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9. ABSTRACT

Phosphate-induced chlorosis was produced experimentally in mature macademia trees. Based on observations, it was concluded that: 1) Phosphate fertilizer rates should be based on good soil information. 2) The initial high phosphate rates required for young trees growing on new land (or land which initially is very phosphate-deficient) probably can be scaled down in later years. 3) Use both foliar analyses and soil tests to check the adequacy of the fertilizer program. 4) Put little or no faith in foliar analyses for iron. 5) If chlorosis already has developed due to excess phosphate, drastically reduce or eliminate phosphate from the fertilizer. 6) Check on the balance of several micronutrients. Sometimes what was a borderline deficiency of iron becomes a serious problem.

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Excess Phosphate and Micronutrient Deficiency in Macadamia

Robert L. Fox and Robert M. Warner

Macadamia grows wild in the rainforests of tropical Australia. As a backyard tree, it is scattered widely in the tropics and subtropics. So far the only significant commercial production is on the Island of Hawaii, where it has been a commercial crop for about 20 years. With such a short history of development and cultivation, it is not surprising that there is still much to be learned about macadamia growing. A nutritional problem now causing concern is phosphate-induced chlorosis, a yellowing of leaves, especially young leaves (Figure 1, page 1). Symptom is associated with excessive uptake of phosphate.

SOME COMPLICATING FACTORS

The problem is complicated by the crop itself and by complex chemical reactions, both in the plant and in the soil, between phosphorus and some micronutrients, especially iron and zinc. Several factors have contributed to the present problem.

- Like most tree crops, macadamia may respond slowly to cultural practices. The effects of phosphate fertilization are not immediately obvious.
- The soil effects of phosphate fertilization, more than other macronutrients, are cumulative.
- It is generally believed that response to phosphorus by nut-bearing trees is rare[1] but in Hawaii macadamia responds readily to phosphate, as has been demonstrated by Cooil and his coworkers.[2]
- Macadamia grows on very diverse soils. Some production is on soils developed from highly weathered volcanic ash. These soils are notorious for their capacity to adsorb (fix) phosphate. Other production is on *aa* rock lands which, although extremely phosphate deficient, have relatively low capacities to adsorb phosphate. Problems arise when aa soils are phosphate fertilized with amounts of fertilizer appropriate to soils developed from ash.
- Many macadamia plantings are on virgin lands. Rates of fertilization were established by early experience with young trees growing on raw land and have been extrapolated to older trees using formulas based on tree size or age. Rates of phosphate fertilization initially required to overcome soil adsorption may be unrealistic for long-term production.
- In young orchards, most of the phosphate was applied close to the trunk. Roots growing outward explored soil which had received relatively little fertilizer. Initially trees had the advantage of high phosphorus availability close in and available micronutrients (iron at least) further out.
- Phosphate movement is extremely slow in most soils, including aa rocklands. But as phosphates accumulate near the soil surface, phosphorus will move even if only a few inches. For plants such as macadamia with superficial root systems, the most important zone of nutrient extraction—the surface soil—eventually becomes sufficiently saturated with phosphate to upset the nutrition of the tree.

EXPERIMENTAL

Phosphate-induced chlorosis has been produced experimentally in mature macadamia trees growing on Waialua soil at the Waimanalo Experimental Farm of the Hawaii Agricultural Experiment Station. Phosphate was applied at 5 rates: 0, 2, 4, 8, and 16 pounds P (phosphorus) per tree per year (4.8 pounds treble superphosphate = 1 pound P). The phosphate was applied in 3 installments per year beginning in 1965 and continued for 2 years. Phosphate was placed in shallow holes dug in 3 concentric rings under the canopy of each tree.

VISUAL SYMPTOMS

Only minor growth responses from the phosphate could be seen after 1 year. But later, growth of lateral branches and foliage increased rapidly. Soon chlorosis appeared on trees which were receiving the highest phosphate (*see* Figure 1, page 1). Later, and to a lesser degree, trees which received 8 pounds P per year became chlorotic also. The chlorosis was typical of iron deficiency symptoms.

Although chlorosis became so severe on young leaves that some terminals were white, old leaves remained green and rapid foliage growth continued. This produced a dense crown which was extremely susceptible to wind damage. Of 6 trees in the high-phosphate treatment, all but 2 were severely damaged in a windstorm which caused only minor damage in the rest of the orchard. (One of the undamaged trees was adjacent to a windbreak.) Wind damage was the most immediate cause of serious yield decline.

Chlorosis is a symptom of many nutritional (and some pathological) disorders. Deficiencies of individual nutrients may, or may not, give characteristic symptoms. There are many similarities among chloroses produced by several nutrients, and multiple deficiencies are difficult to diagnose. The pattern of chlorosis shown in Figure

[1]Proebsting, E. L., and E. F. Serr. 1966. Edible nuts. *In* Childers, N. F., Ed., Nutrition of Fruit Crops, Horticultural Publications, Rutgers, N. J. pages 262-275.
[2]Cooil, B. J., Y. Watanabe, and S. Nakata. 1966. Relationships of phosphorus supply to growth, yield and leaf composition in macadamia. Hawaii Agr. Exp. Sta. Tech. Bull. 66. 71 p.

