APPARENT PHOSPHORUS UPTAKE AND CHANGE IN NITROGEN CONTENT OF *PINUS RADIATA* GROWING ON SOILS OF DIFFERENT PHOSPHORUS RETENTION, TREATED WITH SUPERPHOSPHATE AND A-GRADE ROCK PHOSPHATE*

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ABSTRACT

The apparent uptake of fertiliser phosphorus and the differential uptake of nitrogen at three sites in a *Pinus radiata* D. Don fertiliser trial were calculated by the difference between untreated plots and plots treated with 150 kg P/ha as rock phosphate or as superphosphate. Seven years after the fertiliser was applied, the treated plots contained approximately 10% of the applied phosphorus. A further 3% was present in the forest floor. The understorey contained very little phosphorus and the understorey in the treated plots contained very little more than in the control plots. The soils at the three sites differed markedly in their phosphorus retention characteristics (from 0 to 93% phosphorus retention) but this appeared to have little effect on utilisation of applied phosphorus by the trees. At the site with the very low phosphorus retention, leaching of phosphorus seemed to occur. At the sites with the higher phosphorus retention, enhanced availability of phosphorus was restricted to the top 10 cm. Both the rock phosphate and the superphosphate treated trees contained similar additional amounts of phosphorus. We conclude that rock phosphate is as effective a fertiliser as superphosphate The difference in nitrogen content after phosphorus application was inconsistent. At two sites there were only small changes in nitrogen content but at the third site application of phosphorus alone caused a 41% increase in nitrogen uptake.

Keywords: phosphorus; nitrogen; phosphate rock; phosphorus uptake; biomass; *Pinus radiata*.

INTRODUCTION

Studies of the amount of phosphorus taken up by trees after fertiliser application are rare. Mead & Pritchett (1975) studied uptake of nitrogen and phosphorus in a *Pinus elliottii* Engelm. (slash pine) ecosystem using labelled fertiliser. However, they followed the fate of phosphorus for only 71 days. Over that time phosphorus uptake was slower than nitrogen uptake but looked as if it would be more sustained. Barrow (1977) worked with very young seedlings of *P. radiata*, *Eucalyptus* spp., *Acacia* spp., and *Banksia* spp. He found that the

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pine did not appear to allocate a higher proportion of photosynthate to root forming as phosphorus supply declined. Taber & McFee (1972) showed that nitrogen pretreatment of very small *P. radiata* seedlings could increase phosphorus uptake in pot studies. Neilsen *et al.* (1984) quantified the amount of nitrogen and phosphorus taken up by *P. radiata* 3 years after fertiliser application at time of planting. They estimated that only 5% of the applied phosphorus and 14% of the applied nitrogen was taken up by the trees. Flinn *et al.* (1982) studied the amount of phosphorus taken up by 7-year-old *P. radiata* treated with various rates of superphosphate 3 years previously. The trees were growing on a soil of very high phosphorus fixation. Flinn *et al.* quantified above-ground biomass and showed a 7.6% to 10% uptake, but used approximations based on available literature to estimate root biomass and nutrient content. They estimated that between 8% and 12% of the applied fertiliser was taken up above and below ground, with the lower efficiencies being at the higher rates applied. They suggested that high phosphorus adsorption by the soil might be a factor in the low uptake.

Thus, it is apparent that relatively little is known about the uptake of applied phosphorus by *P. radiata*, that the studies that have been done were conducted over short time periods after fertiliser application, that the apparent uptake appears to be low and might be influenced by soil conditions, and that the previous studies concentrated on highly soluble forms of phosphorus fertiliser.

We had established a trial series in 1978 over a range of three sites with contrasting phosphorus retention characteristics, in which young *P. radiata* was treated with various grades of rock phosphate and with superphosphate at two rates (75 and 150 kg P/ha). The types of rock phosphate used were A-grade, C-grade, and Citraphos rock from Christmas Island. Results to 3 years after fertiliser application have been summarised by Hunter & Graham (1983). In the first 3 years, one site (with medium phosphorus retention) responded strongly to fertiliser, with superphosphate giving the strongest response. At this site A-grade rock gave greater responses than Citraphos or C-grade rock. The other two sites (with very high and very low phosphorus retention) showed only small responses and no clear difference between fertiliser types. There was no difference between fertiliser rates at any site. In 1985, 7 years after the fertiliser had been applied, the stands in which the trials were located were scheduled by the forest management for thinning. We decided that this activity presented a significant opportunity to contribute to understanding the fate of phosphorus fertiliser in softwood plantations. Because of the scale of the study we selected only three of the nine available treatments—the treatment without fertiliser, A-grade rock phosphate, and superphosphate, both at 150 kg P/ha.

