POT TRIAL EVALUATION AND COMPARISON OF SIX POTENTIAL SOURCES OF PHOSPHATE FOR FORESTRY

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ABSTRACT

The relative effectiveness of six phosphorus (P) fertilisers for growth of radiata pine seedlings was examined by means of an intensive cropping technique in which three successive crops of pine seedlings were raised, under glass (a) in pots of a P-deficient clay soil without added P fertiliser, and (b) in pots of the same soil, each with one of the six fertilisers applied at a rate equivalent to 120 kg total P per ha, or 1,250 kg superphosphate per ha (10 cwt superphosphate per acre).

The net percentages of applied P recovered from the soil of the various treatments and the order of fertiliser effectiveness based on yields, height growth, P concentration, and P uptake from fertiliser for successive crops were:

(1) dolomite-reverted superphosphate (1 : 1 mixture)	20
(2) superphosphate	15
(3) calcined Christmas Island "C" phosphate ore (Calciphos)	11
(4) spent bone char	8
(5) Christmas Island "C" phosphate ore	4
(6) red phosphorus	2

The trial results suggest that Calciphos, with a higher total P content than superphosphate (about 13% compared with 9%), would be slightly more effective than superphosphate on a fertiliser weight-for-weight basis. This is of particular interest since outlets are sought for the stockpiled "C" phosphate ore, which is unsuitable for superphosphate manufacture.

INTRODUCTION

Weston (1956, 1958) and more recently Mead (1968) found that superphosphate applications greatly improved unthrifty and moribund stands of exotic pines in Riverhead Forest. Subsequently, this forest, which is located 20 miles north of Auckland, has been extensively topdressed with superphosphate in an effort to obtain more even growth and productivity. With every prospect of continuing and increasing usage of phosphate fertilisers in this and other forests, it was decided to compare several other fertilisers with superphosphate to discover whether they could be considered as acceptable alternatives. Superphosphate has been widely used in forestry for its effectiveness in correcting P deficiency, its availability in bulk, its suitability for aerial application, and its comparatively low cost. The sulphate content of superphosphate is probably a luxury so far as the trees are concerned. Since much of the phosphate applied to these avidly P-fixing Riverhead Forest soils is inevitably used to saturate the soil sorption complex, a cheaper but nonetheless effective source of phosphate, preferably with a higher P analysis and lower rate of dissolution, would be very acceptable in forestry.

PHOSPHATE SOURCES

The six P sources which were selected for trial were:

1. Superphosphate

A typical Nauru superphosphate has the following basic composition:

		%
$Ca(H_2PO_4)_2.\ H_2O$	(primary calcium orthophosphate	33
H_3PO_4	(phosphoric acid)	3
$CaHPO_4.\ 2H_2O$	(secondary calcium orthophosphate)	2
Residual phosphate rock (apatite)		3
$CaSO_4$	(anhydrite)	49
Moisture (and other water of hydration)		10

The primary orthophosphate and free phosphoric acid are readily soluble in water giving a very acid solution whereas the secondary orthophosphate and residual apatite are only slightly soluble. Superphosphate has been used to good effect over much of Riverhead Forest and was used in this experiment as a yardstick with which to compare the effectiveness of the other fertilisers.

2. Dolomite-Reverted Superphosphate (1 : 1)

The process of reversion with dolomite involves the conversion of the more soluble primary calcium orthophosphate to the much-less-soluble secondary calcium and magnesium orthophosphates. This conversion renders the phosphate less prone to rapid fixation through double decomposition with iron and aluminium compounds in the soil. Dolomite, which is an approximately equimolecular mixture of calcium and magnesium carbonates, also assists in maintaining high soil levels of calcium and magnesium whilst retarding acidification of the soil. The work of Mulder (1952) has shown that magnesium is important in the phosphate transport mechanism of plants; it is thought that magnesium also assists P uptake from the soil in some way.

3. Christmas Island "C" Phosphate Ore

The Christmas Island phosphate reserves, which amount to some 200 million tons, are jointly owned by Australia and New Zealand. Tyrer (1968) gives a comprehensive account of the island industry from its early beginnings to 1968. The reserves fall into three categories: (1) the "A" phosphate, which is predominantly hydroxy- and fluor-apatite, a tertiary calcium phosphate used in the manufacture of superphosphate, (2) the "C" phosphate which is a mixture of the clay-like overburden of iron-alumino phosphate minerals (crandallite, millisite, and barrandite with apatite and hydrated iron oxide (goethite) and (3) the "B" phosphate which is, in effect, a mixture of "A" and "C" ores.

