TECHNICAL BULLETIN NO. 66 DECEMBER 1966

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ACKNOWLEDGMENT

The authors gratefully acknowledge the contribution of the Royal Hawaiian Macadamia Nut Company in providing the trees, fertilization, growth measurements, yield data, and collection of leaf samples for the experiments reported here. Our heartfelt thanks are extended to Minoru Awada, Ramon de la Pena, Harvey Miura, and Dr. Kobe Shoji, all of whom assisted in one or more phases of this study.

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INTRODUCTION

An extensive commercial planting of macadamia *(Macadamia integrifolia)* on aa lava rockland near Keaau, Hawaii, provided the opportunity for this study of phosphorus requirements under conditions of low natural fertility. Macadamia trees grown in this area require fertilization with nitrogen, potassium, and phosphorus *(3)*. Although the fertility is low, drainage is good and the climate generally excellent. Hence, the site of this orchard provides conditions approaching rock culture, where nutrition can be controlled, while complicating factors characteristic of weathered soils are not involved.

The range in temperature at Keaau Orchard is quite similar from year to year. During the months of December through May, mean monthly maximum temperatures generally range from 76° to 81° F with mean monthly minima between 59° and 65° F. The warmest months are from July through October, when mean monthly maxima commonly range between 82° and 85° F and minima between 65° and 68° F. During the years 1956 through 1963, annual rainfall varied from 75 inches in 1962 to 160 inches in 1956. Mean annual rainfall for the 8-year period was 121 inches. In few cases has it been possible to relate variations in responses from year to year with climatic factors.

Although some flowering may occur in any month of the year, the major flowering periods at Keaau Orchard are in the months of January through March. The peak month for nut drop is usually October, although September and November are also months of heavy yield. From a study on seedling trees Jones *(13)* reported that little oil formation takes place in the macadamia embryo prior to 90 days after flowering. The major expansion of the embryo and accumulation of oil therein occurs between the 90th and 215th days after flowering. Hence, at Keaau Orchard the flowering period coincides with the cooler months and the major period of oil formation in the embryos is during the warmer months of the year.

The first experiment reported here was with young trees. Within its span were periods of rapid growth and early bearing. Some of the early results from this experiment have been reported previously *(4)*.

The second experiment was with bearing trees which were initially deficient in phosphorus. One of the purposes was to determine how rapidly phosphorus deficiency can be corrected and how much phosphorus is required.

The third experiment was a study of phosphorus nutrition over a period of 8 years—which included a range of stages of development from pre-bearing to nearly full production. Short accounts of some of the results from the second and third experiments have been given elsewhere *(1, 2)*.

The results from these experiments permit construction of a composite picture of responses to phosphorus during various stages of tree development. Relationships are shown between phosphorus concentrations in the leaves and growth rate of young trees. In bearing trees, consistent relationships between leaf phosphorus and yield are evident. Factors which affect leaf phosphorus values were found to vary with stage of tree development. From a study of these factors the phosphorus requirements are estimated for various stages.

GENERAL PROCEDURES AND METHODS

The three varieties recommended for commercial planting *(12)* were used: Keauhou in Experiments 1 and 2, Kakea in Experiment 2, and Ikaika in Experiment 3. In each case, scions of the selected varieties were grafted to seedling rootstocks in a nursery. The square system of planting with 25 feet between trees was used in the orchard. Randomized block designs were used for all experiments, details of each design being determined by the distribution of trees of the selected variety available in the orchard. Fertilizers were applied by broadcast application on the surface of the ground under the crown of each tree, except as otherwise noted. Phosphorus applications were made four times each year except for one treatment in Experiment 1.

At the beginning of each experiment each tree was marked at a point near the base of the trunk. The circumference of each tree was measured at this point semiannually. The mean rate of circumference increase, in millimeters per day, was calculated from these measurements. The Trunk Size Index, here defined as $\frac{(\text{circumference in cm})^2}{10}$, was determined from measurements made near the end of each year, usually in December. The Trunk Size Index was also used to calculate the Relative Rate of Phosphorus Application, defined as:

$$\frac{\text{Pounds of phosphorus applied during the year}}{\text{Trunk Size Index at end of year previous to the year of application}} \times 10^2$$

Mature nuts falling from each tree were harvested at biweekly intervals in the months of August through December and at less frequent intervals in other months depending upon nut drop. The fresh weight of nuts from each tree was determined at each harvest. Weights of husked (in-shell) nuts were estimated by multiplying in-husk weights by 0.55.

Leaf samples were taken each March as previously described *(4)*: One mature leaf was taken from the second whorl below the tip of a main, outside branch just prior to, or at the beginning of, the first flush of growth from that branch during the year. At least two leaves were taken from separate branches of each tree. Leaves from all trees in the same treatment plot were combined into a sample of not less than eight leaves. In most cases a second sampling was made in June from the same whorls sampled in March. The March samples consisted of young mature leaves about 3 months old and the June leaves were 3 months older.

The leaves sampled from Experiment 1 in March of 1956 and 1957 were divided into blades and "petioles." The petiole samples actually included the lower half of the midrib. These petiole samples represented somewhat less than 10 percent of the whole leaf samples. In all the other samplings the whole leaves were dried and ground without separation of blade from petiole. The samples were dried at 75° C in a forced-draft oven. After grinding, a suitable portion was ignited and ashed at 500° to 550° C overnight. The ash was dissolved in 4N HCl, filtered, and made to a volume to give a final concentration of 0.4N HCl. An aliquot was used for the determination of phosphorus by the procedure of Kitson and Mellon *(14)*. Separate aliquots were used for determination of potassium and calcium by flame spectrophotometry *(20)* and for colorimetric determination of magnesium *(24)*. A separate portion of the ground sample was used for determination of total nitrogen by the Kjeldahl method *(15)*.

Growth, yield, and analytical data were analyzed by variance and covariance methods as described by Snedecor *(23)*, except that Duncan's multiple range test *(6)* was used to determine the significance of differences between treatments. Least significant differences (LSD's) are also reported. Although these values are only valid for comparisons between results adjacent in rank, they provide useful reference points for relative variation. Methods of correlation and regression analysis described by Ezekiel and Fox *(10)* were also used.

EXPERIMENTATION

Experiment 1—Young Trees of Keauhou

Nursery trees of variety Keauhou were transplanted to Keaau Orchard on July 14, 1953. The experiment consisted of six treatments in four randomized blocks. Each treatment plot contained three trees. The first circumference measurements were made on August 19, 1953. At this time trunk circumferences ranged from 1.3 cm to 4.6 cm, the mean being 2.2 cm. The experiment was continued through 1960. The amounts of phosphorus applied throughout the experiment are shown in table 1. The original objectives were to investigate response to application of raw rock phosphate under the trees at the time of planting as well as those which might result from different levels of application at regular intervals. Raw rock phosphate was the only carrier used prior to April 1956. At this time, leaf analyses, growth data, and deficiency symptoms suggested phosphorus was not sufficiently available from this carrier. Beginning with an application on April 9, 1956, superphosphate was used as the carrier. In February 1957 the treatments were modified to provide for five levels of phosphorus. In the sixth treatment the phosphorus was applied at the same annual rate as used in the third level, but in only two applications per year instead of four. This treatment was modified in 1959. The amounts applied were modified at frequent intervals in an effort to maintain differences in leaf phosphorus values and growth rates among the treatments.

TABLE 1. Phosphorus applied in Experiment 1

TREAT-MENT	ROCK PHOSPHATE AT PLANTING (circa 0.25 lb)	MONTH OF APPLICATION								
		July Oct. 1953	Jan. Apr. July Oct. 1954 and 1955	Jan. 1956[1]	Apr. July Oct. 1956	Feb. Mar. July Oct. 1957	Jan. Apr. June Oct. 1958	Jan. Apr. June 1959	Oct. 1959	Jan. Apr. July Oct. 1960
		Pounds of phosphorus per tree								
1	–	0	0	0	0	.011	.022	.023	.027	.036
2	+	0	0	0	0	.022	.033	.045	.085	.106
3	+	.010	.010	.010	.021	.033	.044	.061	.192	.236
4	+	.021	.021	.021	.041	.044	.055	.102	.277	.332
5	+	.041	.041	.041	.083	.065	.065	.135	.577	.700
6	–	.021	.021	.021	.041	.065[2]	.087[2]	.070[2]	.323[2]	.400[2]

[1] Applications through January 1956 were all in the form of raw rock phosphate (16% P); thereafter, superphosphate (9.7% P) was used in all applications.
[2] In 1957 and the following years, treatment 6 received applications in only 2 of the 4 months indicated for each year.

TABLE 2. Nitrogen, potassium, and magnesium applications throughout Experiment 1[1]

YEAR	NUMBER OF APPLICATIONS PER YEAR	NITROGEN	POTASSIUM	MAGNESIUM
		Pounds per application		
1953	2	.04	.07	.01
1954	3	.06	.11	.01
1955	3	.06	.11	.01
1956	3	.13	.23	.07
1957	4	.10	.10	.09
1958	4	.11	.13	.12
1959	4	.26	.27	.17
1960	4	.42	.27	.27

[1] Nitrogen was supplied as ammonium sulfate (21% N), potassium as sulfate of potash (43.6% K), magnesium as kieserite (17.5% Mg).

Nitrogen, potassium, and magnesium were supplied as shown in table 2.

Scope. The scope of this experiment is depicted in figure 1, where data for the lowest and highest phosphorus treatments are shown for the period from 1956 through 1960.

Trunk growth rate and Trunk Size Index. During the period from the first measurement on August 19, 1953 to January 10, 1956, there were no significant differences among treatments in rate of trunk growth. The mean trunk circumference increased during this period from 2.2 cm to 7.4 cm, representing a mean rate of increase of 0.059 mm per day. Mean rates of circumference growth for intervals subsequent to January 10, 1956 are shown for all treatments in table 3 and for treatments 1 and 5 in figure 1. Circumference growth rate in treatment 5 increased sharply in 1956 after applications of superphosphate were begun. Rates in this treatment remained nearly constant in 1957 and early 1958, increased somewhat in late 1958, then fell to a lower level which was maintained through 1960. The relatively high dosage applied to treatment 6 in February 1957 resulted in a higher growth rate in this treatment than in treatment 3 during the first interval of 1957, but growth rates in these two treatments did not differ significantly in subsequent intervals. The rate of growth in treatment 5 during 1957 and 1958 was in the neighborhood of 0.2 mm per day, in contrast to the mean growth rate of 0.059 mm per day during the years previous to superphosphate application. Differences among treatments were statistically significant in the second interval of 1956 and in each succeeding interval until December 1958. In 1959 and 1960 none of the differences among treatments were statistically significant.

The cumulative effects of the differences in growth rates among treatments are shown by data for the Trunk Size Index (figure 1 and table 4). Differences among treatments became statistically significant by the end of 1957, when trunks of treatments 4, 5, and 6 were all larger than those of treatment 1. In the 3 subsequent years of the experiment, trees of treatment 1 had significantly smaller trunks than did those of the other treatments. The increase in Trunk Size Index with time in

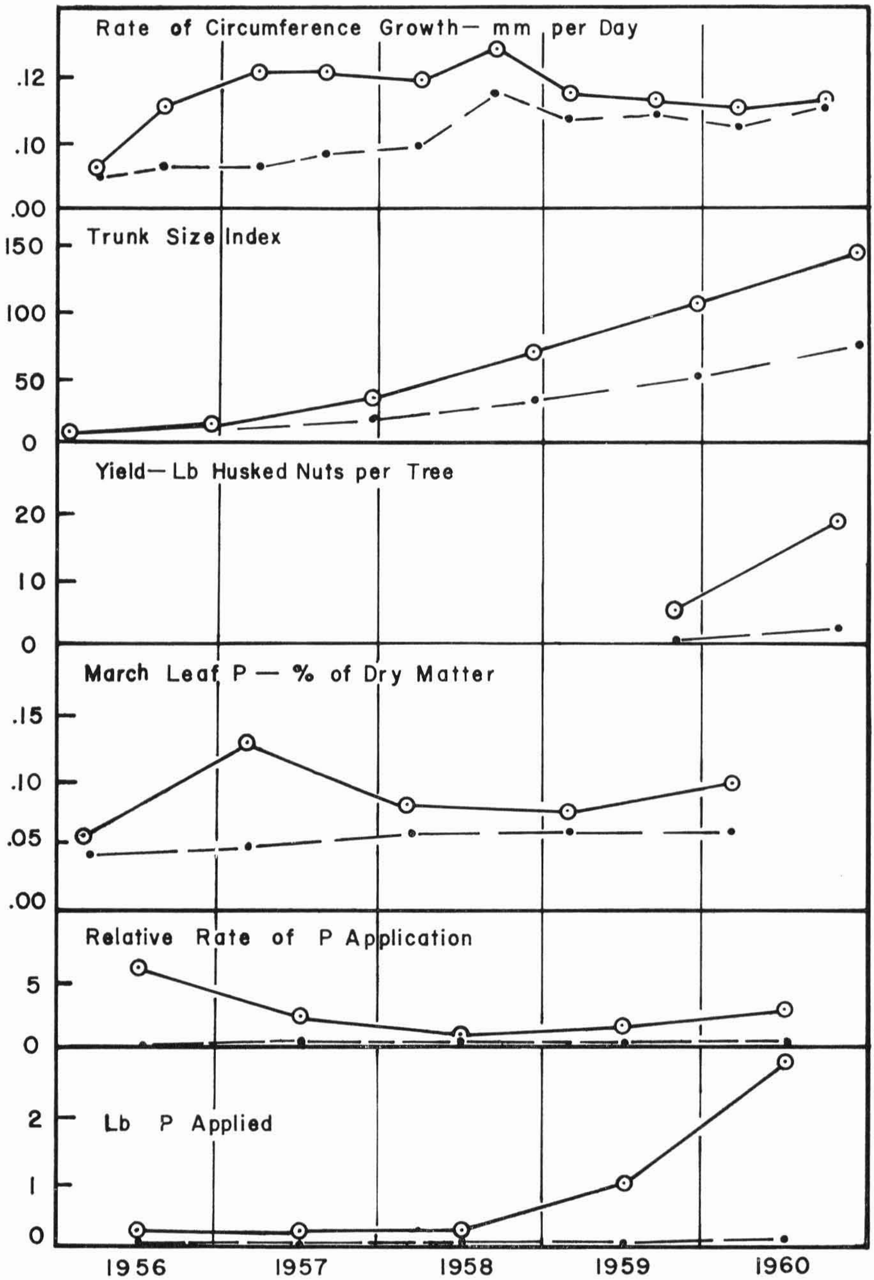

FIGURE 1. The scope of Experiment 1 as illustrated by records for a 5-year period from treatment 1 (•) and treatment 5 (○), the lowest and highest phosphorus treatments, respectively.

TABLE 3. Rates of trunk circumference growth in Experiment 1

YEAR	1956		1957		1958		1959		1960	
Period	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*
Duration (days)	157	206	149	184	189	185	175	196	165	185
Treatment	*Mean increase in circumference (mm per day)*[1]									
1	.05	.06^{c}	.06^{c}	.08^{b}	.09^{c}	.17^{b}	.13	.14	.12	.15
2	.08	.09^{bc}	.16^{b}	.15^{a}	.11^{bc}	.19^{ab}	.16	.15	.16	.14
3	.07	.11^{ab}	.17^{b}	.17^{a}	.14^{b}	.21^{ab}	.18	.14	.11	.15
4	.07	.16^{a}	.20^{ab}	.17^{a}	.15^{ab}	.21^{ab}	.16	.15	.14	.14
5	.06	.15^{ab}	.20^{ab}	.20^{a}	.19^{a}	.24^{a}	.17	.16	.15	.16
6	.06	.15^{ab}	.22^{a}	.19^{a}	.15^{ab}	.22^{a}	.16	.15	.14	.15
LSD 5%[1]	n.s.	.056	.038	.052	.047	.051	n.s.	n.s.	n.s.	n.s.

[1] Significant differences between treatment means for each growth interval as computed by Duncan's multiple range test (6) are denoted by superscripts. Values for a given period not having the same letter in their superscripts differ significantly ($p < 0.05$). Least significant differences are also shown. These apply, of course, only to differences between means adjacent in rank. n.s. denotes no significant differences.

TABLE 4. Trunk Size Index at the end of each year in Experiment 1[1]

TREATMENT	1955	1956	1957	1958	1959	1960
1	6.8	10.6	17.0[b]	30.3[b]	50.3[b]	74.5[b]
2	6.4	15.4	27.4[ab]	55.5[a]	86.5[a]	122.6[a]
3	6.2	15.8	28.7[ab]	58.5[a]	89.8[a]	121.4[a]
4	5.7	14.4	32.1[a]	60.8[a]	92.0[a]	125.1[a]
5	4.4	12.6	34.2[a]	68.5[a]	102.3[a]	142.7[a]
6	5.5	13.0	33.0[a]	63.5[a]	95.5[a]	129.1[a]
LSD 5%[1]	n.s.	n.s.	12.0	18.2	25.6	32.7
1%			16.6	25.2	35.4	45.3

[1] Statistical symbols as in table 3.

treatment 5 (figure 1) was exponential in 1956, 1957, and 1958 but essentially linear in subsequent years.

Branch elongation. Elongation of branches was estimated for the period between March and July 1957. Results of these estimates are shown in table 5. Deficiency of phosphorus greatly curtailed stem growth in treatment 1. However, it was found that the variability of elongation measurements was very great. An additional disadvantage in using elongation as a growth index arises from the observation that high phosphorus trees have much more branching than low phosphorus trees. It is evident, therefore, that a measurement of elongation of marked branches does not fully represent the amount of total stem elongation.

TABLE 5. Mean elongation of branches for the period from March 1957 to July 1957 in Experiment 1

TREATMENT	ELONGATION[1]
	cm
1	14.3[c]
2	25.5[b]
3	28.4[ab]
4	30.7[ab]
5	29.7[ab]
6	37.0[a]
LSD 5%	8.6
1%	11.9

[1] Supe scripts as in table 3.

Deficiency symptoms. During the spring of 1956 a purplish coloration of some of the older leaves could be detected. At this time some trees of each treatment had this symptom. During subsequent years this symptom could rarely be detected on trees other than those of treatment 1. This symptom appears suitable for diagnosis only in cases of extreme deficiency.

Trees of treatment 1 and a few trees of treatment 2 had much greater leaf drop than did those of other treatments. Defoliation was particularly evident on the terminal stem. In some cases all leaves dropped from the terminal and the terminal stem died.

Yield. The first year when yield of nuts was sufficient to warrant collection of data was 1959. Mean yields for the six treatments are shown in table 6. In each of the 2 years of record, treatment 5, the highest phosphorus treatment, had the highest yield. In 1959, treatment 5 had significantly higher yield than any of the other treatments. In 1960, yield in treatment 5 was significantly higher than in treatment 1 or 2.

TABLE 6. Yields of young Keauhou trees (pounds of husked nuts per tree)[1]

TREATMENT	UNADJUSTED MEANS		MEANS ADJUSTED FOR TRUNK SIZE INDEX	
	1959	1960	1959	1960
1	0.4[d]	2.4[c]	1.8[b]	9.5[bc]
2	0.9[cd]	7.5[bc]	0.9[b]	7.4[c]
3	2.3[bc]	12.3[ab]	2.2[b]	11.5[abc]
4	2.3[bc]	13.6[ab]	2.1[b]	12.4[ab]
5	5.0[a]	18.5[a]	4.4[a]	15.3[a]
6	2.6[b]	16.0[a]	2.2[b]	14.1[a]
LSD 5%	1.48	6.13	1.33	4.05

[1] Superscripts as in table 3.

These data clearly show that trees supplied with insufficient phosphorus over a period of several years may yield only a small fraction of the yields possible where phosphorus fertilization is maintained at an adequate level. The question which now arises is: to what extent are the differences in yield among treatments attributable to the phosphorus nutrition during the immediate years involved and to what extent are they the indirect result of differences in size of trees brought about by different growth rates over a period of several preceding years? This question can be answered at least in part by a covariance analysis of the yield data, wherein the treatment means for yield are adjusted for the index of trunk size (table 4). The Trunk Size Indexes used were those determined at the end of the year previous to that of the yield. Results of these analyses are shown in the last two columns of table 6. Comparison of these results with those of the unadjusted yields indicates that a considerable proportion of the differences in yield among treatments can be ascribed to differences in size of the trees each year. Nevertheless there are significant differences among the adjusted means, particularly between treatment 5 and each of the other treatments in 1959 and between treatments 5 or 6 and 1 or 2 in 1960. These results suggest that the current phosphorus nutrition of the trees has an influence on yield in addition to the influence exerted on growth rate of the trunk during previous years.

Nutrient element content of leaves. Phosphorus concentrations of the leaf samples obtained from each treatment in 1956 and subsequent years are shown in table 7 and those from treatments 1 and 5 in figure 1. In 1956, leaves from all replicates of the same treatment were combined into a single sample, so no statistical treatment of the data for that year is possible. However, judging from the LSD values for subsequent samplings, it appears that by June 1956 the differential phosphorus treatments had had some influence on the leaf phosphorus values.

TABLE 7. Phosphorus concentrations in leaf samples of Experiment 1 (percent dry matter)[1]

TREATMENT	1956[2]	1957	1958	1959	1960
			March samples		
1	.045	.051[d]	.060[b]	.060[c]	.060[c]
2	.066	.069[c]	.060[b]	.062[bc]	.068[bc]
3	.051	.069[c]	.065[b]	.063[abc]	.068[bc]
4	.055	.094[b]	.071[ab]	.072[ab]	.077[b]
5	.056	.126[a]	.079[a]	.075[a]	.095[a]
6	.048	.099[b]	.071[ab]	.068[abc]	.079[b]
LSD 5%	–	.0180	.0116	.0095	.0154
			June samples		
1	.037	.047[c]	.044[d]	.042[b]	.045[c]
2	.046	.056[bc]	.048[cd]	.048[b]	.051[bc]
3	.043	.059[bc]	.055[bc]	.049[ab]	.053[bc]
4	.062	.066[b]	.058[ab]	.050[ab]	.058[b]
5	.082	.082[a]	.065[a]	.057[a]	.076[a]
6	.048	.070[ab]	.055[bc]	.046[b]	.059[b]
LSD 5%	–	.0149	.0081	.0087	.0113

[1] Superscripts as in table 3.
[2] In 1956, leaves were sampled by treatments, so no statistical analysis of differences between treatments is possible for that year.

