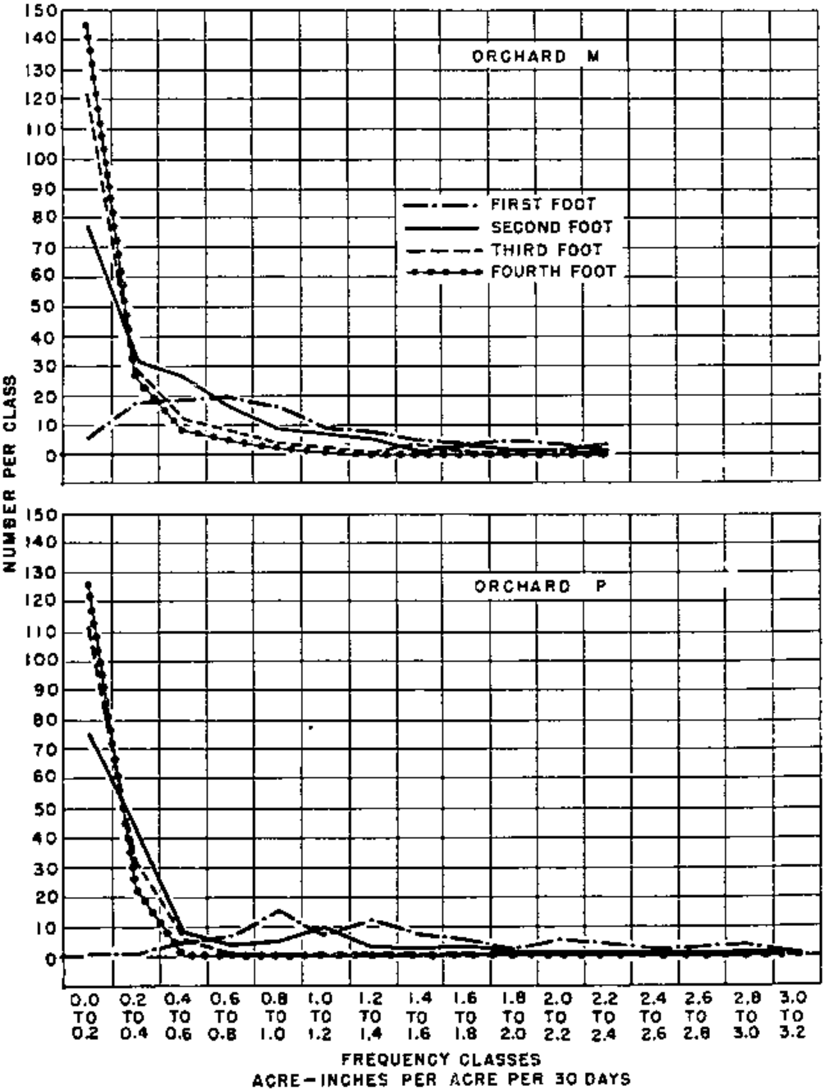

FIGURE 15.—Frequency distribution of rates of extraction of soil moisture in orchards M and P, May 15 to October 15, 1932.

of the root zone requires irrigation. It has been shown (*8*) that there is a ready cross transfer of water even in old lemon trees with fluted trunks; hence the tree may get ample water from the irrigation of limited parts of the root zone provided extraction rates are high enough in the portion wetted. The variations in proportion of soil wetted within the limits used on orchards M and P apparently made little difference in the water supply to the trees, even though there was considerable difference in the total amounts of water applied to different plots.

INFLUENCE OF MOISTURE CONTENT IN ONE PART OF THE ROOT ZONE ON EXTRACTION OF WATER FROM SOIL IN OTHER PARTS

Results of the experiments in orchard M failed to show that a measurable reduction in the water supply of the tree occurred when only 50 to 60 percent of the soil area was wetted at each irrigation. It might be supposed from this result that the rate of extraction of water from the irrigated zone alone was higher than it would have been if the entire soil area occupied by the tree had been wetted at each irrigation. An experiment was carried out to determine whether the rate of extraction of moisture from the wetted soil in one part of the root zone may be affected by leaving unirrigated various proportions of the soil area occupied by the tree. Four mature Washington Navel orange trees were used for this test. These trees were growing in a loam soil that has a rather uniform field capacity of 15 percent in the top foot. It was originally planned to use three trees in this experiment and to determine "base" rates of extraction under uniform treatment before applying the differential irrigation treatments. However, at the time these treatments were applied a tree from another test plot (tree D) was added to this experiment. This accounts for the variation in treatment of tree D from that given the other three trees (A, B, and C) which will appear from the following description of the determination of the base rates of extraction that were obtained before the differential treatments were applied.

On August 7 approximately 100 percent of the soil area occupied by trees A, B, and C was wetted to 3 feet or more in depth. Samples were taken from four locations around each tree to a depth of 3 feet at approximately weekly intervals until September 8.

The top foot of soil appeared to be the most uniform zone with respect to field capacity and rate of extraction, and the average rate of extraction from the top foot of soil around each tree from August 7 to 19 was taken as the base rate of extraction. The last irrigation water that tree D received before the differential treatments were given was applied on July 13 to approximately 80 percent of the area occupied by the tree. The rate of extraction of moisture from the top foot of wetted soil around tree D from July 13 to 30 was taken as the base rate for this tree. Obviously, the base rate of tree D is not quite comparable to the base rates of trees A, B, and C.

On September 8 water was applied to different proportions of the areas occupied by each tree as follows: Tree A, 100 percent; tree B, 50 percent; tree C, 25 percent; tree D, 6 percent. Just before this application of water was made, trees A, B, and C had been subjected to only slight water deficit, as indicated by apparent fruit-growth records, but tree D was suffering severe water shortage. The rates of extraction of moisture by trees A, B, C, and D from the top foot of wetted soil (below the plow mulch), in percentage of moisture per day, and the relative rates (based upon tree A=100) are given in table 5 for periods before and after the differential treatments were applied.

TABLE 5.—*Rates of extraction of moisture by Washington Navel orange trees from the top foot of soil before and after differential irrigation treatments*

Tree	Preliminary treatment					Differential treatment				
	Area wetted		Rate of extraction from wetted area			Area wetted		Rate of extraction from wetted area		
	Date	Percent	Period	Actual (percent per day)	Relative[1] (percent per day)	Date	Percent	Period	Actual (percent per day)	Relative[1] (percent per day)
A	Aug. 7	100	Aug. 7–19	0.35	100	Sept. 8	100	Sept. 8–24	0.256	100
B	do	100	do	.375	107	do	50	do	.331	129
C	do	100	do	.40	114	do	25	do	.400	156
D	July 13	80	July 13–30	.253	72	Sept. 10	6	Sept. 10–14	.98	383
						Sept. 14	6	Sept. 14–22	.612	239

[1] On basis of tree A = 100.

From the data in table 5 it is apparent that the relative rate of extraction from the wetted soil was increased slightly when the wetted area was reduced from 100 percent to 50 percent of the total occupied by the tree, was increased somewhat more when reduced to 25 percent, and was greatly increased when the wetted area was reduced to 6 percent of the total. The rate of extraction from the wetted soil of tree D during the period September 10 to 14 was almost 1 percent per day. Rates of this order have been obtained with pot cultures, in which the concentration of roots per unit of soil was abnormally high, but have not been obtained under usual orchard conditions. In this experiment tree D was subjected to severe water shortage before water was supplied to the wetted area; and though the water deficit, as indicated by fruit measurements, was reduced appreciably by the application of water to 6 percent of the soil area, the water supply received from the small part of the root system in wet soil was not sufficient to enable the tree to recover full turgor during the night or to prevent temporary wilting during midday. Absorption by the roots in moist soil must have been continuous and at high rates for 24 hours per day.

Though the relative rates of extraction from the wetted soil of trees B and C were increased following the reduction in the area wetted, the increase in rate was not proportional to the decrease in area wetted. It may be presumed that the total water supply of the trees was reduced slightly or greatly depending upon the proportion of the soil wetted. The apparent growth rates of fruit on tree D after September 8 showed clearly that this tree suffered severe water shortage, but the apparent growth rates on trees A, B, and C appeared to be unaffected by differences in water supply from September 8 to 19. From September 19 until the trees were irrigated on October 6 the apparent growth rate of fruit on tree C gradually declined as compared with that of trees A and B. No difference was apparent between trees A and B. In spite of the fact that the base rate of extraction from the wetted soil of tree D was not entirely comparable to the base rates of trees A, B, and C, it seems unlikely that this could have appreciably affected the results, since the change in the rate of extraction in the wetted soil of tree D was so great.

While this field experiment was not extensive, and somewhat different relative rates of extraction would doubtless be obtained if the experiment were repeated on other trees, the general conclusion that the rates of extraction in the wetted portions of the soil may be higher

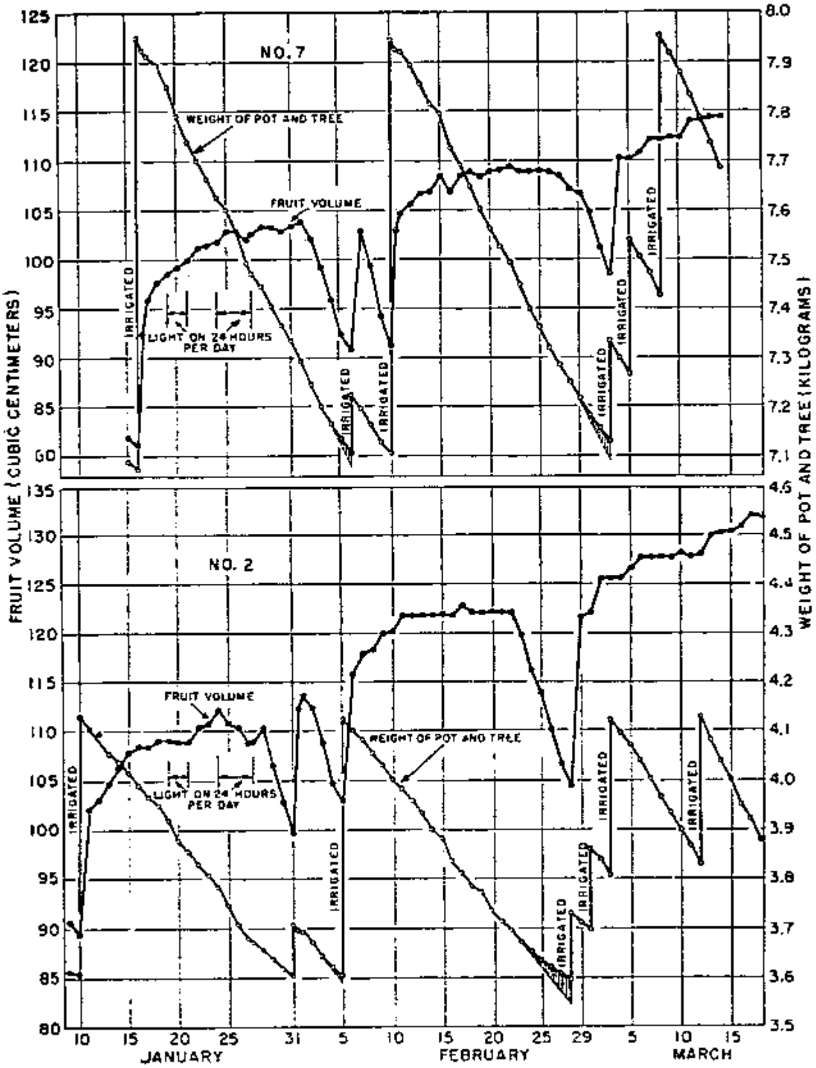

FIGURE 16.—Fruit volume changes and transpiration rate (as weight loss of pot and tree) of potted lemon trees Nos. 7 and 8 following wetting all or some part of the soil to field capacity.

when part of the soil in the root zone is left unirrigated than they would have been if the entire soil mass occupied by the tree had been wetted has been confirmed by transpiration experiments with potted lemon trees.

Figure 16 shows the transpiration rates, as loss of weight of pot and tree, and the changes in fruit volume following wetting of all or of some part of the soil. These plants were grown under artificial light at relatively uniform temperature and relative humidity. The plants were exposed to light for about 14 hours per day except for two periods when the light remained on for 24 hours per day.