In order to mine the "A" ore considerable quantities of the "B" and "C" phosphates have to be shifted and stockpiled elsewhere.

As the "C" ore overburden makes up about half the total amount of the estimated phosphate reserve, suitable commercial outlets are keenly sought for this material. Although the phosphorus content of this ore ranges from 11% to 15%, it is not readily available to most crops since it is largely bonded to iron and aluminium.

4. *Calcined Christmas Island "C" Phosphate Ore*

When the "C" phosphate ore is calcined at a comparatively low temperature (*ca.* 450°C) for about half an hour the mineral lattice alters in such a way that the ammonium citrate solubility of the phosphate (an index of plant availability) is greatly enhanced (Doak *et al., 1965*). This calcined ore is registered in New Zealand as Calciphos by the Christmas Island Phosphate Commission.

5. *Spent Bone Char*

The high P content (16%), low cost, and ready, if limited, supplies of this by-product from the New Zealand sugar industry were the reasons for including this fertiliser in the trial.

6. *Red Phosphate*

Since the rotation period for exotic pine crops is normally 25-30 years, phosphate fertiliser used to correct phosphate deficient forest soils should ideally provide the tree crop with a sustained, slow but steady supply of phosphate for as much of this period as possible. Other criteria for a sound forestry fertiliser are availability of bulk supplies, suitability for large scale application from the air, and economical price.

Rothbaum (1966) has focussed attention on the feasibility of using red phosphorus as an agricultural fertiliser and has discussed its prospects at some length. Red phosphorus is a rather expensive commodity, since the small scale batch production employed is only sufficient to meet the limited present-day demands. More efficient methods of larger scale production, according to Rothbaum, might well bring about a reduction in cost which could enable red phosphorus to compete in price per unit P with superphosphate.

It was decided to use a pot trial to evaluate these P sources, for the following reasons:

(1) Factors contributing to variability in results are more easily controlled in glass-house pot trials than in field experiments; a much higher experimental error is usual in field trials.

(2) By restricting roots to a limited volume of soil the plants can be made more dependent upon added P fertiliser as a source of P. By this means, differences in P-supplying power can be amplified and more subtle differences detected.

(3) Growth differences in fast-growing seedlings are more pronounced than in mature plants or trees. This allows more facile measurements and recognition of the responses.

(4) If differences are not detectable in the pot trial then comparisons under the more variable field conditions are probably not worth while. Conversely, further experiments in the field are probably justified if noteworthy differences between treatments are shown in the glasshouse experiment.

METHODS

1. *Soil Sampling*

Topsoil was collected from a site adjacent to the untreated control plot A90c of a fertiliser trial established in 1952 in Cpt 11 of Riverhead Forest. The soil, a brown granular clay, was sampled to a depth of about 30 cm (12 in.) after removal of the surface litter and humus. The soil type was tentatively identified as Parau clay (NZ Soil Bureau, 1954). This is derived from parent material consisting of a conglomerate of andesitic tuff and sediments.

The magnitude of the response of unthrifty trees on this site to a 2,500 kg/ha (20 cwt/acre) dressing of superphosphate applied in 1952, can be judged from the following unpublished Forest Research Institute data for the year 1969:

Total increments for 1962-1969 period

	Mean height increment	Mean basal area increment per tree
Untreated control plot	97 cm (3 ft)	112 cm^2 (0.12 sq ft)
Superphosphate treated plot (A90)	335 cm (11 ft)	336 cm^2 (0.36 sq ft)

The soil collected was air dried, thoroughly mixed, and broken down to a manageable tilth for the pot trial. Twenty-four plastic flower pots, with the basal drainage holes securely plugged with rubber bungs, were each filled with 4.7 kg (10.4lb) of the air-dried soil after a little perlite had first been placed in the bottom to improve soil drainage.

2. *Experimental Design*

The pots were sorted into eight groups of three to afford three replicates for each treatment. The pots, after establishment of the trial, were frequently reshuffled to obviate microclimate effects in the glasshouse.