Significant differences in leaf phosphorus concentrations were found at each sampling date in 1957 and subsequent years. The greatest range in concentrations between treatments was obtained in March 1957 when treatment 5 had a value significantly higher than any other treatment, and treatment 1 a value significantly lower than any other treatment. When the leaf phosphorus concentrations for March 1957 are compared with the rates of trunk growth for the first period of 1957 (table 3), it is seen that although treatment 5 had a higher leaf phosphorus value than other treatments, there were no differences in growth rate among treatments 4, 5, and 6. It appears, therefore, that these three treatments were in the range where phosphorus was adequate for growth. In March 1958, leaf phosphorus values for these three treatments were not as high and the growth data for the first period of 1958, although showing no significant differences among these three treatments, suggest that only in treatment 5 did phosphorus approach adequacy. In 1959 and 1960 no significant differences in growth rate resulted despite a rather wide range in phosphorus values among treatments. However, during these latter 2 years, differences in leaf phosphorus values were associated with differences in yield (table 6).

The samples collected in June had phosphorus concentrations consistently lower than did the March samples. However, the range of concentrations in June leaves was of similar magnitude to that in March leaves.

In no case was there a significant effect of the treatments on nitrogen, potassium, calcium, or magnesium concentrations of the leaf samples in this experiment. The ranges and mean concentrations of these elements are shown in table 8. Results from other experiments with this variety (Keauhou) indicate that growth is not curtailed when leaf nitrogen values remain above 1.45 percent of the dry weight, and leaf potassium concentrations remain above 0.40 percent in March leaves *(5)*. It appears that nitrogen nutrition of these trees was adequate and that potassium nutrition was generally adequate, with the possible exception of one treatment plot in 1958. Magnesium values of 0.065 percent and below are associated with a deficiency symptom. Some of the trees in this experiment had values in this range at times. However, attempts to associate these low magnesium values with curtailed growth rate or yield have been indecisive thus far.

The data of table 8 show the older June leaves to have consistently lower nitrogen values than March leaves. Potassium was usually lower in June leaves, but not in all years. Calcium was invariably higher in June leaves, but magnesium showed no consistent difference due to time of sampling.

TABLE 8. Ranges and mean values for leaf concentrations of nitrogen, potassium, calcium, and magnesium in Experiment 1 (percent of dry matter)

YEAR	NITROGEN		POTASSIUM		CALCIUM		MAGNESIUM	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
				March samples				
1956[1]	1.62–1.82	1.69	.63–.74	.68	0.30–0.44	0.38	.057–.072	.063
1957	1.82–2.82	2.15	.52–.95	.66	0.23–0.61	0.47	.065–.105	.080
1958	1.60–2.41	1.85	.35–.68	.51	0.31–0.68	0.51	.044–.111	.089
1959	1.46–1.87	1.61	.40–.66	.52	0.31–1.00	0.70	.072–.112	.092
1960	1.54–1.78	1.64	.43–.71	.60	0.37–0.62	0.51	.060–.095	.079
				June samples				
1956[1]	1.35–1.74	1.53	.50–.66	.57	0.50–0.55	0.53	.052–.064	.057
1957	1.60–2.60	1.91	.37–.65	.50	0.48–0.93	0.74	.047–.099	.070
1958	1.36–2.20	1.64	.37–.66	.50	0.38–0.94	0.67	.069–.126	.087
1959	1.39–1.76	1.54	.38–.68	.54	0.54–1.19	0.83	.075–.123	.092
1960	1.42–1.68	1.52	.33–.89	.49	0.58–1.02	0.82	.059–.112	.084

[1] Leaves were sampled in 1956 on a treatment basis, in subsequent years on a plot basis.

Relationship of growth rate to leaf phosphorus. In a previous report dealing with the early stages of this experiment *(4)*, the increase in the Trunk Size Index during the first growth interval of 1957 was used as a growth index. It was shown that about 90 percent of the variance in this growth index can be accounted for in terms of the Trunk Size Index at the beginning of the interval and a curvilinear relationship with leaf phosphorus concentrations of March 1957. The relationship is well described by a third degree polynomial of leaf phosphorus concentrations and a linear partial regression on initial Trunk Size Index. More of the variance in growth index was accounted for by leaf blade phosphorus than by "petiole phosphorus."

Figure 1 shows that the Trunk Size Index, based on the square of the circumference, was undergoing an exponential increase with time during 1957. During the same period of time the rate of circumference increase was essentially constant. These observations suggest that at this stage of tree development the relationship of growth to leaf phosphorus might be expressed more simply by using the linear circumference measurement, than by using the square of the circumference. Results of correlation analyses of these two growth indexes are shown in table 9. From these analyses it may be seen that the initial Trunk Size Index (X) was significantly correlated with each measure of trunk growth when simple correlations were used. However, when the third degree polynomial of leaf phosphorus (L) was

TABLE 9. A comparison of correlation analyses to account for variance in linear and squared expressions of trunk growth in Experiment 1 for the period between January and June 1957

"INDEPENDENT" VARIABLES	COEFFICIENT OF DETERMINATION ($\bar{R}^2$)	F VALUE FOR REDUCTION IN UNACCOUNTED FOR VARIANCE BY ADDITION OF: X	L	L^2	L^3
		Increase in circumference as dependent variable			
X	.4322				
L	.3859				
L,X	.6084	13.52**	27.95**		
L,L^2	.7945			44.75**	
L,L^2,X	.8404	7.04*		31.48**	
L,L^2,L^3	.8919				20.00**
L,L^2,L^3,X	.8973	2.01 n.s.			12.09**
		Increase in squared circumference as dependent variable			
X	.4151				
L	.1158				
L,X	.7256	38.32**	15.92**		
L,L^2	.6313			26.83**	
L,L^2,X	.8709	39.99**		24.63**	
L,L^2,L^3	.7845				15.94**
L,L^2,L^3,X	.9026	25.23**			7.04*

* Significant at the 5 percent level.
** Significant at the 1 percent level.
n.s.: Not significant.

introduced into the multiple correlations, the initial Trunk Size Index as an independent variable made a significant contribution towards accounting for variance in growth as measured by increase of the squared circumference, but not to the variance in circumference increase. When growth in circumference is used as the dependent variable, 89.2 percent of its variance is accounted for in terms of the third degree polynomial of leaf phosphorus. Adding the initial Trunk Size Index as an independent variable increases the variance accounted for only to 89.7 percent, an increase which is not statistically significant. The third degree polynomial is shown as the broken line in figure 2. However, essentially the same percentage of variance in circumference growth rate can be accounted for by the freehand curve represented by the solid line of figure 2 (the index of determination for the freehand line is 0.9094). The latter curve appears more meaningful from a phys-

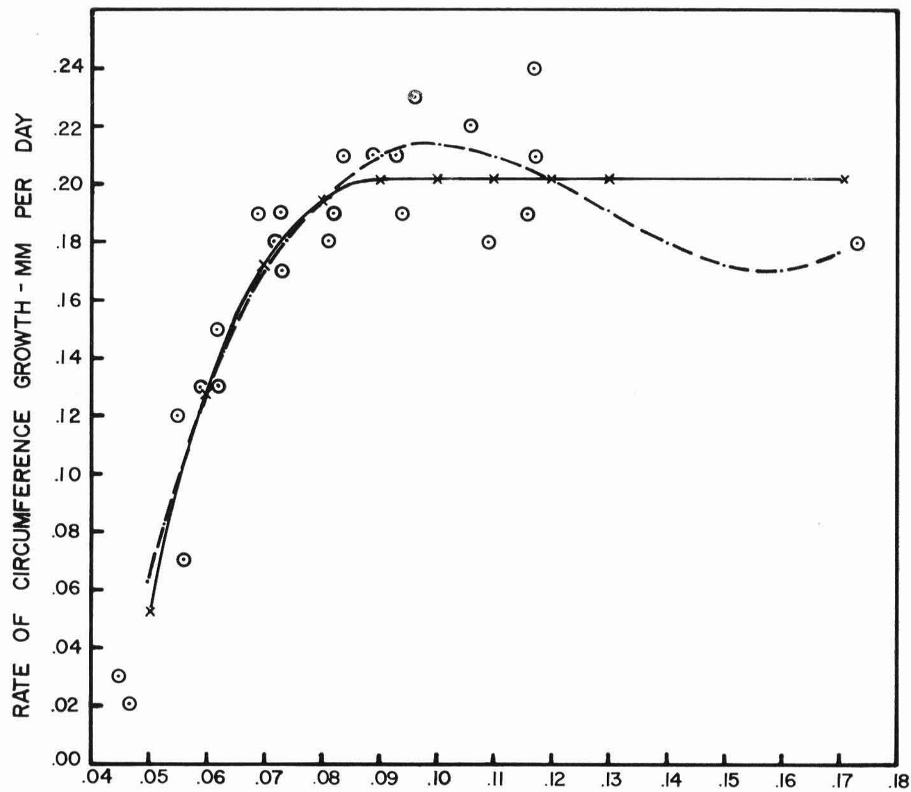

FIGURE 2. Relationship between rate of circumference growth during the first interval of 1957 (C), and leaf phosphorus concentrations in March (L), as represented by the polynomial: $C = -0.625 + 21.41\ L - 175.9\ L^2 + 456.9\ L^3$, broken line; and freehand curve, solid line.

TABLE 10. Simple and multiple correlation coefficients relating the mean rate of circumference increase during a year with phosphorus percentages in March and June of that year

PHOSPHORUS POLYNOMIAL DEGREE	COEFFICIENT OF DETERMINATION ($\bar{R}^2$)	F VALUE FOR REDUCTION IN UNACCOUNTED FOR VARIANCE BY ADDITION OF THE LAST DEGREE OF THE POLYNOMIAL[1]
	Independent variable(s): Leaf phosphorus in March 1957 and its polynomials Dependent variable: 1957 rate of circumference increase	
First	.5903	–
Second	.8335	25.84**
Third	.8882	8.83**
	Independent variable(s): Leaf phosphorus in June 1957 and its polynomials Dependent variable: 1957 rate of circumference increase	
First	.7307	
Second	.8009	10.71**
Third	.7893	1.0 n.s.
	Independent variable(s): Leaf phosphorus in March 1958 and its polynomials Dependent variable: 1958 rate of circumference increase	
First	.2842	
Second	.3855	4.08[2]

[1] n.s.: Not significant; ** significant at the 1 percent level.
[2] F value required at 5 percent = 4.49.

iological standpoint. In any case the conclusion from either of these curves is similar to that reached previously *(4)* ". . . it appears that values in the range above 0.08 percent phosphorus give reasonable assurance of adequate phosphorus for growth."

March leaf phosphorus for 1957 is also closely related to the mean rate of circumference increase during the whole year of 1957. An analysis of this relationship is shown in table 10 and illustrated in figure 3. The third degree polynomial and the freehand curve indicate maximum growth rate associated with March leaf phosphorus values of about 0.08 percent and above.

Phosphorus values for leaves collected in June 1957 were also correlated with mean rate of circumference growth during 1957 (table 10). However, the proportion of variance in growth rate related to June leaf phosphorus was less than the proportion related to March leaf phosphorus.

In 1958 there was again a considerable response in circumference growth rate to the phosphorus treatments (figure 1 and table 3), but leaf phosphorus values in 1958 did not have as large a range as they had in 1957. In addition, growth rates were more variable in 1958. Growth rates were significantly correlated with March leaf phosphorus values in 1958, and the test for curvilinearity approached

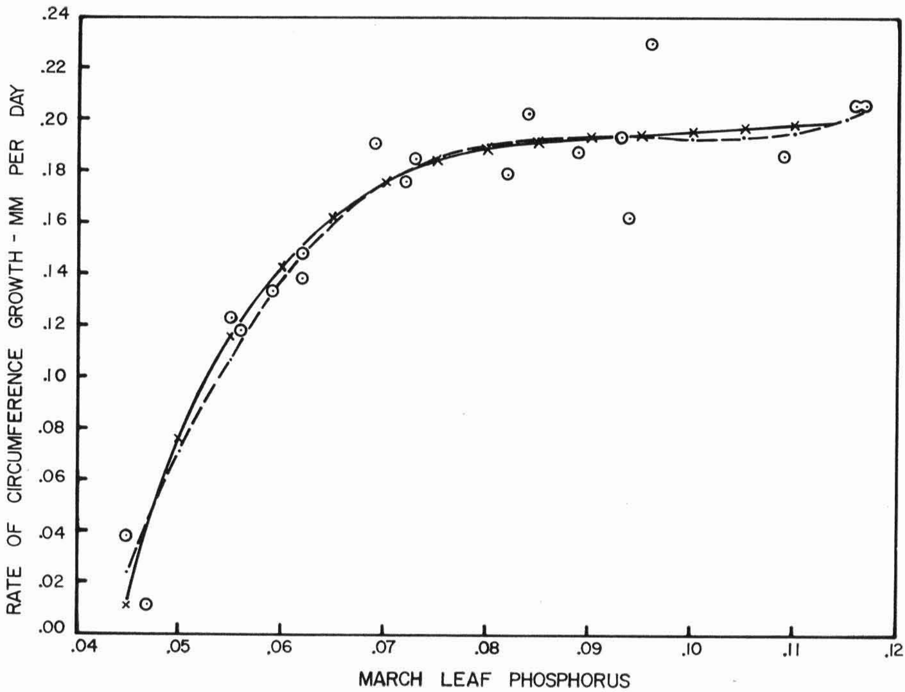

FIGURE 3. Relationship of mean rate of circumference growth in 1957 to March leaf phosphorus as represented by the polynomial: $C = -0.999 + 37.84 L - 389.58 L^2 + 1{,}394.0 L^3$ ($R^2 = 0.9068$), broken line; and freehand curve ($i^2 = 0.9229$), solid line.

but did not reach the requirement for significance at the 5 percent level. The curvilinear equation is $C = -0.352 + 13.335 L - 80.85 L^2$, where:

C = Mean rate of circumference growth

L = Percentage phosphorus in March leaves.

The derivative of this equation is $\frac{dC}{dL} = 13.335 - 161.71 L$. On solving for L at $\frac{dC}{dL} = 0$, a value of 0.0824 percent phosphorus is obtained. Thus, if this type of curve best depicted the relationship, growth rate would cease to increase at this leaf phosphorus value. It may be concluded that these results for 1958, within the range of leaf phosphorus values found, are consistent with the 1957 results.

Relationship between leaf concentrations of phosphorus and amounts of phosphorus applied. In the earlier report on 1957 results from this experiment *(4)*, highly significant correlations were shown between leaf phosphorus concentration in March and amounts of phosphorus applied. The latter were expressed in terms of pounds of P_2O_5 per inch diameter. These correlations appeared quite adequate for the single year of 1957. However, when similar relationships are sought for successive years where trees of increasing size are involved the data do not fit this pattern at all well. In figure *4A,* leaf phosphorus values for treatment means are plotted against the ratio of the amount of phosphorus applied to the circumference. From these plots it is evident that such an expression for relative rate of application is totally inadequate for use over a range of tree sizes. Thus, to obtain comparable leaf phosphorus values, much higher rates per unit of circumference were required in 1960 when the trees were larger than in 1957 when the trees were smaller. When, however, the ratio of phosphorus applied to the square of the circumference is used as an expression of Relative Rate of Phosphorus Application (figure *4B*) the data obtained from several years appear to fit into a general pattern quite well. Correlation and regression coefficients for this relationship were determined by using the treatment plot as the unit. These coefficients are shown in table 11, and the regression lines illustrated in figure 5. Regression coefficients differed somewhat from year to year. These fluctuations may be associated with seasonal climatic factors. For example, the low value for 1958 may be related to the fact that January, February, and March of 1958 each had abnormally low rainfall. There does not seem to be any consistent trend in changes of the slopes of the regression lines associated with time and tree size. Covariance analysis shows there are no significant differences among the regression coefficients for individual years. The line for total regression is shown as the central broken line of figure 5. Broken lines indicate the limits for predicting an individual event at the 5 percent level. It should be noted that the total regression is dominated by the influence of the 1957 values, because of the greater ranges in leaf phosphorus and Relative Rate of Phosphorus Application values for that year than for subsequent years. However, on using the total regression line we find that a Relative Rate of Phosphorus Application of 1.9 would result in leaf phosphorus values of 0 08 percent or higher 50 percent of the time. For assurance that 95 percent of the leaf phosphorus values would be above 0.08 percent, a Relative Rate of Phosphorus Application of 3.5 would be required.

TABLE 11. Correlation and regression coefficients for the relationship of March leaf phosphorus to the Relative Rate of Phosphorus Application (A) during the previous year in Experiment 1

YEAR OF LEAF P	LEAF P		A		COEFFICIENTS OF: Correlation (r)	COEFFICIENTS OF: Determination (r^2)	INTERCEPT (a)	SLOPE (b)
	Range	Mean	Range	Mean				
1957	.045–.173	.085	0.11–7.98	2.20	.9145**	.836	.056	.012,83
1958	.047–.094	.068	0.32–3.23	1.40	.6746**	.455	.055	.009,10
1959	.053–.084	.066	0.30–1.41	0.73	.6962**	.485	.055	.015,90
1960	.065–.111	.077	0.29–2.60	1.23	.7691**	.592	.058	.016,27
Total	.045–.173		0.11–7.98		.8624**	.744	.056	.012,60

** Significant at the 1 percent level.

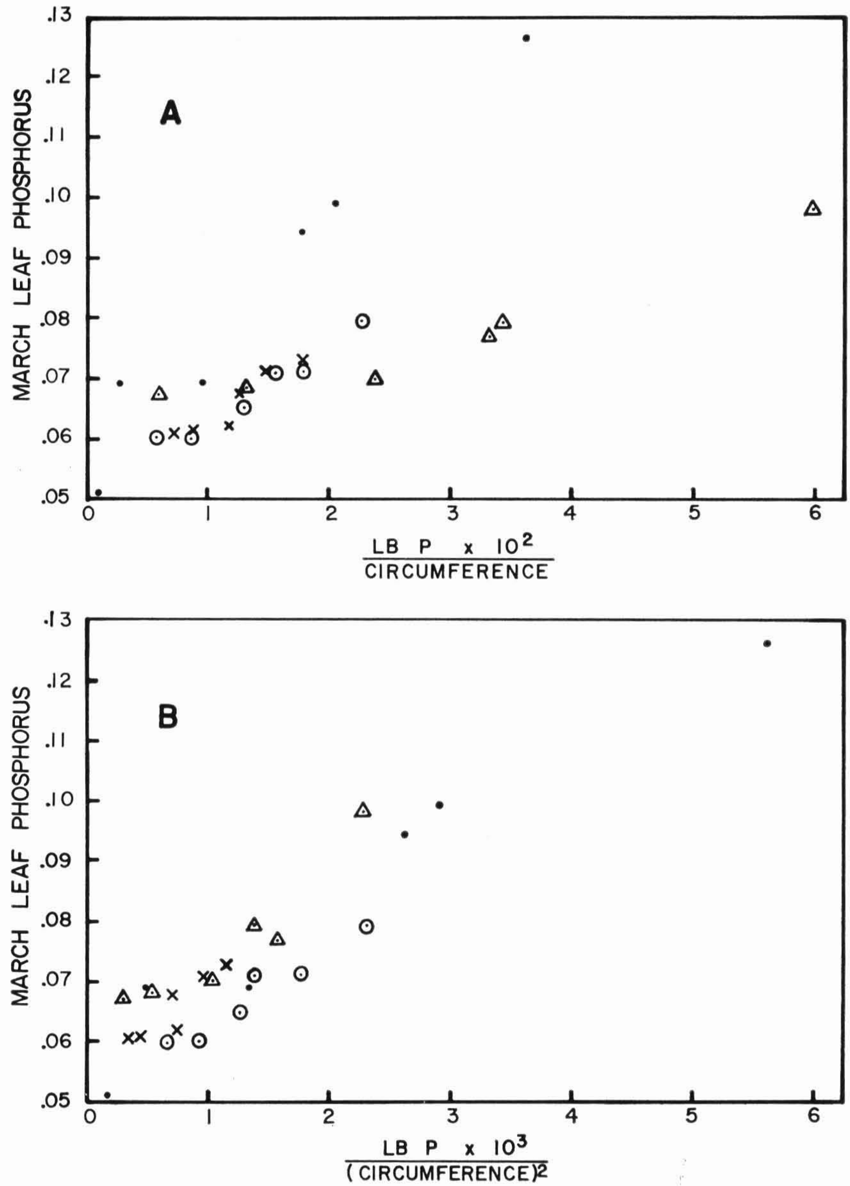

FIGURE 4. Treatment means for March leaf phosphorus values plotted against rates of phosphorus application during the year preceding the leaf analysis. March phosphorus values are for 1957 (•), 1958 (○), 1959 (x), and 1960 (△). In *4A,* rates of phosphorus application are expressed as pounds of P applied during the year $\times 10^2$ divided by the trunk circumference in centimeters at the beginning of the year of application. In *4B,* phosphorus rates are represented as the number of pounds of P applied during the year $\times 10^3$ divided by the square of the trunk circumference at the beginning of the year of application.