The soil in which tree 7 was grown was raised above field capacity January 16. From February 1 to 6 a marked decrease in fruit volume occurred. There was a decrease in transpiration from February 4 to 6 because of water shortage. The departure from the unrestricted rate of transpiration is shown by the shaded area on the graph. It may be assumed that on February 6 the soil was in the wilting range. On this date the moisture content of approximately one-third of the soil was raised to field capacity by irrigation. From February 6 to 7 the fruit swelled to almost the size that it had attained on February 1, but decreased in size from February 7 to 10. On February 10 the volume was about the same as on February 6. The transpiration rate as shown by the loss of weight of pot and tree was only slightly less from February 6 to 10 (29.7 g per day) than during the period of February 2 to 6 (34.2 g per day). That is, with about the same total amount of available water the transpiration rate was not greatly different, though for the period of February 2 to 6 this amount was distributed throughout the soil of the entire root system, while for the period of February 6 to 10 it was contained in the soil of about one-third of the root system. On February 10 the soil of the entire root system was wetted above field capacity. On March 3 the soil was again in the wilting range. On this date less than half of the soil was wetted to field capacity. From March 3 to 5 the average transpiration rate was 33 g per day, while the rate for the comparable period with about the same amount of water distributed throughout the whole soil mass, February 25 to 28, was 37 g per day. On March 5 more of the soil was wetted to field capacity. From March 5 to 8 the transpiration rate was 36.6 g per day. This was only slightly less than the average rate for the period of February 10 to 25, 39.9 g per day.

The soil mass in which tree 2 was grown was about half that in which tree 7 was grown, yet the response of tree 2 to treatments similar to that given tree 7 was about the same. In each case the transpiration rate was slightly less when some fraction of the soil was wetted to field capacity than when it was all wetted to field capacity, but it appears that the rate of moisture extraction must have been appreciably increased in the wetted part of the soil when the remainder of the soil was in the wilting range.

In the two foregoing experiments the discussion was confined to the effect of wetting to field capacity a part of the soil while the remainder was left relatively dry. It is not to be supposed from the results of these experiments that in the irrigated part of the soil the rates of extraction are increased without further irrigation in the zones of low root concentration after the soil has become relatively dry in the zones of high root concentration.

Beckett, Blaney, and Taylor (*3*) have shown that the rates of extraction of moisture from the lower depths of soil do not increase as the soil in the upper layers dries out to the wilting range. Likewise, in the present investigation it has been found that the rates of extraction in the zones of low root concentration do not increase as the moisture content of the soil in the zones of higher root concentration approaches the wilting range. This is not a surprising result, since, doubtless, the increase in the energy required to move water to the root surface through considerable distances in the soil at least keeps pace with the increase in suction pressure of the roots as the soil dries out.

It has been demonstrated that when water deficit in the tree is caused by removal of part of the root system the turgor of the fruit on the different main branches is affected alike (*8*). It seems reasonable to suppose that when the tree is suffering water shortage the turgor deficit of all parts of the root system is also nearly the same. However, when considerable differences exist in the average moisture content of soil in different parts of the root zone, probably equilibrium in suction pressure is never quite attained between roots in regions of high and low average soil-moisture content. Except for this difference, the suction pressure acting on the soil moisture at the root surface must be about the same in all parts of the root system. If this is true, it is obvious that the rate of extraction of moisture from soil in different parts of the root zone is affected by the magnitude of the suction pressure of the roots, by the concentration of roots per unit volume of soil, and by the moisture content of the soil.

This theory seems entirely consistent with the observed facts. It explains the fact that the soil dries out most rapidly in the zones of highest root concentration, and that when the soil in most of the root zone is relatively dry and the water deficit of the tree high, the rate of extraction from soil wetted to field capacity in a small part of the root zone is extraordinarily high.

If this conception is correct it is to be expected that, in orchards where a part of the soil in the root zone is wetted at each irrigation and a part left without irrigation during the dry season, the extraction of moisture from the soil in the unirrigated zone ceases before all of the available moisture has been extracted, if the trees received sufficient water from the wetted zone to prevent wilting.

Throughout the course of these investigations it was generally found that all available moisture was not extracted from the soil in the unirrigated area along tree rows in furrow-irrigated plots, even though this soil was not wetted by rain or irrigation water for 6 months or more during the hottest part of the year.

Furthermore, it appears that the average minimum moisture content to which the unirrigated soil in the tree line was reduced was largely determined by the duration and severity of water deficit to which the trees were subjected. In plots that were maintained at such high moisture contents in the irrigated zone that the trees recovered approximately full turgor each night, the moisture content of the soil in the unirrigated tree line was reduced to approximately the upper end of the wilting range. In plots in which the soil of the irrigated zone was periodically allowed to become so dry that the trees were subjected to temporary wilting, the moisture content of the soil in nonirrigated zones was reduced to values near the ultimate wilting point.

Data illustrating this principle are shown in table 6. These data were taken from the records of experiments, described more fully later in this bulletin, which were carried out in orchards S, M–W, and W. Orchard S is on heavy soil, M–W on medium soil, and W on light soil. The treatments applied on plots A, B, and C of these orchards are briefly as follows: In the irrigated zones of the A plots the soil was kept relatively moist all the time; that of the C plots was allowed to dry out before each irrigation until the trees were subjected to moderate water deficit; in the B plots the soil of the irrigated zone was allowed to dry before each irrigation until the trees showed severe water shortage.

TABLE 6.—*Average soil-moisture content in unirrigated and irrigated sections of orchards M–W, S, and W, in 1935*

Orchard, date, and plot	Unirrigated section				Irrigated section			
	First foot	Second foot	Third foot	Fourth foot	First foot	Second foot	Third foot	Fourth foot
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Orchard M–W, Aug. 16:								
Plot A	13.4	15.1	15.2	15.0	-------	-------	-------	-------
Plot B	10.6	12.3	13.1	14.2	10.0	11.3	12.2	13.7
Orchard S, Sept. 26 to Oct. 7:								
Plot A	15.7	19.0	18.8	19.0	23.6	25.0	24.6	23.8
Plot B	15.8	18.1	17.6	17.0	19.0	20.1	20.5	20.0
Plot C	17.3	18.4	19.9	19.7	21.1	20.6	21.8	21.1
					Under trees		In middles	
					First foot	Second foot	First foot	Second foot
Orchard W, Oct. 9 to 14:								
Plot A	6.6	5.8	6.0	-------	10.2	7.5	12.6	9.1
Plot B	2.6	2.7	2.5	-------	3.9	-------	8.0	6.6

On August 16 water had not yet been applied to plot B of orchard M–W, while plot A had been irrigated three times and the moisture content of very few samples from the irrigated zones of plot A had been reduced to the wilting range up to August 16. It may be noted from table 6 that the moisture content of the unirrigated section of plot B is appreciably below that of plot A.

In September and October, when the samples were taken in orchard S, the trees of plot B were not under as severe water deficit as they had been just before the irrigation of August 30, but it may be noted that the moisture content of the nonirrigated section of plot B is lower than that of plots A and C.

The dry tree lines of orchard W were sampled October 11, when the trees of plot B were suffering from severe water shortage. The moisture content of the irrigated section of plot A was so high all season that the trees on this plot did not suffer from shortage of water. The moisture content of the nonirrigated section of plot B was only slightly above the ultimate wilting point on October 11, while that of plot A was above the wilting range.

It is apparent that this principle—that the absorption of moisture from the soil by roots in one part of the root zone is affected by the magnitude of the water deficit in the tree and by higher or lower soil-moisture contents in other parts of the root zone—is of considerable significance in interpreting the results of field experiments in which irrigation water is applied to the soil in only a part of the root zone.

In the spring the entire soil mass occupied by the tree is usually near field capacity. By midsummer extraction has practically ceased in the nonirrigated tree line, yet trees apparently receive an adequate water supply from the part of the root system in the wetted soil. Doubtless the water supply of the trees would be better, at least during periods of severe weather, and probably the trees would attain greater size at maturity, if all the soil were irrigated; but undoubtedly under usual weather conditions the reduction in absorption caused by drying of the soil in the nonirrigated zone is partly compensated for by increased rate of absorption by the roots in the wetted zone.

The fact that all available moisture is not absorbed in the dry tree line as long as the trees are prevented from permanent wilting by wetting the irrigated zone explains why the roots in the nonirrigated zone are not injured by desiccation.

With this theory as a basis, the writers have attached little importance to the average soil-moisture percentage of the irrigated zone, but rather have considered that reduction into the wilting range of the moisture content of the soil of even a small proportion of the irrigated zone indicated that the trees were subjected to more or less water deficit. That is, the reduction of the moisture content of a part of the soil from field capacity into the wilting range in the relatively short period of an irrigation interval indicates that the tree as a whole developed fairly high suction pressure, since it was found that after months without irrigation the moisture content of the soil in the dry tree lines in the A plots of orchards S, M–W, and W had been reduced to only about the upper end of the wilting range.

EFFECT ON FRUIT GROWTH OF DIFFERENCES IN IRRIGATION INTERVAL

The work on orchards M and P demonstrated that it would not be sound practice to use soil-moisture records for establishing basic differences in plot treatments. Varying the degrees of water deficit as indicated from measurements of fruit appeared to be the more logical method to use in setting up plot variations. Accordingly, it was determined that plot differences for the 1935 season would be based on the degree of water deficit as indicated from fruit measurements.

Plots of lemon trees were chosen in three orchards, one on a stony sandy loam, another on a loam, and a third on clay loam. Three treatments were used on each soil type so that the time interval between irrigations was short, medium, and long. Because the furrows in the orchard on the medium soil type were 500 feet long, two plots were set up for each treatment, one located in the upper 250 feet of tree row and a duplicate plot located in the last 250 feet of the same tree row. The treatments on each orchard were designated as A, B, and C; A for the short interval between irrigations, B for the long interval, and C intermediate. The differences were to be determined as follows:

Treatment A (short interval).—Irrigation water was applied at such short intervals that little or no decrease in apparent growth rate of fruit occurred as a result of water deficit.

Treatment B (long interval).—Irrigation water was applied when apparent fruit growth had almost or entirely ceased, or when the trees began to show excessive leaf drop or rolling of the leaves.

Treatment C (intermediate).—Irrigation water was applied at the first significant decrease in the apparent growth rate that could be attributed to water deficit in the tree.

Trees under treatment A recovered approximately full turgor each night; those under treatment B at the time of irrigation were at a stage of water deficit probably corresponding to temporary wilting of thin-leaved plants that show wilting readily; those under treatment C at the time of irrigation were under a relatively slight water deficit.

The purposes of these experiments were:

(1) To determine how the total fruit growth for the season is influenced by periodically subjecting trees to little or no measurable water deficit, to severe water deficit, and to moderate water deficit, as indicated by the apparent growth rate of fruit.

(2) To determine the relation between apparent growth rate of fruit and the moisture content of the soil.

(3) To compare the response of trees on widely different soil types to the several degrees of water deficit described.

Inasmuch as the plots kept under little or no measurable water deficit would receive irrigations more frequently than in usual commercial practice, these plots were watched for evidence of injury from overirrigation. In this sense the use of the term overirrigation is meant to imply the maintenance of a relatively high level of soil-moisture content throughout the irrigation season.

ORCHARD W (LIGHT SOIL)

Orchard W is located on an outwash fan, which had been cleared of large boulders before the trees were planted. The surface soil is stony sandy loam, dark brown, and fairly high in organic matter. At a depth of 2 to 4 feet the surface soil of the plots is underlain by coarse gray sand and gravel, practically free of silt. Many large rocks are scattered through the soil. As shown in figure 17, the coarse sand-gravel layer contains almost no roots. The greatest concentration of roots occurs along the tree lines, that is, within about 5 feet of the tree trunk. The soil in the middles, i. e., about midway between tree rows, has been packed by heavy implements, tractors, etc. In some areas few roots are found in the top foot of soil in the middles. Though the root zone is irregular, it is in general confined to a layer of soil 2 to 4 feet thick.

In spite of the limited root zone of the trees in orchard W, they are quite vigorous and highly productive. This type of soil is considered particularly well suited to lemons. The trees are Eureka lemon on sour orange rootstock and were 20 years old in 1935.

The curves representing the average volume per fruit, the lines representing the observed wilting range, the observed ultimate wilting point, and field capacity, and the bar graphs showing the percentage of moisture in each soil sample of plots A, B, and C, are shown in figure 18. Plots A, B, and C were given treatments A, B, and C, respectively.

From the time the fruits of plot A had attained a volume of about 20 cc until October 15, when hot, dry winds occurred, the volume curves form almost straight lines.