The objectives of the study were to quantify (by difference between the control and treated plots) the apparent uptake of phosphorus, to establish whether the phosphorus retention of the soil affected uptake, and whether the form in which phosphorus was supplied affected its distribution in the ecosystem.

METHODS

The Trial Site

The three sites were:

(a) In Tairua State Forest on a clay soil derived from old deeply weathered volcanic ash with a phosphorus retention of 93% in the topsoil;

(b) In Riverhead State Forest on a Waikare silt loam–Okaka clay and silty clay complex, with a phosphorus retention of 48% in the top 10 cm of soil;

(c) In Waipoua State Forest north of Dargaville on a Tangitiki sand–Te Kopuru sand complex, with a phosphorus retention of 0%.

In 1978 the stands at Riverhead and Tairua were 4 years old and the stand in Waipoua was 7 years old. Three randomised blocks had been established at each site with fertiliser-treated plots 36 × 36 m and inner measurement plots 20 × 20 m containing numbered measurement trees. All the stands were unpruned and standing at their original planted stocking. The first post-treatment foliage sampling showed that two of the sites were adequate for all major elements except phosphorus; the site at Waipoua appeared to be in danger of becoming nitrogen and potassium deficient. Urea fertiliser at 200 kg N/ha and muriate of potash at 80 kg K/ha were applied to all plots in Waipoua in 1979 (Hunter & Graham 1983). Tree diameter and height in the trials were measured in winter 1979, 1981, 1984, and 1985. Foliage samples were collected from first-year foliage on secondary branchlets in autumn 1980, 1982, and 1984. These foliage samples were analysed for nitrogen, phosphorus, potassium, calcium, and magnesium (Nicholson 1984).

In 1985 the three trees per plot that were to be sampled for biomass determination were selected from random number tables in order to avoid any bias that might occur with field selection. The sample trees were felled, and total tree height and height to base of green crown were measured for each sample tree. The green crown was divided into six zones of equal length, and one representative sample branch was selected from each zone. All the branches from each zone, including the dead branches below the green crown, were pruned flush with the stem and weighed. The sample branch was then removed and weighed separately prior to further subdividing. The stem was cut into sections at the boundary of each zone, and a subsample of usually six disks each 2–3 cm thick was taken per tree. The total stem was weighed green, then the subsample was extracted and weighed separately. Each green sample branch was separated into needle age-classes and branch wood: first-, second-, and third-year foliage and a composite of all older ages (if present). The stem wood discs were divided into bark and wood. All these samples were dried at 70°C for a period of 10 days and oven-dry weight was obtained. The samples were then ground and analysed for nitrogen and phosphorus. Dry sample weights and the product of these weights and nutrient concentrations were converted to a per hectare basis, for each individual plot, using the basal area ratio method (Madgwick 1981). Apparent uptake of phosphorus and differential content of nitrogen were calculated by the difference between the content in the treated plots and that in the controls.

Two of the three sites had a dense understory of 2- to 3-m-tall manuka (*Leptospermum scoparium* J.R. et G.Forster) which in 1985 was being shaded out by the tree canopy. The other site, Riverhead, had an understorey of manuka mixed with native hardwoods and tall grasses (*Cortaderia selloana* (Schult.) Asch et Graeb.). Six random co-ordinates per plot were selected before working in the field. A 1.128-m-diameter plastic hoop was used to define an area, with the centre of the hoop being placed on the co-ordinate. All understorey that fell inside the hoop was clipped off at ground level and bulked together for each plot, dried, and weighed. The weight per square metre was converted to a per hectare basis. The dried ground sample was analysed for nitrogen and phosphorus content (Nicholson 1984). A sample of the forest floor was taken using a 0.25-m^2 metal frame at 12 random positions per plot. This sample was weighed wet, and a subsample of approximately 10% taken and weighed. The subsample was oven-dried, oven-dry weight was obtained, and the total weight of the forest floor was calculated for each plot. The sample was ground and analysed for nitrogen and phosphorus (Nicholson 1984).