3. *Treatments*

The eight treatments were:

(1) Control A: plus basal dressing of N, K, Mg
(2) Control B: no basal dressing of N, K, Mg
(3) Superphosphate (ordinary)
(4) Dolomite*-reverted superphosphate (1 : 1 mixture)
(5) Christmas I. "C" phosphate ore† (97% passing 100 mesh B.S.S.)
(6) Calcined Christmas I. "C" phosphate ore‡
(7) Spent bone char
(8) Red phosphorus§ screened to pass through 100 mesh B.S.S.

(3)–(8): All received basal dressings of N, K, Mg four months after establishment of second crop

* "Calmag" dolomite: formula given as 36-41% $MgCO_3$ 58-63% $CaCO_3$, 70-75% passing 150 mesh B.S.S. The reverted superphosphate was prepared from equal weights of normal superphosphate and dolomite which were intimately mixed and then allowed to interact during a brief period of storage.

† Sample taken from a ton shipment brought to New Zealand for investigation by the Christmas Island Phosphate Commission in 1962.

‡ The "C" phosphate ore was calcined at 450°C for 30 min in an electric muffle furnace in the laboratory. The time and temperature were those recommended by the New Zealand Fertiliser Manufacturers' Research Association (Inc.), Otara. See p. 24, section 4.

§ The red phosphorus was shaken with 5% NaOH before use to extract traces of the alkali-soluble yellow allotrope which is phytotoxic.

4. *Rates, Frequency, and Mode of Application*

(1) *Rates of Application*

The various P sources were all applied at rates equivalent in total P content to 1,250 kg superphosphate per hectare (10 cwt per acre) as shown in Table 1.

TABLE 1—Rates of application

	Total P content %	Weight per pot (= 0.54 g P) g
Superphosphate	9.0	6.0
Dolomite-reverted superphosphate (1 : 1 mixture)	4.5	12.0 (7.1 + 4.9)
Christmas Island "C" phosphate ore	11.0	4.9
Calcined Christmas Island "C" phosphate ore	12.8	4.2
Spent bone char	16.0	3.4
Red phosphorus	100.0	0.54

(2) *Time of Application*

The various P fertilisers, with the exception of the dolomite-reverted superphosphate, were applied as a single dressing shortly before planting. A second application of the dolomite-reverted superphosphate had to be applied 2 months later when it was found that the compounded fertiliser contained less superphosphate than was previously believed.

(3) *Mode of Application*

The fertilisers were applied by layering (banding) them at a depth of about 5 cm (2 in.) in the appropriate numbered pots. A basal dressing of supplemental nutrients (nitrogen, potassium, and magnesium) was applied to the second crop of seedlings once they had become established, i.e., approximately 2 months after germination. This basal dressing was applied to all treatments, except one series of control replicates, to ensure that sufficient nutrients other than P were available.

5. *Establishment and Crop Culture Conditions*

Three annual crops of *Pinus radiata* seedlings were grown in each pot. These grew for the following periods:

First crop: August 1963 until May 1964 inclusive (10 months)
Second crop: October 1964 until June 1965 inclusive (9 months)
Third crop: Mid-November 1965 until mid-November 1966 inclusive (12 months).

To establish the first crop, eight seedlings were transplanted from perlite into each pot. These were later thinned to six after they had become established.

The second and third crops were raised from seed in the pots themselves. Eight seedlings were grown in each pot after early thinning. Some variation from this number occurred because some plants died of fungal infection.

The first and second crops were raised in an unheated glasshouse. The third crop, because facilities were reorganised, was transferred to a temperature-regulated glass-house (18°C) for the last 6 months of growth before harvest.

All pots were surface watered to weight several times a week with deionised water to maintain the soil moisture content at about two-thirds of field capacity. Heights were measured at intervals and prior to harvesting. After harvesting, seedlings were divided into needles, stems, and roots. Dry weights of these components were determined for each pot.

6. *Analysis of Plant Material*

After grinding in a Thomas-Wiley mill (model ED-5) the dried plant samples were analysed for N, P, K, Mg, and Ca. The final crop was analysed for P, Ca, and Mg content only.

The methods of analysis used for the various nutrients were as follows:

N: micro-Kjeldahl method (Metson, 1956)

P: Vanadomolybdo-phosphoric yellow colour method (Jackson, 1958)

K, Na: flame emission photometry

Ca, Mg: atomic absorption flame spectrophotometry (David, 1959; Allan, 1958).

