Effects of Soil Moisture Stress on Growth and Yield of Macadamia (Macadamia integrifolia)

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INTRODUCTION

In Hawaii, macadamia is usually grown without irrigation. In some areas, drought conditions are at times sufficiently severe to seriously curtail production of nuts. This experiment was initiated in order to study growth and yield response of macadamia to various soil moisture regimes.

Taylor, Evans, and Kemper (18) have discussed ably the theoretical basis of evaluating soil water and methods of measuring it. Richards and Marsh (13) have pointed out in particular the advantages of the use of tensiometers in irrigation practices. Perrier and Evans (11) have evaluated four different types of tensiometers with respect to precision between types and have also determined the effective range of soil moisture tension which is possible with this instrument. Furthermore, they have used tensiometers in the field to make moisture release curves in situ and compared them with those made from core soil samples and disturbed soil samples determined with the use of the pressure membrane apparatus developed by Richards (12).

Tensiometers and resistance blocks have been used by some investigators to follow the changes in soil moisture tension at depths occupied by the roots of plants. For instance, Richards, Weeks, and Johnston (14) used tensiometers and fiberglass resistance blocks to indicate the soil moisture tension range of ½ bar to 10 bars in studying the growth response of avocado to soil moisture stress. Flocker and Lingle (8) successfully used tensiometers and gypsum resistance blocks for irrigation studies of avocado. Waterhouse and Clements (21) have used tensiometers for their irrigation studies on sugar cane, while Ewart (7) and Robinson (15) have used the gypsum blocks to indicate changes in soil moisture tension in this crop.

Tensiometers can be used to indicate the soil moisture tension in the “wet” range of soil moisture while the gypsum resistance blocks are more suitable to indicate soil moisture tension in the “dry” range. By using both of these soil moisture indicators experimentally, a wide range in soil moisture tension can be imposed on the plant and its effect on plant responses can be studied. Furthermore, correct timing of irrigation applications can be developed for specific crops and for specific localities.
MATERIALS AND METHODS

This experiment was conducted at Waimanalo Experimental Farm of the Hawaii Agricultural Experiment Station from July 1962 to the spring of 1965. The macadamia trees were of the Keauhou variety, one of the commercial varieties in Hawaii. They were 10 years old at the beginning of the experiment and had been in nut production for several years.

Rainfall in this area is distributed unevenly throughout the year and falls mostly during the winter and spring. During the irrigation treatment periods of July 23, 1962 to December 10, 1962, 7.1 inches of rain was recorded, of which 3.1 inches fell between October 17 to October 25. In 1963, 5.8 inches fell during June 7 to September 30, of which 1.9 inches and 1.8 inches fell during the latter part of July and the middle of September, respectively. An unusually heavy rain of 20 inches, 19 inches, and 20 inches was recorded during January, March, and April of 1963, respectively. In 1964, 15.5 inches of rain fell between May 15 to December 1. Of this total rainfall, 3.3 inches fell during the latter part of July, 2.7 inches during the middle of October, and 4.5 inches in November. Monthly temperature and rainfall records of this area are presented in another report (20).

The soil in the orchard belongs to the Low Humic Latosols, Waimanalo family, Waimanalo series (1). It is a silty clay soil and is moderately high in exchangeable magnesium. The X-ray analysis of the soil indicated that the clay is composed predominantly of a hydrated halloysite with lesser amounts of montmorillonite.

The surface soil in this orchard is moderately dark and extends to about 15 to 18 inches from the surface. The color of the soil profile begins to change at about this depth from a moderately dark to a brownish black and finally to a brownish soil at about the 30-inch depth. In association with this change in color the soil tends to become more dense. Most of the roots are distributed in the surface soil.

In each treatment was a row of 11 trees which were 30 feet apart. Treatment rows were separated from each other by border rows. Growth and yield data were obtained separately from each tree.

The experimental layout of the orchard is presented in figure 1.

In making a probability statement of the treatment means, the confidence intervals using a specified “t” value were calculated. Where the confidence interval of one mean did not overlap that of another, the hypothesis that the means were from the same population, was rejected, and a probability statement was made.

The confidence intervals were calculated for growth, yield, and portions of the soil moisture tension data. The yield data, however, were adjusted since the regressions of yield on the initial size of the trees were highly significant each year. The purpose of the adjustment was to eliminate the effect of initial size of the trees on yield. The cross-sectional trunk areas
of the trees on July 16, 1962, before the treatments took effect, were used for this purpose. The common regression coefficients were calculated and used in the adjustments, as described in Snedecor (17) on covariance analysis.

