FERTILISER USE IN ESTABLISHED RADIATA PINE STANDS IN NEW ZEALAND

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ABSTRACT

Investigations into and use of phosphate fertilisers on impoverished soils in Auckland Conservancy started in the 1950s and routine aerial applications of superphosphate are now accepted as standard management practice in both Auckland and Nelson Conservancies. Foliar analysis is used to monitor the crop P status and superphosphate is applied to keep foliar P levels above 0.12% dry weight. The usual application rate is between 55 and 110 kg/ha P and on poorer sites several dressings are required during the first rotation. Fertiliser trials and other studies have provided a good basis for these practices and correction of acute P-deficiency by applying high rates of P often results in volume responses of about 30 m^3/ha/year.

Nitrogenous fertilisers applied at about 200 kg/ha N will increase productivity on many sites. At mid-rotation on fertile Central North Island soils, volume responses often exceed 8 m^3/ha/year; on more infertile sites in the Nelson region responses to N + P fertiliser are about 17 m^3/ha/year. However, on the infertile soils responses to N have usually been short-lived (4-5 years). Best responses have been obtained where applications are made within 2 years of thinning. Foliar analysis is currently an unsatisfactory basis for recommending N prescriptions. **Lupinus arboreus** has been effective in improving the N economy of forests planted on coastal sands.

Boron and copper fertilisers are required on some sites to prevent malformation of trees. The use of boron fertilisers, applied at between 4 and 12 kg/ha B, is a common practice in several South Island forests. Copper deficiency occurring in limited areas of sand dune forests in Northland is corrected by the application of 5 kg/ha Cu. Foliage analysis and the appearance of symptoms are the main diagnostic techniques used in deciding where and when to apply these two micronutrients.

Deficiencies of potassium and magnesium occur only to a limited extent and are of little practical significance. The main areas of K deficiency are on soils derived from ultrabasic rocks. Magnesium deficiency has been found on the yellow-brown pumice soils of Rotorua Conservancy, on soils derived from the Moutere gravels in Nelson Conservancy and on certain gley-podzols in Westland Conservancy.

INTRODUCTION

The use of fertilisers in established New Zealand forests began in the early 1950s with investigations into tree nutrition problems on the impoverished soils of North

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Auckland. These soils, which are now known to be primarily phosphate deficient but low in other nutrients as well, are podzolised and strongly weathered clays and sands which had at one time supported kauri and kauri-podocarp-broadleaf forest; they had also frequently undergone further degradation due to man's activities. In 1952 several trials with high rates of a superphosphate compound and zinc treatments were established; the response to phosphate was immediate but there was no response to Zn (Weston, 1956). Within 3 years the first aerial phosphate applications were being tried (Conway, 1962; Mead, 1968).

In 1955 further trials were laid out in order to investigate superphosphate application rates. These were supplemented in the late 1960s with trials in younger radiata pine stands to test both rates and timing of fertiliser applications.

In this early period, the management practice for radiata pine on the P-deficient soils was to aerially topdress with 55 kg/ha P as superphosphate. Topdressing was concentrated on the mature stands in Riverhead, Maramarua, Tairua and Waipoua Forests. In the late 1960s it became obvious that it was also important to topdress younger stands. Signs of phosphate deficiency were often apparent as early as age 4 years even when the trees had been hand-topdressed with superphosphate at planting. Later, in the early 1970s, it became apparent that 55 kg/ha P provided only a transitory response on many soils. There were also difficulties in ensuring an even distribution with aerial applications and many areas within a stand received far too low a dressing (Ballard and Will, 1971). The application rate was therefore doubled in 1971; 100 to 110 kg/ha P is still the standard recommended rate for most sites. Foliage analysis techniques were studied in detail (Will, 1965) and in 1972 a system of monitoring the P status of the crop using foliage analysis was made available to forest managers (Mead and Will, 1976). Phosphate dressings are prescribed when foliage P levels drop below 0.12%.