We had made a pre-treatment collection of soil from the trial sites and the results of this collection, along with estimates of phosphorus retention in the soil, have been presented by Hunter & Graham (1983). Phosphorus retention was estimated by the method of Nicholson (1984) and is the percentage reduction in the phosphorus content of a stock solution shaken in contact with the soil for 24 hours. In order to calculate the residual effect of fertiliser, a sample of 150 cores per plot to a depth of 10 cm was taken with a Hoffer tube, and 15 cores per treatment were taken with a Dutch clay auger to a depth of 10–30 cm and 30–60 cm. Bulk density cores were taken. Soils were analysed for Bray-phosphorus ("available" phosphorus), total phosphorus, and organic phosphorus (Nicholson 1984).

Statistical Analyses

Since the data were calculated in such as way as to yield nine observations for each trait for each site (three treatments by three replications), each trait at each site was subjected to analysis of variance.

RESULTS

In 1985, 7 years after phosphorus application, the trees at Riverhead and Tairua were 11 years old and those at Waipoua were 13. There was a statistically non-significant 3.7 m^2/ha gain in basal area to all types of phosphate fertilisers at Waipoua. There was a strongly significant 4.9 m^2/ha gain to rock phosphate and a 1.6 m^2/ha gain to superphosphate at Tairua. At Riverhead there was a much larger and strongly significant 8.9 m^2/ha gain to superphosphate and 7.5 m^2/ha gain to rock phosphate .

In Table 1 the response pattern is given as a percentage gain over the control for four increment periods from the time the trial was laid out.

Foliar nitrogen concentrations were marginal or adequate at all times at Riverhead and Tairua (Table 2). Foliar nitrogen concentrations showed an immediate response to nitrogen fertiliser at Waipoua but then became moderately deficient. Foliar phosphorus concentrations were deficient in the controls at Riverhead at all times, from 1982 onwards at Tairua, and in

TABLE 1–Basal area increment as a percentage of that in the control, by treatment and site

Site and treatment		Increment period			
		1978–79	1979–81	1981–84	1984–85
Tairua	Superphosphate	98	108	104	101
	A-grade rock	107	114	114	115
Riverhead	Superphosphate	140	151	138	125
	A-grade rock	90	135	142	128
Waipoua	Superphosphate	108	105	120	126
	A-grade rock	105	103	119	143

TABLE 2–Foliar phosphorus concentrations by year, treatment, and site

Site and treatment		Foliar nitrogen and phosphorus (% d.w.)					
		1980		1982		1984	
		N	P	N	P	N	P
Tairua	Control	1.43	0.11	1.37	0.10	1.57	0.09
	A-grade rock	1.40	0.12	1.39	0.12	1.40	0.11
	Superphosphate	1.43	0.13	1.40	0.12	1.41	0.12
Riverhead	Control	1.41	0.09	1.30	0.08	1.44	0.08
	A-grade rock	1.33	0.13	1.34	0.11	1.24	0.11
	Superphosphate	1.37	0.15	1.31	0.12	1.31	0.13
Waipoua	Control	1.67	0.12	1.10	0.12	1.12	0.10
	A-grade rock	1.52	0.19	1.13	0.17	1.18	0.16
	Superphosphate	1.68	0.22	1.16	0.19	1.18	0.17

1984 at Waipoua. Phosphorus fertiliser increased foliar phosphorus slightly at Tairua, more so at Riverhead, and increased it markedly at Waipoua. These changes in foliar phosphorus concentration were clearly related to the phosphorus retention of the soil.

