INCREASED PHOSPHORUS UPTAKE BY RADIATA PINE IN RIVERHEAD FOREST FOLLOWING SUPER-PHOSPHATE APPLICATIONS

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SYNOPSIS

One ton of superphosphate per acre applied to phosphate-deficient stands in Riverhead Forest resulted in higher concentrations of P in the foliage, bark, and sapwood. In the living bark, levels of N, K, and Mg also increased. Eight years after treatment the rejuvenated stand and litter layer contained an estimated extra 25 to 30 lb per acre of P (equivalent to 2½ to 3 cwt of superphosphate).

Severely checked stands in this forest that are markedly deficient in phosphorus appear to require between a half and one ton of superphosphate per acre to enable them to make vigorous growth. Smaller amounts are probably sufficient where stands have not degenerated to the stage of dead tops and greatly reduced canopy.

The foliage P content of radiata pine is a good indicator of the adequacy of the P supply. Analyses of samples from a number of forests show that the critical level is about 0.11% of the oven-dry weight.

INTRODUCTION

Infertile "gumland" soils occur in a number of forests in the northern part of the North Island, New Zealand. Plantations of radiata pine (*Pinus radiata* D.Don) on these soils are usually healthy for the first few years, but in many areas tree vigour deteriorates rapidly between ages five and ten years. Affected trees are characteristically narrow-crowned with sparse foliage and, in severe cases, dead tops. These symptoms are similar to those induced in Australia by phosphorus deficiency (Stoate, 1950). In 1952, fertilizer trials were established in Riverhead Forest and it was shown that stands which had stagnated could be rejuvenated by 1 ton of superphosphate per acre (Weston, 1956). Since then similar responses to superphosphate have been obtained in other forests.

Soon after the excellent response to 1 ton of superphosphate became noticeable at Riverhead Forest, further trials were carried out in which different amounts of superphosphate per acre were distributed from aircraft. Again responses were excellent and it is now standard practice (based on these results) to apply 5 cwt of superphosphate per acre from the air to all forests as soon as there is evidence that a shortage of P is limiting growth (Conway, 1962). Application at this rate has given good results so far, but the optimum rates for plantations of different ages and on different soil types, and the necessary frequency of application, have not yet been determined.

Foliage analysis has been found useful for determining the adequacy of nutrient supplies to many types of plants, including forest trees. Critical foliage levels of P below which growth is adversely

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affected have been established for several species of pines — *e.g.*, loblolly and Virginia pines 0.10% P (Fowells and Krauss, 1959), and Scots pine 0.10% P (Ingestad, 1960). In other studies it has been shown that certain levels indicate an adequate supply — *e.g.*, Corsican pine 0.15% P (Leyton, 1958), slash pine 0.11% P (Mergen and Voigt, 1960). It seems that 0.13% P in the foliage of most species of pine indicates an adequate supply while 0.09% P or less indicates that phosphorus is a limiting factor.

Will (1961) found that these general levels held good for radiata pine seedlings, and stated in the same paper that he had found levels in adult trees to be in the same range. The present paper gives details of the foliage analyses of the trees referred to.

The effects of phosphates on the growth of pines in the field have been reported in some of the papers already referred to. Further trials have been carried out — by Young (1948), Richards (1956), Pritchett and Swinford (1961), Brockwell and Ludbrook (1962) and Binns (1962). These studies did not consider the uptake of P following the application of fertilizers or the efficiency of utilization of the P applied in the fertilizer, questions which are discussed below.

METHODS

General Approach: Five aspects of phosphorus uptake by trees were studied: (1) To determine the relationship between tree vigour and the P content of foliage, and to provide a standard by which to evaluate the P levels found in the samples from Riverhead Forest, needle samples for analysis were taken from radiata pine growing on a wide range of soil types in many New Zealand forests. (2) Changes in the level of P in the foliage of individual trees and of plots in Riverhead Forest were followed after the application of superphosphate. (3) and (4) In a limited number of trees, changes in the P content of bark and wood were studied to allow (5) an estimate to be made of the increased amount of P contained in a stand that had been rejuvenated by the application of 1 ton of superphosphate per acre.