In the early 1950s an effort was made to study the use of fertilisers on other soils but in all cases the results were negative. Zinc was tried without success on a variety of sites in Northland, the central North Island and the Nelson region. Phosphate was tried in Woodhill Forest where, as is now known, only N is limiting. Low rates of N were used on the phosphate-deficient soils of Northland, and in Nelson P alone was applied where it is now apparent that multiple deficiencies of N, P and B exist.

Research starting in 1961 in Nelson Conservancy clearly demonstrated that B deficiency caused leader dieback in that part of the country (Stone and Will, 1965a). Furthermore, it was shown that both N and P and occasionally Mg were limiting growth on these soils (Stone and Will, 1965b; Appleton and Slow, 1966). The first aerial applications of B fertilisers were applied in 1964 (Appleton and Slow, 1966) and later boronated superphosphate (40 kg/ha P + 8 kg/ha B) was used extensively. The use of N fertilisers in the region did not become a management practice because of a lack of growth response information on which to base cost-benefit evaluations.

To obtain good growth response data two large N × P factorial experiments were established on the Moutere gravel soils of the Nelson region in 1968. Both trials clearly demonstrated the economic benefit of applying N in addition to P and B fertilisers (Mead, 1974a; 1976a). As the results of these trials became available, new trials were established with the object of determining the optimum rate of N to apply in operational programmes.

The above account outlines progress made in the two main regions where nutrient problems were obvious. However, as early as 1964 it was decided that the potential of fertilisers should be investigated in areas which did not show obvious signs of nutrient deficiency. A trial was therefore established in a 6-year-old stand in Kaingaroa forest, using a heavy, repeated dressing of a mixed fertiliser. A small response was apparent in the early years (Ballard, 1971). Three years later a trial was established in a 14-year-old stand belonging to N.Z. Forest Products Ltd, and here a more obvious response was observed (Woollons and Will, 1975). This led to the establishment of a series of trials on the central North Island pumice soils during the early 1970s and eventually to commercial applications of N in thinned stands. At about the same time there was a gradual expansion of fertiliser trials to other parts of New Zealand which had previously been considered to have a satisfactory nutrient status.

From the above outline it can be seen that fertiliser research started in the worst problem areas and has gradually been moving out to areas where the trees are apparently healthy. Research methods have also changed. Positive results from early "hit or miss" trials were confirmed by soil and foliage analysis and provided the basis for intensive investigation with larger, better-designed trials. Because there are strong economic reasons for finding alternatives to conventional N fertilisers, the potential for using legumes in forestry is also under investigation.

PHOSPHORUS

Growth Responses

The earliest successful trials were laid out in 1952 in radiata pine at Riverhead State Forest, Auckland Conservancy (Weston, 1956; 1958). These were pilot trials with paired 0 and 225 kg/ha P treatments, the P being applied as a superphosphate compound (75% superphosphate, 15% ground Nauru rock phosphate and 10% ground serpentine rock). Several blocks of these plots were established in 20- to 24-year-old stands of unthrifty radiata pine. The results were spectacular as illustrated by the mean increases in basal area in three of the blocks (Fig. 1). There were similar increases in predominant mean height and volume; 24 years after topdressing the average predominant mean height in the control and fertilised plots was 19.5 and 33.1 m, and the standing volumes were 206 and 981 m^3/ha respectively.

In 1955 larger experiments were laid out in a 24-year-old stand (A159) and a 27-year-old stand of lower site quality (A160). Details of the methods used in these and the earlier 1952 trials are given by Weston (1958) and Will (1965). The trials included zinc treatments in combination with the phosphate but the effect of the zinc was to produce only a slight negative response. This slight zinc effect has been ignored for the purpose of this paper and the zinc plots used to increase the replication. Basal area and volume showed a marked response to phosphate treatment (Tables 1 and 2). However 22.5 and 45 kg/ha P were insufficient to sustain the maximum growth rate. The average net volume growth (i.e., excluding dead trees) over a 14-year period was 10, 40, 317 and 378 m^3/ha for application rates of 0, 22.5, 45 and 220 kg/ha respectively. This was equivalent to an increase in stand volume of 7, 37, 189 and 265% respectively. The net increment in control plots was very low, partly because of high mortality; the application of P, even at low rates, substantially reduced mortality. In A160 the average stocking decrease over a period of 21 years was 62, 41, 16 and 28%