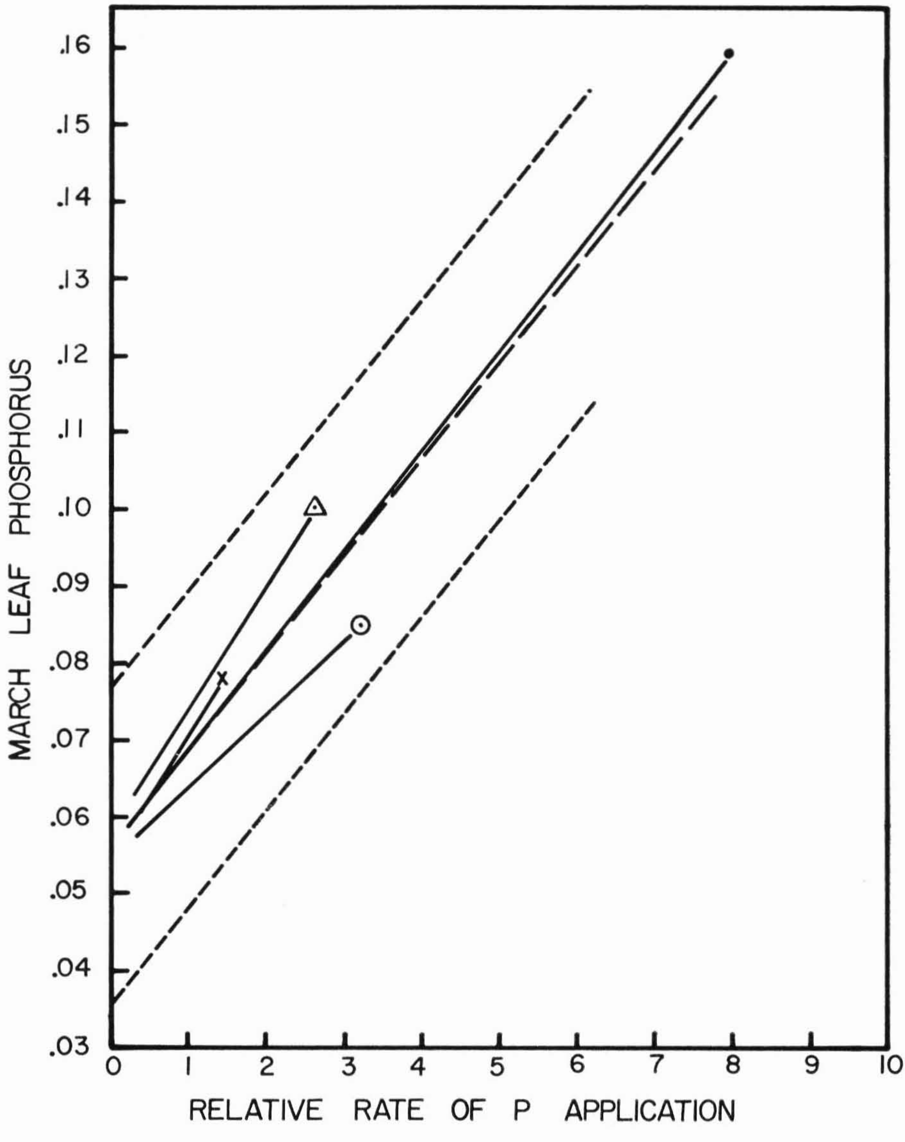

FIGURE 5. Regression lines for leaf phosphorus values in March on Relative Rate of Phosphorus Application. The ranges of values are denoted by the ends of the lines. Solid lines are for leaf phosphorus values in 1957 (•), 1958 (○), 1959 (x), and 1960 (△). The central broken line denotes total regression. The limiting broken lines denote the limits at the 5 percent level for predicting an individual event (*23*, pp. 138–141).

Experiment 2—Bearing Trees of Keauhou and Kakea

The trees used for this study had been transplanted into the orchard from a nursery in October and November 1949. During their first 9 years of growth they received various fertilizer treatments in accord with the changing practices of the orchard. The fertilizer formulations used had in common relatively high potassium and low phosphorus contents. By 1958 many of these trees displayed considerable defoliation, particularly evident on the terminal stems. On a number of these trees defoliation of the terminal was complete and the terminal stem had died. With preliminary results of Experiment 1 at hand, these symptoms suggested phosphorus deficiency. Phosphorus concentrations in the leaves of these trees were found to be well below the 0.08 percent value—known to indicate adequacy for maximum growth of younger trees (figures 2 and 3).

Experimentation was begun with the main objective of determining how rapidly the deficiency could be corrected and what quantities of phosphorus would be required. Secondary objectives were to determine the relative response to nitrogen at two rates and to determine the relative efficiency to be expected in drip-line placement as compared to broadcast application of phosphorus. Because of the arrangement of the trees in the orchard it was necessary to use separate replication designs for the two varieties. The fertilizer treatments, however, were identical.

For variety Keauhou each treatment plot consisted of four trees in a square. Of 120 trees used, 106 were surrounded on all sides by other trees and the other 14 were adjacent to field roads, so were exposed on one side. Treatments for this variety were in five randomized blocks. For variety Kakea each treatment plot consisted of two adjacent trees, one of which was adjacent to a field road, so exposed on one side. Eight randomized blocks were used. Amounts of fertilizer applied and other particulars of the treatments are shown in table 12. Treatments were begun in July 1958, nearly 9 years after the trees had been transplanted to the orchard. At the outset the six treatments provided comparisons among trees supplied at four levels of phosphorus (treatments B, C, D, and E), two levels of nitrogen at the highest phosphorus level (treatments A and E), and two modes of phosphorus placement at a moderate rate (treatments C and F). At the beginning of the experiment, trees of treatments A through E received superphosphate in a band approximately 1 foot wide under the drip line. In treatment F the superphosphate was broadcast under the entire canopy of each tree. Beginning with the first application in 1960 the placement treatments were revised so that only trees of treatment F received the drip-line application. Trees of the other five treatments received broadcast applications. This alteration was made because there was some indication that trunk growth was inhibited in the higher phosphorus treatments, an explanation for which could be application of too much fertilizer salt to the limited surface area under the drip line.

As can be seen from table 12 many other alterations were made during the course of the experiment. However, aside from the switch in phosphorus placement the initial scheme of treatments was maintained through 1960 with the actual amounts applied changing frequently pursuant to results obtained year by year. The first major change in the scheme was made in February 1961, when the amount

TABLE 12. Fertilizer applications in Experiment 2

TREATMENT	MONTH OF APPLICATION																	
	July, Oct. 1958		Feb., Apr. 1959		July, Oct. 1959		Jan., Apr., July, Nov. 1960		Feb., Apr., July, Oct. 1961		Feb., Apr. 1962		July, Oct. 1962		Feb. 1963		Apr., July, Oct. 1963	
	Pounds N and P per tree each application[1]																	
	N	P	N	P	N	P	N	P	N	P	N	P	N	P	N	P	N	P
A	0.42	0.48[2]	0.42	0.51[2]	0.42	1.19[2]	0.80	1.31	0.52	1.53	0.52	1.26	0.52	0	0.52	0	0.42	0.29
B	0.58	0.10[2]	0.63	0.10[2]	0.63	0.19[2]	1.28	0.22	1.05	0.98	1.05	0.63	1.05	0.63	1.05	0.63	0.84	0.58
C	0.58	0.17[2]	0.63	0.17[2]	0.63	0.39[2]	1.28	0.44	1.05	0.49	1.05	0.29	1.05	0.29	1.05	0.29	0.84	0.29
D	0.58	0.33[2]	0.63	0.34[2]	0.63	0.78[2]	1.28	0.87	1.05	0.98	1.05	0.63	1.05	0.63	1.05	0.63	0.84	0.58
E	0.58	0.48[2]	0.63	0.51[2]	0.63	1.19[2]	1.28	1.31	1.05	1.53	1.05	1.26	1.05	0	1.05	0	0.84	0.29
F	0.58	0.17	0.63	0.17	0.63	0.39	1.28	0.44[2]	1.05	0.49[2]	1.05	0.29[2]	1.05	0.29[2]	1.05	0.29[2]	0.84	0.29[2]
	Pounds K and Mg per tree each application[1]																	
	K	Mg	K	Mg	K	Mg	K	Mg	K	Mg	K	Mg	K	Mg	K	Mg		
A–F	0.66	0.27	0.70	0.39	0.70	0.39	2.18	0.49	2.61	0.52	1.74	0.83	1.74	0.83	1.74	0.83		

[1] Phosphorus was supplied as superphosphate. Carriers for N, K, and Mg were as in table 2.

[2] Phosphate was applied in a 1-foot band under the drip line. In the other treatments phosphate was distributed under the entire canopy of the tree.

of phosphorus supplied in treatment B was increased. Trees in this low phosphorus treatment had remained in very poor condition, since defoliation and death of terminals continued to progress. The higher phosphorus rate begun in 1961 provided for observations on recovery and possibly prevented death of these trees.

Beginning in July 1962, application of phosphorus to trees of treatments A and E was discontinued for three rounds. The large amounts of phosphorus which had been applied to these trees had resulted in leaf concentrations of phosphorus which seemed considerably higher than necessary. In addition chlorosis and marginal scorch of young leaves were observed. Correction of these symptoms was observed on most trees after phosphorus supply was discontinued.

Experimentation on Kakea was terminated at the end of 1962 except for leaf sampling. Observations on Keauhou and leaf sampling of Kakea were continued through 1963, although by this time the phosphorus status of all trees was adequate.

During 1960, branches of adjacent trees became intertwined. On December 5, 6, and 7, 1960, lower branches of all trees were removed. By July 1961 many of the trees had grown together again. Hence, trees in this experiment were nearly closed in when the treatments were begun and by 1960 the only ground area not covered by foliage of the trees was at the corners of the 25-foot squares centered by the trees.

In January 1963 there was a severe wind storm which resulted in loss of some of the experimental trees. Although some of the trees which were blown over were pruned very heavily and braced in upright position again, the data presented for 1963 include only trees which remained upright during this storm.

Scope. The amounts of phosphorus applied as well as the principal results from the highest and lowest phosphorus treatments (E and B, respectively) are plotted chronologically for variety Keauhou in figure 6. This figure serves to show the range of results obtained each year in response to phosphorus treatments and changes in trends with time as a result of treatment alterations.

Growth and Trunk Size Index. The rates of increase in trunk circumference for each period are shown in table 13. There was no case where application of higher amounts of phosphorus resulted in a significant increase in rate of trunk growth. In fact the only significant differences among treatments were associated with reductions in growth in higher phosphorus treatments. Cases of such reduction were found for Keauhou in the second growth period of 1959 when the value for treatment E was significantly lower than that for treatment D. In the second growth period of 1960 the value for treatment E was significantly lower than for treatments B, D, or F. In the first growth period of 1961, treatments A and D had values significantly lower than treatments B, C, or F. The only significant effect of treatments on trunk growth rate in Kakea was during the first period of 1959 when the values for treatments B and F were significantly higher than that for treatment D.

In no growth period did the differences in amounts of nitrogen applied result in significant differences in rates of trunk growth (comparisons between treatments A and E). Differences in placement of phosphorus (drip line or broadcast) at a moderate rate did not result in significant differences in rates of trunk growth in

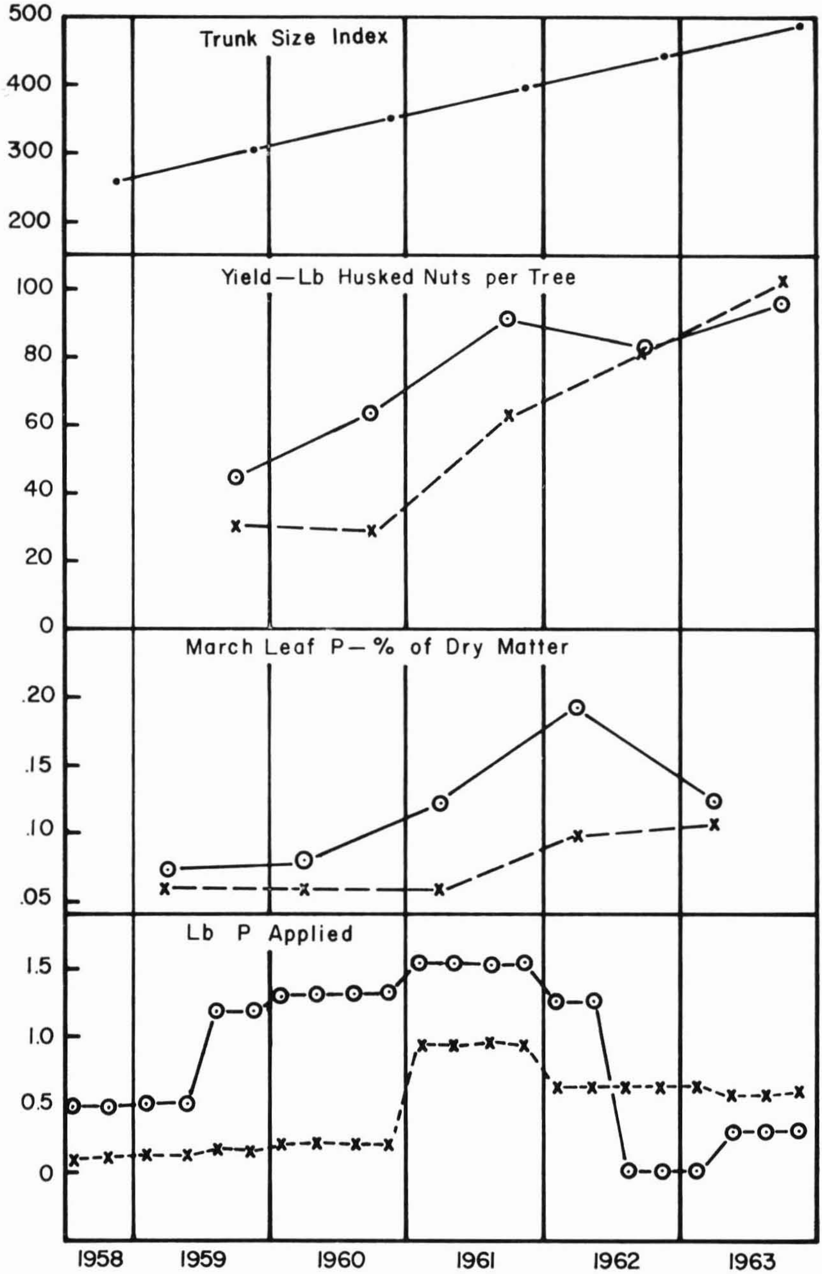

FIGURE 6. Scope of Experiment 2, variety Keauhou, as illustrated by data from treatments B (x) and E (○); and mean Trunk Size Index from all treatments (•).

TABLE 13. Rates of circumference growth in Experiment 2 (mm per day)[1]

YEAR	1958	1959		1960		1961		1962		1963	
Period	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*
Duration (days)	181	176	195	168	179	187	181	196	171	189	175
TREATMENT						*Keauhou*					
A	.19	.10	.12^{ab}	.13	.11^{ab}	.09^{b}	.07^{bc}	.08	.10	.07	.12
B	.18	.13	.12^{ab}	.14	.13^{a}	.11^{a}	.09^{a}	.08	.11	.06	.14
C	.18	.13	.12^{ab}	.15	.12^{ab}	.12^{a}	.08^{ab}	.08	.12	.07	.14
D	.19	.12	.14^{a}	.13	.13^{a}	.09^{b}	.08^{ab}	.07	.11	.09	.14
E	.18	.13	.10^{b}	.14	.09^{b}	.10^{ab}	.06^{c}	.08	.10	.07	.16
F	.18	.13	.13^{ab}	.13	.13^{a}	.11^{a}	.09^{a}	.08	.10	.07	.13
LSD 5%[1]	n.s.	n.s.	.028	n.s.	.026	.015	.021	n.s.	n.s.	n.s.	n.s.
						Kakea					
A	.18	.12^{ab}	.10	.10	.11	.08	.08	.07	.11		
B	.16	.14^{a}	.10	.12	.11	.09	.08	.07	.12		
C	.15	.11^{ab}	.09	.12	.10	.08	.07	.06	.11		
D	.17	.10^{b}	.09	.11	.09	.08	.07	.06	.11		
E	.16	.12^{ab}	.10	.11	.11	.08	.08	.06	.12		
F	.15	.13^{a}	.11	.13	.11	.10	.07	.08	.10		
LSD 5%	n.s.	.025	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.		

[1] Statistical symbols as in table 3.

any of the growth intervals (comparisons between treatments C and F after 1959). From a comparison of mean growth rate values between periods, it appears that low rates in one period of a year tend to be compensated for by higher rates in the other period of the same year. One exception to this tendency is found in 1961, when growth rates were relatively low during both periods.

Differences in Trunk Size Index between treatments B and E were not sufficiently great to represent in figure 6, so the size index shown represents the mean of all six treatments. The average Trunk Size Index increased from year to year in a linear fashion. Trunk Size Index values for each treatment calculated from circumference measurements of December each year are shown in table 14. Also shown are values for the increase in size index for the 3-year period between December 1958 and December 1961. This period covers the time during which responses to phosphorus might be expected (figure 6). Comparison of these increases in trunk size in variety Keauhou reveals that the two high phosphorus treatments (A and E) had less total growth during the 3 years than did the other treatments in this variety. This difference is statistically significant when the technique of single degrees of freedom is used for comparing the combined values for A and E with the other four treatments. No significance was found among the increases in Kakea.

Despite the significant reduction in growth of the trunks of Keauhou by high phosphorus, no significant difference among treatments can be found for Trunk Size Index on any date. This is hardly surprising, since the variation in trunk size was great. At the time of the first trunk measurement in July 1958 the range in Trunk Size Index for Keauhou was from 93 to 370 and for Kakea, from 99 to

TABLE 14. Trunk Size Index and increase in index during 3 years of phosphorus differential (measurements made in December of each year)

TREATMENT	1958	1959	1960	1961	1962	1963	INCREASE: 1958 TO 1961
				Keauhou			
A	255	299	344	378	421	463	123
B	241	287	338	382	443	475	141
C	251	299	352	397	456	500	146
D	274	326	381	420	463	514	146
E	260	303	349	384	430	477	124
F	243	292	343	387	430	475	144
Mean	254	301	351	391	440	484	
				Kakea			
A	213	238	274	307	348	–	94
B	235	281	329	358	399	–	123
C	201	235	273	302	336	–	101
D	190	223	256	285	317	–	95
E	207	246	285	329	354	–	122
F	211	253	301	335	362	–	124
Mean	209	246	286	319	353		

FIGURE 7. Trees of treatment E (*left*) and treatment B (*right*) on September 30, 1960.

289. These differences among trees of the same age are highly correlated with yield variance, as will be shown presently. Hence, despite the lack of significance among treatments, the differences found have a bearing on yield. The total growth response in this experiment was not measurable in terms of growth in trunk size. Photographs of trees in treatments B and E taken September 30, 1960 are shown in figure 7. The profuse growth of lateral branches in treatment E contrasted strikingly with the very sparse branch growth in treatment B. There was also contrast in the degree of leaf retention between these treatments. This increase in growth of lateral branches and density of foliage was evident within 2 years after initiation of the high phosphorus treatment. Thus the total growth of the tree was greatly increased by high phosphorus application, but this growth was in lateral branches and not in trunk girth.

Yield. Highly significant effects of treatments upon yield were found in both varieties. Keauhou showed significant effects of phosphorus treatments in 1959, 1960, and 1961 (table 15, figure 6). In variety Kakea significant effects were confined to 1960 and 1961. In no year was there a significant effect of nitrogen level (comparisons of A and E), or of phosphorus placement (comparisons of C and F).

TABLE 15. Yields of Experiment 2 (pounds of husked nuts per tree)[1]

TREATMENT	1959	1960	1961	1962	1963
			Unadjusted means		
			Keauhou		
A	43.8[a]	65.8[a]	90.1[ab]	82.7	90.7
B	31.1[b]	28.1[b]	62.7[c]	81.6	101.7
C	35.4[ab]	43.7[b]	78.1[bc]	85.2	107.3
D	44.2[a]	66.0[a]	99.4[a]	89.8	101.3
E	44.7[a]	63.6[a]	91.6[ab]	83.1	95.2
F	37.0[ab]	45.7[b]	68.9[c]	84.8	102.2
LSD 5%[1]	10.6	13.2	18.4	n.s.	n.s.
1%	14.4	18.0	20.1		
			Kakea		
A	47.0	56.3[a]	96.2[a]	87.5	
B	39.4	36.6[c]	75.1[b]	84.4	
C	36.1	41.0[bc]	71.1[b]	78.7	
D	39.3	52.2[ab]	81.4[ab]	80.2	
E	44.6	57.9[a]	89.9[ab]	88.6	
F	39.9	48.5[abc]	78.5[ab]	82.6	
LSD 5%	n.s.	12.3	18.2	n.s.	
1%		16.5	24.4		

[1] Statistical symbols as in table 3.

Yield was significantly correlated with the Trunk Size Index each year (table 16). Hence, it was possible to increase the precision of comparisons among treatments by adjusting the yield data for Trunk Size Index. This was done by using the Trunk Size Indexes of table 14, and the regression coefficients of table 16. The adjusted yields are shown in table 17.

TABLE 16. Correlation coefficients and regression coefficients of yield on Trunk Size Index in the December previous to the year of yield (based on error terms for corrected sums of squares and products)

YEAR	KEAUHOU		KAKEA	
	(r)	(b)	(r)	(b)
1959	.7568	.1969	.7605	.1692
1960	.6679	.1885	.7282	.2028
1961	.7294	.2518	.8160	.2920
1962	.6764	.1791	.7487	.2441
1963	.5245	.1201		

TABLE 17. Yields of Experiment 2 adjusted for Trunk Size Index[1]

TREATMENT	1959	1960	1961	1962	1963
			Keauhou		
A	43.6[a]	66.2[a]	91.9[a]	85.0	93.0
B	33.7[b]	30.7[c]	66.0[b]	83.2	101.4
C	36.0[ab]	44.1[b]	77.8[b]	84.1	105.4
D	40.3[ab]	61.3[a]	91.8[a]	84.6	98.6
E	43.5[a]	63.2[a]	92.0[a]	84.4	96.4
F	39.2[ab]	47.4[b]	70.9[b]	85.5	103.5
LSD 5%[1]	7.3	10.2	13.2	n.s.	n.s.
1%	9.9	13.8	18.1		
			Kakea		
A	46.4[a]	57.9[a]	99.7[a]	90.6[a]	
B	35.1[d]	29.5[c]	62.5[c]	74.6[b]	
C	37.5[cd]	43.2[b]	74.9[b]	82.9[ab]	
D	42.6[abc]	56.9[a]	90.2[a]	88.6[a]	
E	44.9[ab]	57.9[a]	90.2[a]	86.2[ab]	
F	39.7[bcd]	46.9[b]	74.1[b]	78.8[ab]	
LSD 5%	6.2	8.9	11.0	12.2	
1%	8.3	12.0	14.7	16.4	

[1] Statistical symbols as in table 3.

Keauhou in 1959 showed progressive increases in adjusted yield with each increment of phosphorus increase. However, only the comparisons between the lowest (B) and the highest (A and E) phosphorus treatments were statistically significant. In 1960 the difference between the lowest (B) and the next higher treatments (C and F) was significant, and the third increment of phosphorus (D) produced significantly more than the second. Differences between the two highest increments (comparisons between D and E or between D and A) were not significant. In 1961 the lower two phosphorus treatments resulted in yields significantly lower than the higher two. In 1962 and 1963 there were no significant differences among treatments for Keauhou. The treatments had, of course, been altered as shown in table 12 and figure 6, so that trees in all treatments had evidently received adequate phosphorus by 1962.