Dry weight (kg/ha) of the various tree components by treatment and site is given in Table 3. Waipoua had the lowest over-all productivity, despite being 3 years older than the

TABLE 3 –Total oven-dry weights (tonnes/ha) of tree components

Site and component	Control	A-grade rock	Superphosphate
Tairua			
First-year foliage	4.9	7.1	6.2
Second-year foliage	4.5	5.3	4.5
Third-year foliage	2.1	2.6	2.4
Other foliage	0.5	0.5	0.4
Dead branches	6.0	10.7	8.8
Branch wood	23.5	29.8	21.6
Stem wood	79.7	105.0	98.1
Bark	11.5	11.2	9.9
Riverhead			
First-year foliage	3.7	6.3	5.2
Second-year foliage	2.7	5.0	4.7
Third-year foliage	1.9	1.2	2.0
Other foliage	0.6	0.1	0.1
Dead branches	3.1	8.0	5.1
Branch wood	14.0	23.9	14.8
Stem wood	62.8	95.9	92.4
Bark	7.2	9.2	8.3
Waipoua			
First-year foliage	2.2	3.1	2.6
Second-year foliage	1.7	2.1	1.9
Third-year foliage	0.8	1.3	1.0
Other foliage	0.4	0.6	0.4
Dead branches	2.4	3.5	3.4
Branch wood	7.7	8.0	7.8
Stem wood	71.3	85.4	76.5
Bark	8.1	9.9	8.7

other two sites. At all three sites the rock phosphate treatment had the greatest dry weight. The mass of 1- and 2-year-old needles was increased by phosphorus fertiliser application.

In Table 4 the phosphorus content of the tree components is given and in Table 5 the nitrogen content, with the probability of the difference between the three treatments. At Waipoua, only the phosphorus in the foliage was significantly different between treatments. At Riverhead there were several differences: first-year and composite foliage, dead branches and stem wood in both nutrients, and second-year foliage in phosphorus. At Tairua the only significant differences were in the phosphorus content of first-year foliage and stem wood. The differences in the total amount of nitrogen and phosphorus taken up by the controls indicated that Waipoua was the least fertile site of the three, and Tairua the most fertile.

TABLE 4—Total weights (kg/ha) of phosphorus in the trees at each site and for each treatment, with the probability of difference between the three treatments

Site and component	Control	A-grade rock	Superphosphate	Prob.
Tairua				
First-year foliage	4.5	8.6	8.0	0.02
Second-year foliage	3.8	5.3	4.7	0.12
Third-year foliage	1.6	2.2	2.2	0.52
Other foliage	0.3	0.5	0.4	0.40
Dead branches	0.5	1.0	0.8	0.51
Branch wood	4.4	6.5	5.1	0.19
Stem wood	4.6	8.2	9.4	0.02
Bark	4.5	4.6	4.6	0.99
Riverhead				
First-year foliage	3.7	7.8	6.7	0.06
Second-year foliage	2.2	5.0	5.4	0.08
Third-year foliage	1.4	1.1	2.3	0.22
Other foliage	0.4	0.1	0.1	0.04
Dead branches	0.3	1.0	0.8	0.01
Branch wood	3.4	8.1	6.4	0.11
Stem wood	6.4	11.6	11.5	0.05
Bark	2.8	5.0	4.8	0.15
Waipoua				
First-year foliage	2.7	5.2	5.4	0.01
Second-year foliage	1.8	3.3	4.0	0.01
Third-year foliage	0.9	2.2	2.3	0.03
Other foliage	0.3	0.9	0.9	0.50
Dead branches	0.3	0.7	0.8	0.13
Branch wood	3.4	5.5	5.5	0.28
Stem wood	4.6	9.2	9.2	0.24
Bark	2.6	4.3	4.3	0.09

Values for apparent uptake of fertiliser phosphorus and uptake of nitrogen (Table 6) were calculated by subtracting the nutrient contents in the control from those in the fertilised plots. We call these values the apparent uptake because we cannot prove that the additional phosphorus in the trees actually came from the fertiliser. It could have been native soil displaced by the fertiliser action on the soil, either directly by the added phosphorus or indirectly through some side-effect of the fertiliser formulation. The results indicate that between 7% and 12.5% of the applied phosphorus had apparently been taken up by the trees

TABLE 5–Total weights (kg/ha) of nitrogen in the trees at each site and for each treatment, with the probability of difference between the three treatments