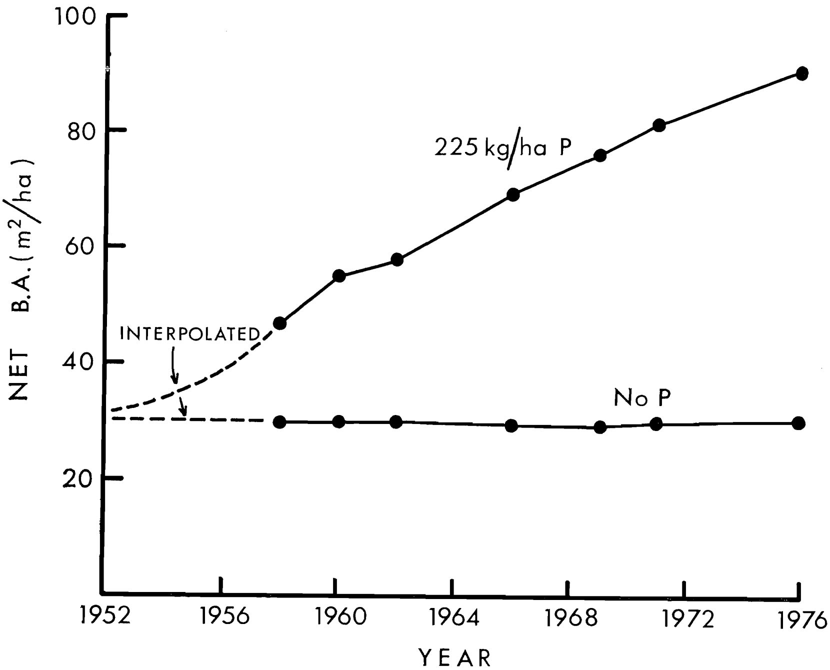

FIG. 1—Basal area response to phosphate in 20- to 24-year-old stands of radiata pine, Riverhead Forest.

for the control, 22.5, 45 and 220 kg/ha P treatments respectively. The response to the 45 kg/ha P dressing was not as rapid or sustained as that produced by the very heavy dressing. The optimum application rate on these soils probably lies between 45 and 220 kg/ha P.

In the late 1960s a large trial (A286) was established in 5- to 8-year-old stands in four forests in Auckland Conservancy with the object of determining the optimum combination of rate and frequency of application. The only data available so far are for responses to the first application of fertiliser; as some plots are scheduled to have repeat applications there is sufficient replication within blocks to test the block × treatment interaction for this initial treatment.

The trial is located at Whangapoua (Blocks 1-3), Glenbervie (Block 4), Maramarua (Block 5) and Riverhead (Block 6). The most productive site is in Glenbervie Forest and the poorest site is at Riverhead Forest. Phosphate was applied at 0, 56, and 112 kg/ha P in all blocks and also at 224 kg/ha P in blocks 4, 5 and 6. Block 6 at Riverhead included additional treatments (N + P and a "balanced" fertiliser) and had greater internal replication. Individual plots are 0.04 ha in area with treated surrounds of 8.2 m width.

An analysis of covariance of basal area (using initial basal area as covariate) of the 0, 56 and 112 kg/ha P treatments 3 years after topdressing indicated that treatment and block effects were significant. There was no suggestion of treatment × block interaction. The average basal area response to 56 and 112 kg/ha P was 0.69 and 0.90 m^2/ha/year respectively (Table 3).

TABLE 1—Basal area growth of first crop radiata pine at Riverhead Forest as influenced by phosphate fertiliser applied in 1955 (Trials A159, A160)

Trial	Treatment P (kg/ha)	No. of plots	PMAI 1955-62 Net	PMAI 1955-62 Gross	PMAI 1962-69 Net	PMAI 1962-69 Gross	PMAI 1969-76 Net	PMAI 1969-76 Gross
			— — — —	— — — —	— m²/ha/year —	— — — —	— — — —	— — — —
A159	0	2	—0.44	0.77	0.80	1.19	*	*
	45	2	1.78	2.08	2.57	2.64	*	*
	220	1	2.27	2.31	3.40	3.41	*	*
A160	0	1	—1.00	0.43	—0.42	0.27	—0.64	—0.04
	22.5	3	—0.02	0.46	0.52	0.67	0.30	0.41
	45	1	1.20	1.61	1.47	1.47	0.81	1.04
	220	1	0.67	1.10	2.79	2.79	2.17	2.18

* No data; trial felled in 1971.

