RESPONSE OF YOUNG *PINUS RADIATA* TO CULTIVATION AND FERTILISER NEAR MOTUEKA, NEW ZEALAND

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ABSTRACT

Heavy broadcast applications of superphosphate (112 kg P/ha at planting and 75 kg P/ha at age 7) improved growth rates of *Pinus radiata* D. Don during the 11-year study period by two or three times over the untreated plots. However, even these rates were unable to maintain phosphorus concentrations at non-limiting levels for more than a few years after application. Boron fertiliser prevented dieback, although there was no response in tree volume. Individual-tree doses of nitrogen fertiliser (17 g/tree) applied along with phosphorus and boron in the first two growing seasons, resulted by age 5 years in a 0.6-m height growth increase over plots treated with phosphorus and boron alone. However, a volume response was not detectable at age 7. Application of 150 kg N/ha with phosphorus and boron after thinning at age 7 years led to a 12% volume response over the phosphorus plus boron treatment by age 11 years. However, this response was only short-lived. There was no response to nitrogen in the absence of phosphorus and boron. Associated with the response to phosphorus were increases in branch size.

Ripping to 0.75 m improved growth rates but discing had no effect. The response in volume to ripping was 13 and 27 m^3/ha at ages 7 and 11 years, respectively.

Keywords: nitrogen; phosphorus; boron; fertiliser; cultivation; *Pinus radiata*.

INTRODUCTION

The growth of *Pinus radiata* on weathered soils of the Moutere gravels in the Nelson region of New Zealand is severely limited by nutrient deficiencies, poor soil structure, and weed competition (Ballard 1978; Mead & Gadgil 1978; Stone & Will 1965; Whyte 1973). Growth is particularly slow on the ridge tops where topsoil has been eroded.

The purpose of this study was to measure the longer-term benefits of ameliorative treatments applied to a young *P. radiata* plantation on one of these poor sites. The results of the two trials described here are potentially important for the management of similar sites in the region.

METHODS

Site

The two trials were sited on infertile Rosedale hill soils (Chittenden *et al.* 1966) in the former Motueka State Forest of the New Zealand Forest Service. The 0–10 cm depth soil sampled from the control plots at age 7 years had only 0.11–0.12% total nitrogen and 1–2 ppm Bray-2 phosphorus levels. Phosphorus retention was about 30%. Topography was gently rolling. Rainfall was about 1200 mm/year.

Prior to planting the area had been grazed but it had not been oversown with grass or received fertiliser. It had also been periodically burnt and supported gorse (*Ulex europaeus* L.), manuka (*Leptospermum scoparium* J.R. et G.Forst.), and bracken (*Pteridium aquilinum* (Forst. f.) Kuhn) at the time of afforestation. To clear the site for the trials the area was burnt in April after tractor crushing.

Experimental Design

Both trials were laid out in randomised block designs with three replications. Individual plots were 0.04 ha in area and had an additional 5-m-wide treated surround.

The *P. radiata* were planted in July at 2.4 × 2.4 m spacing. At age 7 years the trials were thinned to 740 stems/ha, with 60% of the basal area being removed from each plot. Periodically the gorse regrowth had to be cut to release the trees and improve access into the stands.

Trial A—Nitrogen, Phosphorus, and Boron Fertiliser Trial

The five treatments were:

(1) Control, no fertiliser

(2) Boron (B)

(3) Nitrogen plus boron (N+B)

(4) Phosphorus plus boron (P+B)

(5) Nitrogen plus phosphorus plus boron (N+P+B).

Treatments (2) to (5) may be considered as a 2^2 factorial in nitrogen and phosphorus with a basal dressing of boron.

Prior to planting the whole trial area was disced. Boron fertiliser was broadcast, as borax, at 2 kg B/ha at establishment and a second dressing of 4 kg B/ha was given at age 6. Phosphorus was broadcast as ordinary superphosphate with 112 kg P/ha being applied at planting time and 75 kg/ha after thinning at age 7 years. Nitrogen was applied three times. At planting 28 g calcium nitrate (17% N) was applied per tree and in the spring of the second growing season each tree received a further 56 g calcium ammonium nitrate (22% N). In the spring, at the time of thinning, 150 kg N/ha was broadcast as calcium nitrate.