In variety Kakea, similar trends are seen; progressive increases in yields with increasing amounts of phosphorus applied in 1959, 1960, and 1961, but with significant differences confined to comparisons among the lowest three rates of phosphorus application. In no case was yield at the highest phosphorus treatments (A and E) significantly higher than at the second highest (D).

One interesting difference between behavior of the two varieties is seen in 1962, where, in Kakea, treatment B yielded significantly less than treatments A or D. This was despite the fact that application of phosphorus to B in large amounts had begun in February 1961. These comparisons suggest some residual effect of the previous low phosphorus applications in B. On the other hand, Keauhou trees of treatment B seem to have recovered by 1962, at least in terms of yield response.

In both varieties, adjusted yields were nearly identical in treatments C and F, the placement comparison. Treatment A, which received smaller amounts of nitrogen, had adjusted yields as high as treatment E each year in each variety.

Another aspect of the yield responses to high phosphorus application is revealed by comparisons of yields harvested at intervals throughout the bearing season (figure 8). The cumulative yields during the progress of harvesting show that trees of the low phosphorus treatment (B) produced essentially the same yield as the high phosphorus trees through the month of September each year. Practically all yield difference for the year is found during the remainder of the season. Yield of low phosphorus trees decreases sharply at an early date while production of nuts on the high phosphorus trees continues. This trend is evident during each year when there were significant differences in total yield among these treatments.

Nutrient element content of leaves. As shown in figure 6, leaf phosphorus values varied with time and treatment in response to phosphorus application, although the sensitivity of this response appears to increase with time. Yields were generally related to leaf phosphorus when the leaf phosphorus values were lower than about 0.10 percent. One exception to this is treatment B in 1961, where yield increased greatly over that of the previous year, with no increase in leaf phosphorus.

Phosphorus concentrations in the leaves are shown in table 18 for all treatments. By March 1959, leaf phosphorus values had responded to the treatments which had begun in July 1958. In Keauhou, treatments A and E had significantly higher values than did the other treatments. In Kakea, treatment B had significantly lower leaf phosphorus than did any of the other treatments except F. By March 1960 the range in values had increased somewhat in both varieties. Treatment A of Keauhou had a significantly higher value than B, C, D, or F. In Kakea, treatments A, D, and E had values significantly higher than treatments B, C, and F. In March 1961 the range of leaf phosphorus values was even greater. In both varieties, values for the highest phosphorus treatment were significantly higher than those for the second highest (D), the latter in turn had values higher than those for the two lowest phosphorus treatments. As noted in figure 6, the greater amounts of phosphorus applied to trees of Keauhou in treatment B beginning in February 1961 had not increased the leaf phosphorus values for this treatment by the following month. However, in Kakea the leaf phosphorus value for treatment B was higher than it had been the previous year. Leaf phosphorus values for Keauhou in treatment A were significantly higher than in E in March 1961. The larger nitrogen applications in treatment E hence resulted in depression of leaf phosphorus. There was a similar difference in Kakea, which was not statistically significant. In March 1962, highly significant differences among treatments were again evident. However, as noted above, these differences were not associated with any large responses in yield, so trees of all treatments apparently had adequate or excessive phosphorus. A large increase in values for treatment B in response to the phosphorus supplied in 1961 was evident. The high values for treatments A and E were clearly above the level required for adequacy. The effect of the higher nitrogen in treatment E

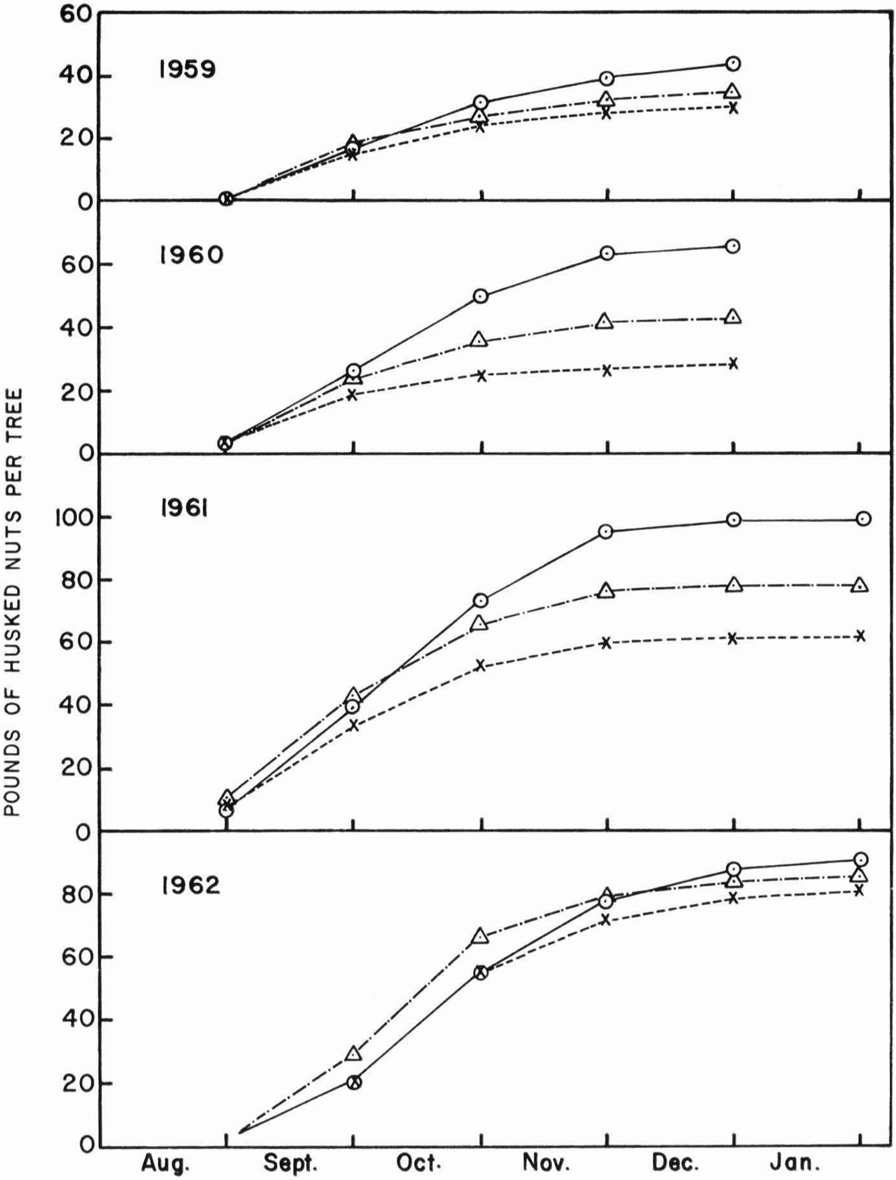

FIGURE 8. Cumulative yields for variety Keauhou treatments B (x), C (△), and D (○).

TABLE 18. Phosphorus concentrations in leaf samples (percent of dry matter)[1]

TREAT-MENT	MARCH SAMPLES					JUNE SAMPLES					
	1959	1960	1961	1962	1963	1958	1959	1960	1961	1962	1963
						Keauhou					
A	.072[a]	.087[a]	.140[a]	.243[a]	.192[a]	.062	.053[a]	.077[a]	.133[a]	.288[a]	.178[a]
B	.061[b]	.058[c]	.058[d]	.098[d]	.107[b]	.057	.046[b]	.045[b]	.053[c]	.091[cd]	.094[b]
C	.060[b]	.061[c]	.069[d]	.084[d]	.075[c]	.056	.046[b]	.052[b]	.056[c]	.072[d]	.069[c]
D	.063[b]	.067[bc]	.091[c]	.140[c]	.119[b]	.057	.048[ab]	.053[b]	.076[c]	.138[c]	.111[b]
E	.073[a]	.079[ab]	.121[b]	.193[b]	.123[b]	.060	.052[a]	.073[a]	.108[b]	.218[b]	.111[b]
F	.064[b]	.065[bc]	.064[d]	.077[d]	.080[c]	.062	.048[ab]	.054[b]	.055[c]	.069[d]	.071[c]
LSD 5%[1]	.0068	.0150	.0186	.0386	.0244		.0054	.0186	.0236	.0572	.0222
1%	.0092	.0204	.0253	.0526	.0332		.0073	.0253	.0322	.0779	.0303
						Kakea					
A	.071[a]	.081[a]	.160[a]	.244[a]	.191[a]	.062	.062[a]	.084[a]	.166[a]	.230[a]	.235[a]
B	.062[b]	.053[b]	.067[c]	.113[d]	.098[c]	.059	.050[c]	.050[b]	.063[c]	.116[bc]	.098[cd]
C	.069[a]	.067[b]	.078[c]	.091[d]	.074[c]	.066	.052[c]	.058[b]	.067[c]	.079[c]	.071[d]
D	.070[a]	.083[a]	.118[b]	.158[c]	.142[b]	.059	.059[ab]	.076[a]	.109[b]	.151[b]	.136[c]
E	.072[a]	.089[a]	.149[a]	.200[b]	.177[ab]	.057	.061[a]	.087[a]	.135[bc]	.205[a]	.182[b]
F	.066[ab]	.063[b]	.067[b]	.110[d]	.091[c]	.063	.055[bc]	.052[b]	.058[c]	.092[c]	.082[d]
LSD 5%	.0070	.0157	.0256	.0374	.0362		.0050	.0148	.0337	.0530	.0453
1%	.0094	.0211	.0343	.0502	.0485		.0067	.0199	.0452	.0711	.0607

[1] Statistical symbols as in table 3.

in reducing leaf phosphorus below that of A was significant in both varieties. The data for March 1963 show some reduction in leaf phosphorus in A and E of both varieties as a result of withholding applications of phosphorus for 9 months (figure 6, table 12).

Leaves sampled in June showed many differences similar to those found in the March leaves. There were generally significant responses to larger phosphorus applications, these becoming greater as the experiment progressed.

In no case did the method of phosphorus placement result in a significant effect on leaf phosphorus values.

Nitrogen concentrations in the leaves are shown in table 19. March samples had small but consistent differences between treatments A and E, those of comparable phosphorus treatment. These differences were statistically significant for Keauhou in 1960 and 1961 and for Kakea in 1960. The statistical significance of differences between these two treatments was more consistent in the June leaves than in the March samples. Leaf nitrogen values below 1.40, even in June leaves, were associated with a lighter green color of foliage. Although the trees of treatment A were evidently on the borderline of nitrogen deficiency, there was no reduction in yield resulting from this treatment (table 17).

None of the treatments had a significant effect on the potassium concentration in the leaves. The mean potassium concentration increased progressively from March 1959 to March 1961 (table 20). The 1961 values appear associated with the increase in amount of potassium supplied beginning in 1960 (table 12). The leaf concentrations indicate that potassium nutrition was adequate each year, if growth response of young trees may be used as a criterion *(5)*.

There was some application of calcium resulting from the presence of this element in the superphosphate. Even though the amount of superphosphate applied varied with treatment, no significant differences in leaf calcium were evident among treatments in this experiment.

Leaf concentrations of magnesium were affected by the treatments employed (table 21). In Kakea, effects were found in both March and June leaves of 1960 and each year thereafter. The lower two phosphorus treatments (B and C) had significantly lower leaf magnesium than the highest phosphorus levels (A and E) at each of these samplings. A relationship between leaf magnesium and superphosphate application is further indicated by the fact that for later samplings, leaf magnesium values in treatment B increased above those of C. This difference was significant in March 1963. This increase appears related to the large amounts of superphosphate applied in this treatment beginning in 1961. March samples for 1963 also had significantly higher magnesium values in treatment D than in C or F. In treatments A and E, there was a trend of increasing leaf magnesium with time. This trend continued through the 1963 samplings despite the fact that no phosphorus was applied to these trees between April 1962 and April 1963. Hence, the leaf magnesium for Kakea in March 1963 was highly correlated with the total amount of superphosphate applied during the 5 years of the experiment ($r = 0.965$, for treatment means) and not directly correlated with amounts applied during the year immediately preceding this sampling. Leaf magnesium values were

TABLE 19. Nitrogen concentrations in leaf samples of Experiment 2 (percent of dry matter)[1]

TREATMENT	MARCH SAMPLES 1959	1960	1961	1962	1963	JUNE SAMPLES 1958	1959	1960	1961	1962	1963
						Keauhou					
A	1.49	1.48^{b}	1.44^{b}	1.49^{b}	1.53	1.58	1.45^{b}	1.35^{e}	1.33^{b}	1.32^{b}	1.36^{b}
B	1.54	1.62^{a}	1.63^{a}	1.63^{a}	1.58	1.50	1.56^{a}	1.51^{b}	1.54^{a}	1.58^{a}	1.46^{a}
C	1.50	1.56^{a}	1.59^{a}	1.57^{ab}	1.57	1.56	1.54^{a}	1.51^{b}	1.54^{a}	1.54^{a}	1.50^{a}
D	1.51	1.59^{a}	1.59^{a}	1.57^{ab}	1.60	1.62	1.47^{b}	1.41^{d}	1.50^{a}	1.49^{a}	1.48^{a}
E	1.52	1.55^{a}	1.58^{a}	1.55^{ab}	1.60	1.61	1.48^{b}	1.46^{c}	1.52^{a}	1.45^{ab}	1.47^{a}
F	1.56	1.58^{a}	1.58^{a}	1.58^{ab}	1.57	1.62	1.55^{a}	1.56^{a}	1.56^{a}	1.50^{a}	1.47^{a}
LSD 5%[1]	n.s.	0.072	0.073	0.115	n.s.		0.054	0.048	0.079	0.132	0.087
1%		0.098	0.100	0.157			0.072	0.064	0.107	0.180	0.119
						Kakea					
A	1.52	1.47^{b}	1.49^{c}	1.50^{b}	1.55	1.49	1.52^{b}	1.36^{b}	1.46^{c}	1.40^{b}	1.43^{b}
B	1.59	1.53^{ab}	1.63^{a}	1.58^{a}	1.57	1.59	1.55^{ab}	1.43^{a}	1.58^{ab}	1.53^{a}	1.53^{a}
C	1.55	1.56^{a}	1.59^{ab}	1.58^{a}	1.61	1.57	1.55^{ab}	1.47^{a}	1.57^{ab}	1.51^{a}	1.50^{ab}
D	1.57	1.58^{a}	1.55^{bc}	1.53^{ab}	1.59	1.50	1.56^{ab}	1.46^{a}	1.53^{b}	1.50^{a}	1.53^{a}
E	1.59	1.58^{a}	1.53^{bc}	1.54^{ab}	1.58	1.58	1.56^{ab}	1.45^{a}	1.53^{b}	1.49^{a}	1.52^{a}
F	1.60	1.55^{a}	1.57^{ab}	1.53^{ab}	1.62	1.60	1.61^{a}	1.46^{a}	1.60^{a}	1.51^{a}	1.56^{a}
LSD 5%	n.s.	0.073	0.063	0.068	n.s.		0.054	0.055	0.053	0.069	0.073
1%		0.098	0.085	0.091			0.073	0.073	0.071	0.093	0.098

[1] Statistical symbols as in table 3.

TABLE 20. Ranges and mean values for potassium and calcium concentrations in leaves sampled in March of each year (percent of dry matter)

YEAR	POTASSIUM		CALCIUM	
	Range	Mean	Range	Mean
Keauhou				
1959	.53–.71	.62	0.49–0.82	.68
1960	.46–.78	.67	0.54–0.90	.75
1961	.58–.90	.79	0.58–1.15	.80
1962	.60–.95	.75	0.45–0.92	.65
1963	.59–.96	.75	– –	–
Kakea				
1959	.54–.76	.66	0.40–0.96	.61
1960	.56–.80	.68	0.46–1.00	.74
1961	.62–.80	.71	0.44–1.08	.72
1962	.50–.75	.64	0.31–0.85	.66
1963	.54–.71	.62	0.58–1.15	.92

generally higher in treatment A than in E for Kakea. These differences were significant in March 1961 and in June of 1960 and 1961. In this variety, then, the lower nitrogen application, at the high phosphorus level, resulted in more leaf magnesium.

In variety Keauhou, leaf magnesium concentrations did not differ significantly among treatments until the March 1962 sampling. At that time values for treatments A and B were significantly higher than those for C and F. In March 1963, leaf magnesium was significantly higher in treatment E than in C. At the final sampling in June 1963, values for treatments A, D, and E were all higher than those for treatments C or F. Hence, in Keauhou, leaf magnesium responses to superphosphate application, when they did occur, were similar in direction to those in Kakea, but in Keauhou the responses developed much more slowly and the differences when they did develop were not as great as in Kakea. No effect of the nitrogen variable was found in Keauhou.

Relationships of yield to leaf phosphorus and Trunk Size Index. In figures 9*A* and 9*B* are shown values for the treatment means of March leaf phosphorus of table 18 plotted against the yields adjusted for Trunk Size Index of table 17. In Keauhou (figure 9*A*), curvilinear relationships are evident for each year in which there was a significant yield response to treatments. In 1959 and 1960 it is not clear that maximum yield was attained by the highest phosphorus levels, although in these 2 years there was no significant difference in adjusted yield among treatments representing the higher two phosphorus rates (A, E, and D). In 1961, maximum yield was clearly achieved in treatment D at a leaf phosphorus value of 0.091 percent. The plot for treatment B is not fitted to the 1961 curve, because some yield response can be attributed to the increased amounts of phosphorus supplied beginning in February 1961, only 1 month previous to the March leaf sampling. In 1962, maximum yields were attained at leaf phosphorus values as

TABLE 21. Magnesium concentrations in leaf samples from Experiment 2[1]

TREAT-MENT	MARCH SAMPLES 1959	1960	1961	1962	1963	JUNE SAMPLES 1958	1959	1960	1961	1962	1963
						Keauhou					
A	.073	.079	.080	.085[a]	.103[ab]	.075	.076	.074	.070	.083	.096[a]
B	.079	.081	.075	.085[a]	.095[ab]	.086	.080	.075	.066	.079	.087[ab]
C	.069	.073	.076	.072[b]	.089[b]	.068	.075	.080	.070	.068	.078[b]
D	.073	.074	.080	.081[ab]	.105[ab]	.081	.075	.074	.078	.078	.096[a]
E	.075	.082	.080	.082[ab]	.109[a]	.081	.088	.077	.076	.078	.097[a]
F	.074	.076	.069	.071[b]	.091[ab]	.079	.081	.073	.063	.068	.077[b]
LSD 5%[1]	n.s.	n.s.	n.s.	.0120	.0714	–	n.s.	n.s.	n.s.	n.s.	.0138
1%				.0163	.0237						.0188
						Kakea					
A	.085	.092[a]	.099[a]	.101[a]	.131[a]	.098	.082	.092[a]	.101[a]	.102[a]	.127[a]
B	.080	.069[c]	.076[cd]	.076[b]	.095[b]	.078	.073	.058[c]	.062[c]	.073[b]	.088[bc]
C	.080	.072[c]	.076[cd]	.069[b]	.079[c]	.077	.075	.067[c]	.067[c]	.059[b]	.072[c]
D	.075	.077[bc]	.078[c]	.076[b]	.099[b]	.078	.072	.068[c]	.066[c]	.067[b]	.094[b]
E	.079	.084[ab]	.088[b]	.092[a]	.121[a]	.062	.077	.079[b]	.084[b]	.090[a]	.113[a]
F	.070	.076[bc]	.068[d]	.066[b]	.077[c]	.065	.070	.063[c]	.057[c]	.057[b]	.074[bc]
LSD 5%	–	.0096	.0082	.0125	.0160	–	n.s.	.0104	.0103	.0158	.0190
1%		.0129	.0110	.0168	.0214			.0139	.0137	.0212	.0255

[1] Statistical symbols as in table 3.

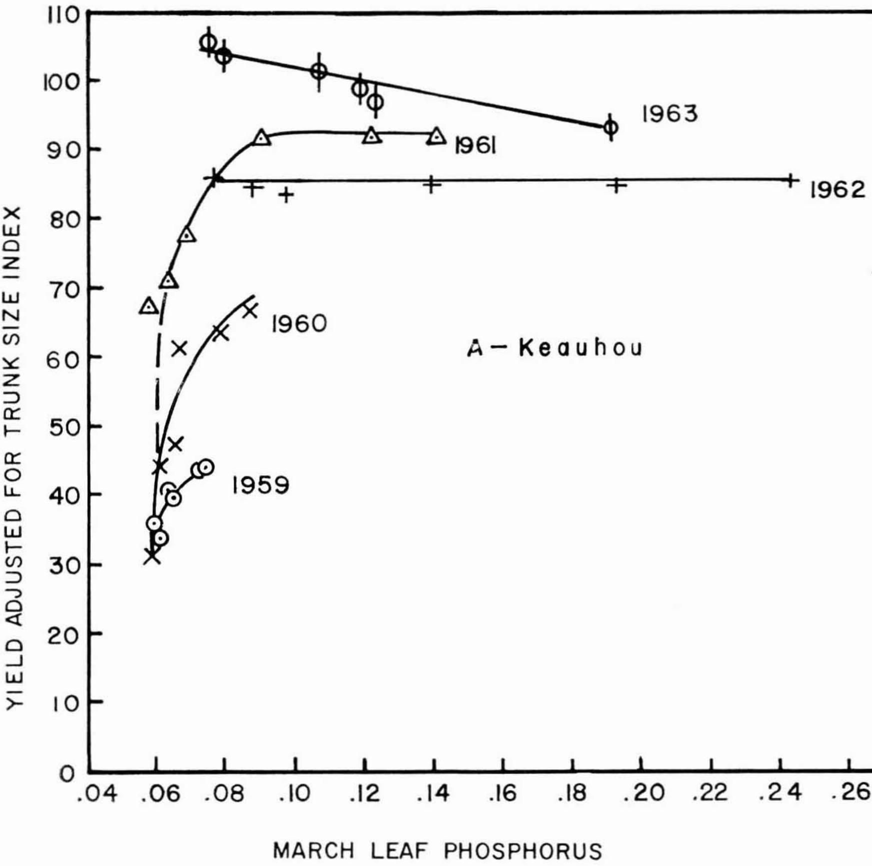

FIGURE 9A. Relationship between adjusted yields and leaf phosphorus in Keauhou.

low as 0.077 percent. Yields were remarkably uniform in 1962 and slightly lower than the maximum yields of 1961. In 1963 the highest adjusted yield was attained in treatment C which had a March leaf phosphorus value of 0.075 percent. In this year, there was a slight negative regression of adjusted yield on leaf phosphorus. However, the significance of this is questionable since there were no significant differences among treatments in adjusted yield (table 17). The yields for 1963 were uniformly higher than for 1962. In fact, the variations of maximum yields among the last 3 years of the experiment suggest the significant advent of either climatic factors or a biennial bearing tendency.