7. *Analysis of Soil*

On conclusion of the trial the soil samples from each pot were analysed for total and available P. The methods were:

Extraction of Available P

(1) Bray No. 2 (Bray & Kurtz, 1945): The combination of 0.03 *N* ammonium fluoride and 0.1 *N* hydrochloric acid is designed to extract the easily acid-soluble forms of P, i.e., mono- and di-calcium orthophosphates, aluminium and iron-bound phosphates as well as phosphate absorbed on the surface of soil particles. Instead of the 1 : 7 soil to extractant ratio originally used by Bray and Kurtz, the 1 : 10 ratio used by a number of subsequent workers, was employed. The soil-extractant mixture was shaken by hand for 1 min. Boric acid was used to eliminate possible interference from fluorides in the colour development (Kurtz, 1942).

(2) Olsen bicarbonate method (Olsen et al., 1954): The extractant used in this method is 0.5 *M* sodium bicarbonate buffered to pH 8.5. Because the concentrations of aluminium, iron, and calcium ions remain at a low level in this extractant, secondary precipitation reactions are minimised. Olsen suggests that the main extractive effect of the bicarbonate on acid and neutral soils is through the replacement of the phosphate absorbed on to the surface of soil particles and the phosphate which is bound by aluminium and iron by HCO_3^-, CO_3^{--} and OH^- ions. Extraction time was 30 min. and the soil to extractant ratio was 1 : 20.

Extraction of Total P

Perchloric acid digestion as described by Tandon *et al.* (1968) was used.

Phosphate Estimation

The phosphate in the above three extracts was determined by development of a molybdenum blue colour by the ascorbic acid method described by Watanabe and Olsen (1965).

RESULTS AND DISCUSSION

Assessment of the trial was made on the basis of (1) height growth, (2) dry matter production, (3) uptake of P from fertiliser applied, (4) foliar P content, and (5) residual available and total P in the soil after intensive cropping.

(1) Effect of Treatments on Seedling Height Growth (see Table 2)

First crop

By the end of the first two months of growth in pots the seedlings of the dolomite-reverted superphosphate and superphosphate treatments were growing faster than the other treatments. From this stage on, however, there was no further increase in the height difference. When the seedlings were harvested no phosphate deficiency symptoms were evident in any of the treatments. Even though the soil used for the pot trial is well known from field trials to be very deficient in available P, it appears that the physical disturbance of the soil and change in environment resulted in increased mobility of the soil phosphate during the first year of the experiment.

The height lead, which the seedlings of the dolomite-reverted superphosphate treatment had earlier established over other treatments, was maintained until harvest. The average seedling heights for all other treatments at time of harvest did not differ appreciably from one another.

Second crop

Height differences between treatments were more marked in the second year of the trial. At time of harvest, all six of the original P treatments resulted in taller seedling crops than those of the controls. The seedlings of the dolomite-reverted superhosphate treatment were again taller than those of any other treatments and more than twice the height of control seedlings. The seedlings grown with superphosphate, calcined "C" phosphate ore, and bone char treatments were of much the same average height, measuring approximately 1.7 times the height of control seedlings (*See* Fig. 1).

Third crop

Again the six different fertilisers applied at the start of the experiment resulted in the growth of seedlings in the six treatments being better than that of the control seedlings to a varying degree. The three best treatments were much on a par with each other as regards seedling height; these were dolomite-reverted superphosphate, superphosphate, and calcined "C" phosphate ore. The seedlings of these treatments were approximately twice as high as the control seedlings. Red phosphorus resulted in the poorest height response while "C" phosphate ore and bone char were intermediate between the best and poorest.

(2) Effect of Treatment on Dry Matter Production (See Table 2)

First crop

The only treatments which yielded appreciably more dry matter in the first year of the experiment were dolomite-reverted superphosphate and superphosphate. These yielded respectively 1.5 and 1.3 times the dry weight of the controls.

Second crop

All six P sources resulted in markedly better yields than those obtained from untreated soil. The yield from the dolomite-reverted superphosphate treatment nearly

FIG. 1—**Pinus radiata** seedlings grown in P-deficient soil treated with one of six phosphorus fertilisers. Second crop of seedlings prior to harvest. 1, control A (plus basal N, K, Mg supplement); 2, superphosphate; 3, Christmas Island "C" phosphate ore; 4, calcined Christmas Island "C" phosphate ore; 5, red phosphorus; 6, dolomite-reverted superphosphate (1 : 1 mixture); 7, spent bone char; 8, control B (no basal N, K, Mg supplement).