Trees of all plots were furrow-irrigated in the spring of each year when the irrigation treatments were begun. The amount of water which was applied at each irrigation was not measured. Irrigation was continued until all of the tensiometers (30-inch depth) responded to the water. Whenever treatment C plot (moderately dry) was irrigated, the application of water was continued for about an hour and a half after water reached the last tree in the row. This length of time in irrigation application gave assurance that the soil profile was wet at least to the 30-inch depth.

Since the most suitable placement of the soil moisture indicators was being studied during the summer of 1962, soil moisture tension data for that year comparable with those of 1963 and 1964 are not available. The two dry plots (B and C) received only one irrigation in 1962, on July 23. In plot A, 11 irrigations were applied at a mean irrigation interval of 13 days. In this plot, the last irrigation in 1962 was applied on December 10.

During the summer of 1962, tensiometers were used to study the most suitable placement of the soil moisture indicators. They were placed in the irrigation furrow of the "wet" plot at distances of 4 feet, 5½ feet, and 7 feet from the trunk of the trees at depths of 18 and 24 inches in order to study the distribution of roots and the extraction pattern of soil moisture. Several days after the trees were irrigated, tensiometer readings were taken and such a record was taken at regular intervals thereafter. The results indicated that, in general, readings of tensiometers placed nearer to the plant increased more rapidly than readings of those farther away. From the
results obtained from this study, it was decided to place the soil moisture indicators in the irrigation furrow at a depth of 30 inches and at a distance of 6 feet from the trunk of the trees during the following summers.

Tensiometers were used in the “wet” treatment plot (A) while the gypsum resistance blocks were used in the two “drier” plots (B and C). In the latter plots, in addition to the 30-inch depth, the gypsum blocks were also placed at the 18-inch depth.

Soil moisture indicators were installed at seven selected sites in each treatment plot. The soil moisture tension data were obtained twice a week, usually before 8 o’clock in the morning.

Three irrigation regimes were imposed on the trees during the summers of 1963 and 1964. Trees of treatment A were irrigated when the soil moisture tension reached about 0.6 atmosphere. Those of treatment B were irrigated only once with an application in the spring of each year. Those of treatment C were irrigated twice during 1963 and thrice during 1964. The irrigation treatments which were in effect during 1963 and 1964 are presented in tables 1 and 2, respectively.

<table>
<thead>
<tr>
<th>Irrigation treatment plot</th>
<th>Number of applications</th>
<th>Mean irrigation intervals (days)</th>
<th>Soil moisture tension before irrigation (atmospheres)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, Wet</td>
<td>6</td>
<td>23</td>
<td>0.63 ± 0.07</td>
</tr>
<tr>
<td>B, Dry</td>
<td>1</td>
<td>–</td>
<td>10.5</td>
</tr>
<tr>
<td>C, Moderately dry</td>
<td>2</td>
<td>91</td>
<td>17.8</td>
</tr>
</tbody>
</table>

*The mean of treatment A is expressed with its standard error.
**The soil moisture tension for this treatment and depth was not determined.
***The soil moisture tensions at the 18-inch depth and 30-inch depth were measured on September 12 and September 19, respectively.

Tensiometers which were used were of the dial type and were obtained commercially. They were tested for accuracy with a calibrated gauge which was obtained commercially.

Gypsum resistance blocks which were used were obtained commercially and were plastic impregnated. They contained screen electrodes. The

1Irrometer Co., P. O. Box 2424, Riverside, California.
2Industrial Instruments, Inc., 89 Commerce Road, Cedar Grove, New Jersey.
Table 2. Irrigation treatments during 1964

<table>
<thead>
<tr>
<th>Irrigation treatment plot</th>
<th>Number of applications</th>
<th>Mean irrigation intervals (days)</th>
<th>Soil moisture tension before irrigation (atmospheres)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, Wet</td>
<td>9</td>
<td>21</td>
<td>0.63 ± 0.02</td>
</tr>
<tr>
<td>B, Dry***</td>
<td>1</td>
<td>–</td>
<td>12.7</td>
</tr>
<tr>
<td>C, Moderately dry</td>
<td>3</td>
<td>56</td>
<td>15.7 ± 0.1 7.0 ± 0.2</td>
</tr>
</tbody>
</table>

*Means are expressed with their standard errors. **The soil moisture tension for this treatment and depth was not determined. ***The soil moisture tension was measured on October 15, 1964.

