THREE-YEAR RESPONSE OF PINUS RADIATA TO SEVERAL TYPES AND RATES OF PHOSPHORUS FERTILISER ON SOILS OF CONTRASTING PHOSPHORUS RETENTION

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(Received for publication 27 April 1983; revision 26 May 1983)

ABSTRACT

Superphosphate and three types of rock phosphate were applied to phosphorus-deficient young **Pinus radiata** D. Don crops growing on soils of contrasting phosphorus retention. On the soil of medium (50%) retention there were strong responses to the fertiliser after 3 years and the response was in proportion to the citric acid solubility of the material (i.e., superphosphate gave the greatest response – an unreactive aluminium phosphate the least). At the site of high phosphorus retention (92%) no statistically significant differences have yet emerged either between types of fertiliser or between plots with and without fertiliser. At the zero phosphorus-retention site, plots with fertiliser have grown slightly more than those without but no difference between fertiliser types has emerged.

INTRODUCTION

As Will (1981) has shown, 67% of the 1140 tonnes of phosphorus applied in 1980 to New Zealand forests was applied as superphosphate. The remainder was also applied as highly water-soluble compound fertilisers (23% as DAP – diammonium phosphate). None was applied as ground phosphate rock (GPR). Yet the effectiveness of GPR as a source of phosphorus for *P. radiata* has been known in New Zealand (Mead 1974) and Australia (CSIRO 1975) for several years, and it has been used as the main source of phosphorus for forest application in Great Britain and Ireland for some time (Dickson 1971; Mayhead 1976; Binns & Grayson 1967).

The reasons why New Zealand forest management has used superphosphate are complex. Forest owners use less than 1% of the annual consumption of phosphorus fertiliser in a market which is dominated by the agricultural use of superphosphate as a maintenance dressing for grass/clover pasture. Alternatives to superphosphate have not been as readily available. Moreover, a system of applying fertiliser to forests has developed which is more suited to rapidly soluble fertilisers. Soon after planting, young trees receive 150 g superphosphate in a spade slit beside them. Subsequently the crop is monitored by foliage analysis and, as it becomes deficient (i.e., phosphorus content of foliage less than 0.13% of dry weight), superphosphate fertiliser is flown on at rates of approximately 1 tonne/ha. This system is effective as this form of fertiliser allows rapid release of plant-available phosphorus.

Circumstances are changing, however. Superphosphate fertiliser was very cheap owing to Government subsidies, a fairly local supply of rock phosphate, and a low-cost method of manufacture. Latterly, as local supplies became either uneconomic to work or became worked out forcing purchase on the world market, and subsidies were removed, the cost of superphosphate has risen rapidly in real terms. Moreover it has recently been realised that, under the existing system, some tree crops have received cumulatively 500 kg P/ha as fertiliser, approximately 10 times the content of the above-ground biomass of mature, adequately phosphorus-nourished *P. radiata* (Madgwick *et al.* 1977). This apparent inefficiency of utilisation from rapidly soluble fertiliser, and the rise in cost, provided the impetus for further and more detailed investigation of rock phosphate.

This paper reports the first 3 years' results from a series of trials located in young (4- to 7-year-old) *P. radiata* comparing three rock phosphate types with superphosphate, all at equivalent rates of phosphorus. The three trials were deliberately located on soils of contrasting phosphorus retention.

MATERIALS AND METHODS

Site Selection

Having located homogeneous areas of young (4- to 7-year-old) *P. radiata* on soils known to be generally responsive to phosphorus fertiliser, composite soil samples consisting of at least thirty 2-cm-diameter soil cores were collected from the top 0–10 cm and analysed for phosphorus retention (Blakemore *et al.* 1972). As a result of these analyses three areas were chosen: a podzolised sand of very low (0%) phosphorus retention at Waipoua State Forest in North Auckland; a weakly podzolised clay of medium (50%) phosphorus retention at Riverhead State Forest just north of Auckland; an old deeply weathered ash of high (92%) phosphorus retention in Tairua State Forest on the Coromandel Peninsula.