Site and component	Control	A-grade rock	Superphosphate	Prob.
Tairua				
First-year foliage	77.6	103.6	88.7	0.18
Second-year foliage	64.0	65.3	54.7	0.29
Third-year foliage	25.7	27.3	24.7	0.94
Other foliage	4.5	4.8	3.5	0.75
Dead branches	7.8	12.9	10.1	0.58
Branch wood	51.0	55.9	38.3	0.19
Stem wood	63.8	70.8	74.6	0.22
Bark	44.4	37.0	32.0	0.10
Riverhead				
First-year foliage	57.0	96.8	74.8	0.08
Second-year foliage	37.0	60.5	56.7	0.18
Third-year foliage	22.5	13.4	21.8	0.26
Other foliage	6.7	1.2	0.7	0.03
Dead branches	3.9	8.8	6.8	0.03
Branch wood	32.4	49.0	38.6	0.29
Stem wood	37.5	59.2	69.9	0.06
Bark	23.3	31.1	32.4	0.22
Waipoua				
First-year foliage	28.7	40.1	34.3	0.34
Second-year foliage	18.6	22.3	20.3	0.14
Third-year foliage	08.2	12.8	10.5	0.15
Other foliage	3.1	5.2	3.4	0.63
Dead branches	2.7	4.7	4.3	0.50
Branch wood	20.2	22.0	23.0	0.84
Stem wood	31.0	40.2	37.1	0.62
Bark	20.7	24.8	23.9	0.68

TABLE 6 –Apparent uptake of phosphorus by the trees and differential content of nitrogen (kg/ha)

Site	A-grade rock		Superphosphate	
	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Tairua	39	13	–19	11
Riverhead	100	19	81	18
Waipoua	39	15	24	15

over 7 years. At Riverhead the uptake of nitrogen increased markedly after application of phosphorus but at the other two sites there was only a very small effect on nitrogen uptake.

There were only small differences between the treatments within sites in forest floor weight and in forest floor nitrogen, but the forest floor in plots with fertiliser had a higher phosphorus concentration and therefore a higher phosphorus content (Table 7).

Understorey weight and the nutrient content of the understorey (Table 8) showed that there was very little phosphorus actually taken up by the understorey at this stage in its development, most being taken up in Waipoua and least in Tairua. A different conclusion might have been reached if the understorey mass had been quantified earlier in the trial when the trees were smaller and the understorey was larger, both absolutely and relatively.

TABLE 7–Oven-dry weight and weight of nutrients in litter on forest floor (kg/ha), with the probability of difference between the three treatments

	Control	A-grade rock	Superphosphate	Prob.
Oven-dry weight				
Tairua	10 839	12 243	10 220	0.59
Riverhead	13 008	12 632	11 682	0.80
Waipoua	8 143	11 982	11 823	0.20
Nitrogen content				
Tairua	148	155	143	0.90
Riverhead	128	123	128	0.98
Waipoua	68	109	98	0.22
Phosphorus content				
Tairua	7	13	10	0.06
Riverhead	6	9	10	0.29
Waipoua	4	8	8	0.13

TABLE 8–Oven-dry weight and weight of nutrients in the understorey vegetation (kg/ha), with the probability of difference between the three treatments

	Control	A-grade rock	Superphosphate	Prob.
Weight				
Tairua	4885	3512	1743	0.13
Riverhead	5955	6389	2682	0.23
Waipoua	8434	6809	9732	0.61
Phosphorus content				
Tairua	1.8	2.6	1.5	0.42
Riverhead	1.7	3.0	1.7	0.32
Waipoua	3.6	3.5	5.7	0.42
Nitrogen content				
Tairua	29	24	12	0.18
Riverhead	28	25	17	0.28
Waipoua	36	25	37	0.41

Waipoua had the greatest amount of understorey in 1985 and Tairua the least. This difference was a reflection of the relative amounts of shade cast by the different tree crops.

At all sites there was still a substantially increased level of available phosphorus, as assayed by Bray phosphorus, 7 years after application of superphosphate or rock phosphate (Table 9). There was no clear difference in total phosphorus between treatments. There were very large differences between sites in organic phosphorus content of the soil, with Tairua having 8% of its total phosphorus in organic form and Waipoua only 1.5%. Differences between treatments were either small and non-significant or, as in Waipoua, difficult to interpret.