An attempt was made to calibrate the electrical resistance of the gypsum blocks to atmospheres of soil moisture tension by placing the blocks in soil in the pressure membrane apparatus (12). However, consistent results were not obtained. Therefore, the resistance of the gypsum blocks was calibrated to soil moisture percentages while the soil moisture was being depleted by sunflower plants.

The following procedure was followed in the calibration of the gypsum block resistance to soil moisture percentages. A gypsum block was placed in the center of an 800-cc. can containing a known weight of soil (oven-dry basis). A sunflower plant was grown in the can until it had at least four matured leaves. The soil surface and holes in the can were then sealed. Periodic weighings of the can corresponding to certain resistances were made in order to obtain the soil moisture percentages. However, before this determination, the plant was placed in a high humidity atmosphere in the dark for a period of 16 hours or more so that the water potential in the plant and in the soil was at an approximate equilibrium. This procedure was repeated until the permanent wilting point was determined. The procedure of Furr and Reeve (9) was followed in the determination of the first permanent wilting point. Estimates of soil moisture tensions beyond 15 atmospheres were obtained by extrapolation of the curve obtained by plotting the electrical resistance of the blocks against soil moisture tension.

Estimates of soil moisture tension corresponding to gypsum block resistance readings were made by first converting resistance readings to moisture content values using the relationship found in the sunflower moisture depletion test; these moisture content values were then converted to moisture tensions by use of the moisture release curves.
Soils were sampled for the determination of the moisture release curves from four selected sites in the field at depths of 6 to 18 inches and from 18 to 36 inches. The moisture release curves were determined on these disturbed soil samples by use of the pressure membrane apparatus.

Fertilizers equivalent to 0.75 pound of N, 0.97 pound of P₂O₅, and 0.75 pound of K₂O were applied to each tree during the winter of 1962. The rates of application during the winter of 1963 were increased to a fertilizer equivalent to 1.5 pounds each of N, P₂O₅, and K₂O.

Leaf samplings for chemical analyses of these elements were usually made in the spring and fall of each year. These analyses were made in order to compare with those of macadamia trees which were considered adequately supplied with these elements and grown on aa lava at Keaau Orchard, Hawaii (2, 3, 4, 5, 6). Although critical levels for fruiting macadamia trees have not yet been reported for nitrogen and potassium, the one for phosphorus has been established (6). Comparisons of nitrogen and potassium levels of vegetative and fruiting macadamia trees at the two localities suggested that these two elements were adequate, or nearly so. However, the analyses indicated that the phosphorus concentration was low. It was 0.063% for the October 1963 sampling and 0.067% for the May 1964 sampling. The critical level established by Cooil et al. is 0.08% (6). The comparison indicated especially a need for applications of a phosphorus carrier fertilizer.

The girth of trunks of the trees was measured at a marked point about 6 inches from the ground at the time treatments commenced, usually in the spring of each year. It was measured again in the fall when treatments were discontinued for that year. These girth measurements were converted to cross-sectional areas before they were used in evaluating the growth status of the trees.

The yield of the trees was taken from August through December of each year usually at weekly intervals. Nuts were husked and graded for size, before they were weighed.

RESULTS

Soil Moisture Tension

The moisture release curves, determined with the pressure membrane apparatus (figure 2), indicate that the soil has a moderately high moisture-holding capacity. If the soil moisture percentages at ½ and 15 atmospheres are considered to be the upper and lower limits of available water, respectively, then the amount of available water is 12.0% and 14.3% for the soils sampled from the 6- to 18-inch and 18- to 36-inch depths, respectively. They also indicate that soil moisture is released over a wider range of soil moisture tension than some Low Humic Latosol soils, which contain the kaolinitic type of clay (19).

The relationship of resistances of the gypsum blocks to soil moisture
percentages is presented in figure 3. The relationship appears to be a simple exponential function between 270 ohms to about 110,000 ohms and from 210 ohms to 270 ohms. A change in slope is indicated below 270 ohms.