Phosphorus Fertilisers

The three rock phosphates used in the trial (A grade rock, C grade rock, and "citraphos") came from Christmas Island, which lies 320 km south of the Sunda Straits separating Java and Sumatra. The A grade rock is largely apatite and is found at the base of the phosphate deposits on the island. C grade rock is mainly complex aluminium phosphates, crandallite, and millisite, from the surface of the deposit. After calcining at 550°C, C grade rock becomes amorphous and its surface area is increased, greatly increasing its citric acid solubility. The fines from this process are known as "citraphos". All of these rock types would be labelled "unreactive" by agronomists – that is to say, their solubility in the soil would be considered unacceptably slow for crops or pasture.

Superphosphate is rock phosphate acidulated with sulphuric acid. The phosphorus is thereby made largely water soluble and almost entirely citric acid soluble. Currently the rock phosphate used mostly in New Zealand superphosphate manufacture is a 1 : 1 mixture of Christmas Island A grade and Nauru Rock.

Plot Layout and Fertiliser Application

At each site a randomised complete block design with three replications of nine treatments (seven at Waipoua) was laid out. Each plot was 20 × 20 m plus a treated surround of 8 m. Further composite soil samples, encompassing the whole of the eventual area of each trial, were collected from 0–10 and 10–20 cm depths. Each of the four (three at Waipoua) types of phosphorus fertiliser was applied at 75 and 150 kg P/ha rates (i.e., varying amounts of fertiliser depending on the phosphorus content as given by the importer). C grade rock was omitted at Waipoua because of lack of space and material. Fertiliser was applied by hand to the surface in October 1978.

At both Tairua and Riverhead the unthinned, unpruned *P. radiata* trees were 4 years old.

At Waipoua the unthinned, unpruned, 7-year-old *P. radiata* was growing very poorly on a wet, weed-infested site. After phosphorus application, and possibly consequent upon it, growth improved, the site became drier, and nitrogen and potassium deficiency became evident from foliage analysis. This was rectified by an over-all plot application of 200 kg N/ha as urea and 80 kg K/ha as muriate of potash in 1979.

At plot establishment trees in the inner plot were measured for diameter at breast height and a sample of 10 trees per plot was measured for height. Breast height was marked for subsequent measurement and tree were numbered. After 3 years all the tree were remeasurd.

Foliage samples were collected annually in autumn from at least seven dominant trees per plot.

Laboratory Analyses

Soils: Soils were analysed for total nitrogen (Searle 1974), pH, Bray phosphorus (Bray & Kurtz 1945), Bray cations (magnesium, potassium, calcium – Ballard 1978), and phosphorus retention.

Foliage: Foliage samples were dried to constant weight at 60°C then ground. For nitrogen, phosphorus, potassium, calcium, and magnesium, ground samples were digested using sulphuric acid and hydrogen peroxide in the presence of lithium sulphate and selenium (Parkinson & Allen 1975). Nitrogen was determined by the indophenol-blue method and phosphorus by the vanadomolybdate yellow method. Potassium, calcium, and magnesium were determined by atomic absorption (Nicholson, in press).

Fertiliser particle-size analysis: Four 50-g samples of each pelletised rock phosphate were wet sieved after 5 min beating with a rotary beater in 500 ml of water. The stack comprised sieves of 2.0-mm, 1.0-mm, 0.5-mm, 0.15-mm, and 0.104-mm openings. Any aggregates were lightly rubbed through the three coarsest sieves using fingertips and a flow of water. The material remaining on each sieve was transferred to an aluminium dish and dried at 105°C for 16 hours. Oven-dry weights and the percentage of the oven-dry samples they represented were then determined.

Fertiliser phosphorus content: Samples of each fertiliser were passed through a 0.5-mm sieve. Four-gram subsamples underwent six successive extractions with fresh portions of 250 ml of 2% citric acid. Shaking time was 30 min on a wrist-action shaker followed by centrifuging at 3000 r.p.m. for 3 min. An aliquot was then removed for phosphorus determination by the vanadomolybdate yellow method on an auto-analyser.

Analyses and extractions were performed within a temperature range of 21°–26°C.

Statistical methods: An analysis of covariance of basal area in 1981 on basal area in 1978 was made. The control was tested against the average of all the fertiliser plots which were themselves analysed as a factorial in fertiliser types by fertiliser rates. An identical structure was used to analyse foliar phosphorus concentrations in 1979 and 1982.