DISCUSSION

The fertiliser growth response was largest at Riverhead and least at Waipoua. Growth in the controls was least at Waipoua (despite the fact that this site is 3 years older than the other two) and best at Tairua. These differences seem to relate to the nitrogen status of the site as

TABLE 9 –Total, organic, and "available" phosphorus (kg/ha) by site and treatment, with the probability of difference between the three treatments

		Control	A-grade rock	Superphosphate	Prob.
Soil total phosphorus					
Tairua		930	968	827	0.19
Riverhead		1300	1639	1294	0.62
Waipoua		466	495	709	0.40
Available phosphorus					
Tairua	0–10 cm	2	15	7	0.21
	10–30 cm	2	3	1	0.34
	30–60 cm	2	2	2	0.55
Riverhead	0–10 cm	4	62	52	0.01
	10–30 cm	5	12	10	0.29
	30–60 cm	4	8	11	0.18
Waipoua	0–10 cm	5	14	15	0.12
	10–30 cm	22	45	58	0.24
	30–60 cm	16	36	112	0.09
Organic phosphorus					
Tairua		78	68	67	0.45
Riverhead		56	103	64	0.19
Waipoua		8	8	18	0.01

well as the phosphorus status and what happened to both nutrients when phosphorus was applied. Previously (Hunter & Graham 1983) we tabulated average foliar nitrogen concentrations of 1.27% at Waipoua, 1.39% at Riverhead, and 1.42% at Tairua. Here we show that foliar nitrogen concentrations were marginal to adequate at all times at Tairua and Riverhead. However, at Waipoua there was a transient effect of the applied nitrogen fertiliser which raised foliar nitrogen to nearly 1.6% the year after application. Subsequently, foliar nitrogen concentrations declined to a deficient level. In this study Waipoua had the poorest nitrogen and phosphorus contents in the controls and, while phosphorus fertiliser markedly improved the phosphorus status, it did not have as consistently strong an effect on nitrogen as it had at Riverhead where both nitrogen and phosphorus were increased by phosphorus application. At Tairua, nitrogen status was already high (by comparison with the stands studied by Madgwick *et al.* 1977) and was relatively unaffected by phosphorus application. The Waipoua stand had a low nitrogen status and a low canopy weight for a closed-canopy stand (Madgwick *et al.* 1977). Beets & Madgwick (1988) showed that low nitrogen supply reduced canopy mass to levels similar to those reported at Waipoua. This low canopy mass would have affected its growth and its response to the phosphorus fertiliser. We do not understand the circumstances under which nitrogen nutrition is affected by phosphorus application sufficiently to be able to predict the effect. It is important that we do, however, since in the one case phosphorus application is likely to be ineffective and a waste of money while in the other it can be both effective and financially very rewarding.

In the various ecosystem pools there is a remarkable consistency in the apparent uptake of phosphorus from the applied fertiliser (Table 10). Between 11 and 19 kg extra P/ha were found in the treatments with fertiliser, regardless of site or fertiliser type. However, the apparent uptake was least at Tairua and marginally greater from rock phosphate than from superphosphate. On average, only 10% of the applied fertiliser was found in the above-ground part of the tree. Differing phosphorus retention in the soil and differing initial tree

TABLE 10–Phosphorus content of ecosystem pools (kg/ha)

	Control	A-grade rock	Superphosphate
Soil available phosphorus			
Tairua	6	20	10
Riverhead	13	82	73
Waipoua	43	95	185
Soil organic phosphorus			
Tairua	78	68	67
Riverhead	56	103	64
Waipoua	8	8	18
Forest floor			
Tairua	7	13	10
Riverhead	6	9	10
Waipoua	4	8	8
Understorey vegetation			
Tairua	1.8	2.6	1.5
Riverhead	1.7	3.0	1.7
Waipoua	3.6	3.5	5.7
Tree foliage			
Tairua	9.9	16.1	14.9
Riverhead	7.3	13.9	14.4
Waipoua	5.4	10.7	11.7
Tree bark, branches, and wood			
Tairua	14.3	20.8	20.3
Riverhead	13.3	25.8	23.6
Waipoua	11.2	20.6	20.7