TABLE 1. Phosphorus and micronutrient content of macadamia leaves associated with increasing rates of phosphate fertilizer. Leaves analyzed were the first fully expanded leaf sampled at flowering, March 18, 1968

Nutrient determined	Phosphate applied (pounds P/tree/year)				
	0	2	4	8	16
Phosphorus (%)	.057	.063	.066	.079	.105
Iron (ppm)	62	53	47	46	62
Manganese (ppm)	2000	1980	1530	670	780
Zinc (ppm)[a]	14	14	14	15	14
Copper (ppm)	4.6	3.8	3.8	4.6	3.9

[a]Soils had received a blanket application of zinc.

1 is quite straightforward. Iron, one of the most immobile nutrients in plants, does not move readily from one leaf to another. Frequently, old leaves are normal in appearance while young leaves on the same branch have symptoms of severe deficiency. Even within a leaf, boundaries between green tissues near the veins and chlorotic tissue between veins are abrupt (Figure 2, Page 1). Patterns help distinguish iron chlorosis from deficiencies of more mobile nutrients (such as nitrogen) where the usual pattern is for older leaves to become light green or yellow green first and for the chlorosis to affect the leaf more uniformly.

Phosphate-induced chlorosis is difficult to correct. Salts and chelates of iron, manganese, zinc, copper, and magnesium were sprayed on selected leaves of chlorotic trees at Waimanalo. The only treatments which were in any way effective were those containing iron. These treatments were effective only around insect punctures and sometimes along leaf margins. Acidulated iron sulfate sprays have successfully re-greened chlorotic macadamia trees in California[3] but the California trees were apparently grown on alkaline soils where lime-induced chlorosis is expected. Some results of micronutrient analyses of chlorotic macadamia leaves have been published by Wallace.[4] Manganese was 80 parts per million—very low compared with most Hawaii macadamia (Table 1). The poor showing of foliar applied iron in Hawaii may be related to high manganese coupled with high phosphorus in the leaves.

Iron deficiency may result from insufficient iron in the plant or it may result from inefficient use of iron. In the case of phosphate-induced iron chlorosis, the problem is primarily one of inefficient use of the iron taken up; there being as much or more iron in leaves from chlorotic trees as from nonchlorotic ones (Table 1). At the present state of knowledge, it is impossible to establish optimum levels for iron in macadamia. However, it should be possible to set a limit below which deficiency is reasonably certain, but above which little can be said with confidence.

A CRITICAL PHOSPHORUS CONCENTRATION

The work reported here indicates there is no unique critical leaf-phosphorus concentration for macadamia. Concentrations associated with maximum short-term growth will likely lead to chlorosis in the long run. Until more efficient means are developed for meeting iron requirements, phosphorus levels will need to be a compromise between optimum phosphorus nutrition and acceptable iron levels. There is considerable variation in iron composition and susceptibility to chlorosis among macadamia seedlings, which suggests the possibility of screening root stocks against chlorosis and eventually of developing chlorosis-resistant varieties.

SOIL (EXTERNAL) PHOSPHORUS REQUIREMENT

In the meantime, more precise control of the phosphate supply will help. A factor influencing phosphate uptake by plants is phosphorus concentration in the soil solution. Phosphate in solution is regulated by several factors, but probably the most important is the amount of adsorbed phosphate a soil holds in relation to the capacity of that soil to hold phosphate. The practical implication is this: For 2 soils having equal amounts of adsorbed phosphate, the soil with the lowest capacity to adsorb phosphate will have the highest concentration of phosphate in the soil solution. Figure 3 is a generalized curve showing the relationship between phosphate retained (sorbed) by or withdrawn (desorbed) from the soil and phosphate concentration in solution. These data are conveniently expressed as parts phosphorus per million parts of solution (ppm). When no phosphate is added or withdrawn, P in solution is the same (X_1) for both soil A and soil B. But soil A will require (sorb) much more phosphate (Y_2) to raise its solution to X_2 than soil B (Y_1). Phosphorus applied in equal amounts to both soils will be

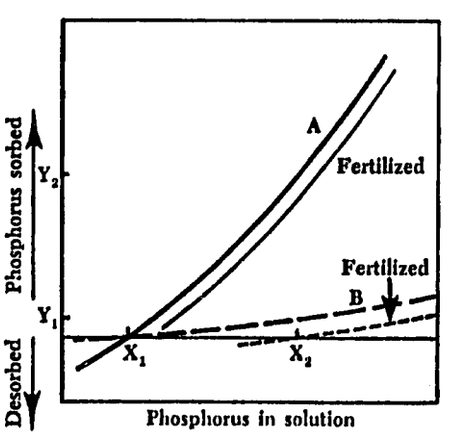


FIGURE 3. Idealized phosphate adsorption curves for 2 soils, *A* with high capacity to adsorb phosphate and *B* with low capacity, showing the effect of phosphate fertilization on phosphate in solution.

[3]Wallace, A., and A. A. Bedri. 1958. Fe and Zn foliage sprays. California Agr. 12(3):8.