The relationship between yield and leaf phosphorus is also evident in variety Kakea (figure 9*B*). In 1960, maximum yield was apparently attained at a leaf phosphorus value of 0.081 percent (treatment A), and the same yield was found in treatment E where the phosphorus value was 0.089 percent. In 1961 the leaf

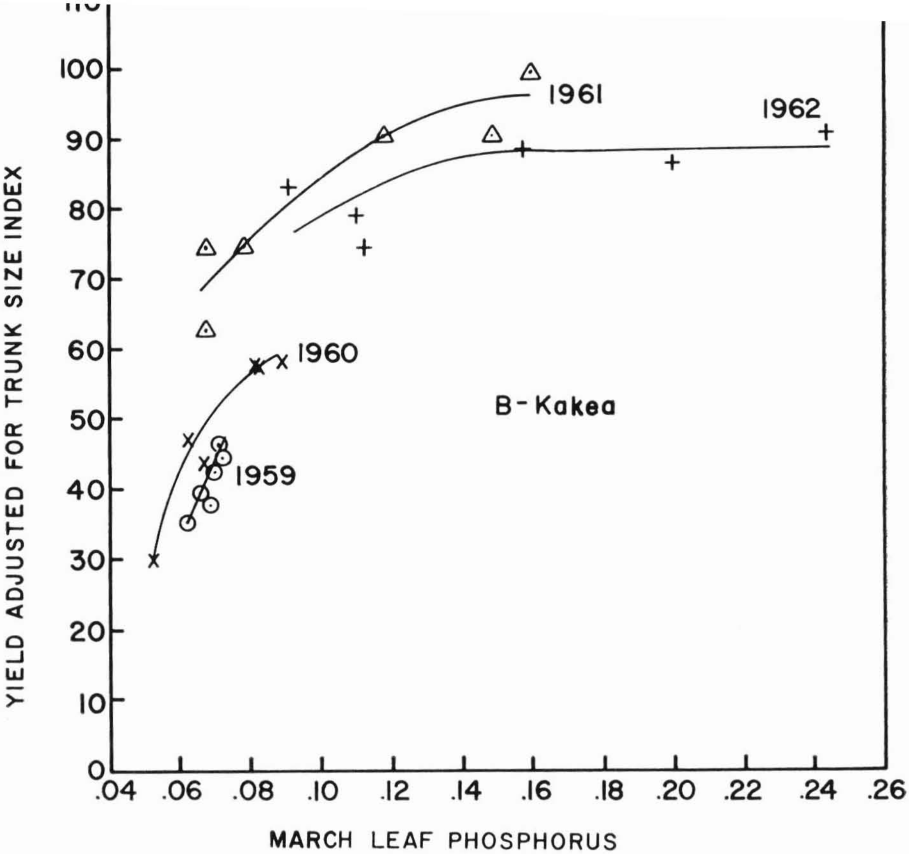

FIGURE 9*B*. Relationship between adjusted yields and leaf phosphorus in Kakea.

phosphorus value corresponding to maximum yield lies somewhere above 0.078 (treatment C) and evidently below 0.118 (treatment D). The difference between adjusted yields of these two treatments was statistically significant (table 17). In 1962 the yield of treatment B was significantly lower than yields in A or D. Treatment B had a leaf phosphorus value of 0.098 in March 1963, reflecting the increased rates of phosphorus application begun in 1961 and continued through 1962. Hence, the lower yield in B in 1962 does not appear associated with inadequate current phosphorus status, but may be the result of damage of a more lasting type inflicted by prolonged phosphorus deficiency prior to 1961. Incidentally, there was no parallel to this result in variety Keauhou. The curves of figure 9*B* tend to imply that a higher leaf phosphorus value is required to assure maximum yield in Kakea than in Keauhou. This may be a fortuitous impression, however, since considerable difference in yield between treatments is required for significance (table 17).

The yield data of table 17 and figures *9A* and *9B* were adjusted for variance in Trunk Size Index within each year, but do not reflect any adjustment for the increase in size index from 1 year to the next. In addition, the adjustments are based on all the trees, some of which were suffering from phosphorus deficiency at times. Where phosphorus is also limiting yield, a lower regression of yield on trunk size might be expected. To determine the relationship of yield to trunk size under conditions approaching adequate phosphorus nutrition, treatment plots were selected in which the March leaf phosphorus was greater than 0.080 percent. The data of figure *9A* indicate that little or no loss of yield due to phosphorus deficiency is to be expected for trees having March leaf phosphorus values above this level. To provide as wide a range of size index values as possible, plots from Experiment 1 which meet the specified requirement ($L>0.08$) are included. The ranges of values and means for yield and Trunk Size Index as well as coefficients of correlation and regression are shown in table 22. Regression lines for Keauhou are shown in figure 10. In variety Keauhou the coefficients clearly fall into two classes: one includes the data for 1960 and 1961 and is characterized by relatively high and similar regression coefficients and relatively high correlation coefficients. The other includes the data for 1962 and 1963, which are less well correlated and have lower regression coefficients. Coefficients for the combined data within these two classes are also shown in table 22. The regression lines for the classes are shown as the dotted lines of figure 10. The difference between the slopes of these two regressions was found to be highly significant, when compared by covariance analysis ($F = 11.8$). The lower regression and correlation coefficients for the 1962–63 class are thought to be associated with the high density of foliage of all trees during those years. With the approach to complete coverage of the orchard area, the yield per tree is expected to be more limited by the light the tree can intercept and less related to trunk size. In contrast the data for the 1960–61 class represent a situation where half of the trees or fewer have dense foliage (see figure 7). Hence, it appears that trunk size is highly correlated with yield when phosphorus nutrition is adequate and light is not limiting. The coefficient of determination for the 1960–61 class shows that 93.0 percent of the variance in yield was accounted for by the Trunk Size Index; whereas, in the 1962–63 class only 40.3 percent was accounted for by this factor (table 22).

In variety Kakea, correlation coefficients were highly significant, but regression coefficients differed from year to year in such a manner as to preclude a neat classification. This may be accounted for by the fact that one-half of the Kakea trees were on the outside of the field block adjacent to roadways. These trees were exposed to more direct sunlight than the Keauhou trees, all but 14 of which were surrounded by other trees.

The regression line for the 1960–61 class of data for Keauhou represents a reasonably linear relationship of yield to the Trunk Size Index over a wide range of the two variables, for plants at essentially adequate leaf phosphorus values where competition for light was not important. The intercept of this regression on the

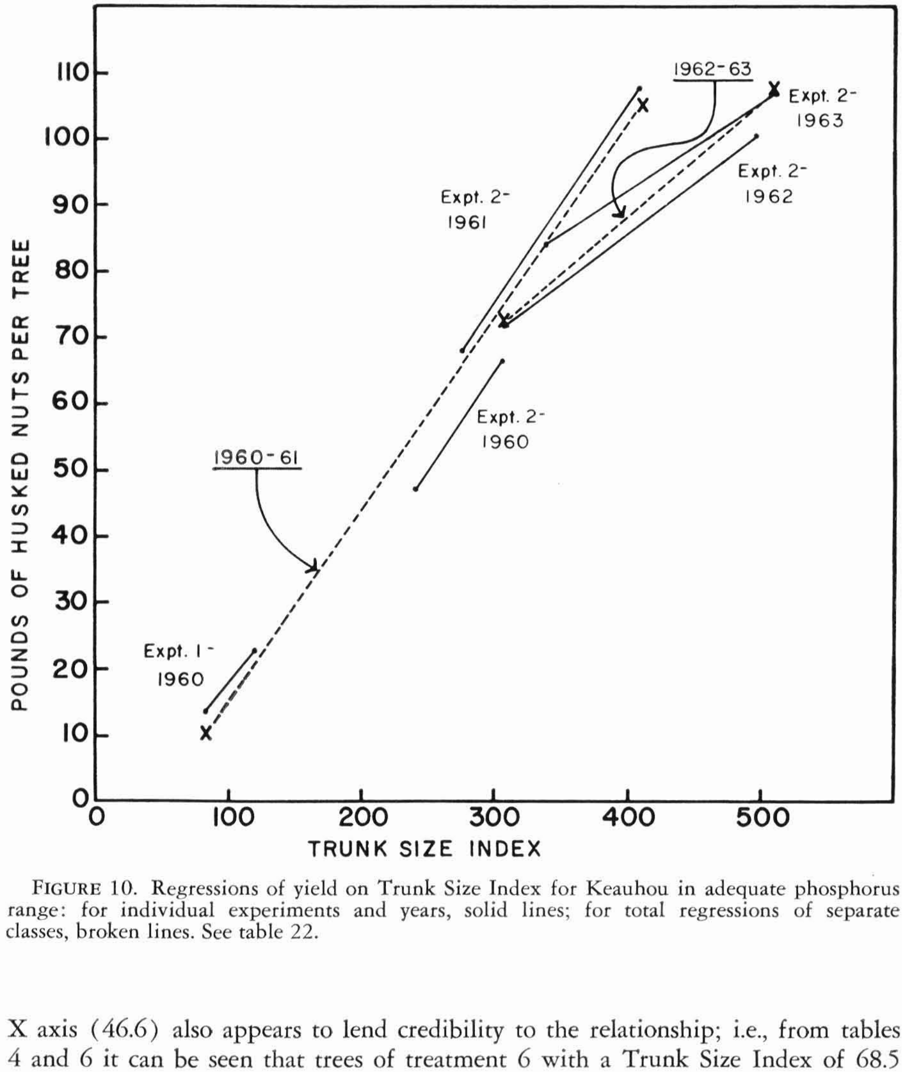

FIGURE 10. Regressions of yield on Trunk Size Index for Keauhou in adequate phosphorus range: for individual experiments and years, solid lines; for total regressions of separate classes, broken lines. See table 22.

X axis (46.6) also appears to lend credibility to the relationship; i.e., from tables 4 and 6 it can be seen that trees of treatment 6 with a Trunk Size Index of 68.5 in December 1958 yielded 5.0 pounds of nuts in 1959. A year earlier these trees had no yield and the Trunk Size Index was 34.2.

From the 1960–61 regression for Keauhou has been calculated for each treatment in 1959, 1960, and 1961 the yield which could be expected had the leaf phosphorus values been in the range above 0.08 percent. The actual yields for the corresponding treatments and years are then expressed as percentage of these potential yields and plotted against leaf phosphorus values in figure 11. The fact that the highest phosphorus treatments resulted in yields slightly higher than 100 percent in 1961 suggests that the specified leaf phosphorus value of 0.080 percent

TABLE 22. Relationships between yield and Trunk Size Index in the range of adequate phosphorus nutrition

SOURCE	n	SIZE INDEX (x)		YIELD (y)		COEFFICIENTS OF:		SLOPE	INTERCEPT
		Range	Mean	Range	Mean	Correlation (r)	Determination (r^2)	(b)	(a)
Keauhou									
Expt. 1, 1960	5	82–120	97.6	13.2– 23.2	17.32	.955*	.903	.2457	− 6.66
Expt. 2, 1960	5	239–303	282.6	46.3– 74.3	60.40	.7854	.617	.3016	−24.8
Expt. 2, 1961	13	275–407	353.9	58.0–117.1	91.94	.7712**	.595	.2992	−13.9
Expt. 2, 1962	25	306–495	390.1	67.0–118.0	84.65	.5893**	.347	.1508	+25.8
Expt. 2, 1963	22	337–510	432.6	76.3–125.4	96.74	.4883*	.238	.1330	+39.2
Combined:									
1960–1961	23	82–407	282.7	13.2–117.1	68.86	.9644**	.930	.2916	−13.6
1962–1963	47	306–510	410.0	67.0–125.4	90.31	.6350**	.403	.1703	+20.5
Kakea									
Expt. 2, 1960	12	177–367	250.7	41.0– 84.0	63.38	.8585**	.767	.2309	+55.0
Expt. 2, 1961	27	181–419	271.8	55.3–135.5	86.78	.7926**	.628	.3227	− 0.9
Expt. 2, 1962	43	197–452	319.8	52.6–126.5	84.35	.6735**	.454	.2064	+18.4

* Significant at the 5 percent level.
** Significant at the 1 percent level.

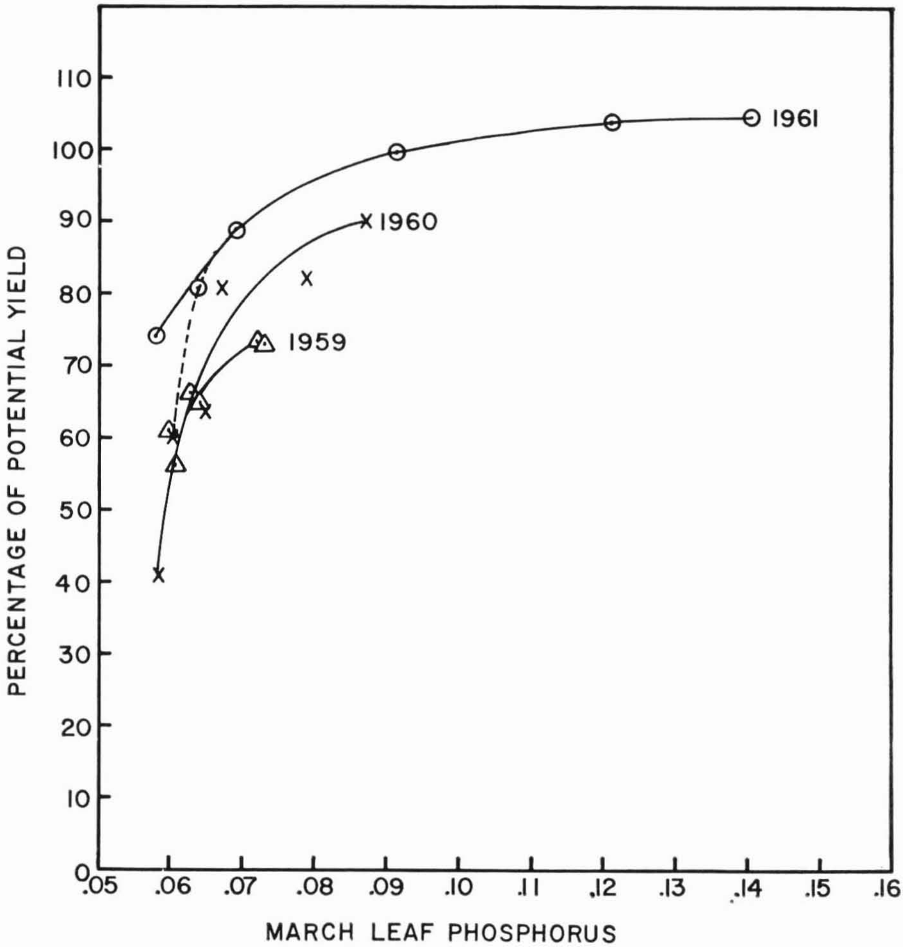

FIGURE 11. Percentage of potential yield as related to March leaf phosphorus in Keauhou.

used in selecting the data for table 22 and figure 9 may have been slightly lower than that required for real adequacy. The slopes of the curves also indicate this. The discrepancy resulting from the selection used is not great, however. Selection of a higher leaf phosphorus value would necessitate exclusion of additional data from the regression. The curves of figure 11 show relatively less difference in yield between years than do the curves for the same years in figure 9*A*, because figure 11 represents more precisely the relation of yield to leaf phosphorus after correcting for the relation of yield to trunk size between years as well as within years in the adequate phosphorus range. The remaining differences in yield from 1 year to the next (figure 11), particularly at leaf phosphorus values above 0.07 percent

TABLE 23. Comparisons of yields between years for trees in the adequate leaf phosphorus range (pounds of husked nuts per tree)

COMPARISONS	YEARS	ACTUAL			ADJUSTED FOR TRUNK SIZE		
		Yield	Difference	F value	Yield	Difference	F value
1961 to 1962	1961	91.9	7.2	3.02 n.s.	96.5	14.2	16.10**
	1962	84.7			82.3		
1962 to 1963	1962	84.7	12.0	12.86**	87.5	6.0	3.55 n.s.
	1963	96.7			93.5		
1961 to 1962–63	1961	91.9	1.6	1 n.s.	100.2	19.7	11.65**
	1962–63	90.3			80.5		

** Significant at the 1 percent level.
n.s.: Not significant.

may be due to progressive increase in density of foliage and proliferation of bearing branches within the canopy of the trees as the time of adequate or near adequate phosphorus nutrition is prolonged. From figure 11 it appears that a March leaf phosphorus value of 0.06 percent would normally indicate an expectation of yield about 55 percent of the potential yield for a tree of a specified Trunk Size Index. All the plots lead to this expectation except treatment B in 1961. This, it is recalled, is the case where phosphorus applications were increased to an adequate rate in February, too late to have an effect on March leaf phosphorus in 1961, but early enough to have some effect on yield that year.

Yield data for 1962 and 1963 cannot be directly compared by use of the linear regression which served as a basis for figure 11, since the regressions of yield on Trunk Size Index were significantly lower than those for earlier years. However, it is possible to compare yields between years in the "adequate" leaf phosphorus range. In table 23 such comparisons are reported for actual yields and for yields adjusted for Trunk Size Index by use of the common regression for each comparison. The comparisons for actual yields, made by variance analysis, show no significant difference between 1961 and 1962 but a highly significant difference between 1962 and 1963. After adjusting for the Trunk Size Index, the relative yield in 1961 was significantly higher than in 1962 or the combination of 1962 and 1963. The difference between adjusted yields of 1962 and 1963 was not significant, indicating that between these 2 years the actual yield difference could be largely accounted for by difference in trunk size.

The significantly higher adjusted yield per tree in 1961 as compared to subsequent years again suggests the larger proportion of above-ground space available to trees in the adequate leaf phosphorus range in 1961 than in the 2 later years. The comparison between 1962 and 1963 indicates a continuing relationship of yield to trunk size after essential saturation of the above-ground space of the orchard, even though a much smaller proportion of variance in yield can be accounted for by variance in the Trunk Size Index (table 22), than is the case before orchard closure.

Factors related to leaf phosphorus. In young trees of Keauhou the leaf phosphorus in March each year was related to the Relative Rate of Phosphorus Application, which was defined as the ratio of pounds of P applied during the previous year to the square of the circumference of the trunk at the beginning of the period of application $\times 10^3$. When these relationships were sought in larger bearing trees the results were as shown in table 24. The leaf phosphorus values of March 1960 are related to Relative Rates of Phosphorus Application much as was the case with younger trees. The regression coefficients of 0.0185 for Keauhou and 0.0182 for Kakea would fall within the range established in figure 5. The intercepts are also consistent with those for younger Keauhou trees. However, in each year subsequent to 1960 a large increase in the regression coefficient is observed in each variety. The high correlation coefficients for 1961 and 1962 are applicable only to data within those specific years, and no regression coefficient which would adequately express a relation of these two factors and be applicable to variance among years as well as within years is possible. It appears *a priori* that approach to completion of the orchard canopy aided by more adequate phosphorus nutrition of an increasing proportion of the trees results in alteration of the relation of phosphorus application to leaf phosphorus in at least two respects. For one thing the area of surface under each tree over which the phosphorus is applied is no longer increasing since the entire surface is now being covered. There should, therefore, be no further need for a term related to the square of the trunk circumference, i.e., the Relative Rate of Phosphorus Application, so the amount of phosphorus applied should itself serve as the independent variable. The other tendency on closing-in which appears indicated by the data is a dependence of the leaf phosphorus on the previous phosphorus status of the trees. With higher initial

TABLE 24. Correlation and regression coefficients of leaf phosphorus index on Relative Rate of Phosphorus Application (A) in bearing trees[1]

YEAR OF LEAF P	LEAF P		A		COEFFICIENT OF CORRELATION (r)	INTER-CEPT (a)	SLOPE (b)
	Range	Mean	Range	Mean			
				Keauhou			
1960	.058–.087	.070	0.29–1.65	0.95	.9594**	.052	.018,52
1961	.058–.140	.091	0.57–1.83	1.09	.9829**	.030	.055,24
1962	.077–.243	.139	0.50–1.70	1.07	.9228**	.016	.115,43
1963	.075–.192	.116	0.22–0.49	0.34	.3108 n.s.	–.167	.831,08
				Kakea			
1960	.058–.089	.075	0.30–2.03	1.19	.9853**	.054	.018,21
1961	.067–.160	.107	0.58–2.29	1.36	.9962**	.034	.053,34
1962	.091–.244	.153	0.58–2.14	1.32	.9566**	.041	.084,67
1963	.074–.191	.129	0.26–0.66	0.42	.3070 n.s.	–.287	.985,95

[1] The treatment mean was used as the unit in determining these coefficients.
** Significant at the 1 percent level.
n.s.: Not significant.

phosphorus status it is to be expected that the roots will more completely permeate the soil under the tree. This should contribute to increased efficiency of phosphorus uptake. A reasonably good index of previous phosphorus status appears to be the leaf phosphorus value 1 year previous to that under consideration. With these factors in mind, multiple regression equations were determined for the 1961, 1962, and 1963 March leaf phosphorus values (Lc) as the dependent variable; the pounds of phosphorus applied (P) and leaf phosphorus of the previous year (Lp) being the independent variables. The treatment mean was the unit used. The equations are: for variety Keauhou, $Lc = 0.711\ Lp + 0.0190\ P - 0.0085$, and for variety Kakea, $Lc = 0.714\ Lp + 0.0188\ P - 0.0044$. The regression coefficients for the two varieties are nearly identical. Coefficients for the simple and multiple correlations and results of tests for significance are shown in table 25. About 88 percent of the variance in leaf phosphorus among treatments and years is accounted for by the two independent variables in variety Keauhou. In variety Kakea the percentage is about 92.