Foliage Sampling: As the mineral-nutrient content of radiata pine foliage is affected by age and position in the tree crown (Will, 1957), the following standard procedure was adopted. In December (early summer), samples of full-length needles were collected from shoots that had developed during spring growth 3 to 4 months earlier. On young trees (up to about 30 ft in height) only shoots in the upper third of the green crown were sampled, while in older trees the sampling position was usually a little above the mid-point of the green crown. All samples were taken from parts of tree crowns where growth was unrestricted by competition from neighbouring trees. The leader and the ends of strong first-order branches were not sampled.

Sampling of Wood and Bark: Discs were removed from felled trees at breast height and from every fifth internode up the stem. Each disc was divided into (a) heartwood, (b) sapwood formed before fertilizer was applied, (c) sapwood formed after fertilizer had been applied, (d) living bark (phloem) and (e) dead bark.

Chemical Analyses: Methods have been described previously by Will (1961) and by Orman and Will (1960).

RESULTS AND DISCUSSION

1. *Relationship between Tree Vigour and P Content of Foliage*

The vigour of trees from which foliage samples were taken ranged from good to very poor; notes on this are given in Table 1, together with the results of analyses of composite samples (at least five trees per sample). As there is no evidence to suggest that poor tree vigour was related to anything other than P deficiency, it seems that foliage P content is a good indicator of the P supply. The critical level of P in the foliage, below which tree vigour is restricted, is about 0.11%. This agrees well with the results obtained from seedlings (Will, 1961) and is in the range found for pines by other workers.

TABLE 1: THE P CONTENT (% O.D. WT) OF RADIATA PINE NEEDLES IN RELATION TO TREE VIGOUR IN VARIOUS FORESTS
(Needle samples composites of at least five trees)

Forest	*Vigour of Trees*	*P Content of Foliage*
Nelson district	good	0.20
Kaingaroa	good	0.14
Woodhill	good	0.14
Riverhead	good	0.13
Tairua	good	0.12
Maramarua	good	0.12
Waitangi	fair–good	0.11
Tairua	poor	0.08
Riverhead	poor	0.07
Maramarua	poor	0.07
Riverhead	very poor	0.05

2. *Effect of Fertilizer on P Content of Foliage — Riverhead Forest*

As reported by Weston (1956), a series of plots was established in 1952 in parts of Riverhead Forest where tree vigour was very poor. Some were treated with 1 ton per acre of superphosphate; others were kept as controls. The vigour in the treated plots improved spectacularly. From 1955 to 1961 foliage samples were collected from two representative sample trees — one in a control plot (A 90C) and one in the adjacent superphosphate plot (A 90). The results of P analyses of these samples are given in Table 2.

TABLE 2: FOLIAGE LEVELS OF P (% O.D. WT) IN TWO PLOTS, COMPT. 11, RIVERHEAD FOREST

	1955	*1957*	*1958*	*1959*	*1960*	*1961*
Control	0.06	0.08	0.08	0.07	0.05	0.07
Super. 1 ton/ac, 1952	0.14	0.19	0.15	0.15	0.13	0.16

Although there have been variations from year to year in both trees, the figures indicate that there has been a continuous deficiency in the control plot, while in the treated plot the supply has been adequate throughout.

In 1955, further trial plots were established in severely checked stands. In one series, superphosphate was applied at two rates — 4 cwt per acre and 1 ton per acre. The results of foliage analyses carried out annually on the same individual trees are given in Table 3.

TABLE 3: FOLIAGE LEVELS OF P (% O.D. WT) IN THREE PLOTS COMPT. 1, RIVERHEAD FOREST

	*1955**	*1957*	*1958*	*1959*	*1960*	*1961*
Control	0.08	0.10	0.10	0.09	0.09	0.10
Super 4 cwt/ac, 1955	0.10	0.18	0.10	0.11	0.10	0.12
Super. 1 ton/ac, 1955	†	†	0.15	0.14	0.14	0.16

* before treatment † not sampled

In a second series, superphosphate was applied at three rates — 2 cwt per acre, 4 cwt per acre, and 1 ton per acre. The results of analyses of composite foliage samples taken in 1960 are given in Table 4.