The mean soil moisture tension data of treatment A (wet) plot for 1964 are presented in figure 4. The confidence intervals shown with each mean soil moisture tension of the first irrigation cycle indicate that as the soil moisture tension began to rise, the confidence intervals became wider. This is probably due to the fact that as soil moisture is absorbed differentially by the roots of each tree in the treatment, concurrently, there would be a far greater difference in soil moisture tension. This difference in soil moisture tension becomes much greater as the soil becomes drier. Another observation is that the irrigation intervals are longer at first, become shorter during the summer and finally become longer again as fall sets in. This is indicative of a change in water requirement of the trees with changes in climatic conditions.

The maximum soil moisture tension at the 18-inch depth in 1963 was substantially higher in plot C than in plot B (figures 5, 6). However, at the 30-inch depth, although a difference existed between the two plots, this was not statistically significant at the 90% level of probability, as indicated by the overlap in the confidence intervals.

The soil moisture tensions for plots C and B in 1964 are presented in figures 7 and 8, respectively. It remained at a high level at the 18-inch depth in plot B for 4½ months. In this plot the soil moisture tension at the 30-inch depth tended to come to a plateau at approximately 6.6 atmospheres.
Figure 3. The relationship between the resistances of the gypsum blocks and the soil moisture percentages. Data are from five blocks. Soil samples are from 6- to 18-inch depths.
Figure 4. The soil moisture tension at 30-inch depth in the A plot, 1964. The 90% confidence intervals are indicated with the first irrigation cycle. Long vertical lines indicate irrigation applications.
Figure 5. The soil moisture tension at the two depths in the C plot, 1963. The 90% confidence intervals are indicated with portions of the soil moisture tension.
Figure 6. The soil moisture tension at the two depths in the B plot, 1963. The 90% confidence intervals are indicated with portions of the soil moisture tension.
Figure 7. The soil moisture tension at the two depths in the C plot, 1964.
Figure 8. The soil moisture tension at the two depths in the B plot, 1964.
Growth

Trees of plot C were significantly smaller than those of plot B at the 95% level of probability (table 3). They were significantly smaller than trees of plot A at the 90% level of probability. The soil in plot C appeared to be more porous than that of the other plots and irrigation may not have been frequent enough for optimum growth before this experiment was initiated.

Table 3. Mean trunk area of the trees at the beginning of the experiment (7/16/62) with the 90% and 95% confidence intervals

<table>
<thead>
<tr>
<th>Irrigation treatment plot</th>
<th>Trunk area (centimeters)</th>
<th>90% confidence intervals</th>
<th>95% confidence intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A, Wet</td>
<td>239.6</td>
<td>217.1–262.1</td>
<td>211.7–267.5</td>
</tr>
<tr>
<td>B, Dry</td>
<td>244.4</td>
<td>224.2–264.6</td>
<td>219.5–269.3</td>
</tr>
<tr>
<td>C, Moderately dry</td>
<td>186.2</td>
<td>161.8–210.6</td>
<td>156.1–216.3</td>
</tr>
</tbody>
</table>

In studying the phosphorus nutrition of young macadamia trees, Cooil et al. (4) found that the initial size of the trees was significantly correlated to growth of the square of the trunk girth. Subsequently this relationship was found to be confined to the period when growth of the squared circumference was increasing exponentially with time (6). In order to check whether a similar relationship existed with fruiting trees which were used in this experiment, regression coefficients were calculated from the relation of growth in cross-sectional trunk area between measurement dates (dependent variable, Y) and the initial trunk area of the trees (independent variable, X). The coefficients were tested for significance and are presented in table 4. In general, they were not significant enough to warrant adjustment of the growth data. Furthermore, they confirm the results obtained by Cooil (6).

The differences between treatments in growth rate of the cross-sectional trunk area were not significant statistically except that existing between treatments A and C during the summer of 1963 (table 5), which was significant at the 90% level of probability. However, the growth rate of trees in treatment A was always higher than those of the other treatments during each of the three summers.

Defoliation and dieback of some branches near the apex of trees in treatment B, which was irrigated only once in the spring of 1963 were observed in the fall of 1963 (figure 9). These symptoms again appeared during the fall of 1964.

The trees in each treatment were rated on the basis of 0 to 5 with the former representing no dieback and the latter, severe dieback. The ratings
Table 4. Regression coefficients ($b$) of growth in trunk area on the initial size of the trees, and their statistical significance. Regression coefficients are expressed as cm$^2$/cm$^2$.