Soil samples taken from the middles between rows and those taken from the irrigated areas under the spread of the branches are shown separately in the graphs. This separation was made because the moisture content of samples from under the trees was consistently lower than that of those from the middles. In the case of plot A it will be noted that all samples taken during the season had moisture contents above the observed wilting range. The break in the fruit-volume curve just before the irrigation of June 29 indicated that the trees of plot A suffered a slight water shortage for a few days before that date, but for the remainder of the season until October 15 plot A suffered no measurable water deficit. Since there was no evidence that the trees on plot A were injured by the relatively high soil-moisture content either during the irrigation season or during the following winter and spring, the apparent growth rates of fruit on plot A may be used as a control with which the apparent growth rates on plots B and C may be compared.

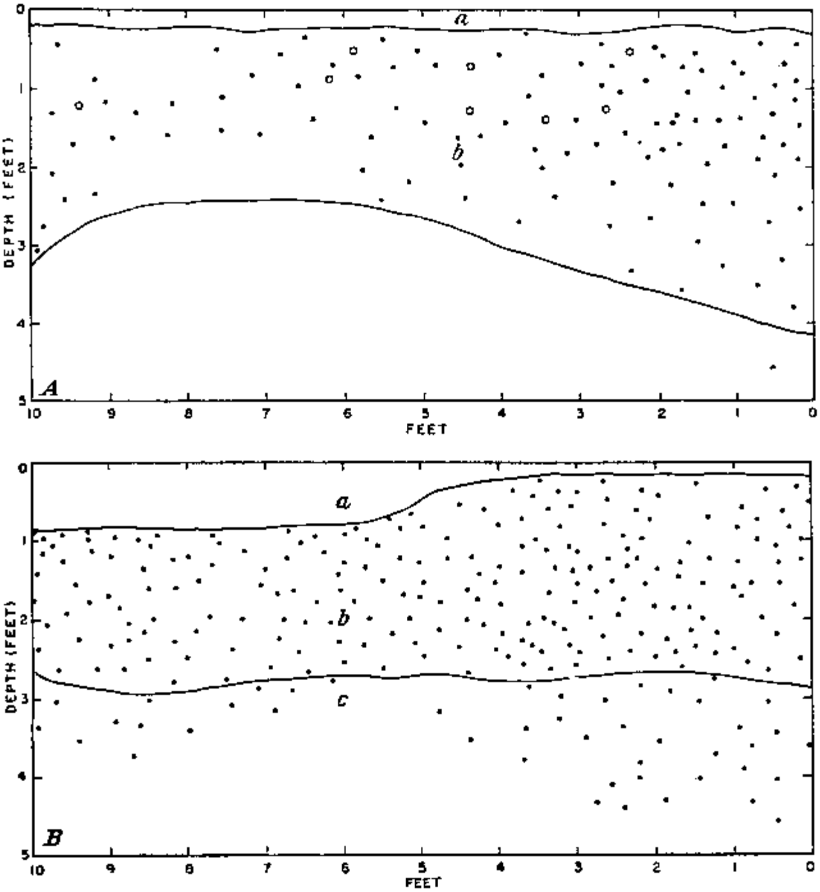

FIGURE 17.—Distribution of lemon tree roots in a soil profile in orchard W, outwash soil. Circles denote lateral roots; dots, feeder roots. *A*, Location 29–7: *a*, Plow mulch; *b*, sandy, gravelly loam, darkened by organic matter, very friable; *c*, coarse sand and gravel, almost free from silt, not compact. *B*, Location 27–7: *a*, Plow mulch and compact soil; *b*, sandy, gravelly loam, darkened by organic matter, very friable; *c*, course sand and gravel, almost free from silt, not compact.

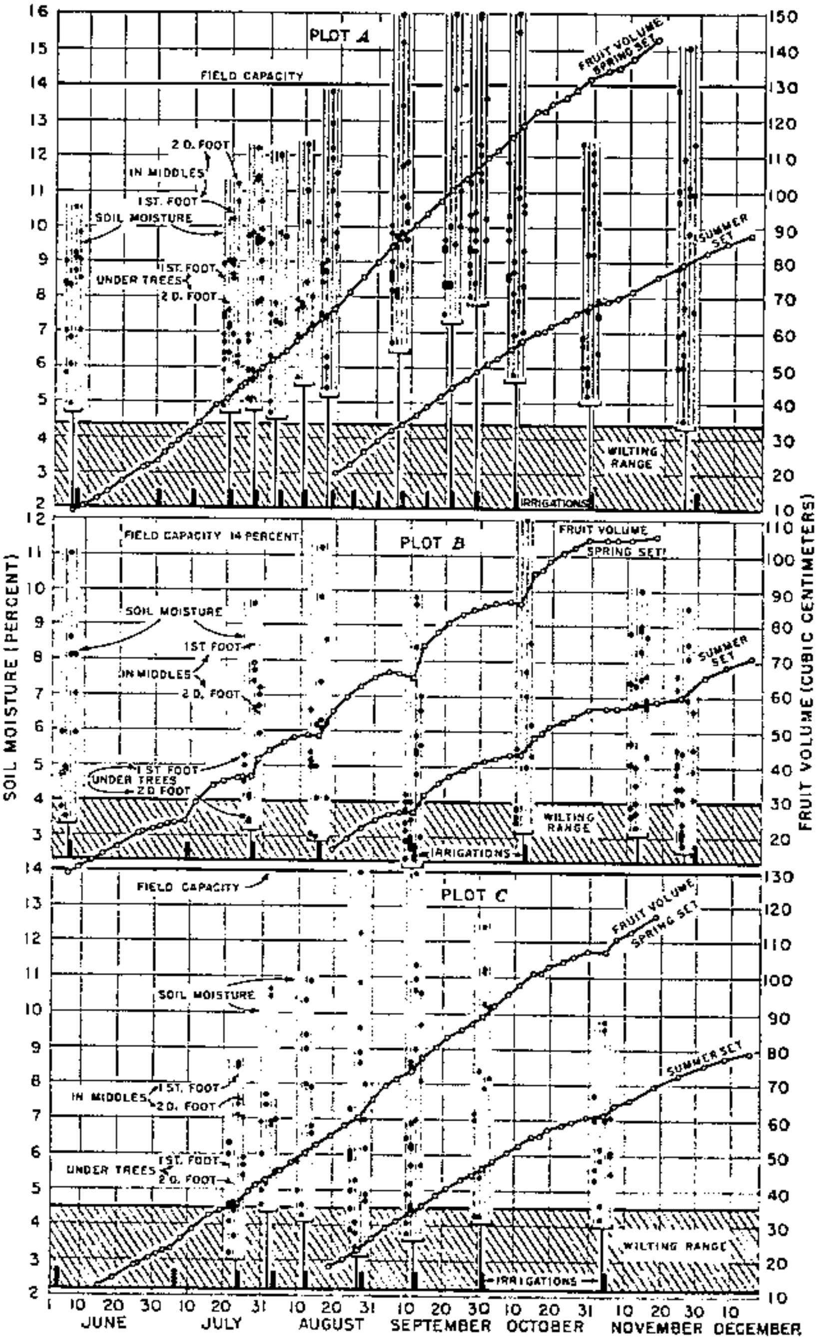

FIGURE 18.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots A, B, and C, orchard W, 1935.

During each irrigation interval, water was withheld from plot B until the apparent growth of fruit had ceased. In some cases the older fruits were shrinking. The fruit volume curves for plot B in figure 18 flatten out or drop just before each irrigation and rise sharply after the application of water.

Because of the extreme difficulty of sampling in this rocky soil, the number of samples taken was not so great as might be desirable. However, the moisture content of the samples from under the trees where root concentration was greatest and most uniform had a rather narrow range of moisture percentages. Probably the samples from under the tree represent fairly accurately the moisture conditions in the zones of high root concentration.

All soil samples from this plot were screened to 2 mm, and the moisture percentages were based on the oven-dry weight of the soil passing the 2-mm screen. This procedure gives higher values for moisture contents than when the moisture content is based on the entire aggregate collected in the sample, but the values are less subject to variation when small samples are taken. An appreciable amount of moisture is held on the rocks just after irrigation, so that the 14-percent value for field capacity appears high. This same soil when free of rocks larger than 2 mm has a field capacity of about 12 percent. At each sampling on the dates of irrigation the moisture contents of some of the samples from under the trees were in the wilting range; and on September 10, the date on which the fruit-volume curves show that the water deficit in the trees was more severe than during any other period of the year, several samples show moisture contents near the ultimate wilting point. The fact that at each sampling date the moisture contents of a few samples were in the wilting range shows that the trees on plot B had developed a high suction pressure as a result of the great water deficit. During the summer months the fruit-volume curves showed a rather abrupt change from volume increase to volume loss, but in November, under conditions of low evaporation, the period of change was rather extended.

The fruit-volume curves for plot C show that the trees were subjected to a moderate water deficit just before each application of water. The soil samples taken just before applications of water show that the moisture content of part of the soil under the trees had been reduced into the wilting range on each sampling date except that of August 3. These data on fruit-volume increase and soil-moisture content show that on this soil type the trees recover approximately full turgor during the night until some part of the soil in the root zone reaches the wilting range.

The results on plots A, B, and C of orchard W indicate that, so long as all the soil in the root zone is above the wilting range, variations in moisture percentages above the wilting range have no measurable effect on the apparent growth rate of fruit. However, it is apparent that the relation between soil-moisture content and apparent fruit growth would be badly obscured if the average soil-moisture content of these plots instead of that of individual samples had been plotted. Even on plot B the average moisture content of the soil was above the wilting range all season. The results on these plots also show the futility of attempting to determine when irrigation water should be applied on this soil type from moisture determinations on composite soil samples or from averages of a number of samples taken without regard to the distribution of roots.

The total growth made during the season by the fruit measured at frequent intervals on plots A, B, and C, and also the growth of a supplementary lot of 100 fruits per plot measured on August 19 and on December 8, are shown in table 7. The differences in fruit growth on plots A and B are unquestionably significant, and possibly the differences between plots A and C are significant. The trees on plot B were badly defoliated by desiccating winds that occurred October 15 to 17, in spite of the fact that plot B had been irrigated on October 12 and suffered less water shortage, as indicated by apparent fruit growth, than plot A during the period of dry winds. At the end of the irrigation season and early in the following spring (1936) the trees on plot A were much more densely foliated and the leaves were a darker green than those of plot B. In May 1936 there were numerous bare twigs that failed to push leaves on the trees of plot B, and some were dead or dying. The appearance of the trees on plot C was poorer than that of the trees on plot A, but those on plot C were somewhat less vigorous than those on the other two plots when the test was started.

TABLE 7.—*Average total volume gain per fruit of spring set and summer-set fruits during the period of measurement, orchard W, 1935*

Plot	Fruit measured at frequent intervals		Supplementary lots of fruit	
	Spring-set, June 15 to Nov. 18	Summer-set, Aug. 19 to Dec. 15	Spring-set, Aug. 19 to Dec. 8	Summer-set, Aug. 19 to Dec. 8
	Cc	*Cc*	*Cc*	*Cc*
A	128.2	67.5	79.7	67.4
B	91.0	54.0	60.7	47.9
C	106.6	60.7	72.4	66.0

ORCHARD M-W (MEDIUM SOIL)

Orchard M-W is located on a Yolo loam soil having a moisture equivalent of 22 to 25 percent. This soil is friable, dark brown, and relatively permeable to water. Trenches were not dug for observations of root distribution in this orchard, but the relatively uniform extraction of soil moisture suggests that root distribution must be fairly uniform in the top 3 feet of soil. The trees are the variety Villafranca, and they were 19 years old at the time the experiments were conducted.

In this orchard the irrigation runs were 25 trees long. Plots A, B, and C were laid out in the upper half and plots D, E, and F in the lower half of the irrigation run.

Plots A and D were given treatment A, plots B and E were given treatment B, and plots C and F were given treatment C, as described on pages 43 and 44.

In figure 19 the fruit-growth and soil-moisture data for plots A, B, and C are shown graphically. The lines representing the wilting range and the ultimate wilting points are the observed values obtained by growing sunflowers in closed containers of the soil.