RESULTS

On all sites the soils were very low in extractable phosphorus and moderately to strongly acid (Table 1). Tairua had, for a forest soil, a high total nitrogen and Waipoua was extremely low.

TABLE 1—Soil chemical analyses at 0–10 cm and 10–20 cm for the three sites

Site	Depth (cm)	Bray P (μg/g)	P retention (%)	Total N (%)	Bray cations (m.e./100 g) Ca	Mg	K	pH
Tairua	0–10	2	93	0.44	1.2	0.7	0.2	5.4
	10–20	1	92	0.31	0.3	0.2	0.1	5.4
Riverhead	0–10	2	48	0.19	2.6	2.7	0.3	4.9
	10–20	1	51	0.15	1.3	2.1	0.2	4.9
Waipoua	0–10	1	0	0.02	0.2	0.6	0.1	4.5
	10–20	1	0	composite 0–20 cm				4.5

Superphosphate was described by the manufacturer as being 10% P and the extraction data (Fig. 1) indicate that that amount was fully available very rapidly. The importer stated (Dr D. J. Udy, pers. comm.) that, allowing for dilution in pelletising, the A grade rock should contain 14.6% P, C grade 10.8% P, and "citraphos" 14.0% P. Using a sodium carbonate fusion method, we obtained from subsamples total phosphorus values that were very close to those for C grade rock, but a lower (11.2%) value for "citraphos". Independent determination on some subsamples by the New Zealand Fertiliser Manufacturers' Research Association Inc. (Dr Laing, pers. comm.) also showed close agreement for A and C grade rock but indicated 11.6% P in "citraphos". It is difficult to explain this apparent discrepancy in "citraphos" concentration. The British Phosphate Commissioners had commissioned a very thorough chemical analysis of the whole batch (Dr D. J. Udy, pers. comm.) and natural variability within the shipment seems unlikely to be large enough to alone explain the difference. There may have been some variation in dilution during the pelletising procedure. However, in interpreting the results of these trials it is important to weigh the consequences of the "citraphos" fertiliser having possibly been applied at lower rates than designed.

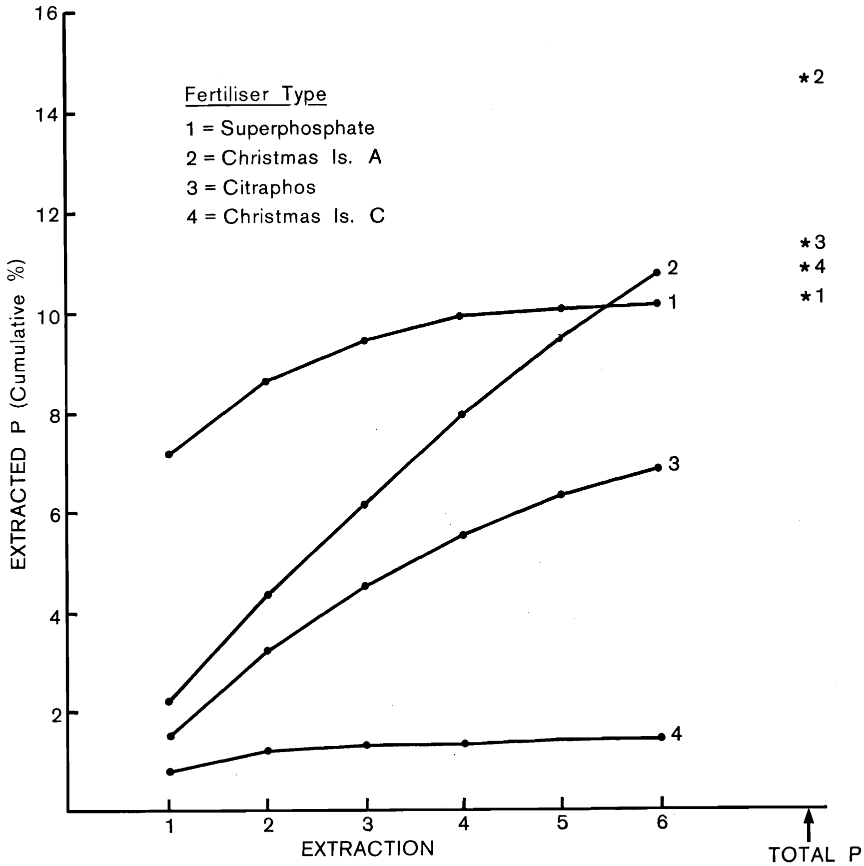

FIG. 1—Cumulative amount of phosphorus extracted from four phosphorus fertilisers by six successive leachings with 2% citric acid.