<table>
<thead>
<tr>
<th>Irrigation treatment plot</th>
<th>Growth measurement dates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7/16/62-10/31/62</td>
</tr>
<tr>
<td>A, Wet</td>
<td>-.020 n.s.</td>
</tr>
<tr>
<td>B, Dry</td>
<td>+.061*</td>
</tr>
<tr>
<td>C, Moderately dry</td>
<td>-.003 n.s.</td>
</tr>
</tbody>
</table>

n.s.—not significant.

*—significant at probability of 90%.

**—significant at probability of 95%.
Figure 9. Effect of a sustained high soil moisture stress on defoliation and dieback of branches near the apex of a macadamia tree. Top, a tree from treatment B plot (dry). Bottom, a tree from treatment A plot (wet).
were made on February 2, 1965. The mean rating for treatment A was 0.7; treatment B, 3.0; and treatment C, 1.1.

Some matured leaves of trees in treatments B and C showed signs of tipburn. It was also observed in the fall of 1964 that leaves of trees in treatment B had a more yellow hue than leaves on trees of treatment C. Trees of treatment A, on the other hand, were green and lacked tipburn throughout the experimental period.

**Yield**

The regression coefficients of yield on the initial size of the plants (7/16/62) are presented in table 6. In general, all of the regression coefficients for each treatment are statistically significant at the indicated probabilities in 1962, although the regression coefficients for treatments B and C only are significant in 1963 and 1964. In 1964, the level of significance in these treatments was lower than in the other years. However, they were not significantly different statistically from each other during each year. Therefore, the common regression coefficient for each year was used to adjust the corresponding yields of each treatment.

**Table 6.** Regression coefficients (b) of yields (pounds per tree) on trunk area (cm²) of trees and their statistical significance

<table>
<thead>
<tr>
<th>Regression coefficient of:</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1962</td>
</tr>
<tr>
<td>Treatment A</td>
<td>0.299**</td>
</tr>
<tr>
<td>Treatment B</td>
<td>0.270***</td>
</tr>
<tr>
<td>Treatment C</td>
<td>0.132***</td>
</tr>
<tr>
<td>Common (A, B, C)</td>
<td>0.219***</td>
</tr>
<tr>
<td>Total</td>
<td>0.246*****</td>
</tr>
</tbody>
</table>

n.s.—not significant.

*—significant at probability = 90%.

**—significant at probability = 95%.

***—significant at probability = 99%.

****—significant at probability = 99.9%.
The yields of plot A were significantly higher at the 95% level of probability than those of plot C in each of the 3 years (table 7). In addition, in 1963 the yield of plot B was significantly higher than that of plot C. However, these yields (table 7) were not adjusted to eliminate the effect of size of the trees on yield.

**Table 7.** The mean yields with the confidence intervals expressed as pounds of husked nuts per tree. Unadjusted data

<table>
<thead>
<tr>
<th>Irrigation treatment plot</th>
<th>1962</th>
<th>1963</th>
<th>1964</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95% c.i.</td>
<td>95% c.i.</td>
<td>99% c.i.</td>
</tr>
<tr>
<td>A, Wet</td>
<td>46.4 ± 11.2</td>
<td>43.3 ± 7.9</td>
<td>± 11.5</td>
</tr>
<tr>
<td>B, Dry</td>
<td>37.8 ± 8.9</td>
<td>36.3 ± 6.8</td>
<td>± 9.7</td>
</tr>
<tr>
<td>C, Moderately dry</td>
<td>24.7 ± 4.9</td>
<td>24.6 ± 4.7</td>
<td>± 6.7</td>
</tr>
</tbody>
</table>

*Confidence intervals.

The adjusted yields (table 8) indicate that although the yield of plot A in 1962 was higher than those of treatments B or C, the differences were not significant statistically. In 1963, however, the yield of plot A was significantly heavier at the 90% level of probability than that of treatment C. In 1964, the yield of plot A was significantly higher at the 90% level of probability than that of plot B.

**Table 8.** The mean yields with the confidence intervals expressed as pounds of husked nuts per tree. Adjusted data

<table>
<thead>
<tr>
<th>Irrigation treatment plot</th>
<th>1962</th>
<th>1963</th>
<th>1964</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90% c.i.</td>
<td>90% c.i.</td>
<td>90% c.i.</td>
</tr>
<tr>
<td>A, Wet</td>
<td>42.8 ± 9.1</td>
<td>41.0 ± 6.4</td>
<td>63.8 ± 6.8</td>
</tr>
<tr>
<td>B, Dry</td>
<td>33.0 ± 7.2</td>
<td>33.4 ± 5.5</td>
<td>48.9 ± 7.4</td>
</tr>
<tr>
<td>C, Moderately dry</td>
<td>32.8 ± 4.0</td>
<td>29.6 ± 3.8</td>
<td>54.7 ± 7.1</td>
</tr>
</tbody>
</table>

*Confidence intervals.