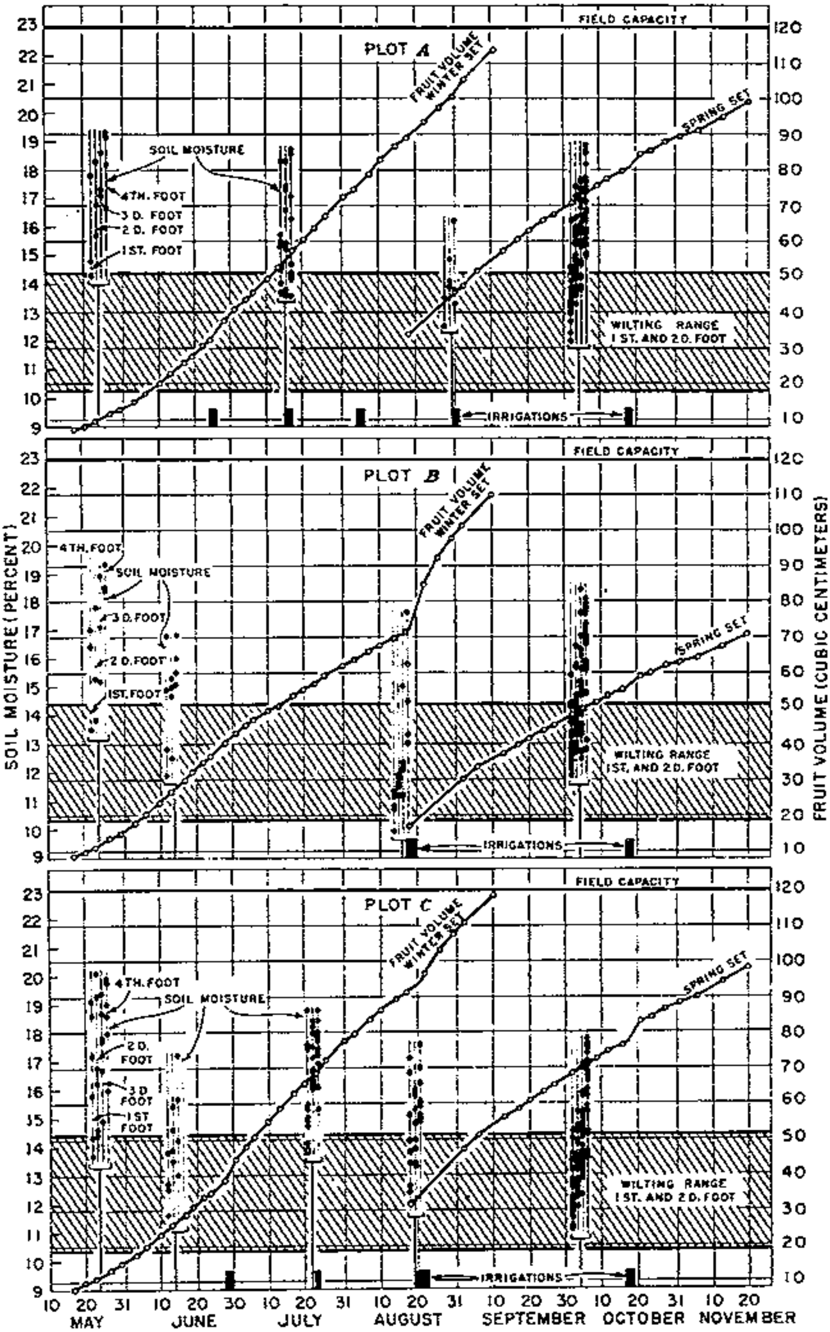

FIGURE 19.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots A, B, and C, orchard M-W, 1935.

The fruit-volume curve for the winter-set fruit on plot A is an approximately straight line from June 10 when the fruits were about 20 cc in volume until the fruits were harvested, September 10. The slight increase in apparent growth rate just after the applications of irrigation water on June 24, July 15, August 4, and August 30 indicates that these trees were subjected to a slight water deficit just prior to these irrigations. Several of the soil samples taken from the top 3 feet of soil on July 15 and on August 30 had moisture contents in the wilting range. The soil samples taken on October 4 show that the moisture content of an appreciable part of the top 3 feet of soil had been reduced into the wilting range.

To have maintained the scheduled treatments on plots A and D, water should have been applied about September 25, but because of unavoidable circumstances it was not possible to apply water until October 17. By that time the soil was drier and there had developed a water deficit greater than that at the time of the earlier irrigations.

The fruit-volume curve for plot B shows that the winter-set fruit made approximately uniform increases in volume from June 6, when the fruit had a volume of 20 cc, until about July 1; but from July 1 until water was applied on August 17, the trees on this plot suffered a gradually increasing water deficit. The soil samples taken on June 14 showed two samples in the first foot and one in the second foot in the wilting range, but the fruit-volume curve indicated no water shortage in the trees until about 2 weeks later

The soil samples taken on August 16, just before irrigation, indicate that practically all of the first 2 feet of soil and most of the third foot were in the wilting range. The appearance of these trees just before they were irrigated on August 17 clearly showed that they were suffering a severe water shortage. The leaves were slightly curled during midday and were a much lighter green than the leaves on plots A and C, and the old leaves had begun to drop. In spite of the severe water shortage, the fruits were still making about half of the normal volume gain per day. The response of these trees to water shortage is typical of that of trees with an extensive and deep root system. The response to water shortage made by trees on the outwash land of orchard W, where most of the roots are confined to a layer of soil a few feet thick, shows some resemblance to the response of trees growing in a small mass of soil in a pot; that is, the water supply is apparently exhausted relatively more abruptly, as compared with the gradual decrease in soil-moisture supply of the trees on heavier soil. The behavior of the trees in orchard M-W suggests that moisture obtained by roots at depths below 3 feet was sufficient to cause partial recovery of turgor at night and to allow photosynthesis to occur for at least a part of the normal daily period for a long time after readily available moisture was depleted in the upper zones of soil.

The soil samples taken October 4 show that on this date the moisture content of about half of the soil in the top 3 feet had been reduced into the wilting range again. The change in apparent growth rate after the irrigation of October 17 suggests that the trees were not suffering a severe water deficit in spite of the low soil-moisture content in the top 3 feet of soil. Apparently during the cool weather and short days of October the reduction in soil-moisture content had less effect in increasing the moisture deficit of the trees than earlier in the season.

On plot C the fruit-volume curve for the winter-set fruit shows two periods of moderate water shortage. The soil samples taken on June 14, 2 weeks before the irrigation of June 30, show that part of the soil in the top 3 feet had reached the wilting range, and by June 30 doubtless a larger proportion of the soil was in the wilting range. The decrease in the rate of fruit-volume gain was scarcely significant just before the irrigation of July 23, and the soil samples taken on July 22 show that most of the soil was above the wilting range. The decrease in volume gain just before the irrigation of August 20 was more pronounced, and the soil samples taken on August 19 show that part of the soil in the first 2 feet was in the wilting range.

The fruit-volume curve representing the spring-set fruit of plot C indicates a slight water deficit in the trees about October 4, the date on which soil samples were taken. At this time the moisture content of over half of the soil in the top 3 feet had been reduced into the wilting range. Apparently, under conditions of relatively low evaporation, the trees did not suffer water shortage until the moisture content of a larger proportion of the soil had reached the wilting range than was the case during the summer months.

The results obtained on plots D, E, and F are shown in figure 20. These plots were duplications of A, B, and C, except that they were on the lower end of the irrigation runs and the soil was not wetted to as great a depth by the irrigation water as on plots A, B, and C. This effect was most pronounced on plot F, and water deficits of trees on plot F were higher than on plot C, resulting in growth rates on plot F being more comparable to that on dry than on intermediate treatments.

With this exception, the general trend of the fruit-volume curves is the same on the duplicate plots. On plot E the soil samples taken on August 16 and October 4 approach the ultimate wilting point more closely than the samples taken on plot B on the same dates, and it was observed, just prior to the irrigation of August 17, that the drop of old leaves was heavier on plot E than on plot B.

A comparison of the total gain in volume of fruits is given in table 8. The total growth was less on the plots on the lower halves of the irrigation runs in all cases. Also, the total growth on plots B and E was significantly less than under the other treatments.

TABLE 8.—*Average volume of winter-set and spring-set fruits at the beginning and end of the period of measurement, and total average volume gain per fruit for the season, orchard M-W, 1935*

Plot	Winter-set fruit			Spring-set fruit		
	Volume		Volume gain, May 17 to Sept. 10	Volume		Volume gain, Aug 18 to Nov. 20
	May 17	Sept. 10		Aug. 18	Nov. 20	
	Cc	*Cc*	*Cc*	*Cc*	*Cc*	*Cc*
A	7.0	113.6	106.6	33.4	98.8	65.4
B	8.1	109.9	101.8	16.5	70.1	53.6
C	7.9	118.2	110.3	31.5	98.3	66.8
D	10.5	104.7	94.2	32.7	94.8	62.1
E	10.7	101.3	90.6	15.3	64.4	49.1
F	12.3	106.3	94.0	25.7	80.7	55.0

The most striking effect of the period of water shortage was on the size of the spring-set fruit. The flush of bloom that gave rise to the spring-set fruit occurred at the same time on all plots, so that the age of the spring-set fruit was approximately the same on all plots. The largest fruits of this set were selected for measurement on all plots, so that the samples tagged were comparable. It may be noted in table 8 that on August 18 the fruits on plots B and E were about half the size of those on plots A, C, D, and F. The growth rate of the spring-set fruit on plots B and E was obviously greatly reduced during the period of water shortage in July and August. The rather narrow range of soil-moisture percentages found on the different sampling dates is evidence that root distribution in orchard M–W was fairly uniform; and the fact that growth of the fruit continued on plots B and E up to August 17, when water was applied, in spite of the fact that most of the soil in the top 3 feet was in the wilting range on August 16, shows that many roots extended considerably below 3 feet in depth.

The results on orchard M–W show that apparent growth rate of fruit was not reduced as a result of decreasing soil-moisture content until the moisture content of some of the soil in the top 3 feet reached the wilting range. The total average growth per fruit for the season was not reduced as a result of the moisture content of appreciable parts of the soil in the top 3 feet being reduced into the wilting range, even though, as was indicated by reduced apparent fruit growth, there was moderate water deficit in the tree. From the results on plots B and E it appears that reducing the moisture content of most of the soil in the top 3 feet into the wilting range and allowing it to remain dry for a considerable period caused a significant reduction in the total growth and final size of the fruit. However, the reduction in the final size of the older fruit on plots B and E of orchard M–W, which were subjected to one rather prolonged period of water shortage during the season, was much less than the reduction in final size of the older fruits of plot B, orchard W, which were subjected to several short periods of severe water shortage.

ORCHARD S (HEAVY SOIL)

Orchard S is located on a clay loam soil of the Yolo series. This soil has a field capacity of 26 to 32 percent, is highly fertile, appears black when wet, is very permeable to water, and when cultivated at the proper moisture content breaks into small angular aggregates.

The trees in orchard S are Eureka lemon on a sour rootstock, and they were about 20 years old in 1935.

The distribution of roots in the top 5 feet is shown in figure 21. Though the spacing of roots is not uniform, there appears to be relatively little decrease in root concentration to a depth of 5 feet, and samples taken with a soil tube to a depth of 10 feet showed that rootlets were fairly numerous to that depth.

Plots A, B, and C of orchard S were given, respectively, treatments A, B, and C (pp. 43 and 44).

Figure 22 shows the fruit-volume curves, the soil-moisture percentages, observed wilting range, and observed ultimate wilting-point values for plots A, B, and C.