health did not appear to affect this proportion greatly. Higher percentage phosphorus uptake is probably achievable, however. The evidence for this is as follows. This study was over a longer time period since fertiliser application than that of Flinn *et al.* (1982) and studied a fertiliser rate slightly higher than the highest rate in their study. They achieved an above-ground uptake of 9.6 kg P/ha out of the 126 kg P/ha applied, or 7.6%, after 3 years. In both their study and this one soil analysis indicated continued availability of applied phosphorus and so it is reasonable to expect that phosphorus uptake will continue to increase with time. We also know from other trials that very satisfactory growth has been achieved over the 15 years after fertiliser application with rates as low as 60 kg P/ha (Hunter & Graham 1982). If only the same total amount were taken up, this would imply an eventual uptake in excess of 25%.

The uptake of phosphorus in the controls divided by tree age can be used to give an indication of the average above-ground minimum demand necessary to sustain tree growth—2 kg/ha/yr. A higher figure (between 3 and 4 kg/ha/yr) is necessary for the more satisfactory growth seen in the plots with fertiliser. These calculations cannot, unfortunately, be reconciled with the results of the soil analyses presented in Tables 9 and 10. There is more than enough "available" phosphorus at all sites in all treatments to satisfy 1 year's demand. Therefore the amount designated "available" is an unreliable guide to real phosphorus availability. Fertiliser has elevated the amount of "available" phosphorus, particularly in the topsoil. At Waipoua, with 0% phosphorus retention, the elevated phosphorus availability extends all the way down the profile and seems to indicate a leaching of phosphorus which is more marked for superphosphate than for rock phosphate. At Riverhead there is only slight evidence of downward movement and at Tairua none. The lack of resolution in the total phosphorus results is particularly disappointing. Despite taking 150 topsoil soil cores per plot to contain variability, the variation is too great to enable us to account for the remaining fertiliser.

One of the most striking differences between the sites is in the relative proportions of organic phosphorus and Bray available phosphorus. Tairua has, in the control, the least Bray phosphorus (largely inorganic phosphorus), the most organic phosphorus, and the best growth without fertiliser. Waipoua has the least organic phosphorus and the most Bray phosphorus and the poorest growth without fertiliser. These differences generate several intriguing and largely unexplored hypotheses as to the relative importance of the two pools for tree nutrition and the mechanism by which phosphorus application might release nitrogen to the trees.

At all three sites the forest floor was becoming an important pool of phosphorus, containing approximately 25% of the tree above-ground pool, whether treated with fertiliser or not. On average, a further 3% of the applied phosphorus was located in the enhanced phosphorus content of the forest floor in the treated plots. While the understorey presented a significant hindrance to human mobility throughout the trial, it did not amount to much in dry weight or relative nutrient content. It had, however, been far more significant in the early years of the trial when the trees were smaller, and it would be dangerous to conclude from this study alone that the understorey is never a significant component of nutrient cycling.

CONCLUSIONS

Uptake of phosphorus by *P. radiata* does not seem to be greatly affected by the phosphorus retention characteristics of the soil in which the trees are growing or the form of the fertiliser—being approximately 10% in all three sites and with both fertiliser types. However, there are differences between the three sites which could have affected the amount of phosphorus taken up. Therefore, global conclusions regarding uptake of phosphorus on different soil types cannot be made using these data. The foliar phosphorus concentrations changed in inverse relationship to the phosphorus-retention characteristics of the soil, suggesting that the more soluble form of phosphorus fertiliser is more available in the low phosphorus-retention soil.

The over-all growth of the trees at the three sites appeared to be strongly related to the nitrogen status of the soils and the nitrogen dynamics when phosphorus fertiliser was applied. This latter area warrants further study. The two forms of phosphorus fertiliser were distributed similarly in the ecosystem with the exception that slightly more A-grade rock than superphosphate appeared to be in the soil-available pool in the two clay soils, and superphosphate-phosphorus seemed to have leached further down the profile in the podsolised sand soil. Therefore, the rock phosphate is more suitable for use on the low phosphorus-retention soil and seems equally effective on soils with higher phosphorus-retention.

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