TABLE 4: FOLIAGE LEVELS OF P (% O.D. WT) IN PLOTS TOPDRESSED WITH SUPERPHOSPHATE, COMPT. 8, RIVERHEAD FOREST

Treatment (1955)	*Sampled 1960*
Control (2 plots)	0.09 0.095
2 cwt per ac (2 plots)	0.095, 0.09
4 cwt per ac (1 plot)	0.10
1 ton per ac (1 plot)	0.16

It appears from these foliage analyses that, five years after treatment, 1 ton per acre of superphosphate is providing a more than adequate source of P, while after the same period 2 cwt per acre is having no effect. Four hundredweight per acre was sufficient to give an adequate supply for two years but thereafter the supply has been barely sufficient. From the 1952 trials, Weston (1956) found that needle colour and length improved within a year after the application of 1 ton of superphosphate (per acre), but that it took at least three years for seriously P deficient stands to resume normal growth; they needed this period of time to redevelop a canopy. It would appear from the figures in Table 3 that, at the site of these plots, 4 cwt per acre was initially sufficient to provide an adequate amount of P but that, during the period of increasing canopy and resumption of normal growth rate, the supply became marginal and little better than that present in the control plots.

As mentioned earlier, young trees grow well on many sites for several years before showing deficiency symptoms and reduced growth rates. Apparently the P supply is adequate at first and then decreases — possibly when the available rooting space has been fully exploited. The decrease in the availability of P is illustrated by some young volunteer trees growing on a firebreak adjacent to the plots of Table 4. In 1959, the trees were about 5 to

7 ft high and healthy in appearance; the P content of the foliage was 0.12%. In 1960, the content was 0.09% P and in 1961, 0.08% P. This decrease was paralleled by a deterioration in tree vigour.

In December, 1960, it was decided to fell trees for stem analyses in both control and treated (1 ton per acre) plots of the original 1952 series. To ensure that the stocking of these 1/10 acre plots was not materially altered, felling was restricted to one tree in each of three treated and three control plots. Foliage was collected from the upper and mid-portions of each tree crown. The results are given in Table 5; the P content is well above the critical level

TABLE 5: COMPOSITION OF FOLIAGE FROM SIX TREES FELLED DECEMBER, 1960

	Crown Position	*Percentage of Oven-dry Weight*				
		N	*P*	*K*	*Ca*	*Mg*
TREES FROM TREATED PLOTS						
Tree 1	mid third	1.39	0.15	0.93	0.10	0.11
	top third	1.84	0.16	0.80	0.12	0.17
Tree 3	mid third	1.16	0.11	0.84	0.18	0.20
	top third	1.67	0.11	0.95	0.12	0.19
Tree 4	mid third	1.21	0.10	0.94	0.08	0.16
	top third	1.32	0.11	1.10	0.13	0.15
TREES FROM CONTROL PLOTS						
Tree 2	mid third	0.99	0.08	0.79	0.13	0.20
	top third	0.92	0.06	1.32	0.10	0.18
Tree 5	mid third	1.12	0.09	1.05	0.14	0.10
	top third	1.49	0.10	1.00	0.15	0.15
Tree 6	mid third	1.41	0.08	1.05	0.11	0.12
	top third	1.60	0.09	1.10	0.11	0.14

in tree 1, but in the other two trees from treated plots it is on the border line. In all three trees from control plots the levels are in the deficiency range. Concentrations of potassium and magnesium are well above the critical levels (about 0.4% for K and 0.11% for Mg) in all trees. On the other hand, nitrogen levels for the whole crown in trees 2 and 4 are lower than the critical level of about 1.5% N (Will, 1961). The indications are that the area is to some extent deficient in N.

3. *Effect of Fertilizer on P Content of Bark*

For each of the six trees mentioned above, a composite sample of living bark and another of dead bark were obtained by mixing bark from the sample discs. (Weight per unit area and area of stem surface represented by each disc were used to fix the proportions.) The results of analyses of these samples are given in Table 6.

It can be seen that there are some differences between the treated and control trees in the composition of dead bark, but much greater differences in the composition of the living bark. Since only three trees were taken from each treatment, normal statistical methods cannot be applied to show differences between them. Nevertheless, the fact that all treated trees have higher concentrations of N, P, K, and Mg in the living bark than any of the control trees indicates that there is, over all, a higher nutrient content in the treated trees. This is particularly true of N and P, for the difference between the two groups of three is much greater than the variation within the groups. It should be noted that, in contrast with these results, higher levels of N, K, and Mg are not found in the foliage of phosphate-treated trees. The Ca level in the bark of treated trees is similar to that in the controls.