The fruit-volume curves for plot A show that there was some variation in rate of fruit-volume gain during the season, but there

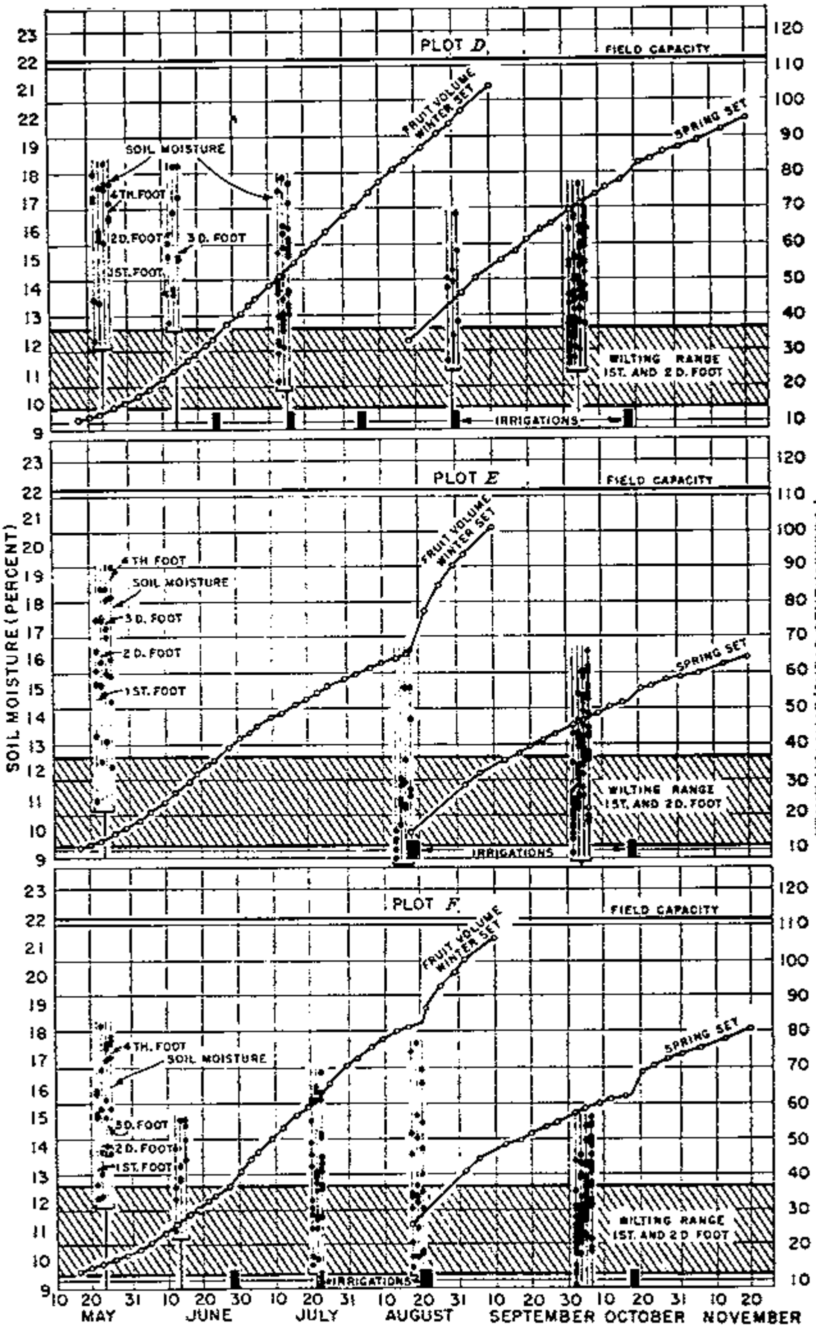

FIGURE 20.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots D, E, and F, orchard M-W, 1935.

was no indication of water shortage. The soil-moisture percentages indicate that the soil in the top 3 feet remained above the wilting range until at least the end of September.

On plot B the first application of water was made August 29. The fruit-volume curve for winter-set fruit shows that the trees did not suffer a water shortage until early July. From about July 5 until the irrigation of August 29 the rate of fruit-volume gain decreased, indicating a gradual increase of moisture deficit in the trees. The soil samples taken just before irrigation on August 29 show that the moisture content of all of the soil in the first 2 feet and practically all of that of the third and fourth feet was in the wilting range. For several days before the application of water the trees on plot B were shedding some of the older leaves and were showing some leaf curl, but there was sufficient recovery of turgor each night to show that the leaf curling corresponded to temporary wilting only, and the fruits were still showing measurable volume gains up to the time water was applied.

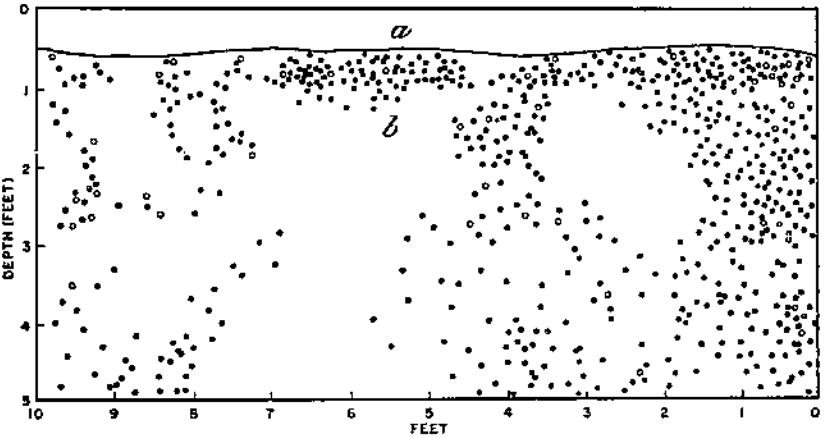

FIGURE 21.—Distribution of lemon tree roots in a soil profile in orchard 8, location 4-5, Yolo clay loam. Circles denote lateral roots; dots, feeder roots: *a*, Plow mulch; *b*, dark-brown clay loam grading into light-brown loam, containing some shale, which increases with depth.

The spring-set fruit of plot B regained full turgor following the irrigation of August 29. The fruit-volume curve for this set of fruit shows no decrease in rate of volume gain until October 3. From October 3 until October 29 there was a decrease in the rate of volume gain on plot B, but there was also a slight decrease in rate of volume gain on plot A during this same period. From October 29 to December 15 growth rate was affected by low temperature and it was difficult to tell whether or not the apparent growth rate was affected by water shortage on plot B. The soil samples taken October 7 show that the moisture content of a fairly large part of the soil in the 4 feet sampled was in the wilting range, and the samples taken December 11 show that the top 4 feet of soil were about as dry on this date as on August 29. The rapid increase in volume of fruit from December 11 to 15 shows that the trees had been subjected to some moisture deficit, but that it was far less severe than that just before the irrigation of August 29. Apparently under the weather conditions of November

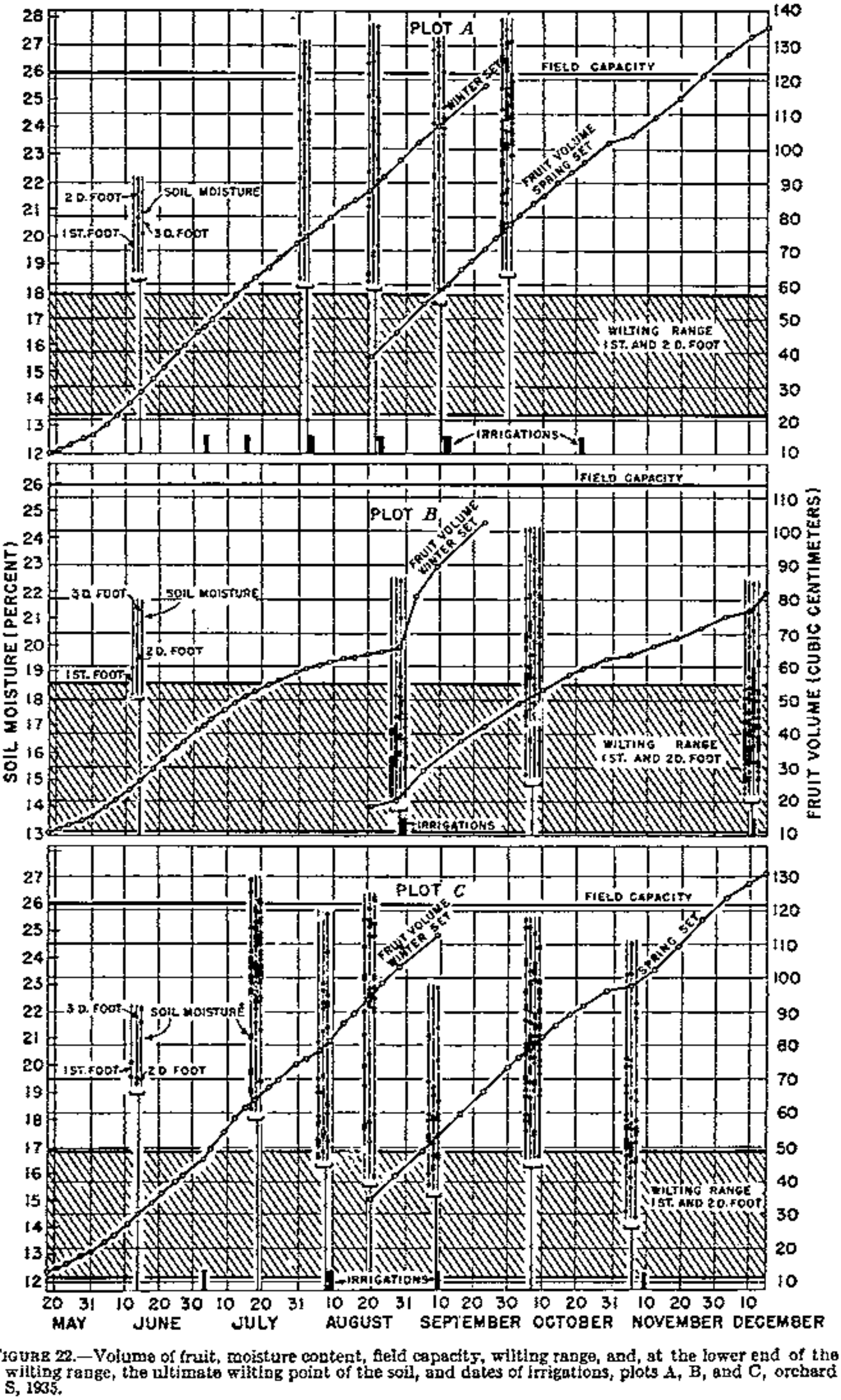

FIGURE 22.—Volume of fruit, moisture content, field capacity, wilting range, and, at the lower end of the wilting range, the ultimate wilting point of the soil, and dates of irrigations, plots A, B, and C, orchard S, 1935.

and December the trees of plot B were able to extract water fast enough to prevent severe water deficits under about the same soil-moisture conditions as prevailed in August when the trees showed severe water deficits.

The fruit-volume curve for the winter-set fruits on plot C shows that the trees on this plot were subjected to a slight water shortage just before the irrigation of July 3, and again from July 30 to August 9. The fruit-volume curve for the spring-set fruit indicates little or no water deficit from August 20 until October 18. From October 18 to November 9 the decrease in apparent growth rate on plot C was greater than on plot A, a fact that suggests some water deficit. The soil samples taken on November 6 show that the moisture contents of a fairly large number of samples were in the wilting range on this date.

In addition to the fruits that were measured at frequent intervals, supplementary lots of 100 spring-set fruit were tagged and were measured on August 19 and December 8. The volume of the winter-set and spring-set fruit of each plot at the beginning and end of the period of measurement and the total gain in volume of each lot of fruit are shown in table 9. The difference in total volume gain for plots A and C was probably not significant, while the total volume gain of plot B was significantly less than that on plots A and C.

TABLE 9.—*Average volume of winter-set and spring-set fruits at the beginning and end of the period of measurement, and total volume gain for the season, orchard S, 1935*

Plot	Winter-set fruit			Spring-set fruit			Spring-set fruit, supplementary		
	Volume		Volume gain, May 18 to Sept. 9	Volume		Volume gain, Aug. 21 to Dec. 15	Volume		Volume gain, Aug. 19 to Dec. 8
	May 18	Sept. 9		Aug. 21	Dec. 15		Aug. 19	Dec. 8	
	Cc	*Cc*	*Cc*	*Cc*	*Cc*	*Cc*	*Cc*	*Cc*	*Cc*
A	9.5	106.8	97.3	38.4	135.7	97.3	33.3	122.1	88.8
B	11.0	89.5	78.5	18.7	81.8	63.1	16.5	76.9	60.4
C	12.6	112.5	99.9	34.2	131.4	97.2	33.5	124.6	91.1

The spring-set fruits on plots A, B, and C were approximately the same age, since they all set from a flush of bloom that occurred simultaneously on the three plots. The largest and most vigorous fruits of this set on each plot were selected for measurement, therefore the fruit on the three plots were comparable samples. It may be seen from table 9 that the spring-set fruits on plot B were about half the size of those on plots A and C on August 21. This difference in size was caused by the long period of water shortage during July and August on plot B.

In general the results in orchard S show that as long as the moisture content of all the soil was above the wilting range the apparent growth rate of fruit was unaffected by variations in soil moisture, which means that as long as all the soil was above the wilting range the trees recovered approximately full turgor at night. A comparison of plots A and C shows that on plot C the moisture content of fairly large proportions of the soil in the principal root zone was reduced into the wilting range several times during the season, and that the apparent growth rate of fruit indicated a slight moisture shortage several times, but that the total growth of fruit for the season was as great on plot C as on plot A, which suffered no moisture shortage. Apparently in this orchard, even during the summer months, the final size of fruit was not reduced until the moisture content of some appreciable part of the soil dropped into the wilting range. But the results on plot B show quite clearly that, before the moisture content of all the soil in even the principal root zone was reduced into the wilting range, the apparent growth and the total growth of fruit for the season were greatly reduced.