During the six citric acid extractions the A grade rock displayed gradual and continual release of up to 70% of total phosphorus contents. C grade released very little in any extraction and cumulatively only 13%. There was also a gradual release from "citraphos" culminating in between 49% and 58% of the possible totals. These results reflect the differences both in particle size distribution (Table 2) and in material solubility.

TABLE 2—Particle-size analysis (percentage of total) of the rock phosphate types

Particle size		A grade rock	C grade rock	"Citraphos"
Retained by	2.0-mm sieve	0.0	7.8	0.21
	1.0-mm sieve	0.0	11.5	0.6
	0.5-mm sieve	0.0	2.4	1.4
	0.15-mm sieve	40.4	20.2	18.5
	0.104-mm sieve	8.4	8.3	10.3
Passed through	0.104-mm sieve	51.2	49.8	68.9

The results of foliage analyses (Table 3) are presented averaged over phosphorus rates because only at Waipoua in 1982 was the effect of rates even weakly significant. At Waipoua the trees were low in nitrogen and potassium as well as phosphorus. By the 1982 analysis phosphorus application had significantly increased foliar phosphorus concentrations over the control (Table 4), although once the site began to dry out phosphorus deficiency was not strongly marked even in the control. Despite applications of nitrogen and potassium fertiliser, nitrogen concentrations remain very low and potassium concentrations, while not deficient, are closer to the deficiency range than normal for *P. radiata* trees in New Zealand.

TABLE 3—Foliar nutrient contents by treatment, year, and site

Site	Treatments	Phosphorus (%)*				Elements (%)†			
		1979	1980	1981	1982	N	K	Ca	Mg
Waipoua	Control	0.14	0.12	0.11	0.12	1.27	0.55	0.23	0.15
	Super	0.19	0.19	0.18	0.17	1.28	0.58	0.27	0.18
	A grade	0.14	0.17	0.16	0.16	1.27	0.56	0.26	0.17
	"Citraphos"	0.16	ns	ns	0.15	1.19	0.51	0.28‡	0.20‡
Riverhead	Control	0.08	0.09	0.09	0.08	1.39	0.93	0.17	0.09
	Super	0.11	0.14	0.12	0.10	1.33	0.98	0.20	0.10
	A grade	0.10	0.13	0.11	0.10	1.36	0.95	0.19	0.09
	"Citraphos"	0.10	ns	ns	0.10	1.31	0.81‡	0.18‡	0.10‡
	C grade	0.09	ns	ns	0.08	1.29	0.79‡	0.19‡	0.10‡
Tairua	Control	0.11	0.11	0.11	0.10	1.42	0.91	0.16	0.11
	Super	0.12	0.12	0.12	0.12	1.41	0.92	0.17	0.12
	A grade	0.10	0.11	0.12	0.12	1.39	0.91	0.18	0.12
	"Citraphos"	0.11	ns	ns	0.12	1.39	0.84‡	0.19‡	0.12‡
	C grade	0.11	ns	ns	0.10	1.39	0.93‡	0.21‡	0.12‡

* Averaged over rates
† Averaged over years and rates
‡ 1979 sample only
ns = Not sampled

At Riverhead nitrogen concentrations were marginal but other tested nutrients, except phosphorus, were adequate. Controls were severely phosphorus deficient. Phosphorus fertiliser significantly increased foliar phosphorus concentrations in both 1979 and 1982 (Table 4). Superphosphate markedly raised foliar phosphorus concentrations throughout the trial period. The A grade rock and "citraphos" were initially less effective but ultimately similar to superphosphate. C grade rock was ineffective.

At Tairua the effect of phosphorus application on foliar phosphorus concentrations appears initially to have been small and non-significant although a pattern of response similar to that at Riverhead occurred in the 1982 samples (Table 4).