TABLE 6: COMPOSITION OF BARK FROM SIX TREES FELLED DECEMBER, 1960

	Percentage of Oven-dry Weight				
	N	*P*	*K*	*Ca*	*Mg*
LIVING BARK					
Treated trees:					
1	0.76	0.17	0.88	0.42	0.25
3	1.01	0.19	1.06	0.61	0.24
4	1.01	0.15	1.04	0.54	0.24
Control Trees:					
2	0.26	0.04	0.55	0.48	0.20
5	0.33	0.06	0.70	0.80	0.15
6	0.36	0.05	0.58	0.58	0.14
DEAD BARK					
Treated trees:					
1	0.29	0.07	0.30	0.29	0.16
3	0.24	0.05	0.27	0.26	0.17
4	0.22	0.03	0.11	0.24	0.05
Control Trees:					
2	0.19	0.03	0.17	0.32	0.16
5	0.21	0.01	0.09	0.24	0.06
6	0.21	0.03	0.10	0.28	0.06

The difference between treated and control trees in average P content of living bark is greater than the corresponding difference in average P content of foliage. This suggests that bark analysis may be as good as, if not better than, foliage analysis in detecting trees affected by P deficiency. However, before bark analysis can be adopted as a diagnostic method, variations in P content with season and position on a tree must be studied. Also it must be noted that the results in Table 6 suggest that, while it may be possible to follow by this method the correction or development of a known deficiency, it would not be possible to diagnose with certainty an unknown deficiency.

4. *Effect of Fertilizer on P Content of Wood*

Composite samples of wood from the heartwood, old sapwood (formed prior to 1952), and new sapwood zones of each tree were obtained from the cross-section discs. The only consistent difference in nutrient content was in P content and then only in the new sapwood — see Table 7. Even in the treated trees the P content is lower than that found in the wood of trees growing on pumice soils (Orman and Will, 1960).

TABLE 7: PHOSPHORUS CONTENT (mg per 100 g) OF WOOD FROM SIX TREES FELLED DECEMBER, 1960

	Treated Trees			*Control Trees*		
Heartwood	1.0	0.6	0.8	0.8	0.4	0.7
Old sapwood	2.1	2.1	2.0	1.7	1.8	2.0
New sapwood	4.8	6.0	4.7	3.0	3.3	2.8

The increase in P content of sapwood brought about by the use of fertilizers suggests that analysis of wood for P may be a means of assessing the P supply. To test this, the last two rings (one was incomplete when the trees were felled) from the breast-height discs of the six trees were analysed. Results were:

Treated trees .... 10.9, 5.6, 6.7 mg per 100 g
Control trees .... 6.1, 5.7, 3.4 mg per 100 g

The fastest growing of the treated trees (tree 3) had 5.6 mg per 100 g in the two outer rings. This is lower than the level in two of the control trees, so that at first sight wood analysis is not a promising diagnostic method. However, further work, in which ring volume and concentration gradients over several rings are taken into account, is needed before the method is rejected.

5. *Uptake of Applied P by Tree Crop*

Litter: In untreated stands in Riverhead Forest, so little litter has fallen in recent years that the litter layer is negligible. Between three and six years after the application of phosphate, the litter layer builds up, and when equilibrium is reached would probably contain 10,000 to 12,000 lb of dry matter per acre with a P content of 0.08% (Will, 1964). These are figures for pumice land; if applicable, they would indicate that 8 lb per acre of the P applied in fertilizer has become incorporated in the new litter layer.

Foliage: Needle fall in vigorous stands of radiata pine is about 4,000 lb per acre per annum (Will, 1959) and foliage remains on the tree for an average of three years (Will, 1957). Again, these are figures for pumice land, but there is no reason for believing that figures for other parts of the country would be very different. A reasonable estimate, then, of the dry matter in the foliage of a healthy stand is 12,000 lb per acre. By comparison, deficient stands in Riverhead Forest would have only a few hundred pounds of foliage per acre. Assuming that the average P content of the rejuvenated canopy is 0.11%, there is an extra 13 lb of P in the foliage on each acre of the treated stand.

Bark: The average rise in P content of the living bark after treatment is 0.12% (Table 6), and measurements show that the weight of living bark amounts to about 1,000 lb per acre. Allowing for the greater diameter growth of treated trees, the extra P in the bark amounts to 1½ lb per acre.