Trial B—Site Preparation and Phosphorus Trial

The eight treatments used in a 2^3 factorial design were:

(1) Control, no site preparation or fertiliser

(2) Phosphorus (P)
(3) Ripping (R)
(4) Phosphorus plus ripping (P+R)
(5) Discing (D)
(6) Phosphorus plus discing (P+D)
(7) Ripping plus discing (R+D)
(8) Phosphorus plus ripping plus discing (P+R+D).

The phosphorus was applied as in Trial A. In addition to the superphosphate, 2 kg B/ha was applied at establishment to the phosphate-treated plots. At age 4 years 11 kg B/ha was broadcast on to all plots. This second application was made because of the appearance of dieback, associated with low boron levels in the foliage, in those plots which had not received boron at establishment. Thus, in effect, the difference in fertiliser treatments may be considered as being due primarily to phosphorus.

The site preparation treatments, ripping to 0.75 m and discing, were applied after burning and before planting.

Assessments

Tree heights were measured at ages 1, 3, and 5 years and plot basal areas annually between 7 and 11 years. Volumes at ages 7 and 11 years were determined by sectionally measuring five trees per plot, the trees being selected to cover the diameter range (Whyte 1971). The 15 trees per treatment were used to obtain volume basal area regressions from which plot volumes were derived (details of the regressions may be obtained from the author).

Samples of foliage were collected at ages 3, 5, 7, 9, 10, and 11 years and analysed for nitrogen, phosphorus, and boron concentrations using methods described by Nicholson (1984). At ages 3 and 5 years samples were collected in mid-winter on a per-treatment basis, but other collections were made in late summer on a per-plot basis. In Trial A, a summer collection was made at age 5 years and this is reported here in preference to the winter collection as it was made closer to the standard sampling time (Will 1985).

Soil samples (0–10 cm) were collected at age 7 years from all plots. These were analysed for Bray-2 "available" phosphorus and bulked samples from the control plots in each trial were analysed for total nitrogen and phosphorus retention using the methods described by Nicholson (1984).

In Trial A, at age 7 years, the frequency of boron deficiency symptoms, as described by Will (1985), was recorded.

At age 10 years branch size was assessed in Trial A to study how fertiliser treatment influenced branch diameters. Branch diameters were measured at right angles to the main stem axis and close to the tree stem. All branches of the first whorl initiated in the season of thinning and the associated fertiliser application were measured on five trees per plot. At age 10 these branches were in the mid crown of most trees. To ensure that a range of trees was sampled, the diameter-at-breast-height distribution was divided into three groups and two trees were randomly selected from both the upper and lower diameter groups and one tree from the middle-sized group.

Data from both trials were subjected to analysis of variance (ANOVA) with orthogonal single degree of freedom contrasts. The 5% level of probability generally was used as the criterion for statistical significance. Where appropriate, details have been given of the actual probabilities and of the 95% confidence intervals around the means.

RESULTS

Nutritional Treatments

The height response to nutrients in Trial A began during the first growing season and became more marked with time (Table 1). The phosphorus main effect was statistically highly significant ($p < 0.01$ at age 1 and $p < 0.001$ at 3 and 5 years) but the nitrogen main effect was not significant at the 5% test level. The nitrogen-phosphorus interaction was statistically significant at the 5% test level at age 3 and at the 10% level at age 5 years. Thus, by age 5 the trees treated with P+B and N+P+B were taller than the controls by 1.8 m and 2.4 m, respectively. It is apparent that the response to the small dressings of nitrogen was not as marked as that due to the phosphorus. The height response to boron alone was small (Table 1).

