RELATIONSHIPS BETWEEN RAINFALL AND COFFEE YIELDS IN THE KONA DISTRICT, HAWAII

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INTRODUCTION

The production of coffee in the Hawaiian Islands was begun more than a hundred years ago, although exports were not recorded until 1845. Since the turn of the century over 90 percent of the production has been centered in the Kona district on the island of Hawaii.

An inspection of crop census reports reveals large annual fluctuations in the amount of coffee produced in Hawaii. Controlled measurements made in conjunction with coffee fertilizer experiments have shown fluctuations in yield amounting to over 100 percent, suggesting some dominant climatic or growth factors. In the present paper it will be shown, by applying modern statistical methods of analysis to small samples of data, that coffee production in Hawaii is highly correlated with rainfall.

THE KONA DISTRICT

The Kona district is a strip of terrain along the lee or southwest coast of the island of Hawaii, rising in a fairly uniform slope from sea level to 3,500 feet in approximately 5 miles. The coffee-producing area is a narrow belt about 22 miles long and 1 mile wide, ranging from 800 to 2,200 feet in elevation and consisting of small, fairly fertile pockets between relatively recent lava flows. At present, approximately 5,000 acres are devoted to the growing of coffee. The geological and geographical features of this area and its agriculture have been described by Powers, Ripperton, and Goto.

The seasonal production of coffee in the Hawaiian Islands from 1900 to 1936 has been estimated by Cady, Maneki, and Murata. The data from 1900 to 1920 were based on exports; those from 1921 to 1936 were based on the crop census reports of the Agricultural Extension Service, University of Hawaii. These data are recognized not to be precise estimates for the Kona district, as during the period not exceeding 5 percent of the total volume of coffee produced in the Hawaiian Islands was in districts other than Kona. Allowing for fluctuations in yield, there has been since 1900 a steady increase in the production of coffee in Kona, which may be attributed to the following factors: (1) Increased acreage, (2) increased age of the trees, and (3) improvements in fertilizer and cultural practices.

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In the Kona district, coffee cherries mature and are harvested, for the most part, during the months from August through December. The blossoming season is in the early spring, usually from January through March. Each tree has two or more distinct periods of flowering, depending, supposedly, upon meteorological conditions.

During the spring, for 6 weeks to 2 months simultaneously with and following the flowering, occurs the maximum growth of laterals (wood which will blossom and bear fruit the following year). Thus the coffee tree is preparing for the next year's crop at the same time that it sets and develops the current year's fruit. This is illustrated...
in figure 1, which shows a lateral with flowers and a flush of new growth.

RAINFALL DATA

Rainfall records at Kealakekua, which is fairly close to the center of the coffee area, are available for the years since 1891. Unfortunately, records for one station, at an elevation of 1,580 feet, were kept only until 1914, and those of a second station (elevation of 1,450 feet) which were available from 1901 proved not to be analogous during the overlapping 14-year period. For this reason only the second set of data is used in this study.

The annual fluctuations in rainfall during the period 1901 to 1936 were leveled somewhat by obtaining running 5-year means, as charted in figure 2. It is evident that precipitation was distinctly heavy up to 1905 and from 1925 to 1936; from 1905 to 1915 rainfall was very light, and from 1920 to 1925 it was slightly subnormal.

The monthly distribution of rainfall expressed as means of a 36-year period and the standard errors of these means are given in the following tabulation:

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean rainfall (inches)</th>
<th>Month</th>
<th>Mean rainfall (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>3.68 ± 2.83</td>
<td>July</td>
<td>6.88 ± 2.30</td>
</tr>
<tr>
<td>February</td>
<td>3.28 ± 3.98</td>
<td>August</td>
<td>6.99 ± 2.15</td>
</tr>
<tr>
<td>March</td>
<td>4.02 ± 2.40</td>
<td>September</td>
<td>7.48 ± 3.25</td>
</tr>
<tr>
<td>April</td>
<td>4.92 ± 3.16</td>
<td>October</td>
<td>6.06 ± 3.22</td>
</tr>
<tr>
<td>May</td>
<td>6.48 ± 2.82</td>
<td>November</td>
<td>3.71 ± 1.74</td>
</tr>
<tr>
<td>June</td>
<td>6.67 ± 2.69</td>
<td>December</td>
<td>3.88 ± 3.73</td>
</tr>
</tbody>
</table>

*P value = 0.05-0.02; †P value = 0.02-0.01; ‡P value < 0.01.

These data show that the so-called rainy season in Kona is during the summer months; this is just contrary to what is common in most

*The rainfall records used in these investigations were obtained from the following: United States Weather Bureau: climatological data, Hawaii Section.
districts of the Hawaiian Islands. It may also be noted that the months of high rainfall usually have significant means while those of low rainfall have not; in other words, the months having low mean rainfall have the most irregular rainfall.

EFFECT OF RAINFALL ON COFFEE YIELDS

The relationships between rainfall and yield of coffee (*Coffea arabica* L.) in Kona were studied by calculating partial regression coefficients and their sampling errors. The statistical methods used were those described by Fisher. All regression equations included a term for time in years in order to eliminate the effects of an assumed linear increase in annual production resulting from increased acreage and age of trees and improved cultural practices.