TABLE 2—Mean seedling height and dry matter production data for successive crops of each treatment

Treatment	Seedling height Mean and S.D. (cm)		
	1st crop	2nd crop	3rd crop
Dolomite-reverted superphosphate (1 : 1 mixture)	42.8 ± 3.3	36.8 ± 2.4	30.4 ± 1.4
Superphosphate	38.9 ± 2.1	29.0 ± 2.7	27.9 ± 3.0
Calcined Christmas Island "C" phosphate ore	36.8 ± 0.8	32.1 ± 0.7	29.5 ± 1.2
Spent bone char	38.2 ± 4.4	28.7 ± 1.4	22.4 ± 4.0
Christmas Island "C" phosphate ore	38.2 ± 3.1	28.8 ± 1.1	20.3 ± 2.2
Red phosphorus	39.5 ± 2.9	21.1 ± 1.5	20.0 ± 0.6
Control A (plus basal N. K, Mg dressing)	36.4 ± 2.0	17.3 ± 1.0	15.5 ± 1.3
Control B (no basal N, K, Mg dressing)	38.2 ± 4.4	16.7 ± 1.9	14.6 ± 1.9

trebled that of the controls, while those of the superphosphate, calcined "C" phosphate ore, spent bone char, and "C" phosphate ore all doubled the control yields. Red phosphorus resulted in a less spectacular improvement in yield.

Third crop

Yields from five of the six P treatments were again substantially better than those of the controls though differences from the controls were less marked than in the previous year. The yields from the dolomite-reverted superphosphate, superphosphate, and calcined "C" phosphate ore, were much the same, amounting to approximately twice that of the controls. The spent bone char and "C" phosphate ore treatments yielded between 1.6 and 1.8 times the mean dry matter production for the controls. The red phosphorus treatment was once more the least effective with about 1.5 times the dry matter yielded by the controls.

(3) Uptake of P from Fertilisers (See Table 3)

To derive these data it has been assumed that the difference between the amount of P taken up by seedlings grown with a particular phosphorus fertiliser and that taken up by control seedlings represents the uptake from the fertiliser.

The three crops of control seedlings extracted on average 0.05g P from 4.7 kg air-dry soil, i.e., *ca.* 22 kg P/ha (*ca.* 20 lb P/acre).

Although the uptake of P by successive crops from both reverted superphosphate and superphosphate was consistently higher than from calcined "C" phosphate ore, the latter fertiliser has the compensating advantage of a substantially higher total P content —about 12.8% compared with 4.5% and 9% respectively.

In this trial, differing weights of the individual P fertilisers were applied to furnish each pot with an identical weight of P (0.54 g per pot). Table 4, however, gives some assessment of the relative efficiency of the fertiliser on a weight for weight basis.

TABLE 2 (continued)

Dry matter weight per pot Mean and S.D. (g)			Weight per 3 pots Cumulative totals (g)		
1st crop	2nd crop	3rd crop	1st crop	1st & 2nd crops	1st, 2nd & 3rd crops
61.6 ± 8.6	43.4 ± 3.5	25.8 ± 2.5	185	325	402
52.6 ± 5.6	38.8 ± 5.9	25.5 ± 0.0	158	274	361
44.3 ± 1.1	39.2 ± 4.0	25.3 ± 2.6	133	234	320
44.4 ± 3.8	37.0 ± 5.3	18.6 ± 0.1	133	244	311
43.7 ± 1.7	31.4 ± 1.2	20.7 ± 2.4	131	225	298
41.0 ± 3.9	21.6 ± 4.8	17.3 ± 0.8	123	188	244
40.4 ± 4.0	14.9 ± 1.2	10.5 ± 1.5	121	167	201
42.4 ± 7.3	16.7 ± 3.4	12.5 ± 2.5	127	177	223

TABLE 3—Uptake of fertiliser

	Average P uptake from fertiliser (g/pot)				Percentage of applied P utilised			
	1st crop	2nd crop	3rd crop	Cumulative total	1st crop	2nd crop	3rd crop	Total
Dolomite-reverted superphosphate (1 : 1 mixture)	0.048	0.029	0.028	0.105	8.9	5.4	5.2	19.5
Superphosphate	0.028	0.026	0.027	0.081	5.2	4.8	5.0	15.0
Calcined Christmas Island "C" phosphate ore	0.016	0.023	0.021	0.060	3.0	4.3	3.9	11.2
Spent bone char	0.004	0.024	0.015	0.043	0.7	4.5	2.7	7.9
Christmas Island "C" phosphate ore	nil	0.012	0.008	0.020	—	2.2	1.4	3.6
Red phosphorus	nil	0.004	0.005	0.009	—	0.7	1.0	1.7