TABLE 1–Trial A: Mean tree height at 1, 3, and 5 years of age, and mean branch diameters at age 10 years

Treatment	Height (m)			Branch
	1 year	3 years	5 years	diameters (mm)
Control	0.31	0.92	2.10	21.2
B	0.32	1.00	2.32	19.0
N+B	0.30	0.89	2.07	17.1
P+B	0.43	1.64	3.99	31.0
N+P+B	0.36	2.03	4.52	32.5

Single df contrasts within the ANOVA. for basal area and volume at age 7, showed a highly significant ($p < 0.001$) response to phosphorus but non-significant nitrogen or nitrogen plus phosphorus effects. This response to phosphorus was equivalent to 42.0 $\pm$ 4.53 m^3/ha (95% confidence interval); there was no response to boron alone (Table 2).

TABLE 2–Trial A: Volume, basal area, and stocking at ages 7 and 11 years.

Treatment	Age 7						Age 11		PMAI*
	Before thinning			After thinning					(m^3/ha/year)
	Stems/ha	BA (m^2/ha)	Vol. (m^3/ha)	Stems/ha	BA (m^2/ha)	Vol. (m^3/ha)	BA (m^2/ha)	Vol. (m^3/ha)	
Control	1342	4.09	12.88	733	2.66	8.58	11.10	49.0	10.1
B	1400	4.32	14.26	733	2.65	8.94	10.69	54.4	11.4
N+B	1285	4.00	13.59	733	2.53	8.71	7.82	30.7	5.5
P+B	1392	12.66	52.69	741	7.88	32.76	23.15	173.6	35.2
N+P+B	1400	13.82	58.40	741	8.66	36.85	41.85	193.6	39.2

* Periodic mean annual volume increment between ages 7 and 11 years

After thinning at age 7 years additional nitrogen and phosphorus fertilisers were applied. The single df contrasts within the ANOVA, for basal area and volume 4 years later, again showed highly significant ($p < 0.001$) phosphorus effects. However, the nitrogen-phosphorus interactions were also highly significant at $p = 0.015$ and 0.009 for basal area and volume, respectively. This was reflected in the response to nitrogen in the presence of phosphorus and a tendency for reduced growth where nitrogen was applied without phosphorus (Tables 2 and 3). There was no basal area or volume response to the addition of boron.

The response to the 150 kg N/ha dressing applied with phosphorus and boron was apparently short-lived (Fig. 1). Response reached a peak 2 years after top-dressing, with the current annual increment in basal area being 7.01 m^2/ha compared to 5.15 m^2/ha for the N+P+B and P+B treatments, respectively.

The lack of a height, basal area, or volume response to the application of boron disguises the importance of this nutrient in reducing tree malformation. At age 7 years dieback from boron was common in the control plots with on average 23.6% of the trees being affected, but in the plots treated with this nutrient only 0.8% of trees showed deficiency symptoms.

The ANOVA of mean branch average diameter of the basal whorl of the growing season after thinning (measured at age 10 years) indicated only a response to phosphorus ($p < 0.001$). The average branch diameters are given in Table 1. However, after adjustment for tree sizes, using stem diameter as a covariate, there were no statistically significant treatment differences. This suggests that the relationship of branch diameter to stem diameter did not change as a result of the fertiliser applications.

The foliage analysis data for Trial A indicated that at ages 5, 9, and 10, the nitrogen levels in most treatments were in the deficiency range, despite the presence of gorse which is a

TABLE 3–Trial A: Summary of foliage nitrogen, phosphorus, and boron concentrations.

Treatment*	Age 3	Age 5	Age 7	Age 9	Age 10	Age 11
			Nitrogen (% dry wt)			
Control	2.18	1.53	1.71	1.30	1.27	1.66
B	1.73	1.41	1.65	1.32	1.25	1.83
N+B	2.16	1.28	1.66	1.61	1.43	1.84
P+B	1.91	1.28	1.67	1.36	1.24	1.52
N+P+B	1.93	1.27	1.70	1.11	1.10	1.26
			Phosphorus (% dry wt)			
Control	0.11	0.10	0.09	0.08	0.07	0.08
B	0.11	0.09	0.08	0.08	0.07	0.08
N+B	0.12	0.09	0.08	0.08	0.10	0.07
P+B	0.16	0.11	0.12	0.15	0.12	0.13
N+P+B	0.17	0.11	0.12	0.10	0.11	0.09
			Boron (ppm)			
Control	8	6	7	10	6	4
B	18	10	21	21	18	19
N+B	16	10	23	21	18	17
P+B	17	9	30	22	21	19
N+P+B	18	9	32	19	22	25