There was no indication, either during the irrigation season of 1935 or in the spring of 1936, that the trees on plot A were injured in any way by high soil-moisture content maintained during the irrigation season of 1935.

In all orchards water deficit was observed to increase gradually as the irrigation intervals were extended, so that it cannot be said that these trees either have readily available moisture or have not, as Hendrickson and Veihmeyer concluded from studies with peaches (*9*). With citrus trees a gradual rise in water deficit becomes apparent from fruit measurements as the irrigation interval is extended. Root activity varies so widely (fig. 15) that the tree does not run out of water abruptly, as the readily available moisture is extracted from the whole soil mass. Parts of the soil may reach the wilting range very quickly, and the supply of moisture is obtained with gradually increasing difficulty as more and more of the soil is reduced in moisture content into the wilting range. Higher suction pressures gradually develop in the tree and maintain transpiration even though water is obtained from the soil reservoir with increasing difficulty. Moderate water deficits have no lasting effect, but prolonged periods of water shortage depress total seasonal growth.

In making comparisons of the soil-moisture conditions under the different treatments, the wilting range, as determined with well-established sunflower plants, was considered to represent the range of soil-moisture percentages in which extraction of moisture took place at reduced rates. With soil-moisture contents above the wilting range, sunflower plants obtained water readily and without wilting. Similarly, in the field, zones of greatest root concentration were reduced to the upper end of the wilting range without any measurable decrease in the rate of extraction of moisture from the soil. However, the distribution of roots was not sufficiently uniform in any of the orchards to reduce the moisture content of the soil uniformly. Averages of soil-moisture contents from several sampling locations by foot depths have not been used because the deviations from the means were so great. In the orchard many samples may be found with moisture contents in the wilting range while others are still near field capacity. The moisture contents of zones of greatest root concentration seem to be the most reliable for use in making comparisons between plots.

In the most frequently irrigated plots, moisture contents of some parts of the root zone reached the upper end of the wilting range without affecting growth rates. When the intervals between irrigations were extended, moisture contents dropped farther down into the wilting range and some approached the ultimate wilting point. Nevertheless, it was not possible to reduce the moisture content of all the soil in any zone, such as the top foot, into the wilting range without reducing the true rate of growth of fruit. The proportion that may be reduced to the wilting range is indeterminable from soil-moisture records alone, and fruit-growth records seem to be the most promising index of needs for irrigation.

APPARENT GROWTH RATES OF FRUIT, SEASON OF 1935

The average daily rate of volume gain or loss per fruit of plots A, B, and C in orchards W, M–W, and S for the season of 1935, and the mean daily rate of evaporation of water from a shallow-black-pan evaporimeter are shown in figure 23. The dates on which irrigation water was applied are indicated by the solid bars lettered to indicate the plots irrigated on certain dates. The points on the rate of volume gain or loss curves indicate the mean rate per day of gain or loss in average volume per fruit for the intervals between measurements just preceding the points. The curves for plots A are continuous; those for plots B and plots C are broken at each irrigation date.

The rate of volume gain increased on all plots until the fruit had attained an average volume of about 20 to 25 cc. From that time, which on most plots was about June 20, the rate of gain on plots that received the A treatment (p. 43) was relatively uniform until after October 17. The period after October 17 is shown only for orchard W. The rate curves for orchards M–W and S are for winter-set fruits, which were harvested in September.

The volume gain or loss curves for the B plots of orchards W, M–W, and S show in a striking manner the differences in response of the fruit to decreasing moisture on the three soil types. On the sandy soil of orchard W the decrease in rate of volume gain from one irrigation to the next was abrupt, and after the period of rapid gain just after irrigation the rate decreased with remarkable uniformity until the fruits had ceased to gain or were actually losing in size. On orchard M–W, plot B, the rate of volume gain decreased from about June 19 to July 10, but from this date for over 30 days the rate persisted at between 0.5 and 0.75 cc per day. On plot B of orchard S the rate of volume gain, except for several rather abrupt fluctuations probably caused by weather changes, decreased steadily from June 21 to August 29.

The rate of volume gain of fruit on plots B and C of orchards M–W and S was usually higher than that of fruit on the A plots for some time after irrigation of the B or C plots. It would seem that the trees on plots B and C should have recovered full turgor within 3 or 4 days after irrigation, but, as was shown earlier in this bulletin (fig. 5), after irrigation the increase in percentage of moisture is abnormally high in fruit that had been subjected to appreciable water deficit for some time before irrigation. There is, of course, the possibility that dry-weight gain also was higher on plots B and C than on plots A during the period of accelerated volume gain, but the evidence available on this point is inconclusive.

Citrus fruits have been shown to be sensitive indicators of water deficit within the tree, and apparent growth rate of fruit may be used as an index of need for irrigation. In all plot work conducted in 1935 the relative degrees of water deficit decided upon for the different plots were based on records of apparent growth rates of fruit. Intervals between irrigations were thus established from apparent growth rates.

TRUE GROWTH RATE OF FRUIT, SEASON OF 1935

True growth rates of fruit have been used to measure the differences resulting from the effects of treatments. However, over short-time intervals the true rate of growth is obscured by the continual changes in water content of the fruit on plots with extended intervals between irrigations. Comparisons of water deficits under different treatments are relative only as between plots, and no absolute values were established for degrees of water deficit; hence, no corrections could be applied to apparent growth rate to obtain true growth rate over short intervals of time when the water content of the fruit was changing. For this reason, true growth rates could not be computed for incre-

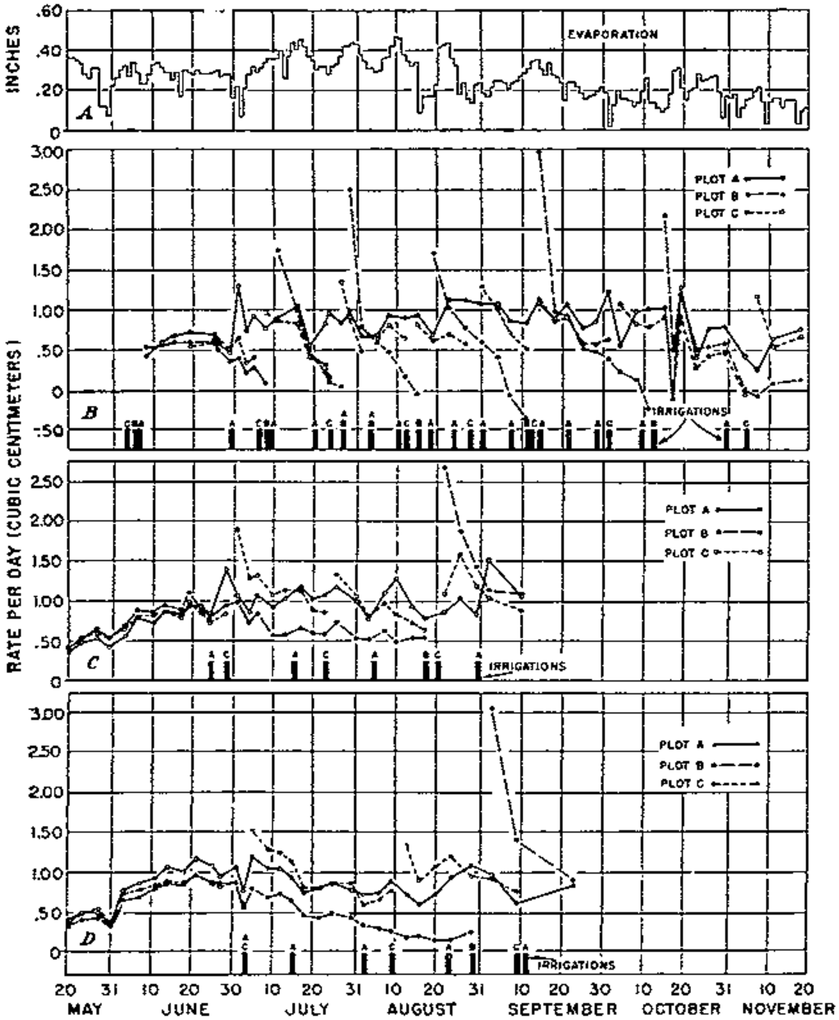

FIGURE 23.—Evaporation rate per day (*A*) and apparent growth rates (fruit volume gain or loss) of lemons in orchards W (*B*), M-W (*C*), and S (*D*).

ments of time shorter than one complete interval between irrigations on the B and C treatments.

Intervals between irrigations on the A treatments were intended to be short enough so that no measurable change would be caused in the regular increase in size of fruit. Under this treatment apparent growth rates tend to approach more closely to true growth rates and the calculations of true growth rates on the A treatments are not limited solely to the time intervals established by irrigations. This permits a more ready comparison of growth rates on the A treatments with weather factors. Effects of weather factors on the B and C treatments are often obscured by the dominating influence of water deficit due to changes in the supply of soil moisture.

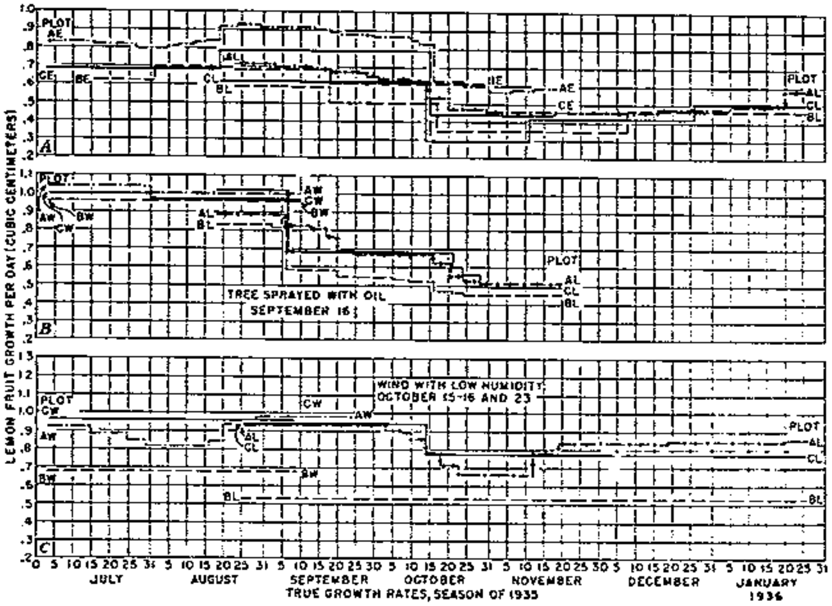

FIGURE 24.—True growth rates of lemons in orchards W (*A*), M–W (*B*), and S (*C*), season of 1935. Growth rates for early spring-set or winter-set fruit are designated by the second letter in the legends, E or W as the case may be. For the late spring-set fruit, the legends carry the letter L.

True growth rates are shown in figure 24 for plots A, B, and C in orchards W, M–W, and S.

Before comparing the effect of different irrigation treatments on each orchard, the influence of weather factors will be discussed briefly. By referring to figure 24, it may be noted that growth rates of fruit in plots A of orchards W and S were higher in September than during midsummer.

On orchard M–W most of the tagged fruits were picked in early September, so that the records were broken. Orchard M–W was also sprayed heavily with oil on September 16, and this operation further interfered with the treatments.

Northeast winds with low humidity occurred on October 15, 16, and 23, and growth rates were decreased on all orchards regardless of treatment. The fact that minimum temperatures were also lower after October 23 may have been a contributing factor, but the general marked drop in growth rates was coincident with the October winds.

In studying the effect of the irrigation treatments it may be noted that in all three orchards the true growth rates were lowest on the B treatments (the treatments with the extended intervals between irrigations). In orchard W, growth rates on the intermediate plot, C, were nearly as low as on plot B in July and August. This effect was due in part to the fact that water deficits on some trees in plot C were higher than originally intended at the early irrigations and were more nearly like those on the B treatment.

The effect of inherent differences in trees cannot be entirely eliminated from comparisons over a single growing season, and the effect appears in figure 24. Trees on plot C in orchard W were not in as good condition as on plots A and B at the start of the season, and this fact would tend to cause lower growth rates on this plot. The record from one other plot (plot D in orchard M–W, not shown in fig. 24) was also affected by weak trees. Aside from these irregularities, the growth rates were consistent with the treatments.