TABLE 4—Relative effectiveness of fertilisers

Fertiliser	Average weight of applied P taken up by three successive crops of seedlings per gram of P fertiliser g
Red phosphorus	0.018
Calcined Christmas Island "C" phosphate ore	0.014
Superphosphate	0.013
Spent bone char	0.012
Dolomite-reverted superphosphate (1 : 1 mixture)	0.009
Christmas Island "C" phosphate ore	0.004

Although red phosphorus nominally heads the list, this elemental form is most unlikely, for both practical and economic reasons, to be seriously considered for use in undiluted form as a forest fertiliser. More significant is the indication that a given weight of calcined "C" phosphate ore is able to furnish *Pinus radiata* seedlings with slightly more P, over the same period and conditions, than an equal weight of superphosphate.

Since the application of phosphatic fertiliser to P-deficient forests in New Zealand is generally made from aircraft, any such prospective fertiliser must be suitable for aerial application; this implies that it must compete satisfactorily in both cost and efficacy per unit weight with superphosphate.

In forestry, the use of calcined "C" phosphate ore with its higher P content and slower availability of phosphate could well lead to lower distribution costs per unit P as well as longer-lasting action, provided that the chemical properties of the material are not altered by pelletting for aerial distribution.

(4) Foliar P Content

The average values for the various treatments in consecutive crops are shown in Table 5. The values inside the rectangle are well below 0.10% which is generally regarded as indicating an adequate supply of phosphorus for healthy growth of radiata pine seedlings (Will, 1960).

TABLE 5—Percentage of P in foliage of successive crops

	% P Oven-dried needles (mean for replicates)		
	1st crop	2nd crop	3rd crop
Dolomite-reverted superphosphate (1 : 1 mixture)	0.15	0.10	0.16
Superphosphate	0.14	0.09	0.16
Calcined Christmas Island "C" phosphate ore	0.13	0.09	0.13
Spent bone char	0.12	0.10	0.13
Christmas Island "C" phosphate ore	0.10	0.06	0.08
Red phosphorus	0.09	0.07	0.08
Control A (plus basal N, K, Mg dressing)	0.10	0.05	0.06
Control B (no basal N, K, Mg dressing)	0.10	0.07	0.06

At time of harvesting the first crop, the foliar P concentrations for all treatments, with one exception, exceeded this critical value. The foliar P concentration of the red phosphorus treatment was only slightly below 0.10%. Together with the average heights and dry matter production figures for the first crop, this indicates that no marked P deficiency occurred in seedlings of any of the treatments during this first year as a result of increased mobility of the natural soil phosphate caused by soil disturbance and relocation. There is some evidence of luxury uptake from the dolomite-reverted superphosphate and superphosphate treatments.

In the second and third years of the experiment the depressed yields and low foliar P concentration, given by seedlings of the controls, red P, and "C" phosphate ore treatments, indicated that these were suffering from severe P deficiency. The higher foliar concentrations recorded for most treatments in the third year were associated with the longer growing season—12 months as against 9 months for the previous crop—and transference to a temperature-regulated glasshouse (18°C) for the final 6 months' growth.

(5) Residual Available and Total P After Intensive Cropping

Available P

For Riverhead soils, Ballard (1970) found the indices of available P which were most successful for relating site productivity to available soil phosphate were those which employed extraction methods that inhibited resorption during extraction. He found a modified Bray No. 2 test (Bray and Kurtz, 1945) the most suitable for soils that had received fertiliser and the Olsen bicarbonate method (Olsen *et al.,* 1954) the best for those that had not. These two indices were therefore used to assess the content of available P in the pot experiment soils after intensive cropping. It was found that, in this trial too, a Bray No. 2 test carried out at the end of the trial gave the best correlation with preceding growth (*see* Table 6).

Total P

All of the fertiliser-treated soils contained about twice the total P content of the control soil on conclusion of the trial (*see* Table 6).