The relationship between yield and initial size of the trees in treatments B and C in 1963 is graphically shown in figure 10. A similar result was obtained with the 1962 yield data with trees in these treatments. Although highly significant regression and correlation coefficients at the 99% level of probability between yield and initial size of the trees were obtained with the 1964 data, they were not as significant statistically as in the other years.
The husked nuts which were weighed at weekly intervals were also graded for size. However, no detectable difference in size between nuts produced in the various treatments was obtained.

The heavier yield produced by trees in the “wet” treatment plot than in the two drier plots (table 9) appears to result from production of more nuts rather than larger nuts.

Table 9. The number of husked nuts produced per tree in the various treatment plots*

<table>
<thead>
<tr>
<th>Irrigation treatment plot</th>
<th>1962</th>
<th>1963</th>
<th>1964</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, Wet</td>
<td>356</td>
<td>2186</td>
<td>3316</td>
</tr>
<tr>
<td>B, Dry</td>
<td>257</td>
<td>1694</td>
<td>2358</td>
</tr>
<tr>
<td>C, Moderately dry</td>
<td>265</td>
<td>1073</td>
<td>2356</td>
</tr>
</tbody>
</table>

*In 1962, nuts harvested during one month from each tree in each treatment were counted. In 1963, counts were made of nuts from four trees in each treatment harvested during the year; and in 1964, nuts from each tree in each treatment harvested during the year.
DISCUSSION

In this experiment, the yield of macadamia nuts was the highest when the trees were maintained under a low soil moisture tension; when high soil moisture tension was allowed to develop, lower yields resulted.

In regard to the soil moisture regimes in treatments B and C, a difference in behavior of the soil moisture tension at the 18-inch depth was observed (figures 5, 6, 7, 8). The soil moisture tension in the C plot at this depth rose much more rapidly with time than in the B plot. This seems to be related to the difference in extent of the surface soil in these plots. In the C plot, apparently the porous surface soil extended to at least the 18-inch depth, while in the B plot the surface soil did not extend to this depth.

The soil moisture tensions at the 30-inch depth in plots B and C were of the same magnitude (figures 5, 6, 7, 8). For example, the soil moisture tension at this depth in plot B on September 6, 1963 was 6.1 atmospheres, while the corresponding value in plot C was 7.6 atmospheres. However, a substantial overlap in the confidence intervals at this date is indicated. Moreover, in 1964, the maximum soil moisture tension developed in these plots at this depth was essentially of the same magnitude as in 1963.

Furthermore, because of the difference in extent of the surface soil between these plots (B and C), root distributions must have been more extensive in the C plot than in the B plot. Field observations made at the time of soil moisture indicators installations indicated that root growth was concentrated largely in the surface soil. Few roots were seen in the dense subsoil.

Although the soil moisture tension was higher in the C plot than in the B plot during 1963, the soil moisture tension remained at a relatively high level in the latter for a longer time. This was especially so during 1964. The uptake of water in trees of the B plot must have been limited during these periods, much more than in the C plot. This was probably the reason the yield was lower in the former than in the latter in 1964. The abscission of leaves in the B plot and the resulting dieback exhibited by branches in trees of this plot is another evidence that the water stress in the plants of this plot must have been higher for a longer time than in the C plot.

It has been reported that defoliation and dieback result from phosphorus deficiency of macadamia trees (6). Since the phosphorus concentration of the leaves from trees of this experiment was comparatively low, an interaction with a high water stress may be operative in this case. An interaction of this sort if present here, apparently was not evident in the C plot, since defoliation symptoms were low. Whatever the mechanism, it is clear that high water stress is directly involved here, since defoliation and dieback were conspicuous only in trees of the B plot, whereas leaf phosphorus values were similar among plots.

When the trees were under high soil moisture stress (figure 10) the
yields of the larger trees tended to be higher than those of the smaller trees. This may be explained on the supposition that a larger tree has more reserve materials and more branches for fruit set than a smaller tree.