Wood: The average increase in volume of the treated trees in the eight years after treatment was 13.9 cu. ft. This represents about 420 lb of dry matter per tree and, at a stocking of about 150 trees per acre, amounts to 63,000 lb per acre. The average P content of the sapwood formed since 1952 in the treated trees is 5.2 mg per 100 g. The total amount of P in this sapwood, then, is 3.3 lb. Similar calculations on the control trees give a total of 0.3 lb of P, so that the extra P contained in the treated stands is 3 lb per acre.

Whole Stands: The figures above indicate that, eight years after the application of 1 ton per acre of superphosphate, a rejuvenated stand in Riverhead Forest contains an extra 25½ lb of P per acre in the litter layer, foliage, bark, and wood. No measurements were made on the branches or roots, but it is not unreasonable to assume that with these parts included the total would probably be about 30 lb of P per acre. As superphosphate contains 9% P, the amount absorbed and remaining in the stand and litter is equivalent to 3 cwt of superphosphate per acre. Russell (1961) concludes that most agricultural crops take up only about 5 to 10% of the P applied in fertilizers. A few may take up 50%, and one exceptional figure of 67% (for elephant grass) has been reported. McConaghy and Stewart (1963), working with radish and ryegrass, have shown that the heavier the application of phosphate, the smaller is the percentage uptake of applied P. The high P recoveries are made by fast-growing crops able to respond quickly to the fertilizer. In contrast, radiata pine responds relatively slowly and is unlikely to be able to take up a high proportion of the added P before it is rendered, at least temporarily, unavailable by fixation in the soil. It seems most unlikely that a stand of radiata pine could take up more than 30% of the applied P in the first few years after treatment. This means that about 10 cwt per acre of superphosphate is needed to supply enough P to rejuvenate stands similar to those studied in Riverhead Forest. But it must be remembered that, in the years immediately following the application of fertilizer and during the period of consequent increased growth, the roots of the trees will be reoccupying soil untapped since the original decline in vigour. There is thus the strong possibility that on many sites this will be followed by penetration of roots into soil never previously occupied. Just how much the phosphorus uptake from these sources will reduce the need for applied phosphate is unknown, but the success of the widely applied 5 cwt per acre indicates that on many sites this amount is sufficient for at least a few years.

As stated by Conway (1962), the frequency of application as well as the optimum rate of application is important. Russell (1961) quotes an example of P deficient soils in which wheat has ceased to respond to P after a total application of 15 to 20 cwt per acre of superphosphate. After an initial period of P fixation, equilibrium is reached in the soil and the fixed P is slowly released. If this release is adequate for the growth of agricultural crops, it should also be adequate for pines, for, once the tree is rejuvenated, the net amount of P immobilized annually is small, being confined to the wood and dead bark. The ability of the pine's mycorrhizae to facilitate the uptake of P should also contribute to the provision of an adequate supply.

This suggests, then, that after, say, two applications of 5 cwt per acre of superphosphate to the first rotation, one further application may be sufficient for a considerable period. Only time will tell but it is a heartening thought!

CONCLUSIONS

The P content of radiata pine foliage gives a good measure of the P supply available to trees. The critical level of P below which tree vigour is restricted is about 0.11% P in foliage of the current season's growth, collected in December (*i.e.*, early summer) from the upper portion of the tree crown.

After superphosphate has been applied to deficient stands, levels of P in the foliage rise markedly. On the sites studied in Riverhead Forest, 1 ton per acre was sufficient to maintain foliage levels above or near the critical level for eight years, 2 cwt per acre was totally inadequate, while 4 cwt per acre allowed foliage levels to return to near the critical level within five years after the phosphate application.

After the application of superphosphate, levels of P also rise in the new sapwood and in the bark. Sapwood and heartwood formed before the application are unaffected.

The levels of N, K, and Mg as well as P in the living bark are significantly greater in trees from plots treated with superphosphate.

Bark and wood analyses show some promise as means of diagnosing deficiencies; more experimental work is needed on both before any definite conclusions can be drawn.

The results of this study, together with data from agricultural experiments, suggest that (a) for severely phosphorus deficient stands ½ ton per acre or more of superphosphate is needed for complete rejuvenation, but (b) for stands that have not seriously deteriorated amounts similar to those being applied on a routine basis are probably sufficient. The need for further applications has yet to be determined but there is some evidence to suggest that, once a total of 15 to 20 cwt per acre of superphosphate has been applied, the need of further applications will have been greatly reduced.

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