TABLE 4—Statistical analyses

Source of variation	Riverhead			Waipoua			Tairua		
	df	MS	F(sig)	df	MS	F(sig)	df	MS	F(sig)
Three-year basal area growth									
Blocks	2	19.67	28.5***	2	41.40	63.6***	2	23.0	13.2**
Control v. fertilised plots	1	15.48	22.4***	1	3.33	5.2*	1	3.89	2.2NS
P Types	3	5.68	8.2***	2	1.15	1.7NS	3	1.30	0.7NS
P Rates	1	2.09	3.0NS	1	0.14	0.2NS	1	0.00	0.0NS
Types * Rates	3	0.11	0.2NS	2	0.28	0.4NS	3	1.23	0.7NS
Residual	15†	0.69		11†	0.65		15†	1.74	
Foliar phosphorus concentrations in 1979									
Blocks	2	1.5 10^{-5}	0.2NS	2	9.0 10^{-6}	0.0NS	2	9.1 10^{-5}	0.9NS
Control v. fertilised	1	4.8 10^{-4}	7.4*	1	2.6 10^{-3}	1.6NS	1	4.6 10^{-5}	0.5NS
P Types	3	6.5 10^{-4}	10.1***	2	6.8 10^{-3}	4.3*	3	2.0 10^{-4}	1.9NS
P Rates	1	1.6 10^{-4}	2.4NS	1	2.5 10^{-3}	1.5NS	1	1.5 10^{-6}	0.0NS
Rates * Types	3	7.5 10^{-5}	1.2NS	2	1.2 10^{-3}	0.8NS	3	6.7 10^{-5}	0.6NS
Residual	16	6.5 10^{-5}		12	1.6 10^{-3}		16	1.0 10^{-4}	
Foliar phosphorus concentrations in 1982									
Blocks	2	3.3 10^{-4}	2.7NS	2	4.1 10^{-4}	0.7NS	2	1.0 10^{-6}	0.0NS
Control v. fertilised	1	9.8 10^{-4}	7.9*	1	6.1 10^{-3}	10.5***	1	4.6 10^{-4}	8.9***
P Types	3	6.4 10^{-4}	5.2**	2	4.5 10^{-5}	0.1NS	3	4.2 10^{-4}	8.2***
P Rates	1	3.5 10^{-4}	2.8NS	1	2.8 10^{-3}	4.8*	1	5.4 10^{-5}	1.0NS
Rates * Types	3	1.2 10^{-5}	0.1NS	2	3.2 10^{-4}	0.6NS	3	4.3 10^{-6}	0.1NS
Residual	16	1.2 10^{-4}		12	5.8 10^{-4}		16	5.2 10^{-5}	

NS = Not significant
* Probability between 0.05 and 0.01
** Probability between 0.01 and 0.001
*** Probability less than 0.001
† 1 df used by covariate

Statistical analysis of each site's basal area data for 1981 showed that no significant differences between the two fertiliser rates had yet emerged (Table 4). This finding is in agreement with the negative quadratic response surface found across phosphorus rates by Hunter & Graham (1982). Thus, in Table 5 covariance-adjusted basal areas are shown by treatment averaged across rates. At Riverhead the control was significantly worse than all the plots with fertiliser. The best growth was elicited by superphosphate followed by A grade and "citraphos", and the worst by the C grade rock. Since this pattern seemed to parallel the citric acid solubility of the fertiliser sources, the relationship was tested via analysis of variance of regression on the cumulative citric acid solubilities. Each fertiliser rate was studied separately. Both sets of regressions were extremely highly significant with peak F values being associated with the second and third extraction period. The relationship would still hold if allowance was made for the uncertainty over the amount of phosphorus applied in "citraphos".