Differences in trunk growth rate between treatment plots during each summer were not large. Apparently, the development of nuts assumes precedence over growth at this stage.

One of the main effects of the abscission of leaves and dieback of branches as manifested by plants in treatment B is the lowered photosynthetic surface area of trees in this treatment in comparison to those grown under low soil moisture tension (treatment A). Furthermore, Hagen and his associates (10) and Schneider and Childers (16) working with ladino clover and apple, respectively, have reported that as the soil moisture approached the wilting point, the photosynthetic rate was lowered while the respiration rate tended to rise. It may be that the macadamia trees in plot B under a high moisture stress for a relatively long time could have had a lowered photosynthetic rate and at the same time an increased rate of respiration which is conducive to low accumulation of reserve materials.

It is indicated in table 8 that the yield of each treatment was approximately the same in 1962 as in 1963. However, a substantial increase in yield in each treatment took place in 1964. This may be due to the fact that the trees at the beginning of the experiment may have been at a nutritional status not high enough to maintain adequate production of nuts. The phosphorus concentration in the leaves was below the level considered to be adequate for optimum growth (4) and yield (6) of macadamia trees grown in aa lava at Keaau Orchard in Hawai‘i. The resulting increases in yield of each treatment plot in 1964, therefore, may be due to response of plants to phosphorus fertilization since the experiment was started.

It was indicated in this study that the higher yield produced by trees in treatment A (wet plot) was due primarily to the increased quantity of nuts produced by trees in this treatment, rather than to size. Whether the primary effect of drought is on the number of fruits set or on the amount of drop of immature nuts is a question which will require further study.

**SUMMARY**

Growth and yield of macadamia trees were compared during 3 years of differential irrigation treatments. During the summer of 1962, plot A was irrigated at a mean interval of 13 days. Two other plots (B and C) received only one irrigation. During the summers of 1963 and 1964, irrigations were applied to plot A when the soil moisture tension reached about 0.6 atmosphere at the 30-inch depth, at a distance of 6 feet from the trunk of the tree. Plot C was irrigated twice in 1963 and thrice in 1964, while plot B was irrigated only once each year.
Soil moisture tension was measured with tensiometers in plot A, while gypsum blocks were used in the other two plots. In the two drier plots (B and C), records of electrical resistances were kept at 18-inch and 30-inch depths, respectively. The resistance was converted to a soil moisture percentage and finally to atmospheres.

Although plot B received fewer irrigations than plot C, the maximum soil moisture tension at the 18-inch depth was higher in the latter than in the former. This was explained on the basis that the porous surface soil extended to a greater depth in the C plot than in the B plot. The mean soil moisture tension at the 30-inch depth was essentially of the same magnitude in plot B as in plot C. Although the maximum soil moisture tension in plot B was lower than in plot C, the former was under a high moisture stress for a longer time.

The growth of the cross-sectional trunk area of the trees under these various soil moisture regimes was studied. It was found that, although trees in the A plot grew faster during the three summers than in the drier plots (B and C), only the difference in growth rate of the cross-sectional trunk area during the summer of 1963 was significant statistically at the 90% level of probability.

Abscission of leaves and dieback of branches were particularly evident in trees of plot B (dry plot) during the fall of 1963 and 1964. The physiological consequences on the trees in this treatment and the possible interaction of high soil moisture stress and low phosphorus composition of the trees are discussed.

Highly significant regression coefficients of yield on initial size of the trees were indicated generally in the two drier plots (B and C) in each year. In plot A, the regression coefficients were not significant statistically in 1963 and 1964. However, they were not significantly different from those of the other treatments. Therefore, the yields were adjusted in each treatment plot to eliminate the effect of initial size of the trees on yields.

Trees grown under a low soil moisture tension (plot A) produced the highest yield during each year of the experiment. The differences in yields between plots A and C were significant statistically in each year. In 1963, the yield of plot B was also significantly higher than that of plot C.

After the yields in each treatment were adjusted, it was found that, in 1962, none of the yields was significantly different from the other. In 1963, however, the yield of plot A was higher than that of plot C at the 90% level of probability, while that of plot B was not significantly different from the yield of plot C. In 1964, the yield of plot A was significantly higher than that of plot B at the 90% level of probability.

The higher yield produced by trees in plot A (wet) over the other plots (B and C) was primarily due to the greater number of nuts produced in this plot, rather than to increased size.
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