* Boron = 2 kg B/ha at planting + 4 kg B/ha at age 6
Nitrogen = 17 g N/tree at establishment + 150 kg N/ha at age 7 (after foliage sampling)
Phosphorus = 112 kg P/ha at planting + 75 kg P/ha at age 7 (after foliage sampling)

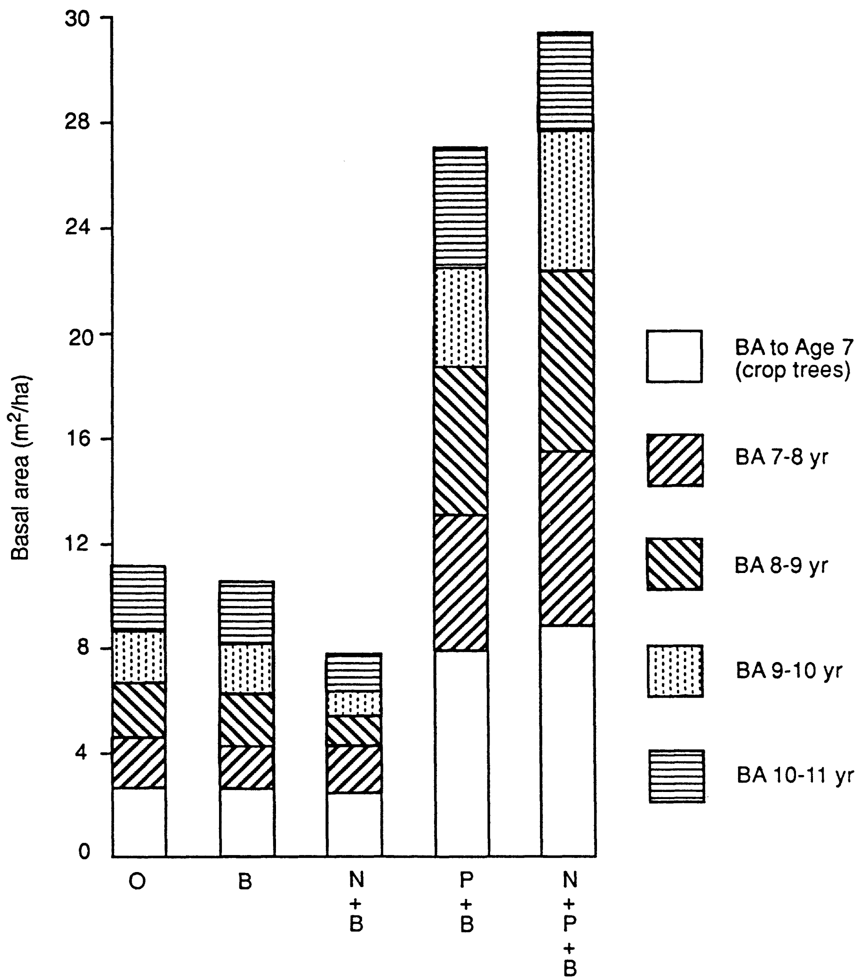

FIG. 1–Trial A: Basal area growth after thinning at age 7 years

legume (Table 3). Will (1985) suggested that foliage nitrogen levels less than 1.2% are low enough to ensure economic fertiliser responses, with growth being restricted below 1.5%. Furthermore, the application of 150 kg N/ha at age 7 resulted in statistically significant nitrogen-phosphorus interactions for the nitrogen and phosphorus foliage levels. Thus, the N+B plot had adequate nitrogen levels at ages 9 to 11 but those in the N+P+B treatment fell well below those of other treatments. The highest foliar phosphorus concentrations were found in the P+B treatment. The low levels of nitrogen and phosphorus in the N+P+B treatment are probable a dilution effect as a large increase of foliage biomass was observed for this treatment.