TABLE 6—Soil analyses for available and total P after three years of intensive cropping (averages of three replicates)

Original treatment	Available P index		Total P Perchloric acid digestion ppm
	Bray No. 2 ppm	Olsen ppm	
Dolomite-reverted superphosphate (1 : 1 mixture)	14.4	16.5	482
Superphosphate	14.4	17.7	491
Calcined Christmas Island "C" phosphate ore	11.2	8.5	520
Spent bone char	7.1	8.2	482
Christmas Island "C" phosphate ore	3.2	3.7	517
Red phosphorus	5.8	5.2	532
Control A (plus basal N, K, Mg dressing)	3.1	2.6	267
Control B (no basal N, K, Mg dressing)	3.1	2.0	285

(6) Crop Foliar Content of Calcium and Magnesium

Table 7 shows that the needles of seedlings grown with dolomite-reverted superphosphate contained consistently higher concentrations of calcium and magnesium than the neeedles from any other treatment, but this appears to be luxury consumption as other studies have shown that foliage levels of 0.2% calcium and 0.08% Mg are consistent with normal healthy growth (Humphreys 1964; Will 1966). The needles of seedlings grown with superphosphate contained more calcium than any except those grown with dolomite-reverted superphosphate.

TABLE 7—Crop foliar contents of calcium and magnesium

Treatment	% Ca			% Mg		
	yr 1	yr 2	yr 3	yr 1	yr 2	yr 3
Dolomite-reverted superphosphate (1 : 1 mixture)	0.23	0.23	0.32	0.16	0.14	0.18
Superphosphate	0.15	0.14	0.16	0.13	0.10	0.12
Calcined Christmas Island "C" phosphate ore	0.12	0.11	0.14	0.12	0.11	0.12
Spent bone char	0.13	0.12	0.15	0.11	0.10	0.13
Christmas Island "C" phosphate ore	0.11	0.10	0.13	0.12	0.10	0.12
Red phosphorus	0.11	0.11	0.12	0.11	0.09	0.11
Control A (plus basal N, K, Mg dressing)	0.11	0.13	0.14	0.13	0.10	0.11
Control B (no basal N, K, Mg dressing)	0.14	0.11	0.11	0.14	0.10	0.11

CONCLUSIONS

The data collated from the pot experiment place the six fertilisers, each of which was applied to an infertile clay soil at Riverhead at a rate equivalent to 1,250 kg superphosphate per hectare (10 cwt/ac), in the following order of effectiveness for *P. radiata* seedlings:

1. Dolomite-reverted superphosphate (1 : 1 mixture).
2. Superphosphate.
3. Calcined Christmas Island "C" phosphate ore.
4. Spent bone char.
5. Christmas Island "C" phosphate ore.
6. Red phosphorus.

The soil used for the experiment, though known to be P deficient in the field, was not grossly deficient in this nutrient in the first year of the trial, due probably to disturbance and change of environment. Three successive crops of seedlings, however, were only able to extract the equivalent of about 22 kg P per hectare (20 lb P per acre) from control pots. Of this amount, about 67% was extracted by the first crop, 20% by the second and 13% by the final.

The fertilisers can be paired according to their rates of release of available P as shown by seedling uptake of P from the six sources.

(a) Dolomite-reverted and ordinary superphosphate: fast initial release resulting in some luxury uptake of P and marked response in seedling growth, even where the soil itself was not grossly P deficient.

(b) Calcined "C" phosphate ore and spent bone char: slower rate of P release sufficient for good response from seedlings growing in otherwise P deficient soil.

(c) "C" phosphate ore and red phosphorus: the very slow rate of release of available P from these sources results in less than optimal response in seedling growth in otherwise P deficient soil; the low foliar P concentrations of seedlings grown with this P source indicate P stress.

It should not be assumed that the conclusions drawn from this pot trial of effectiveness of the various P sources are necessarily valid for field conditions. The glasshouse environment is likely to have modified the soil microflora and fauna population. This could be important because the micro-organisms contribute to phosphate availability through the action of various acids which they secrete; these acids increase the solubility of otherwise virtually insoluble phosphate compounds. Another possibly important factor, excluded from the pot trial, is the effect which forest litter with its dense micro-organism population, might have on the release of surface-applied dressings of the more refractory sources of P such as uncalcined rock phosphate. Also, it is well known that the stage of growth of plants is important in regard to the effects which soluble phosphates exert on them, so considerable caution is needed in translating results obtained with seedlings under a year old to mature trees.