TABLE 5—Basal area (averaged over fertiliser rates) by site and fertiliser type: adjusted by covariance

Treatment	Riverhead (m^2/ha)	Tairua (m^2/ha)	Waipoua (m^2/ha)
Average basal area in 1978	1.54	3.92	6.13
Control in 1981	8.55	17.04	12.51
Superphosphate in 1981	12.89	17.83	13.60
A grade rock in 1981	11.50	18.73	13.20
C grade rock in 1981	10.54	18.66	NT
"Citraphos" in 1981	11.56	18.03	14.10

NT = not tested

At Tairua there were no significant differences between the control and the plots with fertiliser, nor amongst the latter. Bearing in mind that these trees are the same age and at approximately the same stocking as those at Riverhead, growth generally seems to be quite satisfactory and was better in the control at Tairua than in the superphosphate plot at Riverhead. Thus, although these trees are growing on a soil that has low levels of extractable phosphorus and they have foliar phosphorus concentrations below the deficiency level (0.13% d.w.), growth does not seem to be greatly restricted by phosphorus deficiency – pointing to an interesting aspect of phosphorus dynamics not previously encountered.

At Waipoua the control was significantly worse than the average plot with fertiliser but there were no differences between fertiliser materials. At neither Tairua nor Waipoua did the regression approach outlined above yield significant results.

DISCUSSION AND CONCLUSIONS

As no differences could be detected between growth at different application rates in these 3 years, the relative effectiveness of superphosphate and phosphate rock cannot be clearly determined. However, foliar analysis suggests that A grade rock is only slightly inferior to superphosphate, "citraphos" probably slightly less effective, and C grade rock ineffective. These results are a positive encouragement to continuing research into substitution of superphosphate with certain types of rock phosphate. All of the types tested in these experiments are "unreactive". More-reactive rocks can be expected to perform very similarly to superphosphate.

Rock phosphates, a natural product, display enormous variety between provenances. It would be impossible to test all the world's possible sources in the field. It is pleasing to note that at the site where differences between rock types occurred they are in proportion to the degree of citric acid solubility. Results at this site are therefore in line with those observed elsewhere in the world and on other crops (Van Raij & Van Diest 1980; Terman 1976). The test may be of use in evaluating future sources of ground phosphate rock.

One of the more interesting results of this trial series is a by-product of its intention. To the best of our present knowledge most of the existing afforested sites in the Auckland region are similar to the Riverhead site (medium phosphorus retention, low Bray phosphorus, medium total nitrogen) and unlike the other two sites. Certainly our previous phosphorus fertiliser trial experience was largely on soils of those characteristics (Hunter & Graham 1982). It was not realised prior to this series that trees on podzolised sands might be responsive to more than phosphorus alone and indeed might not respond well to phosphorus in the absence of nitrogen and possibly potassium. This characteristic has since been confirmed in other more recent trials (Hunter, in press). Large areas of this soil type are now being planted.

The pattern of response at Tairua was likewise unexpected. In other trials the addition of up to 150 kg P/ha (1500 kg superphosphate/ha) has always been followed by a pronounced rise in foliar phosphorus concentrations. However, at Tairua the rise was small. There is no more available-phosphorus in the Tairua soil than there is in the Riverhead soil and foliar concentrations of phosphorus in the control were deficient; growth in plots without fertiliser should progressively reduce. Yet, as we have commented, that does not seem to be the case. This soil is slightly unusual for a forest soil in that it has a high amount of organic matter (as evidenced by the nitrogen concentration). In highly allophanic soils derived from old volcanic ash, organic matter is thought to become complexed with the allophane (Jackman 1964); however, it may be that pine tree mycorrhizas are able to access this potential source of phosphorus approximately in proportion to the tree's requirements. This soil type covers a significant part of Tairua Forest and other forests in the Coromandel Peninsula. An understanding of the basis for this pattern of response would therefore be of practical value.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the gift of the rock phosphate types by Winstone Limited and the assistance given by Dr D. J. Udy of that company. A group of young technician trainees assisted with plot establishment, fertiliser application, and initial measurements: Steven Young, Lindsay Bullman, Sarah MacLeod, Lance Harvey, Kevin Calvert, and Alan Thorn. The respective forest O/C's provided extra labour. Subsequently the plots have been measured and maintained with the assistance of the NZFS District Technicians - at Riverhead, Keith Elson-Haigh; at Tairua, Brian Jones; and at Waipoua, Bill Lyford and Sue Harrison. Soils analyses were made by Mrs G. M. Nicholson and foliage analyses were made by Mrs J. M. Prince.

The authors are grateful for the helpful comments made on this manuscript by Dr A. G. Sinclair, Professor T. K. Syers, Dr G. M. Will, and Dr D. Mead.

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