At the outset it seemed desirable to determine whether rainfall directly affected current yield, or indirectly affected yield through the growth of laterals (fruiting wood). For this purpose the following three regression equations were used:

\[
(y - \bar{y}) = b_i(t - \bar{t}) + b_{r_1}(r_1 - \bar{r}_1)
\]

\[
(y - \bar{y}) = b_i(t - \bar{t}) + b_{r_2}(r_2 - \bar{r}_2)
\]

\[
(y - \bar{y}) = b_i(t - \bar{t}) + b_{r_3}(r_3 - \bar{r}_3)
\]

where \(y\) = coffee production in million pounds per annum; \(t\) = time in years; \(r_1\) = annual rainfall occurring during the years of fruiting; \(r_2\) = annual rainfall occurring during the years of producing fruiting wood; and \(r_3\) = annual rainfall occurring during the years previous to the production of fruiting wood.

The partial regression coefficients calculated for the above equations and the standard errors of the coefficients are given in table 1. They show that the rainfall occurring during the year in which new fruiting wood is being produced is significantly related to the succeeding year's yield of coffee. In other words, the rainfall that is related to the seasonal fluctuations in coffee yield does not occur in the year of blossoming, maturing, and harvesting of the cherries. Having established that the rainfall occurring during the preceding crop year is related to the yield of coffee, the annual rainfall was divided into the

Table 1.—Partial regression coefficients of coffee production on rainfall occurring during different years of the growth of coffee

<table>
<thead>
<tr>
<th>Equation No.</th>
<th>Annual (January to December) rainfall occurring during—</th>
<th>Partial regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Years of fruiting ((r_1))</td>
<td>0.0025 ± 0.0178</td>
</tr>
<tr>
<td>2.</td>
<td>Years of producing fruiting wood ((r_2))</td>
<td>0.0379 ± 0.0161</td>
</tr>
<tr>
<td>3.</td>
<td>Years previous to years of producing fruiting wood ((r_3))</td>
<td>0.0062 ± 0.0153</td>
</tr>
</tbody>
</table>

\(P\) value = 0.05 to 0.02.
following three periods: $e$, Early rainfall from February to June; $m$, middle rainfall from June to October; and $l$, late rainfall from October to February. The relationships between each of these three periods of rainfall and the following year's yield of coffee were studied, the following regression equations being used:

\[
(y - \overline{y}) = b_t(t - \overline{t}) + b_e(e - \overline{e}) \quad (4)
\]
\[
(y - \overline{y}) = b_t(t - \overline{t}) + b_m(m - \overline{m}) \quad (5)
\]
\[
(y - \overline{y}) = b_t(t - \overline{t}) + b_l(l - \overline{l}) \quad (6)
\]
\[
(y - \overline{y}) = b_t(t - \overline{t}) + b_e(e - \overline{e}) + b_m(m - \overline{m}) + b_l(l - \overline{l}) \quad (7)
\]

The partial regression coefficients and their standard errors calculated for the above equations are given in Table 2. It may be seen that

Table 2.—Partial regression coefficients of coffee production on three seasons of rainfall in Kona

<table>
<thead>
<tr>
<th>Equation No.</th>
<th>Partial regression coefficients $b$ on—</th>
<th>Standard error of partial regression coefficients of production $p$ on—</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time</td>
<td>Early rainfall</td>
</tr>
<tr>
<td>4</td>
<td>1.283 (t)</td>
<td>0.080</td>
</tr>
<tr>
<td>5</td>
<td>1.279 (t)</td>
<td>0.080</td>
</tr>
<tr>
<td>6</td>
<td>1.277 (t)</td>
<td>0.075</td>
</tr>
<tr>
<td>7</td>
<td>1.281 (t)</td>
<td>0.075</td>
</tr>
</tbody>
</table>

\[ P \text{ value} < 0.01. \]

Figure 3.—Comparison of the actual coffee production of Kona with that estimated from the equation $y = 0.285t + 0.08e - 1.67$ (where $y =$ estimated production, $t =$ time, and $e =$ February to May rainfall).
only the rainfall occurring between February and June of the preceding season is significantly related to the annual yield. Substituting the calculated values in equation (4), we have

\[ y = 0.285t + 0.08e^{-1.67} \]

This equation was used in obtaining the estimated production of coffee given in figure 3. From the statistical significance of the partial regression coefficient of yield on early rainfall and the general agreement between actual and estimated productions, a considerable amount of the seasonal fluctuation in Kona coffee production may be ascribed to varying early rainfall.

Annual yields of approximately half an acre of coffee trees measured in conjunction with a fertilizer experiment are available for 8 years. Figure 4 shows the annual fluctuations in yield as compared with annual fluctuations in early rainfall occurring during the years of growth of the fruiting wood. It may be seen that, with the exception of 1 year, the fluctuations are concordant. Because of the limited number of observations, statistical methods were not applied to these data.

**SUMMARY**

Statistical analyses of data on rainfall and coffee production for the years 1901 to 1936 in the Kona district of Hawaii show two distinct periods of heavy rainfall and one period of markedly light precipitation.

The dry season occurs during the winter months, and the months that have low mean rainfall have the most irregular rainfall.

Much of the variability in annual coffee production may be ascribed to fluctuations in the February to June rainfall occurring during the years in which the fruiting wood was produced.