[4]Wallace, A. 1971. Mineral composition of macadamia leaves. *In* Wallace, A., Ed., Regulation of the micronutrient status of plants by chelating agents and other factors. Univ. California, Los Angeles, page 189.

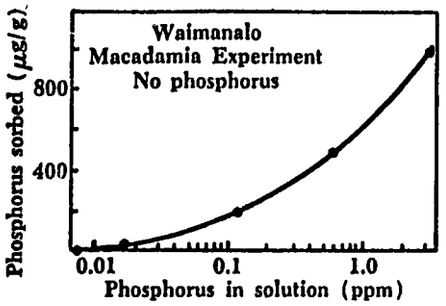


FIGURE 4. Phosphorus adsorbed and phosphorus remaining in solution 6 days after adding phosphate to soil from Waimanalo "no phosphorus" trees. The soil was shaken twice daily in 0.01 M $CaCl_2$

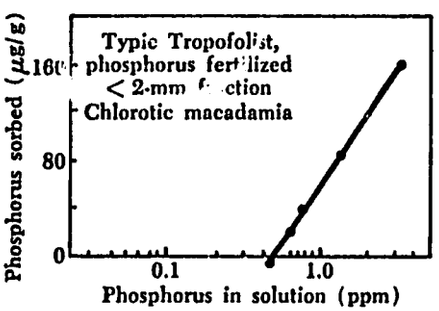
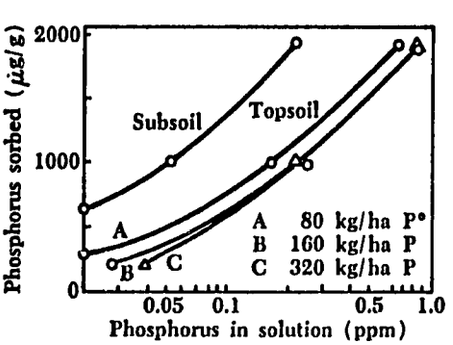


FIGURE 5. A phosphate sorption curve for the < 2-mm fraction of *aa* rock land soil. The tree had been heavily phosphate fertilized and was chlorotic. Phosphate in solution with no phosphorus added was about 0.5 ppm which is 5 to 10 times the concentration which is optimum for corn in other soils.



*Kilograms per hectare approximates pounds per acre.

FIGURE 6. Phosphate adsorption by Honokaa surface soil, which had previously been phosphate fertilized, and by Honokaa subsoil. The Honokaa soil is highly buffered against changes in phosphate concentration. It will not be readily overfertilized because it adsorbs so much phosphate.

Deficiency in Macadamia

(continued from page 3)

much more soluble (available to plants) from soil B.

Actual phosphate sorption curves for soils from 3 macadamia orchards are presented in Figures 4–6. The Waimanalo location, which was moderately phosphate deficient as indicated by depressed nut production when phosphate was withheld, equilibrated at less than 0.01 ppm P in solution (Figure 4). The relationships between phosphate added, phosphate in solution (predicted from the sorption curve based on area fertilized), yield, and tree condition are summarized in Table 2.

These observations agree with foliar symptoms and the phosphate solubility in soil material from rock land. An example is the phosphate sorption curve for soil growing a chlorotic tree (Figure 5). Note that at zero phosphate adsorbed (the soil as sampled) the soil equilibrated at about 0.5 ppm P in solution.

The Honokaa soil which developed from weathered volcanic ash adsorbed much more phosphate (Figure 6). There is less likelihood that this soil will be overfertilized with phosphate.

RECOMMENDATIONS

Based on the above observations the following generalizations seem justified:

1. Phosphate fertilizer rates should be based on good soil information. This should include information on the solubility of phosphate in relation to amounts of fertilizer applied. As a first approximation the limits for P in the soil solution should be 0.05 to 0.1 ppm.
2. The initial high phosphate rates required for young trees growing on new land (or land which is initially very phosphate deficient) probably can be scaled down in later years.
3. Use both foliar analyses and soil tests to check the adequacy of the fertilizer program. It is probable that optimum leaf P is in the range 0.065 to 0.070%, which is a compromise between P required for maximum growth and acceptable micronutrient nutrition.
4. Put little or no faith in foliar analyses for iron. Analytical data may be accurate but interpretation is difficult.
5. If chlorosis has already developed due to excess phosphate, drastically reduce or eliminate phosphate from the fertilizer. Chlorotic trees at Waimanalo have gradually returned to normal color over a period of 3 to 4 years after heavy phosphate fertilization was terminated.
6. Check on the balance of several micronutrients. Sometimes what was a borderline deficiency of iron becomes a serious problem if unneeded copper or zinc is added, for example.

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TABLE 2. Relationships between phosphate added, phosphate in solution (predicted), nut yields, and condition of macadamia trees

	Tree condition				
Factor	Green, phosphorus deficient	Green	Green	Chlorotic	Severe chlorosis, wind damage
Phosphorus added (pounds/tree/year)	0	2	4	8	16
Yield (g/cm^2 of tree trunk)	46	67	65	67	26
Phosphorus in solution (predicted ppm)	.007	.04	.15	.6	3.7