Without added phosphorus, trees in both trials were deficient in this nutrient, with the stress, as judged by foliar phosphorus analyses, increasing after age 3 (Table 3). Similar declines in foliar phosphorus have been described for other phosphorus-stressed stands (Hunter *et al.* 1985). Will (1985) reported that foliar phosphorus levels <0.10% are associated with visual phosphorus-deficiency symptoms; 0.11–0.12% P is the economic borderline for phosphate fertiliser application, and growth is reduced below 0.14%. These criteria suggest that the two heavy dressings (112 kg P/ha at establishment and 75 kg P/ha at age 7 years) were not adequate for more than a few years.

According to Ballard's (1970) interpretation of the Bray-2 phosphorus levels, the initial phosphate dressing should have been adequate. In both trials, available-phosphorus at age 7 years (prior to retreatment) averaged 18–19 ppm where superphosphate had been applied compared to about 2 ppm in plots without added phosphorus. It appears the criteria for judging Bray-2 phosphorus levels are inadequate.

Foliage boron levels showed the response to the application of this nutrient (Table 3). Levels below 8 ppm are normally associated with dieback (Will 1985). This ties in with the deficiency symptoms observed in this trial.

Site Preparation Treatments

The ANOVA of height growth data showed significant responses to ripping and fertiliser but not discing, although there was a significant discing × ripping interaction at 1 and 5 years ($p < 0.05$). There were no other significant interactions.

Ripping the soil to 0.75 m increased growth markedly but not as much as the application of phosphate fertiliser (Table 4). Thus, by year 5 ripping had increased tree heights by 0.7 m or 23% and fertiliser by 1.2 m or 46%. The effects were additive so that both treatments combined produced a response of 1.9 m.

The significant interaction between discing and ripping was a result of discing increasing height growth by 0.65 m at age 5 where ripping was not employed, but decreasing growth by 0.15 m when applied with ripping. Note these responses are averaged over the fertiliser effects.

Basal areas and volumes at ages 7 and 11 years all showed substantial responses to ripping and fertiliser (Table 5); the discing treatment and interactions were not statistically significant. For example, at age 11 years the volume data show the ripping effect was significant at $p = 0.003$ and the fertiliser effect at $p < 0.001$. The average volume response to fertiliser at age 11 years was 89 m^3/ha and to ripping 27 m^3/ha (± 15.9 m^3/ha).

The effects of phosphorus and boron additions on foliar nutrient levels have already been commented on and are given in Table 6. Some of the cultivation treatments also influenced

TABLE 4–Trial B: Mean tree heights (m) at ages 1, 3, 4, and 5 years.

Treatment	Age 1	Age 3	Age 4	Age 5
Control	0.3	1.1	1.5	2.2
Fertiliser (F)	0.3	1.2	2.0	3.0
Ripping (R)	0.3	1.1	1.8	2.9
F+R	0.4	1.7	2.8	4.4
Discing (D)	0.3	1.0	1.7	2.7
F+D	0.4	1.5	2.5	3.8
R+D	0.3	1.1	1.7	2.8
F+R+D	0.4	1.6	2.7	4.2

TABLE 5–Trial B: Basal area and stocking at ages 7 and 11 years.

Treatment	Age 7						Age 11		PMAI*
	Before thinning			After thinning					(m³/ha/year)
	Stems/ha	BA (m²/ha)	Vol. (m³/ha)	Stems/ha	BA (m²/ha)	Vol. (m³/ha)	BA (m²/ha)	Vol. (m³/ha)	
Control	1343	4.60	15.79	725	2.97	10.27	11.91	65.2	13.7
F	1458	8.91	32.34	733	5.69	20.88	24.29	148.5	31.9
R	1425	7.28	26.89	741	4.56	17.06	15.98	90.5	18.4
F+R	1458	13.25	56.74	733	8.13	35.54	27.84	186.1	37.6
D	1310	6.57	22.62	733	4.05	14.31	14.80	79.7	16.3
F+D	1433	10.58	42.98	733	6.57	26.95	23.78	154.2	31.8
R+D	1277	7.38	27.60	725	4.40	16.90	15.91	88.2	17.8
F+R+D	1359	13.59	55.68	733	8.22	33.84	28.00	190.6	39.2

* Periodic mean annual volume increment between ages 7 and 11 years

TABLE 6–Trial B: Summary of foliage nitrogen, phosphorus, and boron concentrations.