Except as noted above, the intermediate treatments with moderate water deficits yielded growth rates that were not materially different from those of the more frequently irrigated plots. Growth rates on the treatments that permitted high water deficits to occur before irrigation water was applied were definitely low. These results are in accord with the fact that there is a wide range of soil moisture available to the tree. Once the soil was moistened thoroughly, there was no advantage from further irrigations until after fruit-growth records indicated measurable water deficits. When appreciable water deficits have been found under orchard conditions, soil-moisture records have shown part of the root zone with moisture contents in the wilting range. Portions of the root zone may have moisture contents in the wilting range and be left unirrigated, yet ample water may be obtained from the irrigated part of the soil.

True growth rates were depressed in these experiments when high water deficits were developed by extending the interval between irrigations until signs of water shortage were apparent from rolling or cupping of the leaves, shedding of leaves from the older flushes of growth, or changes in the color of the foliage. General wilting in the sense that the foliage becomes limp or drooping did not develop in any case. Drying out the trees on the lighter soil was particularly detrimental and weakened the trees so that they were unable to withstand winds in October even though the soil was moist when the winds occurred. These trees were irrigated more frequently the following season but were still definitely poorer than the trees on the A treatment in October 1936.

These experiments have established the fact that reduced growth and abnormal loss of leaves resulted when lemon trees were allowed to go without irrigation until signs of water shortage were clearly evident in the trees. Long before visible signs of water shortage were apparent in the tree, fruit-growth records showed evidence of the rising water deficit and proved to be more reliable than soil-moisture records for establishing differences between treatments.

SEASONAL USE OF WATER IN 1935

Different quantities of water were used on the different plots, but no special effort was made to hold the water applied to any certain predetermined quantity. All plots were irrigated with seven furrows spaced 28 inches apart. The records of irrigations are given in table 10.

TABLE 10.—*Record of irrigations, orchards W, M–W, and S, season of 1935*

Orchard and plot	Date of irrigation	Water per acre
		Acre-inches
Orchard W:		
Plot A	May 21	2.30
	June 6	2.92
	June 29	2.22
	July 9	2.29
	July 20	1.86
	July 27	2.00
	Aug. 3	2.12
	Aug. 10	2.18
	Aug. 17	2.47
	Aug. 24	2.72
	Aug. 31	1.69
	Sept. 7	3.03
	Sept. 14	3.61
	Sept. 21	2.71
	Sept. 28	2.80
	Oct. 9	3.25
	Oct. 30	3.20
	Nov. 29	2.68
	Jan. 25, 1936	2.96
Seasonal total		49.01
Plot B	June 9	1.66
	July 8	2.52
	July 27	1.92
	Aug. 15	2.66
	Sept. 11	3.12
	Oct. 12	2.78
	Nov. 29	2.61
	Jan. 25, 1936	3.25
Seasonal total		20.52
Plot C	June 3	2.06
	July 6	2.79
	July 24	1.62
	Aug. 3	1.65
	Aug. 12	1.54
	Aug. 27	2.57
	Sept. 12	2.57
	Oct. 1	2.85
	Nov. 4	2.90
	Dec. 19	2.69
Seasonal total		22.64
Orchard M–W:		
Plots A and D (average)	June 24	4.70
	July 15–16	3.61
	Aug. 4–5	6.08
	Aug. 30–31	4.33
	Oct. 17	3.18
Seasonal total		21.90
Plots B and E (average)	Aug. 18–19	6.70
	Oct. 17	2.32
Seasonal total		9.02
Plots C and F (average)	June 28–29	4.76
	July 23	2.72
	Aug. 20–21	4.19
	Oct. 17	3.53
Seasonal total		15.20
Orchard S:		
Plot A	July 2–5	6.58
	July 15–17	4.73
	Aug. 2, 3–5	3.72
	Aug. 23–24	3.55
	Sept. 11–13	4.63
	Oct. 21	3.31
Seasonal total		26.52
Plot B	Aug. 29–30	7.12
	Dec. 12	6.71
Seasonal total		13.83
Plot C	July 3–5	7.02
	Aug. 9–10	5.40
	Sept. 9–10	6.89
	Nov. 9–12	4.31
Seasonal total		23.62

In orchard W, on plot A the total application for the season was 49.01 acre-inches per acre with irrigations applied every week during midsummer. More water was applied on this plot than was necessary, but the schedule of frequent irrigations was used in order to make certain that no measurable water deficit would occur. The same result was accomplished the following season with the use of 36 acre-inches per acre. For strict economy in the use of water, it would not have been necessary to apply water in all seven furrows at every irrigation, as there was less root activity under the center furrows. However, for the 1935 season it was decided that all plots should be moistened uniformly at each irrigation.

On plot B the seasonal use of water was 20.52 acre-inches per acre, and since definite injury occurred on this plot, it is safe to say that this amount is insufficient to meet the requirements of the trees.

The seasonal use of water on plot C was but little more than on plot B and amounted to 22.64 acre-inches per acre. More water would have been used on plot C if rain had not ended the irrigation season and taken the place of a scheduled irrigation. During midseason two more irrigations were applied to plot C than on plot B. The records from plot C indicate that still more water could have been used to advantage.

These data suggest that the minimum allotment of water should be somewhat above 24 acre-inches per acre per year on this orchard, since growth was depressed on both plots where less than this amount was used. The soil is rocky and very porous, and large losses are likely to occur by deep percolation. The furrows on these plots were only 200 feet long, and in some furrows a 1-hour run gave the equivalent absorption of 2 acre-inches per acre. Frequent shifting of the water from one furrow to another is necessary, and this adds to the labor cost of irrigation. With irrigation runs longer than 200 feet, more water would have to be allotted to take care of deep percolation losses.

In orchard M–W, plots A and D (average) received a total of 21.90 acre-inches per acre; plots B and E (average) 9.02 acre-inches, and plots C and F (average) 15.20 acre-inches. The soil in this orchard is a rich deep loam that has a large capacity for hold-over storage of winter rains, consequently the first irrigation of the season came a month later than on orchard W.

With furrows 500 feet long, more water was absorbed on plots A, B, and C, near the upper ends of furrows, than on plots D, E, and F, near the lower ends, and the effect is apparent in the growth records for plots D, E, and F. However, weak trees on plot D also affected the growth rate on this plot. Plots A and D received one more irrigation than the intermediate plots C and F. This was on August 4 and 5, when 6.08 acre-inches per acre was applied. This additional midsummer irrigation gained no measurable advantage for plot A over plot C, although it may have resulted in some help to plot D on the lower end of the furrows.

The elimination of early-season irrigations on plots B and E until the soil was thoroughly dried out and the trees were subjected to severe water shortage caused a loss in seasonal growth. The increase in water deficit occurred very gradually, and the apparent growth rates show that an irrigation in July would have been advantageous on plots B and E. These data suggest that the minimum allotment for this orchard should be not less than 15 acre-inches per acre per year. It also is apparent that furrows one-half their present length would increase the efficiency of irrigation.

In orchard S, plots A, B, and C were irrigated with seven furrows in order to conform to the treatments used on the other two orchards. However, sprinklers were used elsewhere in this orchard. The furrows on plots A, B, and C were on a very steep grade, and very small flows were used, to avoid serious erosion. Water progressed along the furrows slowly and had to be held in the furrows a long time in order to obtain satisfactory penetration at the lower ends of the furrows.

Hence, the efficiency of application was relatively low and comparatively large amounts of water were applied. There were obvious advantages gained in efficiency of application when sprinklers were used in this orchard, so that the amounts applied by furrow irrigation cannot be used to estimate the minimum water requirements when sprinklers are used.

The records show that plot C with four irrigations and a seasonal use of 23.62 acre-inches per acre had growth rates that were not materially different from those on plot A, where 26.52 acre-inches of water per acre was used, applied in six irrigations.

The treatment on plot B was extended beyond the limits of usual commercial practice without reducing growth rate to zero. Nevertheless, growth rates were definitely low, and it is not practicable to withhold irrigation so long as was done on this plot. The apparent growth curves indicate that two additional irrigations would have been advantageous.

The four irrigations on plot C maintained a satisfactory growth rate, but there is no doubt that the seasonal total of 23.62 acre-inches per acre could be further reduced by increasing the efficiency of application.

The amount of water used in these experiments was not a primary consideration, as the main objective was to establish the differences in total seasonal growth resulting from different degrees of water deficit. This, in effect, is a determination of the best interval to use between irrigations, starting with a thoroughly moist soil after each irrigation. An effort was made to wet the same proportion of the root zone each time by applying water in seven furrows at each irrigation. This was a practical approach to the condition of having all of the soil wet uniformly to field capacity following each irrigation.

The work in orchards M and P in 1932, 1933, and 1934 indicated that maximum economy in use of water would be attained when only a portion of the soil was moistened at each irrigation. However, alternate wetting of different parts of the soil introduces a variable that it was thought best to eliminate from the 1935 tests.

It is not intended that the values used in this discussion should be considered as representing minimum water requirements for the district. They are applicable to the particular orchards and conditions of the tests and are merely suggestive of broader application. Differences in treatments were purposely made large in order to establish practical limits for more elaborate tests designed to extend over a period of several years. With small differences in plot treatments, several years may elapse before the cumulative effect becomes significant.

The present results show that water deficits high enough to cause visible signs of water shortage reduced the total seasonal growth of fruit. Plots with moderate water deficits had true growth rates as high as when there was no measurable water deficit. Further than this, these experiments have established that the growth rate of lemon fruit is a sensitive indicator of water deficit and serves as a reliable measure of differences in irrigation treatments. The index may be used on any soil type regardless of the proportion of the root zone moistened. Hence, the method has wide application and can be used readily in many situations where soil-moisture records are obtained with extreme difficulty.

DISCUSSION AND APPLICATION OF RESULTS

The results obtained in the field experiments conducted to determine what influence wetting various proportions of the soil in the root zone may have on the growth of fruits and on the water supply of the tree may not be entirely conclusive. Results obtained in the experiments in orchard M, where 50 to 60 percent of the soil occupied by the trees was wetted to depths of 4 feet or more, show that under the conditions of these experiments the growth of fruit and the water supply of the trees were apparently about the same as in the case of trees on plots that had all of the soil wetted. From these results and also from those obtained from experiments in other orchards, where less than the entire soil mass occupied by the trees was wetted it seems that under usual summer weather conditions trees may receive an adequate soil-moisture supply from as little as 50 percent of the root system if the average moisture content of the wetted soil is kept relatively high so that all the roots in the wetted area are kept in contact with soil at moisture contents above the wilting range. In orchards located on soil types that are favorable to deep and extensive rooting, such as was the case in orchards M–W and S, appreciable parts of the top 2 or 3 feet of the soil in the wetted area may reach the wilting range without causing a significant reduction in the total seasonal growth of fruits, even though the wetted area may comprise only 75 to 80 percent of the soil occupied by the tree.

Somewhat limited experiments on the effect of reducing the area of soil wetted on the rate of extraction of moisture from the wetted soil showed that increased rate of extraction in the wetted soil may in part compensate for the reduction in area irrigated. But it appeared that the total amount of water absorbed by the tree progressively decreased as the area of soil wetted was reduced. However, this seemed to have little effect on the rate of apparent growth of Washington Navel oranges until the amount of the root zone wetted was reduced below 50 percent of the total root zone.

The results of the experiments referred to give no information regarding the effect on the size of trees and on total yields of the practice of irrigating only 50 to 80 percent of the soil when such practice is carried on for many years. Observations of trees in an orchard on alluvial fan soil where great variation existed in the depth of surface soil to which most of the roots were confined showed that the size of trees and probably yields of fruit were considerably influenced by the depth of the soil.

Apparently the size of the mature trees had been largely determined by the amount of water that could be stored in the soil occupied by the trees. Trees on soil 2 feet deep wilted at the same time as trees that were about twice as large but were growing nearby in soil about 4 or 5 feet deep. Wilting occurred near the end of the 15-day irrigation interval during a period of unusually hot weather. The apparent growth rate of fruit was about the same on the large and small trees and indicated that all trees regardless of size suffered water shortage near the end of the fixed 15-day irrigation interval, which had been in use during the greater part of the life of the orchard. These observations suggest that if irrigation water is applied to only a part of the soil during the life of the trees the size of the tree at maturity may be considerably affected, and thus over a period of many years the yield of fruit might be appreciably less than if most of the soil were irrigated at suitable intervals.