Although the above relationship accounts for most of the variance in leaf phosphorus over a 3-year period, it was observed that data for 1961 do not fit these equations as well as do data for the other 2 years. This is thought related to lack of full density and spread of canopy in 1961, as indicated by the fact that yields in three of the treatments (B, C, and F) were significantly lower than in the other treatments. For a relationship accounting for leaf phosphorus values of trees in a more completely closed orchard, consideration should be confined to 1962

TABLE 25. Simple correlation coefficients and coefficients of determination for multiple correlations of March leaf phosphorus (Lc) on pounds of phosphorus applied (P) and leaf phosphorus the previous March (Lp)—combined data: treatment means for 1961, 1962, and 1963

SOURCE OF VARIATION	COEFFICIENT OF CORRELATION (r)	COEFFICIENT OF DETERMINATION (R^2)	F VALUE FOR LAST FACTOR ADDED[1]	SIGNIFICANCE[2]
		Keauhou		
P	.6174			**
Lp	.6673			**
Lp after P			65.23	**
P after Lp			56.93	**
P and Lp		.8843		
		Kakea		
P	.6285			**
Lp	.7371			**
Lp after P			93.90	**
P after Lp			68.30	**
P and Lp		.9167		

[1] Results of F tests on reduction of error variance by addition of the last factor.
[2] Significance of simple correlation coefficients and of F values for multiple correlations.
** Significant at the 1 percent level.

and 1963, when yields were similar in all treatments within each year (table 17). During these 2 years an additional factor which influenced leaf phosphorus values was the amount of nitrogen applied; i.e., treatment A had higher leaf phosphorus values than E (table 18). Results of correlation and regression analysis based on these observations are shown in table 26. In Keauhou, nitrogen application contributed significantly in accounting for leaf phosphorus variance, and about 97 percent of the variance among treatments and years is attributable to the three factors: phosphorus applied, previous leaf phosphorus, and nitrogen applied. In Kakea, the influence of nitrogen application was not statistically significant at the 5 percent level, but 94 percent of the variance is accounted for when nitrogen is included. When the data for both varieties are combined the effect of nitrogen is significant and about 94 percent of the variance is accounted for. The applicability of these equations is somewhat hypothetical because in this experiment nitrogen

TABLE 26. Factors correlated with March leaf phosphorus (Lc) in 1962 and 1963

INDEPENDENT VARIABLES	COEFFICIENT OF CORRELATION (r)	COEFFICIENT OF DETERMINATION (r^2 or R^2)	F VALUE FOR REDUCTION IN UNACCOUNTED FOR VARIANCE BY THE LAST FACTOR INCLUDED	SIGNIFICANCE
		Keauhou		
Pounds P (P)	.8093	.6550		**
Leaf P, year previous (Lp)	.6115	.3740		*
Pounds N (N)	-.7693	.5919		**
P, Lp		.9070	51.60	**
P, Lp, N		.9711	17.78	**
		Kakea		
P	.7860	.6179		**
Lp	.7142	.5101		**
N	-.6725	.4523		*
P, Lp		.9285	39.01	**
P, Lp, N		.9412	1.72	n.s.
		Both varieties combined		
P	.7914	.6262		**
Lp	.6673	.4453		**
N	-.7157	.5122		**
P, Lp		.9135	67.73	**
P, Lp, N		.9436	10.67	**

Equations:
- Keauhou $Lc = .1202 + .0209\ P + .2888\ Lp - .0232\ N$
- Kakea $Lc = .0576 + .0199\ P + .4711\ Lp - .0099\ N$
- Both varieties $Lc = .0825 + .0206\ P + .3975\ Lp - .0154\ N$

* Significant at the 5 percent level.
** Significant at the 1 percent level.
n.s.: Not significant.

was varied only at the highest phosphorus level. Whether nitrogen would have a similar effect when moderate amounts of phosphorus are supplied remains open to question. However, the possibility is suggested that relatively little phosphorus may be required to maintain a closed orchard at adequate nutrition when relatively small amounts of nitrogen are applied.

Experiment 3—Trees of Ikaika

In one field at Keaau Orchard a relatively pure stand of Ikaika was planted in April 1954. Nearly 3 years later a portion of this field was allotted to a phosphorus experiment. This experiment consisted of five randomized blocks of four treatments, with three trees in each treatment plot. In all treatments phosphorus applications were altered at frequent intervals with the objective of establishing and maintaining differentials in growth rate, yield, and leaf phosphorus values. Differential applications were begun on February 20, 1957 and continued into 1965. Amounts of nutrient elements applied each year are shown in table 27. During the early years of the experiment the trees occupied a small portion of the total area. By 1962, trees in the higher phosphorus treatments were approaching canopy closure, and in 1964, closure was approaching completion throughout the field.

TABLE 27. Nutrient elements supplied in Experiment 3[1]

TREATMENT	1957	1958	1959	1960	1961	1962	1963	1964
				Pounds P applied per tree				
1	0.00	0.05	0.15	0.31	0.58	0.39	0.39	0.36
2	0.03	0.10	0.30	0.70	1.28	1.07	1.07	0.58[2]
3	0.06	0.20	0.54	1.40	1.94	2.32	2.13	0.65[2]
4	0.11	0.30	0.93	2.10	3.68	4.75	4.26	1.16[2]
				Fertilizer elements applied to all trees (pounds per tree)				
N	0.28	0.52	1.28	2.52	2.96	2.10	1.89	1.52
K	0.28	0.60	1.12	1.92	3.04	2.62	3.49	2.73
Mg	0.10	0.56	0.88	1.08	1.24	1.05	1.05	0.26[3]

[1] Four applications were made at 3-month intervals each year except as noted for 1964. Carriers used were superphosphate (9.7% P), ammonium sulfate (21% N), potassium sulfate (43.6% K), and magnesium sulfate (17.5% Mg).

[2] In 1964 most or all of the phosphorus was supplied in the first application of the year to treatments 2, 3, and 4. February applications were: 0.29 lb in treatment 2, 0.58 lb in treatment 3, and 1.16 lb in treatment 4.

[3] Magnesium applications were discontinued after February 1964.

Scope. The ranges in tree size, growth rate, phosphorus nutrition, and yield represented during the course of this experiment are depicted in figure 12, where data for the highest and lowest phosphorus treatments are plotted. During the course of the experiment the Trunk Size Index increased from 21 to 330 in the high phosphorus treatment (representing an increase in diameter from approxi-

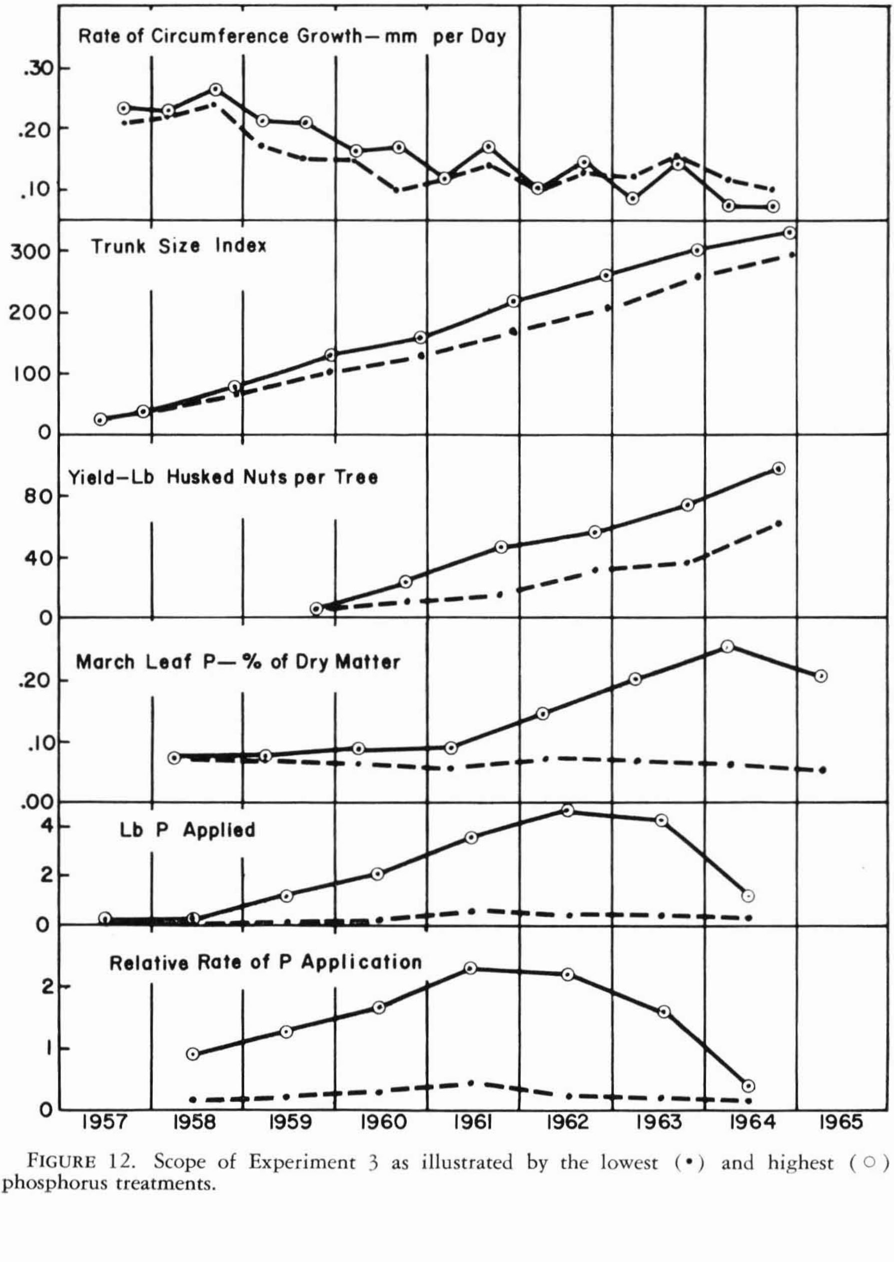

FIGURE 12. Scope of Experiment 3 as illustrated by the lowest (•) and highest (○) phosphorus treatments.

mately 1.8 inches to 7.2 inches). The range of observations covers periods when the trees were too young to bear nuts to a point approaching maximum yield.

Trunk growth and Trunk Size Index. Circumference growth rates, calculated on a semiannual basis, showed seasonal fluctuations as well as a general downward trend after 1958 (figure 12). In the high phosphorus treatment relatively low growth rates during the early part of the year were frequently compensated for by higher rates later in the year. Responses to phosphorus treatment were found more frequently during the second half of the year than during the first half. Circumference growth rates for all treatments during each interval are shown in table 28. In none of the first three intervals were differences among treatments statistically significant, although the rate in treatment 4 was higher than in treatment 1 in each interval. Significant responses to phosphorus treatments were obtained in each interval of 1959 and during the second intervals of 1960 and 1961. Thereafter the only significant differences among treatments appear as negative responses to higher phosphorus treatments. These were found in the first intervals of 1963 and 1964.

The Trunk Size Index increased at a remarkably uniform rate in treatment 4 throughout the experiment, in contrast to the general downward trend in circumference growth rate (figure 12). Trees of treatment 1 showed a slow rate of increase in Trunk Size Index from 1958 through 1962, but in 1963 and 1964 the increase in this treatment was slightly greater than in treatment 4. Mean values for Trunk Size Indexes of all four treatments are shown in table 29. From these data it is seen that trunks of treatment 4 were significantly larger than those of treatment 1 by the end of 1960. By December 1961, treatments 3 and 4 each had higher values than treatment 1, and by the end of 1962, treatment 1 had significantly smaller trunks than any of the other three treatments. In the 2 subsequent years, however, none of the differences between treatments was significant. The higher growth rate in treatment 1 in 1963 and 1964 resulted in trunk sizes in this treatment approaching those of the other treatments by the end of 1964.

Yield. Significant effects of phosphorus treatments upon yield were found each year after nut production became sufficient to warrant harvest (figure 12 and table 30). In 1959, treatment 4 had significantly higher yield than any of the other treatments. In 1960, yield in treatment 4 was superior to that in treatments 1 or 2, and treatment 3 yielded significantly more than treatment 1. In 1961 each increment of phosphorus resulted in a significant increase in yield. In 1962 through 1964, treatment 1 had significantly lower yields than other treatments. Other differences were not significant during this period.

As in the previous experiments, comparison of yields adjusted for Trunk Size Index provides for some refinement as well as some assessment of the more direct effect of phosphorus on yield as distinguished from the long-term, indirect effect brought about by the larger size of trees in the higher phosphorus treatments. Adjusted yields for 1960 were significantly higher in treatment 4 than in treatment 3. Treatment 3 was significantly higher than treatment 1 or 2. Adjusted yields for 1961 show a narrower range among treatments than do the unadjusted yields, but even after adjustment each increment of phosphorus gave a significant yield re-

TABLE 28. Rates of trunk circumference growth in Experiment 3

YEAR	1957	1958		1959		1960		1961		1962		1963		1964	
Period	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*	*First*	*Second*
Duration (days)	169	182	186	176	195	169	181	183	182	189	181	182	178	187	184
Treatment	*Mean increase in circumference (mm per day)*[1]														
1	.207	.219	.241	.166[b]	.150[b]	.149	.104[c]	.117	.135[b]	.101	.134	.120[a]	.155[ab]	.119[a]	.097
2	.218	.218	.228	.168[b]	.195[ab]	.150	.145[b]	.127	.184[a]	.085	.149	.116[ab]	.166[a]	.084[b]	.088
3	.231	.212	.258	.191[ab]	.199[a]	.154	.156[ab]	.109	.187[a]	.101	.134	.119[a]	.124[b]	.087[b]	.077
4	.228	.231	.261	.211[a]	.207[a]	.161	.171[a]	.120	.169[ab]	.101	.144	.089[b]	.153[ab]	.070[b]	.070
LSD 5%[1]	n.s.	n.s.	n.s.	.0316	.0467	n.s.	.0235	n.s.	.0351	n.s.	n.s.	.0277	.0341	.0125	n.s.
1%				.0444	.0656		.0329		.0491			.0389	.0478	.0275	

[1] Statistical symbols as in table 3.

TABLE 29. Trunk Size Indexes for Experiment 3[1]

TREATMENT	DEC. 10 1957	DEC. 15 1958	DEC. 21 1959	DEC. 5 1960	DEC. 5 1961	DEC. 10 1962	DEC. 5 1963	DEC. 10 1964
1	33	70	102	128[b]	168[b]	203[b]	259	292
2	33	70	110	139[ab]	198[ab]	252[a]	299	342
3	33	73	117	148[ab]	204[a]	245[a]	290	324
4	33	74	123	158[a]	214[a]	258[a]	298	330
LSD 5%[1]	n.s.	n.s.	n.s.	26.9	32.9	36.5	n.s.	n.s.
1%				37.7	46.2	51.2		

[1] Statistical symbols as in table 3.

TABLE 30. Yield data for Experiment 3 (pounds of husked nuts per tree)[1]

TREATMENT	YEAR OF HARVEST					
	1959	1960	1961	1962	1963	1964
			Unadjusted means			
1	3.9^{b}	12.3^{c}	16.1^{d}	32.5^{b}	37.3^{b}	61.6^{b}
2	3.7^{b}	14.5^{bc}	25.8^{c}	49.0^{a}	64.7^{a}	107.4^{a}
3	3.8^{b}	19.5^{ab}	37.6^{b}	52.6^{a}	69.2^{a}	102.0^{a}
4	5.9^{a}	24.4^{a}	47.6^{a}	57.6^{a}	75.4^{a}	97.9^{a}
LSD 5%[1]	1.86	5.52	9.35	12.29	14.08	20.39
1%	2.61	7.74	13.12	17.24	19.74	28.60
			Means adjusted for Trunk Size Index			
1	3.9^{ab}	14.8^{c}	20.6^{d}	40.9^{b}	48.1^{b}	76.5^{b}
2	3.8^{b}	15.2^{c}	26.9^{c}	48.4^{ab}	61.1^{a}	100.5^{a}
3	3.8^{b}	18.6^{b}	36.0^{b}	50.2^{a}	67.5^{a}	100.7^{a}
4	5.8^{a}	22.2^{a}	43.2^{a}	52.2^{a}	69.9^{a}	91.4^{a}
LSD 5%	1.98	3.06	5.79	8.67	11.33	13.17
1%	2.79	4.32	8.17	12.24	15.99	18.59

[1] Statistical symbols as in table 3.

sponse. Adjusted yields indicate that adequate phosphorus nutrition was approached or achieved in treatments 2, 3, and 4 by 1962 and maintained in these treatments in 1963 and 1964.

Nutrient element content of leaves. Phosphorus concentrations in leaves sampled in March are shown for treatments 1 and 4 in figure 12 and for all treatments in table 31. In 1958 and 1959, March leaf phosphorus values did not differ significantly among treatments. By 1960, significant differences were evident. Larger differences were achieved and maintained in subsequent years. In 1964, leaf phosphorus values in treatment 4 became very high.

The potassium applied in this experiment (table 27) was adequate to maintain leaf concentrations of this element above 0.40 percent of the dry weight throughout. At no time did the phosphorus treatments affect leaf potassium values significantly.

All trees were supplied with significant amounts of magnesium through 1963 (table 27). The accumulation of this element in the leaves was significantly increased by the higher phosphorus treatments (table 32). The samples collected in March 1962 were the first to show this effect decisively. This difference was maintained in samples of subsequent years. The significant responses in leaf content of magnesium were confined to the highest two phosphorus treatments.

The treatments also had significant effects on the calcium concentrations of the leaf samples (table 32). The results for 1962 might be accounted for by the calcium content of the superphosphate used to implement the phosphorus differentials, since higher leaf calcium values resulted from high phosphorus treatments. Curiously, in 1965, leaf calcium in treatment 4 fell significantly below the value for treatment 2.

TABLE 31. Leaf phosphorus concentrations in Experiment 3 (percent of dry matter)[1]

TREATMENT	1958	1959	1960	1961	1962	1963	1964	1965
				March samples				
1	.065	.065	.063^{c}	.055^{c}	.072^{c}	.068^{c}	.065^{d}	.056^{c}
2	.064	.063	.069^{bc}	.065^{bc}	.080^{c}	.073^{c}	.086^{c}	.062^{c}
3	.068	.067	.077^{b}	.075^{b}	.114^{b}	.131^{b}	.157^{b}	.128^{b}
4	.071	.073	.088^{a}	.087^{a}	.145^{a}	.202^{a}	.258^{a}	.209^{a}
LSD 5%[1]	n.s.	n.s.	.0089	.0120	.0224	.0266	.037	.034
1%			.0124	.0169	.0314	.0373	.053	.047
				June samples				
1	.051^{b}	.047^{b}	.046^{b}	.048^{b}	.066^{c}	.061^{c}		
2	.050^{b}	.049^{b}	.050^{b}	.057^{b}	.072^{c}	.069^{c}		
3	.052^{b}	.049^{b}	.059^{a}	.059^{b}	.105^{b}	.142^{b}		
4	.058^{a}	.054^{a}	.064^{a}	.077^{a}	.137^{a}	.203^{a}		
LSD 5%	.0025	.0042	.0059	.0116	.0289	.0244		
1%	.0034	.0058	.0083	.0162	.0406	.0343		

[1] Statistical symbols as in table 3.

TABLE 32. Magnesium and calcium concentrations in March leaves in Experiment 3[1]

TREATMENT	1958	1959	1960	1961	1962	1963	1964	1965
					Magnesium			
1	.094	.088	.082	.082	.075^{bc}	.097^{b}	.067^{c}	0.067^{b}
2	.078	.080	.076	.075	.074^{c}	.095^{b}	.071^{bc}	0.071^{b}
3	.099	.079	.083	.080	.085^{b}	.115^{a}	.084^{ab}	0.092^{a}
4	.082	.087	.074	.080	.096^{a}	.116^{a}	.093^{a}	0.097^{a}
LSD 5%[1]	n.s.	n.s.	n.s.	n.s.	.0101	.0156	.0148	0.0128
1%					.0141	.0218	.0207	0.0179
					Calcium			
1	.60	.60	.54	.46	.44^{b}	.67	.60^{b}	0.82^{c}
2	.53	.61	.45	.49	.52^{ab}	.83	.78^{ab}	1.12^{a}
3	.64	.54	.56	.55	.62^{a}	.82	.84^{a}	1.08^{ab}
4	.48	.63	.48	.60	.66^{a}	.87	.70^{ab}	0.85^{bc}
LSD 5%	n.s.	n.s.	n.s.	n.s.	.164	n.s.	.178	0.224

[1] Statistical symbols as in table 3.

Observations on symptoms and orchard closure. In this experiment no leaf color symptoms indicative of phosphorus deficiency could be discerned on the low phosphorus trees. During most of the experiment, trees of treatment 1 appeared dark green and generally healthy although the density of the foliage and bearing branches was less in this treatment than in others by the fall of 1960. In May 1962 it was observed that the terminal stem of 1 tree, out of 15 in treatment 1, was dead and that all trees of this treatment had an open appearance due to loss of leaves from the upper branches and paucity of secondary vegetative and fruiting branches. Based on estimates of distances between adjacent trees, the ground area covered by the canopy of these trees averaged about 200 square feet at this time as compared to about 400-square-foot coverage per tree in treatment 4. Hence, it is evident that the total area occupied by low phosphorus trees was much less in proportion to high phosphorus trees than would be indicated by comparison of the Trunk Size Indexes (figure 12). In January 1965, branches of adjacent trees of treatments 2, 3, and 4 were touching or intertwined in many cases, but an average space of about 5 feet remained between adjacent trees of treatment 1. From these observations the ground areas covered were about 490 square feet per tree in treatments 2, 3, and 4 and about 315 square feet in treatment 1, based on circular areas having 25- and 20-foot diameters, respectively.

During 1964 a number of trees in treatment 4 developed chlorotic leaves. In a few cases this chlorosis became severe and was accompanied by marginal burn and defoliation. Leaves from a tree showing the most severe symptoms were sampled separately in March 1964. This sample had a very high phosphorus content (0.324 percent of the dry weight), was abnormally high in potassium, and low in calcium.