Treatment	Age 3	Age 4	Age 5	Age 7	Age 9	Age 10	Age 11
			Nitrogen (% dry wt)				
Control	1.70		1.24	1.38	1.38	1.23	1.61
F	1.80		1.22	1.51	1.38	1.17	1.52
R	1.99		1.41	1.42	1.39	1.22	1.67
F+R	1.95		1.37	1.41	1.39	1.12	1.37
D	2.13		1.29	1.26	1.23	1.08	1.40
F+D	2.10		1.37	1.39	1.40	1.16	1.39
R+D	2.10		1.36	1.24	1.37	1.20	1.53
F+R+D	1.97		1.37	1.46	1.41	1.22	1.49
			Phosphorus (% dry wt)				
Control	0.10		0.07	0.08	0.08	0.07	0.09
F	0.16		0.11	0.13	0.15	0.10	0.13
R	0.11		0.07	0.08	0.08	0.07	0.08
F+R	0.17		0.10	0.11	0.14	0.12	0.14
D	0.12		0.08	0.07	0.08	0.06	0.08
F+D	0.19		0.10	0.12	0.15	0.12	0.13
R+D	0.12		0.08	0.09	0.08	0.06	0.09
F+R+D	0.18		0.11	0.12	0.15	0.11	0.13
			Boron (ppm)				
Control	13	10	29	22	22	17	24
F	18	14	65	24	22	16	21
R	11	9	33	25	20	16	23
F+R	20	14	41	20	23	14	21
D	13	7	27	17	18	17	20
F+D	25	12	30	28	21	18	23
R+D	12	7	29	17	23	16	21
F+R+D	19	14	29	22	24	19	19

* Boron = 2 kg B/ha to F treatment at planting; 11 kg B/ha to all plots at age 4 (after foliage collection)
Phosphorus = 112 kg P/ha at planting + 75 kg P/ha at age 7 (after foliage collection)

nutrient levels and, in particular, nitrogen levels were initially increased by cultivation. At age 3 disced and ripped plots had increased nitrogen concentrations of 0.22% and 0.07%

respectively. By age 7 and at later ages, discing was tending to lead to lower foliage concentration levels, while foliar levels in ripped treatments were similar to the controls. These changes in foliar nitrogen levels may be due to increased mineralisation of soil nitrogen as a result of cultivation or to changes in weed and gorse growth. It was observed that discing promoted grass development and that gorse regrowth was more vigorous on undisced and phosphate-treated plots. The release cutting of gorse and canopy closure at age 5 or 6 years may have increased nitrogen availability, resulting in the higher foliar nitrogen levels in the trees at age 7. The effects of thinning again encouraged weed competition and this may explain the lower nitrogen and phosphorus levels at ages 9 and 10 years.

DISCUSSION AND CONCLUSIONS

These trials showed that nutrition limits growth more than cultivation on this site. Both phosphorus and boron fertilisers are important; adding phosphate will improve growth rates substantially and boron is required to prevent dieback and subsequent malformation. There was a smaller response to nitrogen in the presence of added phosphorus and boron. The small response to the nitrogen applied in the first two growing seasons after planting was almost certainly a result of the low amounts added, coupled with the effects of weed competition. Madgwick (1985) showed that fast-growing *P. radiata* plantations incorporate into their above-ground parts about 7 kg N/ha in their first two growing seasons and a further 124 kg N/ha between ages 2 and 4 years. The application of 30 kg N/ha over the first two growing seasons was reasonable for the trees up to this time but would not meet the large demand after age 2 on soils with low nitrogen status and where there was weed competition. Foliage analyses indicated the P+B plots were becoming marginally deficient in nitrogen at this time of high demand.