Nevertheless, the pot trial indicates the potential value of the various fertilisers as P sources and serves to underline the need for further field trials, particularly with both calcined and unheated Christmas Island "C" phosphate ores. There is every indication that the calcined "C" phosphate ore could provide an acceptable alternative to superphosphate in forestry, provided that it can be competitively marketed and produced in a form suitable for aerial topdressing, without affecting its desirable characteristics. The uncomplicated processing needed, relatively high P content (*ca.* 13%), accessibility of plentiful resources, as well as its effectiveness and slower availability, are attributes which should assure this fertiliser a place in forestry fertiliser practice. Further field trials are needed to establish the extent to which forest litter can influence the availability of P from the "C" phosphate ore which has not undergone heat treatment.

The effectiveness of spent bone char was about the same as calcined "C" phosphate ore over the period of the pot trial.

Red phosphorus alone is unlikely to prove an acceptable forest fertiliser because of high cost, excessively slow rate of phosphate release and the added hazard which it would present in the event of a forest fire. The use of catalysts to accelerate oxidation and so increase phosphate availability from this source was not investigated.

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REFERENCES

ALLAN, J. E. 1953: Atomic absorption spectrophotometry with special reference to the determination of magnesium. **Analyst 83:** 466-71.

BALLARD, R. 1970: The phosphate status of the soils of Riverhead Forest in relation to growth of radiata pine. **New Zealand Journal of Forestry 15:** 88-99.

BRAY, R. G., and KURTZ, L. T. 1945: Determination of total, organic, and available forms of phosphorus in soils. **Soil Science 59:** 39-45.

DAVID, D. J. 1959: The determination of calcium in plant material by atomic absorption spectrophotometry. **Analyst 84:** 536-45.

DOAK, B. V.; GALLAGHER, P. J.; EVANS, L.; and MULLER, F. D. 1965: Low temperature calcination of "C" grade phosphate from Christmas Island. **New Zealand Journal of Agricultural Research 8:** 15-29.

HUMPHREYS, F. R. 1964: The nutrient status of pine plantations in central New South Wales. **Appita 18:** 111-21.

JACKSON, M. L. 1958: "Soil Chemical Analysis". Prentice-Hall, Englewood Cliffs, N. J. Pp. 171-4.

KURTZ, L. T. 1942: Elimination of fluoride interference in the molybdenum blue reaction. **Industrial and Engineering Chemistry. Analytical Edition 14:** 855.

MEAD, D. J. 1968: A growth study in an aerially topdressed **Pinus radiata** stand at Riverhead Forest. **New Zealand Journal of Forestry 13:** 229-38.

METSON, A. J. 1956: Methods of chemical analysis for soil survey samples. **New Zealand Soil Bureau Bulletin 12.**

MULDER, D. 1952: Nutritional studies on fruit trees. II The relationship between K, Mg, and P in apple leaves. **Plant and Soil 4:** 107.

NZ SOIL BUREAU, 1954: General survey of the soils of North Island, New Zealand. **Soil Bureau Bulletin (n.s.) 5.** 286 pp.

OLSEN, S. R.; COLE, C. V.; WATANABE, F. S., and DEAN, L. A. 1954: Estimation of available phosphorus in soils by extraction with sodium bicarbonate. **United States Department of Agriculture Circular No. 939.** 19pp.

ROTHBAUM, H. P. 1966: Red phosphorus as a possible fertiliser. **Outlook on Agriculture 5:** 123-8.

TANDON, H. L. S.; CESCAS, M. P., and TYNER, E. H. 1968: An acid-free vanadate-molybdate reagent for the determination of total P in soils. **Soil Science Society of America Proceedings 32:** 48-51.

TYRER, T. G. 1968: "This is Christmas the Phosphate Island." Published for the Christmas Island Phosphate Commission by the New Zealand Dairy Exporter, Wellington. 63pp.

WATANABE, F. S., and OLSEN, S. R. 1965: Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soils. **Soil Science Society of America Proceedings 29:** 677-8.

WESTON, G. C. 1956: Fertiliser trials in unthrifty pine plantations at Riverhead Forest. **New Zealand Journal of Forestry 7:** 35-46.

——— 1958: The response of radiata pine to fertilisers. **New Zealand Society of Soil Science Proceedings 3:** 13-9.

WILL, G. M. 1960: The mineral requirements of radiata pine seedlings. **New Zealand Journal of Agricultural Research 4:** 309-27.

——— 1966: Magnesium deficiency: the cause of spring needle-tip chlorosis in young pines on pumice soils. **New Zealand Journal of Forestry 11:** 88-94.