Relationship of growth rate to leaf phosphorus. From figure 12 it is seen that rate of circumference growth responded to phosphorus treatment to the greatest extent in 1959 and 1960. Growth rate was significantly correlated with leaf phosphorus both years, but only in 1960 was the relationship significantly curvilinear (table 33). In both years a large proportion of variance in circumference growth rate remains unaccounted for, yet it may not be entirely coincidental that the inflection points of the polynomial curves for the two years are similar. Hence, the equations representing the least squares fit of the second degree polynomials are:

$C = -0.564 + 20.021\,L - 130.52\,L^2$ for 1959, and $C = -0.383 + 12.809\,L - 74.46\,L^2$ for 1960, where:

C = circumference growth rate in mm per day

L = phosphorus concentration in leaves sampled in March

The derivatives of these are:

$$\frac{dC}{dL} = 20.021 - 261.04\,L \text{ for 1959, and}$$

$$\frac{dC}{dL} = 12.809 - 148.90\,L \text{ for 1960.}$$

On solving for L at $\frac{dC}{dL} = 0$, $L = 0.077$ percent P in 1959 and 0.086 percent P in 1960. If this type of curve truly described the relationship, these phosphorus values would represent the point where growth rate ceases to increase with increas-

TABLE 33. Relationship between circumference growth rate and leaf phosphorus in Experiment 3
Circumference growth rate as dependent variable, leaf phosphorus and its second degree polynomial as independent factor

TYPE OF CORRELATION	COEFFICIENTS OF: Correlation (r)	Determination (r^2 or R^2)	F VALUE FOR TEST OF CURVILINEARITY
	1959		
Linear	.4457*	.2077	
Curvilinear		.2448	1.04 n.s.
	1960		
Linear	.4657*	.2169	
Curvilinear		.3868	4.71*

* Significant at the 5 percent level.
n.s.: Not significant.

ing leaf phosphorus values. Considering the limited range of growth and phosphorus values represented by these data and the relatively large proportion of variance in growth rate not accounted for, these inflection points are in excellent agreement. They are also consistent with the results for Keauhou in Experiment 1.

Relationships of yield to leaf phosphorus and Trunk Size Index. In figure 13 are plotted the adjusted yield data of table 30 against the leaf phosphorus data of table 31. Within the limited ranges of leaf phosphorus values encountered in 1960 and 1961 the relationships appear linear. However, the plots for 1962 through 1964 clearly indicate adequate phosphorus for maximum yield in two or three of the treatments each year. For these 3 years the minimum leaf phosphorus associated with maximum adjusted yield appears to lie between 0.075 and 0.100 percent phosphorus.

The yields shown in figure 13 and table 30 have been adjusted for regression on trunk size for all treatments within each year. In these regressions are included yields from trees suffering from phosphorus deficiency. As was the case in Experiment 2, it is to be expected that within the range of phosphorus deficiency the regression of yield on trunk size will be somewhat muted. Hence, if we select only those plots in the adequate range of phosphorus nutrition, perhaps the separate effect of trunk size on yield can be defined more precisely. It will also be of interest to see whether the effect of size index on yield is the same each year. With the indications shown in figure 13 in mind, treatment plots were selected on the basis of leaf phosphorus values: only those plots with leaf phosphorus values in excess of 0.085 were included. The choice of this particular value is somewhat arbitrary, but it falls within the range indicated by figure 13 and has the additional advantage of including a number of treatment plots in each of the years from 1962 through 1964. Linear regressions of yield on Trunk Size Index are shown in figure 14. Coefficients of correlation determination, and regression are shown in table 34 with results of a comparison of the regressions by covariance. A high proportion of the variance in yield was accounted for by the Trunk Size Index each year. The

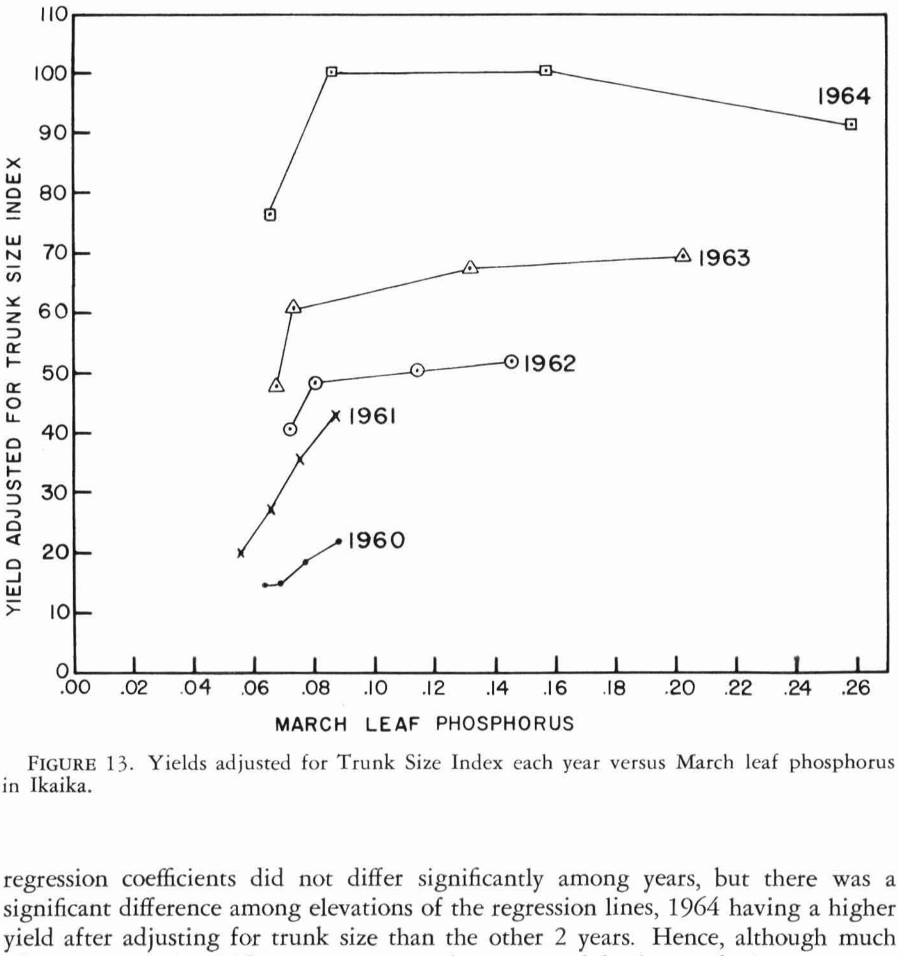

FIGURE 13. Yields adjusted for Trunk Size Index each year versus March leaf phosphorus in Ikaika.

regression coefficients did not differ significantly among years, but there was a significant difference among elevations of the regression lines, 1964 having a higher yield after adjusting for trunk size than the other 2 years. Hence, although much of the variance in yield among years can be accounted for by trunk size, there was some other factor contributing to yield which was associated with nut production in 1964.

The above regressions, it is recalled, were determined after eliminating the treatment plots having leaf phosphorus values of 0.085 or less. However, if these regressions are now used to determine a yield value for all treatment plots each year, this value should represent the potential yield, which would have been attainable had phosphorus been adequate in each plot. A good estimate of the effect of phosphorus *per se* on yield is then attained by determining the percentage of this potential yield represented by actual yield in each plot. Results of these calculations are plotted in figure 15 and fitted with a freehand curve. The index of determination for this curve (i^2) is 0.5922. From this relationship a leaf phosphorus value of about 0.09 or above is indicated for close approach to potential yield.

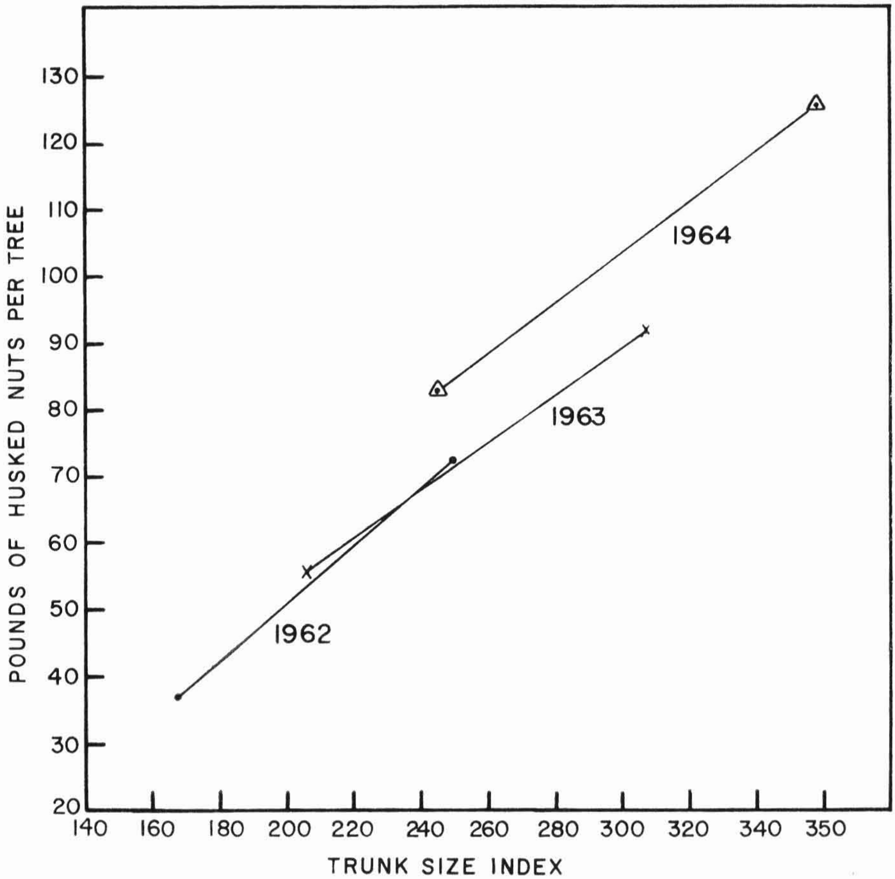

FIGURE 14. Regression lines of yield on Trunk Size Index in adequate phosphorus range for Ikaika.

TABLE 34. Results of correlation, regression, and covariance analysis of yield on Trunk Size Index for plots having leaf phosphorus values above 0.085 in Experiment 3

	1962	1963	1964
Number of treatment plots (n)	10	10	13
Correlation coefficient (r)[1]	0.9116**	0.8887**	0.8833**
Coefficient of determinations (r^2)	0.8310	0.7897	0.7802
Regression coefficient (b)[2]	0.4350	0.3531	0.3763
Intercept (a)	−35.7	−16.6	− 9.3
Adjusted means (lb husked nuts per tree)[3]	72.7[b]	73.4[b]	86.4[a]

[1] Correlation coefficient required for significance at 1 percent level: at 8 degrees of freedom (1962 and 1963), 0.765; at 11 degrees of freedom (1964), 0.684.

[2] Differences among regression coefficients not significant ($F < 1.0$).

[3] LSD for adjusted means at 1 percent level = 10.89.

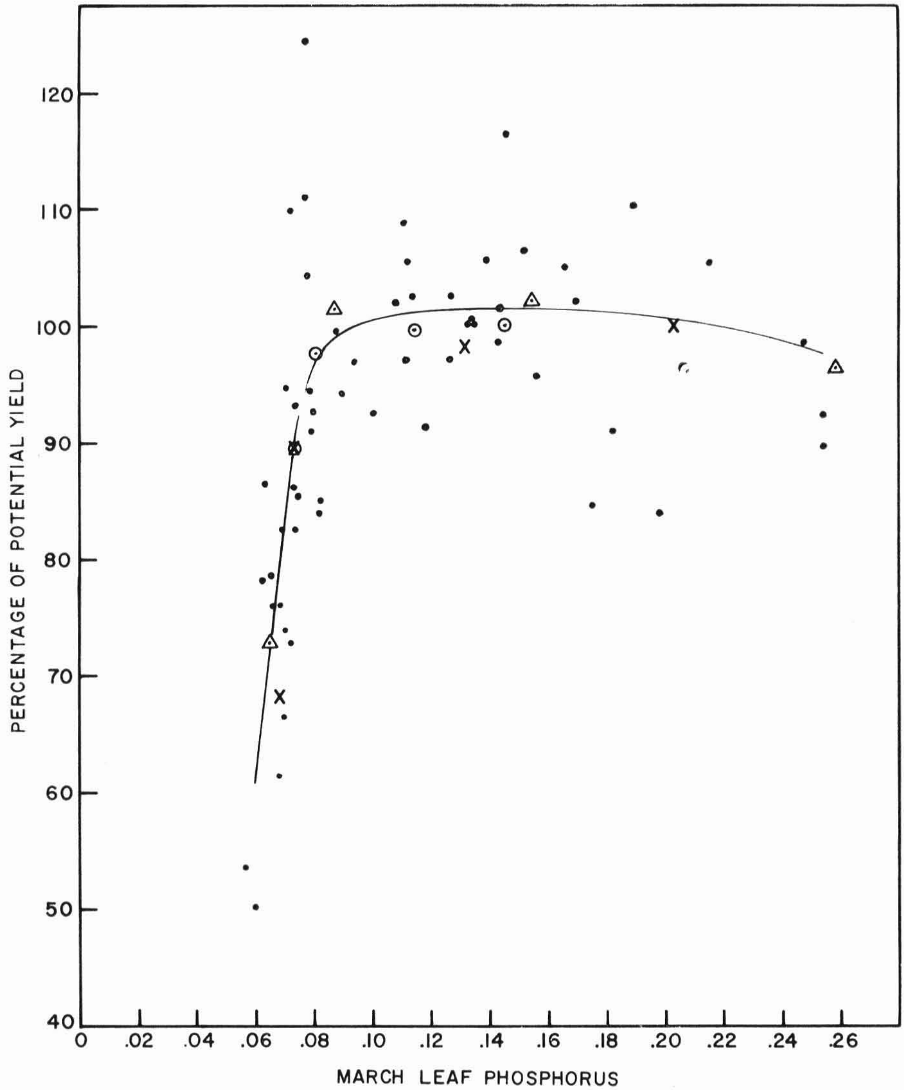

FIGURE 15. Percentage of potential yield in Ikaika as related to March leaf phosphorus. Freehand curve fitted to treatment plots (•) ($i^2 = 0.5912$). Treatment means are also shown: 1962 (○), 1963 (x), and 1964 (△).

Factors related to leaf phosphorus. Coefficients of correlation, determination, and regression of leaf phosphorus on Relative Rate of Phosphorus Application are shown in table 35, and the regression line for each year is shown in figure 16. Comparisons by covariance showed differences among regression coefficients to be not significant for 1959 through 1961. In 1962 through 1964, regression coeffi-

TABLE 35. Coefficients for the relationship between leaf phosphorus in March each year and the Relative Rate of Phosphorus Application (A) in Experiment 3

YEAR OF LEAF P	LEAF P		A		COEFFICIENTS OF:		INTERCEPT	SLOPE
	Range	Mean	Range	Mean	Correlation	Determination	(a)	(b)
1959	.056–.081	.067	0.19–1.35	0.66	.4329 n.s.	.1874	.0620	.007,250
1960	.057–.102	.074	0.21–1.98	0.89	.8390**	.7039	.0600	.016,024
1961	.047–.114	.070	0.27–1.98	1.09	.8223**	.6761	.0493	.019,284
1962	.063–.182	.103	0.41–2.70	1.28	.8494**	.7215	.0582	.032,095
1963	.057–.246	.118	0.21–2.41	0.97	.9133**	.8342	.0476	.073,310
1964	.060–.350	.143	0.17–1.60	0.69	.9268**	.8590	.0287	.165,136
Total for 1959 through 1961	.047–.114	.071	0.19–1.98	0.89	.7535**	.5677	.0567	.015,499
Treatments 1 and 2 only for 1962 and 1963; treatment 1 for 1964	.057–.089	0.72	0.17–1.12	0.45	.6994**	.4892	.0630	.019,160

n.s.: Not significant.
** Significant at the 1 percent level.

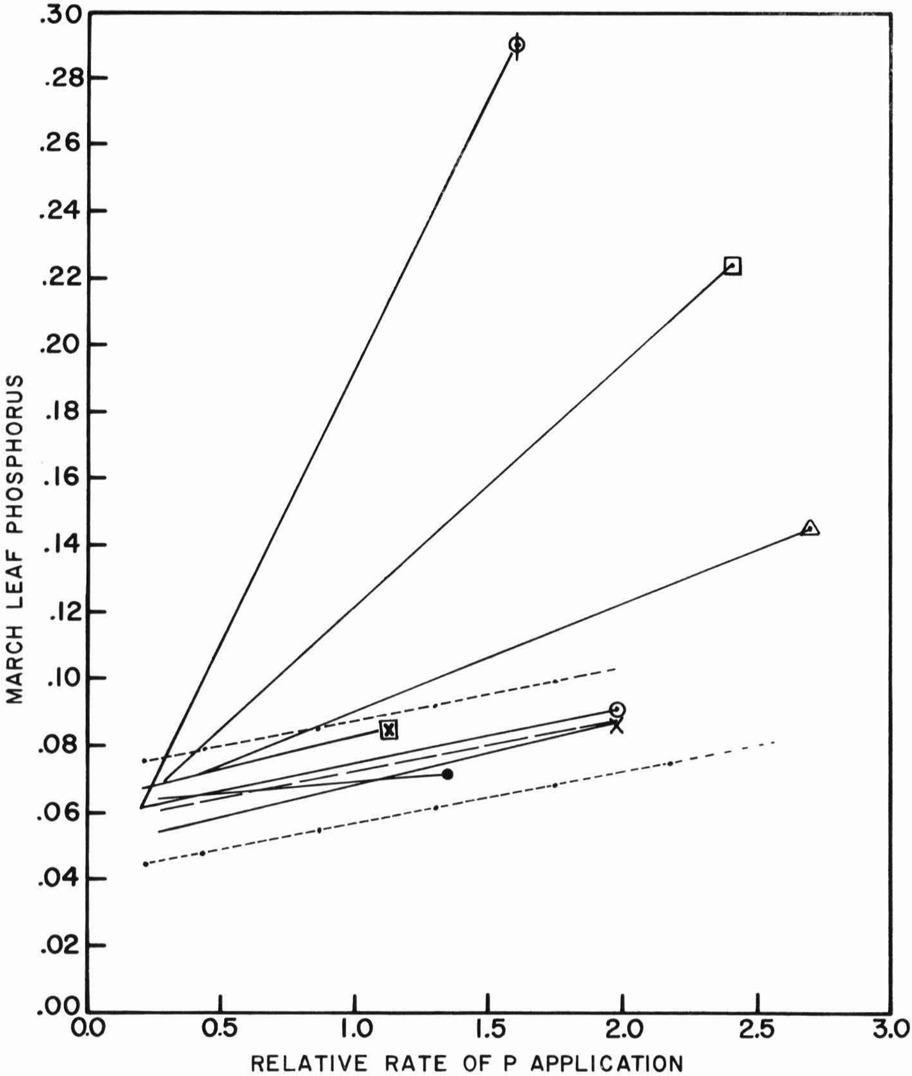

FIGURE 16. Regressions of March leaf phosphorus values on the Relative Rate of Phosphorus Application (A). The range of A values for each year is denoted by the ends of the lines. Solid lines are for leaf phosphorus values in 1959 (•), 1960 (○), 1961 (x), 1962 (△), 1963 (□), 1964 (Φ). One additional solid line (☒) denotes pooled observations for treatments 1 and 2 for 1962 and 1963 and for treatment 1 in 1964. The central broken line denotes total regression for 1959, 1960, and 1961. The limiting broken lines show limits at the 5 percent level for predicting an individual event in 1959, 1960, or 1961.

cients increased significantly each year. Hence, it appears that for relatively young trees, leaf phosphorus is reasonably well defined by relative application rate but that as canopy closure approaches, as was the case for the high phosphorus treatments in 1962 (see p. 55), other factors must be considered. Accordingly, young trees and trees approaching closure are treated separately. The line for total regression of leaf phosphorus on relative application rate for 1959 through 1961 is shown as the broken line in figure 16, with limits at the 5 percent level for predicting an individual event shown as the broken lines. Also shown is a regression for pooled observations of treatments 1 and 2 in 1962 and 1963 and for treatment 1 in 1964. As indicated above, these trees had not approached canopy closure at the times specified. The regression line for these pooled observations falls within the limits based on the 1959 to 1961 total regression. The total regression for 1959 to 1961 shows that a Relative Rate of Phosphorus Application of about 1.6 is required to assure that 50 percent of the three-tree plots will have leaf phosphorus values of 0.080 or above. To assure this leaf phosphorus value for 95 percent of such plots would require a relative application rate of about 2.6, although this is actually beyond the range of the observations on which this regression is based.

Among trees approaching canopy closure the variations in leaf phosphorus among treatments and years (Lc) can be related to the leaf phosphorus content the previous year (Lp) and the pounds of phosphorus applied during the year previous to sampling (P). Means for treatments 3 and 4 in 1962, 1963, and 1964 and for 2, 3, and 4 in 1965 were used ($n = 9$). Results of correlation analysis of these factors are shown in table 36. About 96 percent of the variance in leaf phosphorus among the treatment means of high phosphorus treatments in 1962, 1963, 1964, and 1965 are accounted for. The multiple regression equation is $Lc = 0.0243 P + 0.6984 Lp$. Partial regressions for this relationship are shown in figure 17. This appears to be a useful equation for predicting leaf phosphorus values in the adequate range. Hence, the data fit well for 1965 when the range in P was small and the dominant variable was Lp. The fit is also reasonably good for 1962 and 1963 when the range in Lp was small and the dominant variable was P. According to this relationship, 0.9 pound phosphorus is required to maintain the leaf phosphorus value at 0.08 percent, from 1 year to the next after canopy closure is approached. For 0.10 percent phosphorus, 1.2 pounds of phosphorus would be required.

TABLE 36. Correlation and regression analysis of factors affecting leaf phosphorus in Ikaika trees approaching canopy closure

INDEPENDENT VARIABLES	COEFFICIENTS OF: Correlation[1] (r or R)	Determination (r^2 or R^2)	F VALUE FOR REDUCTION IN UNACCOUNTED FOR VARIANCE BY:[2] Lp	P
Lp	.7473*	.5585		
P	.6376	.4065		
Lp, P	.9806	.9615	86.60**	62.88**

[1] Correlation coefficient required for 5 percent significance: 0.666 at 7 degrees of freedom.

[2] F value required for 1 percent significance: 13.78.