Doubtless closer planting of lemons may be practiced if practically all of the soil is irrigated than if a large part of it remains dry for several months each year. This is especially true in the coarse gravelly alluvial fan soils, which have a low available water capacity.

Lemons on soil types having a shallow surface soil of fairly good texture but a dense subsoil unfavorable for root development have a large proportion of the root system in the surface soil. On soils of this type it is probably good practice to irrigate as large a proportion of the surface soil as is practicable and to irrigate frequently enough to maintain the moisture content of most of the irrigated zone above the wilting range.

In experiments on a soil of this type (orchard P) it was found that after the soil in the zones of high root concentration had become relatively dry the widely dispersed roots in the subsoil continued for long periods without irrigation to extract sufficient moisture to maintain slow growth of the fruit and to prevent wilting of the leaves. Under these conditions, however, a large proportion of the fruit turned yellow before it had reached a desirable marketable size.

Orchards on shallow soil underlain by dense, relatively impervious subsoil present a particularly difficult problem in the management of the irrigation practice. On steep slopes run-off and erosion are excessive, and on relatively level areas drainage through the subsoil is extremely slow. Use of the portable low-head sprinkler system, which is coming into use in a few orchards, may prove to be more desirable than the furrow method on these soils. With the portable low-head sprinkler system it should be possible with careful management to avoid serious erosion on the slopes and to avoid the application of excessive amounts of water, which may cause waterlogging for several days on the relatively level areas.

Results of the experiments carried out in this investigation show that, with the variability in soil and in root distribution found in many of the lemon groves of the Pomona Valley, determinations of the average moisture content of the soil in the principal root zone in many situations may not serve as a satisfactory index to the moisture supply of the tree and as a reliable guide for timing the application of irrigation water. However, in situations where the distribution of roots is relatively uniform, soil-moisture determinations may serve as a satisfactory guide to the timing of applications of water.

These investigations suggest that if the irrigation interval is to be based upon soil-moisture determinations alone it seems advisable to take the soil samples from those parts of the root zone where root concentration is highest, and to apply water soon after the moisture content of the soil in zones of high root concentration, below the influence of surface evaporation, has been reduced to the wilting range. Certain of the commercial laboratories engaged in soil-moisture control work employ this principle in their sampling; that is, samples are taken from the irrigated zone under the spread of the branches where there is little likelihood of plow sole occurring and where the concentration of roots is likely to be high. Large samples are taken with a post-hole auger, and samples that do not contain a fair number of rootlets are discarded.

In many situations where the soil is extremely rocky it is difficult to obtain samples, and in some situations there is likely to be considerable uncertainty as to the zones of highest root concentration. Adequate sampling is so laborious and expensive that the tendency is to take too few samples.

Magness, Degman, and Furr (*11*), as a result of their studies on fruit growth of apples in relation to the soil-moisture supply of the tree, have suggested the use of fruit-growth records as a guide for timing the applications of irrigation water in apple orchards. The present investigations have shown that the apparent growth rate of lemons may be used as an index to the relative moisture deficit of the tree and as a guide for determining approximately the proper time interval between irrigations.

The relative moisture deficit of the lemon tree may be determined with a fair degree of accuracy from the apparent growth rate of the fruits from the time they are about 20 cc in volume until they begin to mature and turn yellow; that is, during this stage of growth the apparent rate of growth on trees amply supplied with water is relatively uniform. It was found possible under experimental conditions to time quite accurately the applications of water so as to bring about certain degrees of moisture deficit just prior to applications of water. Because there is some variability in the apparent growth rate caused by variations in weather conditions, unless some trees are maintained with ample water at all times it is not always possible to tell when the first decrease in apparent growth rate occurs as a result of soil-moisture shortage. However, during the warm season if the rate continues to decrease for several consecutive periods between measurements the cause is probably moisture shortage rather than changes in the weather.

The results of these experiments show that the ultimate size of the fruit will not be reduced by water shortage if water is applied soon after the occurrence of the first significant decrease in the apparent growth rate of fruit caused by water shortage, but that if water is withheld until apparent growth ceases, the ultimate size of the fruit will be greatly reduced and the trees will suffer considerable loss of leaves. Because of the possible danger of injury to the trees from unfavorable soil conditions brought about by maintaining the soil continuously at high moisture contents, it seems inadvisable to apply water before a decrease in apparent growth rate of fruit occurs as a result of water shortage. How far the apparent growth rate may be allowed to fall below that which obtains under conditions of ample moisture supply without causing a significant decrease in the ultimate size of the fruit has not been determined, but the results indicate that a very appreciable decrease in apparent rate may occur without causing other ill effects. With fruit measurements as an index to the relative water deficit of the tree, or with determinations of the moisture content of soil samples taken from the zones of highest root concentration, or, still better, a combination of the two methods, it is possible to avoid the waste of water and possible injury to the trees resulting from too frequent application of water, or to avoid the loss in size of fruits and injury to the tree from too infrequent application of water.

Probably the most practicable use of fruit measurements as a guide to irrigation practice under usual commercial conditions is the use of apparent growth rates merely as a guide for adjusting the established time interval already in use. That is, if the growth records show that the established interval is too long or is shorter than necessary, it may be adjusted accordingly. Though it seems likely that growers will find the use of apparent fruit-growth records a very useful guide in adjusting the time intervals between irrigations, it is not recommended that such records should be used to predict some days in advance when water should be applied. To use growth records as a means of predicting several days in advance when water should be applied it is desirable to maintain a control plot in which the moisture content of the soil is kept at such high values that the trees never suffer water shortage caused by low soil moisture. This is not always feasible under commercial conditions. However, a gradual increase in water deficit will be apparent from fruit-growth records before wilting of the leaves occurs. If the deficit appears to be too great for any one irrigation interval, the following interval may be shortened if weather conditions are similar during the two periods.

A large proportion of the orchards in southern California are supplied water on a fixed schedule by water companies. Fruit-growth records obtained during several seasons in mature orchards on representative soil types will, it is believed, provide a reliable means of adjusting the time interval between irrigations on the several soil types during the different seasons of the year so as to obtain a reasonable degree of efficiency in use of water and yet prevent the general occurrence of periods of severe water shortage on any one soil type. For example, it will probably be found that in some situations the time interval between applications of irrigation water may be profitably lengthened during the spring and shortened in midsummer and early fall.

While the methods proposed for controlling the irrigation of lemon orchards lack the apparent precision of the conventional method of determining from soil samples when the average moisture content of the soil in the principal root zone has been reduced to the wilting point, it is believed that the methods proposed here provide a fairly reliable means of controlling the actual water supply of the tree itself, regardless of variations in the soil or in the distribution of roots.

SUMMARY

Investigations were conducted to determine the response of lemon trees to variations in moisture content of the soil within the root zone, in the proportion of soil wetted, and in the length of time between irrigations.

The basis upon which comparisons of variations in soil-moisture conditions in field plots were made is the wilting range as determined by wilting well-established sunflower plants. The range in moisture content of the soil through the progressive stages of wilting from the permanent wilt of basal leaves to complete wilt of all leaves on the plant was established as the wilting range. When all leaves were completely wilted the soil was considered to be at the ultimate wilting point. In the orchard, trees that were maintained without appreciable water deficit reduced the moisture content of the soil in zones of high root concentration to the upper end of the wilting range. The moisture content of the soil even in zones of high root concentration was not reduced to the ultimate wilting point unless the tree was subjected to severe water deficit for a long time. Before the moisture content of the soil in any part of the root zone was reduced to the ultimate wilting point the trees wilted in the middle of the day.

During extended intervals between irrigations the rate of volume gain of fruit is affected from day to day by changes in the turgor of the fruit. Volume increase for short intervals of time is termed "apparent growth rate"; for intervals from one period of full turgor to the next, "true growth rate." Appreciable fluctuations in apparent growth rate may occur without affecting the true growth rate.

By field and laboratory experiments it was determined that changes in apparent growth rate of lemon fruits serve as an excellent index of the relative water deficit of the tree. With decreasing soil moisture a turgor deficit arises before the first visible sign of wilting appears, or before there is a decrease in transpiration rate, and increases progressively, as the soil dries out, until the plant is completely wilted.

In field experiments, changes in apparent growth rate were used as a measure of the relative water deficit of the trees, and increase in volume of the fruit from one period of full turgor to the next or for an entire growing season was used as a measure of true growth of fruit.

In all lemon orchards where investigations were conducted, root concentration and extraction of soil moisture varied greatly. As time from irrigation increased, the moisture content of regions of highest root concentration was reduced to the wilting range before a water deficit was evident from fruit measurements. As the moisture content of increasing proportions of the root zone reached the wilting range, a gradual increase in water deficit became apparent. Before the moisture content of all the soil of any easily delineated zone, such as the top foot, was within the wilting range, appreciable parts of the soil had remained in the wilting range for long periods and high water deficits had developed in the trees. At the times when apparent fruit growth first showed that water deficit had developed, it was usually possible to find soil-moisture contents varying from within the wilting range to near field capacity. Even in locations where root distribution and soil-moisture extraction were most uniform, variations in soil-moisture content were so great that the use of averages of soil-moisture percentages proved unreliable as a measure of the water supply of the trees.

In field experiments in which water was applied to various proportions of the soil, ranging from one-half to all of the surface area, it was found that if all of the soil in the wetted area was maintained at moisture contents above the wilting range the trees apparently received an ample water supply from as little as one-half of the soil. In these tests apparent growth rate of fruit indicated little difference in water deficit of the trees just before irrigations, and at the end of the season differences in final size of fruit were not significant. Because of variability in root concentration, however, the actual proportion of the soil in the root zone that was reduced into the wilting range without causing severe water deficit or reduction in final size of fruit was indeterminable by ordinary methods of soil sampling.

Laboratory and field experiments showed that the rate of extraction of water from one part of the soil in the root zone was influenced by the moisture content of the soil in other parts of the root zone. The minimum moisture content attained by soil in unirrigated parts of the root zone was influenced by the moisture content maintained in the wetted part and by the relative water deficit to which the plants were subjected.

Field experiments conducted in an orchard on shallow loam soil underlain by dense subsoil showed that the trees suffered sufficient water deficit to cause a reduction in final size of the fruit before the moisture content of all of the soil in the top foot was reduced into the wilting range. The water supply from the subsoil was sufficient to maintain slow growth for long periods and to prevent wilting, but there was always a high water deficit when the moisture content of the topsoil was relatively low. To maintain growth at the maximum rate on soils of this type an ample moisture supply had to be maintained in the topsoil.

Experiments in which the time intervals between irrigations were varied according to the relative water deficit of the trees as indicated by apparent growth rate of fruit were conducted on light, medium, and heavy soils.

On one plot on each soil type, water was applied at such short intervals that the trees showed little or no water deficit. On these plots, which were used as controls, the rate of increase in size of fruit was relatively uniform throughout the main growing season, and the final size of fruit at the end of the season had not been limited by water shortage at any time.

On a second plot on each soil type, water was applied when the apparent growth rate of fruit indicated slight to moderate water deficit. On the medium and heavy soil the final size of fruit was as great as that on plots that suffered no water shortage. On the light soil this treatment resulted in some reduction in the final size of fruit.

On a third plot on each soil type, water was applied when apparent growth of fruit ceased or when the leaves began to roll. On all three soil types this treatment resulted in pronounced reduction in the final size of fruit. There was a loss of leaves from trees under this treatment on all soil types, and on the lighter soil type there was injury to small twigs.

Soil-moisture contents were not generally reduced below the upper end of the wilting range in the most frequently irrigated plots. On those plots that were irrigated when apparent fruit growth ceased or when the leaves began to roll, the moisture content of many of the soil samples was in the wilting range and that of some was near the ultimate wilting point. On plots that were irrigated when the trees showed slight to moderate water deficit, the moisture content of appreciable portions of the soil was within the wilting range.

These experiments indicate that fruit measurements may be used under commercial orchard conditions to establish the most desirable interval between irrigations. It is not recommended that fruit-growth records be used to predict when water should be applied, but rather that they be used to determine whether or not established practices are accomplishing desired results. If fruit growth decreases materially before irrigation and there is a sharp increase in volume just after irrigation, it is evident that there was an appreciable water deficit prior to irrigation. The magnitude of the difference in apparent growth rate during the periods just before and just after irrigation is an index of the water deficit to which the trees were subjected just before irrigation.

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