The response to the 150 kg N/ha applied with phosphorus and boron after thinning was smaller than expected, being about 12% or 20 m^3/ha over phosphorus alone.Foliar analyses suggested that the limited response resulted from inadequate phosphorus availability. This conclusion is also supported by the responses obtained in a nitrogen × phosphorus factorial experiment in a 14-year-old stand at Harakeke, not far from these trials—and also on soils with the same parent material (Mead & Gadgil 1978). In that trial, where the phosphate fertiliser maintained foliar phosphorus levels above 0.16% for at least 3 years, there was a 46% volume increase (73 m^3/ha) to 208 kg N/ha. If nitrogen fertiliser is to be used by forest managers, it is extremely important to ensure that other deficiencies are eliminated. Hunter *et al.* (1986) have also noted that adding nitrogen fertiliser on low-phosphorus sites can be detrimental, although in Trial A described above the reduction in growth was not significantly lower than the controls.

These trials showed that relatively heavy phosphate dressings at planting and at age 7 years were insufficient to maintain optimum foliar phosphorus levels for more than a few years. Mead & Gadgil (1978) also noted that on deficient stands at Riverhead Forest rates of up to 112 kg P/ha did not increase levels above 0.13% for more than 2 years, although an application of 220 kg P/ha was effective for at least 6 years. On less deficient sites or sites with lower phosphorus retention in Northland, responses to the lower rates may be more protracted (Mead & Gadgil 1978; Hunter *et al.* 1985).

This relatively short-term response to phosphate on strongly deficient sites is not unexpected as studies of healthy *P. radiata* stands indicated that they extracted about 40 kg

P/ha from the soil during the first 10 years after planting (Will 1968; Madgwick 1985). Furthermore, Will (1965) and Knight & Will (1971) estimated that pines on deficient forest soils at Riverhead Forest utilised about 15% of the applied superphosphate. Thus, on very deficient soils about 270 kg P/ha would be required to eliminate the deficiency.

However, the amount and type of fertiliser to be used by a forest manager will require consideration of other factors. If the manager is willing to accept less than optimum rates and does not intend to apply heavy nitrogen dressings at first thinning, then the lower rates may be appropriate. Lower rates of phosphate are also appropriate when treating older stands of moderate phosphorus deficiency or on low-phosphorus-retention soils. Hunter & Graham (1982) have shown that repeated applications of small amounts of fertiliser, reapplied as indicated by foliar analysis, gave results similar to those from single large dressings.

The use of superphosphate is suited to these three medium-phosphorus-retention soils, as is suggested by the work of Knight & Will (1971), Mead (1974), and Hunter & Graham (1983). It is unlikely that applying less-soluble sources will, by itself, lead to longer-term responses.

The results also indicate that forest managers should be careful in interpreting soil and foliar analyses often used to prescribe fertiliser treatments. It is apparently unwise to rely on the traditional Bray-2 test to indicate if an area has adequate phosphorus status where the area has had phosphate applied. The apparent dilution effect observed in foliar levels when nitrogen was applied along with phosphorus plus boron fertiliser also indicates that foliar analyses should be used cautiously.

Soil amelioration by ripping was a useful site preparation technique on these sites. The volume response was about 27 m^3/ha by age 11. Discing did not give statistically significant volume responses, although when applied without ripping it led to small height increases at ages 3 and 5 years. Both treatments temporarily increased nitrogen availability, presumably by increased mineralisation. However, these changes do not fully explain the responses and interpretation is further complicated by changes that occurred in weed competition as a result of treatments and canopy closure.

The importance of these silvicultural treatments—ripping and the use of nitrogen, phosphorus, and boron fertilisers—can be illustrated by estimating site index at age 20 years using the equations of Burkhart & Tennent (1977). Site index appears to be increased from 22 m to above 30 m height, provided the responses observed in these trials continue.

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