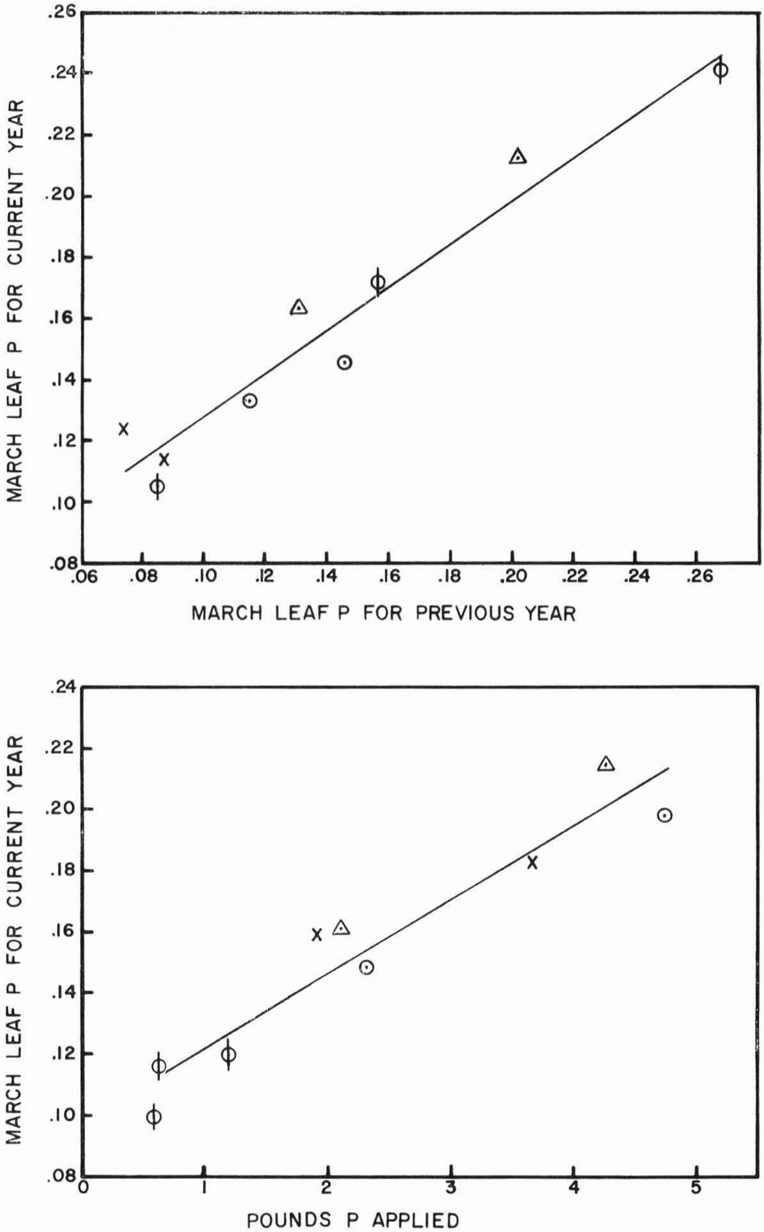

FIGURE 17. Partial regressions of March leaf phosphorus on: leaf phosphorus of the previous March (*above*); and pounds of phosphorus applied (*below*). Mean values for treatments in the adequate phosphorus range are designated: 1962 (x), 1963 (○), 1964 (△), and 1965 (Φ).

DISCUSSION

In leaves of many trees the internal flux of elements is at a minimum during a period between a leaf age of 3 to 6 months *(18, 21)*. For macadamia, phosphorus concentrations were higher in March leaves, at about 3 months of age, than in June leaves, at about 6 months of age, when phosphorus supply was low or moderate. When leaf phosphorus values were in the vicinity of 0.20 percent or above, June leaves had values as high or higher than March leaves (Keauhou and Kakea in 1962, table 18, and Ikaika in 1963, table 31). In these latter cases phosphorus supply was probably excessive as indicated by chlorosis and marginal burn of young leaves on some trees. Decreases in leaf phosphorus values between March and June at low and moderate phosphorus supply are probably due to some withdrawal of phosphorus and movement into the developing flush of growth terminal to the whorl sampled. Leaf phosphorus values for March, obtained prior to this growth flush, serve as a better phosphorus index, since more of the variance in growth rate can be related to the March values (table 10).

It seems appropriate to consider leaf phosphorus values to be related to growth and yield responses indirectly, the direct cause of all responses being rate of phosphorus supply. That this is a correct interpretation is suggested by the relatively high yield in treatment B of Experiment 2 in 1961 (figure 6) coincident with suboptimal March leaf phosphorus values. Here it appears that yields were improved by heavy phosphorus applications early in the same year, even when applied too late to influence March leaf phosphorus values. It appears, then, that leaf phosphorus values are most useful as an index of phosphorus status of the tree when phosphorus is being applied at a relatively uniform rate.

The critical range of leaf phosphorus for growth of young trees is similar to that for yield of bearing trees (compare figures 3, 11, and 15). The critical range of 0.08 to 0.10 percent phosphorus is similar for each of the three varieties of macadamia studied here and similar to critical values for citrus and tung leaves *(17)*.

The factors which influence leaf phosphorus values in March change with changing stages of development of the orchard. As long as the trees are well separated from each other, reasonably consistent relationships are found between the leaf phosphorus values and the Relative Rate of Phosphorus Application—defined as the ratio of phosphorus applied to the square of the circumference—(tables 11 and 35; figures 5 and 16). A rationale for this relationship lies in the assumption that the ground area occupied by the roots of each tree increases in proportion to the cross-sectional area of the trunk until roots of neighboring trees approach each other. If this is true a given Relative Rate of Phosphorus Application represents a specific amount of phosphorus per unit of ground area to which it is applied. As orchard closure is approached the increase in area occupied ceases to be significant, but the initial phosphorus status at the beginning of the year becomes an important factor (tables 25 and 36).

The influence of large nitrogen applications in reducing leaf phosphorus values in Experiment 2 (table 18) may have an important bearing on the phosphorus requirements of macadamia. Depression of leaf phosphorus values resulting from an increase in nitrogen supply has been reported for many plants *(21)*. However, in a number of such cases *(11, 16, 22)* increments in nitrogen supply have been associated with large responses in growth or yield. In such cases lower leaf phosphorus values in plants receiving high nitrogen treatments may not be the result of less phosphorus absorption, but due to greater dilution by more growth. Another feature which all three of the above-cited studies showed was a depression of leaf potassium as well as phosphorus. The results of Experiment 2 appear distinct from this type of leaf phosphorus response to nitrogen supply, since the effect was not accompanied by increments in growth or yield, nor was leaf potassium reduced.

Rate of trunk growth responds to phosphorus only in the relatively early stages of tree development. After young trees of Keauhou were given differential phosphorus treatments for several years, differences among treatments in trunk size became large, so the validity of comparing rates of trunk growth among treatments becomes questionable (e.g., Experiment 1 in 1960—figure 1). However, in the latter stages of Experiment 3 the range in trunk size among treatments was not great, yet large increments in phosphorus supply were ineffective in increasing trunk growth rate in 1961, 1962, and 1963 while responses in nut production were large (figure 12; table 30). In Experiment 2, where bearing trees were initially similar in size, no positive response in rate of trunk growth was found. Branch growth and development shows response to phosphorus in young trees (table 5), and in bearing trees as well (figure 7). Bearing trees moderately deficient in phosphorus show visible responses similar to those reported for phosphorus-deficient orange trees *(9)*. In terms of total vegetative growth, trees appear to respond to phosphorus at all stages, although of the quantitative data obtained in the experiments reported here the most conspicuous response of bearing trees is in production of nuts.

With trees initially deficient in phosphorus, significant yield responses to high rates of application were obtained rather quickly. Specifically in Experiment 2, yields of 1959 were significantly increased in treatments A, D, and E as a result of applications beginning in July 1958 (tables 12 and 15; figure 6). High rates of application in treatment B begun in February 1961 appear to have been the reason for the large increase in 1961 yield over 1960 yield in this treatment. However, it appears that at least 2 years of high phosphorus treatment are required to fully correct the effects of phosphorus deficiency on yield. Hence in treatments A, D, and E, yields of 90 pounds per tree were not attained until 1961 as a result of high rates begun in July 1958. It appears to be impossible to hasten this process by applying even larger amounts of phosphorus. Thus, 1960 yields in treatments A and E were not significantly higher than those for treatment D, although the former two treatments had received a total of 7 pounds of phosphorus per tree from July 1958 through April 1960, and treatment D, 4.6 pounds during this period. The increase in response after the second year of phosphorus treatment may reflect the proliferation of bearing branches taking place during the first year of treatment.

When phosphorus is adequate the relationship of yield to the Trunk Size Index appears to be a linear one from early bearing to essentially complete canopy closure (figure 10). After the branches of adjacent trees become intertwined the variance in yield becomes less related to the Trunk Size Index. Here it appears, light becomes a limiting factor for yield. This is suggested by the lower correlation and regression coefficients of yield on Trunk Size Index in Keauhou for 1962 and 1963, when all trees had adequate phosphorus, than coefficients for previous years when some of the trees were still deficient in phosphorus. The coefficients of table 22 are all for trees having adequate leaf phosphorus values, but because these trees were randomized in the orchard with low phosphorus trees having less foliar density, the high phosphorus trees had access to more light in years prior to 1962 than in subsequent years. The 1962 coefficients for Kakea were not lowered as much as were those for Keauhou (table 22). This may be related to the fact that one of the two trees in each plot of Kakea was exposed to a field road on one side. Hence, light may not have been so limiting for this variety. Correlation and regression coefficients of yield on trunk size remained high for Ikaika in 1964 (table 34). Here, although there was intertwining among branches of trees in the high phosphorus treatments, these three-tree plots were interspersed with low phosphorus plots where the trees were not occupying all of the above-ground area and had lower foliar density.

Exceptionally high yields of Ikaika trees in 1964 (table 34; figure 14), not accountable for in terms of trunk size and phosphorus status, must have climatological origins. It is not evident what factors were involved, although rainfall was heavier than normal during the first 3 months of 1964.

Low rainfall during the first 3 months of 1958 appears responsible for lower March leaf phosphorus values relative to phosphorus supply that year (table 11; figure 5).

Although the annual rainfall at Keaau usually exceeds 100 inches per year, lack of rainfall for even a few weeks can result in drought effects, owing to the very porous nature and low moisture-holding capacity of the substrate. Our semiannual measurements of trunk circumference may not have been made with sufficient frequency to detect reductions in growth rate which might have resulted from 1 to 3 months of low rainfall. It appears that low growth rates in one 6-month period are frequently compensated for by higher rates in subsequent periods. The tendency for higher growth rates of Ikaika during the second half of several years (figure 12; table 28) suggests an influence of temperature on trunk growth, since more high-temperature months are included in the period from June to December than in the earlier half of the year. However, this tendency was not found every year, and with young Keauhou trees, was evident only in 1958 (figure 1). The fluctuations between early and late year trunk growth rate, which were evident in Ikaika in 1961, 1962, and 1963, together with the fact that such fluctuations were generally lacking prior to significant bearing in both Ikaika and Keauhou suggest a relationship to the flowering and fruiting cycle.

Growth rates early in the year are coincident with periods of flowering and early fruit development; whereas, the second growth period each year includes the months of maximum oil formation in the embryos *(13)*.

Large applications of superphosphate resulted in increased concentrations of magnesium in the leaves of Kakea (table 21) and Ikaika (table 32). This effect was less decisive in Keauhou. In Ikaika, leaf calcium values were also increased significantly. Similar results have been obtained from application of treble superphosphate to citrus *(8)* and avocado *(7)*. The calcium contained in the superphosphate carriers is doubtless responsible for the increases in leaf calcium observed, but the mechanism responsible for the leaf magnesium response is not clear. Smith *(21)* evidently considers this type of response a case of synergism, and attributes the magnesium response to the calcium supplied in the phosphate carrier. Shear *et al. (19)* grew young tung trees in sand culture at three levels each of calcium, magnesium, and potassium in factorial combination. Calcium supply was found to increase leaf magnesium values only at the lowest potassium level. At adequate potassium levels, calcium supply either had no effect on leaf magnesium values or decreased them. In macadamia, the leaf magnesium responses to superphosphate were found only after considerable growth and yield response to phosphorus had occurred. In Kakea, leaf magnesium values continued to increase in leaves of high phosphorus trees even during a period when superphosphate was withheld (table 21, treatments A and E, 1963). Furthermore, leaf magnesium was correlated with total phosphorus supplied over several years rather than current rate of supply. These observations suggest that the leaf magnesium response may be a reflection of increased efficiency of absorption, perhaps resulting from a more extensive root system developing in response to high phosphorus treatments.

APPLICATIONS

From experience with other tree crops *(21)* it seems likely that the critical leaf phosphorus range for growth and yield found in the experiments reported here should apply to various climates and soils. The actual amounts of phosphorus which must be applied to maintain adequate leaf phosphorus values will doubtless vary with locality, and be particularly influenced by the phosphorus-fixing capacity of the soil. By use of the leaf phosphorus index, however, it should be possible to determine amounts of phosphorus required to maintain adequate phosphorus nutrition of trees grown on various soils. The aa rockland substrate on which these experiments were conducted probably represents a minimum of phosphorus fixation.

Estimates of phosphorus requirements for trees of various sizes may be made from the regression equations developed in the three experiments reported here. Table 37 shows estimates of requirements for maintaining leaf phosphorus values at 0.10 percent from 1 year to the next. Use of 0.10 percent provides for the expectation that 95 percent or more three-tree plots will have March leaf phosphorus values of 0.08 percent or above (figures 5 and 16), a value above which responses to additional phosphorus are unlikely. These estimates indicate that for a period prior to closure, when trees are about 4 inches in diameter, more phosphorus is required per tree than later, after orchard closure is approached. Young trees of Ikaika appear to require less phosphorus for maintenance than trees of Keauhou. However, the estimates for Ikaika are based on extrapolation beyond the limits of the observations. The estimates for the closed orchard, based on results of Experiment 2, indicate relatively small amounts of phosphorus may be

TABLE 37. Estimated quantities of phosphorus required for maintenance of March leaf phosphorus values at 0.10 percent when trees are grown on aa rockland and spaced 25 feet × 25 feet

TREE SIZE		YOUNG TREES		APPROACHING CLOSURE	CLOSED ORCHARD Keauhou and Kakea[4]	
Diameter (inches)	Size Index	Keauhou[1]	Ikaika[2]	Ikaika[3]	4 lb N	2 lb N
				Pounds P per tree per year		
1	6	0.2				
2	25	0.9	0.7			
3	57	2.0	1.6			
4	102		2.9			
5	159			1.2		
6	229			1.2		
7	312			1.2	1.9	0.4
8	408				1.9	0.4

[1] A = 3.5 at Lc = 0.10, from total regression, table 11.
[2] A = 2.8 at Lc = 0.10, from total regression for 1959 through 1961, table 35.
[3] From total regression equation, p. 62.
[4] From combined regression equation, table 26.

required for maintenance when only 2 pounds of nitrogen are applied. It should be emphasized, however, that the low nitrogen treatment in this experiment was confined to the high phosphorus level. Hence, the estimate of phosphorus required at 2 pounds of nitrogen and a leaf phosphorus value of 0.100 percent is an extrapolation. Fur:her experimentation will be required to determine whether nitrogen has this large an effect in the moderate phosphorus range. Nitrogen was not an experimental variable in the Ikaika experiment, but it should be noted that nitrogen applications during the last 3 years of this experiment ranged between 1.52 and 2.10 pounds per tree per year. Yet the phosphorus requirement estimated for these trees is 1.2 pounds per tree per year. Until more information is available it seems prudent to apply at least this much phosphorus to all three varieties for phosphorus maintenance in a closed orchard, even at low nitrogen rates.

The estimates of table 37 apply only to situations similar to Keaau Orchard where aa rockland is the substrate and the spacing is 25 feet by 25 feet. With more space between trees it is to be expected that the amount of phosphorus required will continue to increase in proportion to the area occupied until the trees have reached a larger size and are approaching closure. However, it seems reasonable to expect that after closure is attained the amount of phosphorus required per acre of orchard should be similar for various spacings.

Even for situations similar to Keaau Orchard the estimates of table 37 should be used only as guidelines. For young, well-separated trees the regression coefficients of tables 11 and 35 did not differ significantly from year to year in a statistical sense, but there were large enough differences among equations for separate years to result in considerable variation in predictions made from them. Climatic factors are doubtless involved in these variations, but these cannot be predicted for any single year. The recommended practice, therefore, is use of table 37 in combination with annual leaf phosphorus analysis. Trunk measurements should be made each year until closure is approached. From these data the best estimate of the phosphorus required can be made each year from the appropriate equations.

SUMMARY

Three phosphorus experiments are reported involving three varieties of macadamia trees in various stages of orchard development on a substrate of low fertility. A leaf phosphorus index is established. The critical range is similar for growth of young trees and yield of bearing trees. All three varieties seem to have the same critical range, one which is comparable to that for citrus and tung trees.

In young trees the rate of trunk growth responds to increments of phosphorus supply. As trees reach the stage of significant production, phosphorus responses are no longer reflected in trunk growth, but very large responses in nut production are obtained. Proliferation and growth of secondary branches are dependent upon phosphorus nutrition at all stages of development.

Leaf phosphorus values are related to phosphorus supply per unit of cross-sectional trunk area up to the point where orchard closure is approached. Thereafter, trunk area loses significance, but previous phosphorus status assumes importance. Results of one experiment indicate that nitrogen supply is also important, since high rates of nitrogen application resulted in reduced leaf phosphorus percentages.

When phosphorus nutrition is adequate, yield has a linear relationship to the Trunk Size Index from stages of early bearing until orchard closure is essentially complete. At this point it is suggested that light becomes limiting with respect to yield.

High rates of superphosphate application were found to increase concentrations of magnesium, and in some cases those of calcium in the leaves. These effects are discussed in relation to similar responses reported for citrus and avocado.

Application of the results to orchard practice is discussed.

LITERATURE CITED

1. COOIL, B. J. 1962. Mineral nutrition of macadamia trees—phosphorus. Proc. Second Annual Meeting, Hawaii Macadamia Producers Assoc. Pp. 33–38.

2. ———. 1965. Fertilizing macadamia orchards that are closing in. Proc. Fifth Annual Meeting, Hawaii Macadamia Producers Assoc. Pp. 28–32.

3. ———, M. AWADA, S. NAKATA, and M. NAKAYAMA. 1953. Leaf concentrations associated with deficiencies of nitrogen, potassium, and phosphorus in macadamia. Hawaii Agr. Exp. Sta. Prog. Notes No. 88. 11 pp.

4. ———, S. NAKATA, and M. AWADA. 1957. Phosphorus nutrition of young macadamia, variety Keauhou. Hawaii Agr. Exp. Sta. Prog. Notes No. 113. 15 pp.

5. ———, ———, and D. M. NOMURA. 1958. Potassium nutrition of young macadamia, varieties Keauhou and Kakea. Hawaii Agr. Exp. Sta. Prog. Notes No. 116. 15 pp.

6. DUNCAN, D. B. 1955. Multiple range and multiple F tests. Biometrics 11: 1–42.

7. EMBLETON, T. W., W. W. JONES, J. D. KIRKPATRICK, and D. GREGORY-ALLEN. 1958. Influence of sampling date, season, and fertilization on macronutrients of Fuerte avocado leaves. Proc. Amer. Soc. Hort. Sci. 72: 309–320.

8. ———, J. D. KIRKPATRICK, W. W. JONES, and C. B. CREE. 1956. Influence of applications of dolomite, potash and phosphate on yield and size of fruit and on composition of leaves of Valencia orange trees. Proc. Amer. Soc. Hort. Sci. 67: 183–190.

9. ———, ———, and E. R. PARKER. 1952. Visible response of phosphorus-deficient orange trees to phosphatic fertilizers, and seasonal changes in mineral constituents of leaves. Proc. Amer. Soc. Hort. Sci. 60: 55–64.

10. EZEKIEL, M., and K. A. FOX. 1959. Methods of Correlation and Regression Analysis. 3rd Ed. John Wiley and Sons, New York.

11. FINCH, A. H., and W. T. MCGEORGE. 1945. Fruiting and physiological responses of marsh grapefruit trees to fertilization. Arizona Agr. Exp. Sta. Tech. Bull. No. 105. Pp. 427–454.

12. HAMILTON, R. A., and E. T. FUKUNAGA. 1959. Growing macadamia nuts in Hawaii. Hawaii Agr. Exp. Sta. Bull. No. 121. 51 pp.

13. JONES, W. W. 1939. A study of developmental changes in composition of the macadamia. Plant Physiol. 14: 755–768.

14. KITSON, R. E., and M. G. MELLON. 1944. Colorimetric determination of phosphorus as molybdevanado-phosphoric acid. Ind. Eng. Chem., Anal. Ed. 16: 379–383.

15. Official and Tentative Methods of Analysis of the Association of Official Agricultural Chemists. 1945. 6th Ed. Washington.

16. REITZ, H. J., and R. C. J. KOO. 1960. Effect of nitrogen and potassium fertilization on yield, fruit quality, and leaf analysis of Valencia orange. Proc. Amer. Soc. Hort. Sci. 75: 244–252.

17. REUTHER, W., T. W. EMBLETON, and W. W. JONES. 1958. Mineral nutrition of tree crops. Ann. Rev. Plant Physiol. 9: 175–206.

18. ——— and P. F. SMITH. 1954. Leaf Analysis of Citrus. Chapter 7 in: Fruit Nutrition, N. F. Childers, Ed. Somerset Press, Somerville, New Jersey.

19. SHEAR, C. B., H. L. CRANE, and A. T. MYERS. 1953. Nutrient element balance: Response of fruit trees growing in sand culture to potassium, magnesium, calcium, and their interactions. U. S. Dept. Agr. Tech. Bull. No. 1085. 52 pp.

20. SHOJI, K., and S. NAKATA. 1954. The rapid determination of potassium, calcium and magnesium in plant material by hydrogen flame spectrophotometry. Proc. Amer. Soc. Hort. Sci. 64: 299–306.

21. SMITH, P. F. 1962. Mineral analysis of plant tissues. Ann. Rev. Plant Physiol. 13: 81–108.

22. ———, W. REUTHER, A. W. SPECHT, and G. HRNCIAR. 1954. Effect of differential nitrogen, potassium, and magnesium supply to young Valencia orange trees in sand culture on mineral composition especially of leaves and fibrous roots. Plant Physiol. 29: 349–355.

23. SNEDECOR, G. W. 1956. Statistical Methods. 5th Ed. Iowa State College Press, Ames.

24. YOUNG, H. Y., and R. F. GILL. 1951. Determination of magnesium in plant tissue with thiazole yellow Anal. Chem. 23: 751–754.

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