TABLE 2—Volume growth* of first crop radiata pine at Riverhead Forest as influenced by phosphate fertiliser applied in 1955 (A160 only)

Trial	Treatment P (kg/ha)	No. of plots	PMAI 1955-62 Net	PMAI 1955-62 Gross	PMAI 1962-69 Net	PMAI 1962-69 Gross	PMAI 1969-76 Net	PMAI 1969-76 Gross
			— — — —	— — — —	— m³/ha/year —	— — — —	— — — —	— — — —
A160	0	1	—3.0	4.7	—1.1	0.9	—5.1	—0.9**
	22.5	3	3.1	5.9	2.7	3.4	3.0	4.0
	45	1	17.2	20.2	12.7	12.9	12.0	14.2
	220	1	7.5	10.4	31.1	32.0	26.1	26.5

* Volume calculated from BA and height data using the formula given in Beekhuis (1966)
** Negative result due to decrease in predominant mean height resulting from tree deaths.

TABLE 3—Treatment means, adjusted by covariance analysis, and their standard errors (S.E.) for gross basal area 3 years after topdressing. A286, Auckland Conservancy

Treatment or Block	Adj. BA m²/ha	S.E.
Control	21.65[b]	0.633
56 kg/ha P	23.71[a]	0.221
112 kg/ha P	24.36[a]	0.308
Block 1	22.40[y]	0.336
Block 2	27.27[x]	0.451
Block 3	19.86[z]	0.483
Block 4	30.70[w]	0.713
Block 5	20.33[yz]	0.295
Block 6	18.87[z]	0.243

Different superscript letters within fertiliser treatments and blocks indicate significant differences at $P \leq 0.05$ using Duncan's test.

A similar analysis of gross basal area data for Blocks 1, 2, 3 and 5, five years after topdressing, again failed to show a treatment × block interaction. The average annual basal area response was 0.96 and 1.12 m^2/ha/year for the 56 and 112 kg/ha P treatments respectively (Table 4).

TABLE 4—Treatment means (adjusted by covariance analysis) and standard errors for gross basal areas 5 years after topdressing. A286, Auckland Conservancy

Treatment or Block	Adj. BA m^2/ha	S.E.
Control	28.68^{b}	0.562
56 kg/ha P	33.46^{a}	0.431
112 kg/ha P	34.26^{a}	1.002
Block 1	31.79^{z}	0.554
Block 2	37.72^{y}	0.806
Block 3	28.68^{z}	0.599
Block 5	30.33^{z}	0.557

Different superscript letters within fertiliser treatments and blocks indicate significant differences at $P \leq 0.05$ using Duncan's test.

A more detailed analysis of data from Block 6 (Riverhead) was possible because of the higher degree of internal replication. Three years after topdressing there was little difference in basal area between the 56 and 112 kg/ha P treatments, but the 224 kg/ha application was definitely superior. Addition of N at 270 kg/ha to the 112 kg/ha P treatment also markedly improved growth rates (Table 5).

TABLE 5—Treatment means (adjusted by covariance analysis) and standard errors for basal areas 3 years after topdressing. A286, Block 6, Riverhead Forest

Treatment	Adj. BA m^2/ha	S.E.
1. Control	5.05^{c}	0.136
2. 56 kg/ha P	7.33^{b}	0.171
3. 112 kg/ha P	7.25^{b}	0.292
4. 224 kg/ha P	8.93^{a}	1.177
5. 112 kg/ha P + 270 kg/ha N	9.67^{a}	0.353
6. As for 5 + K, Mg, Ca, and micronutrients	10.10^{a}	0.199

Different superscript letters indicate significant differences at $P \leq 0.05$ using Duncan's test.

Another trial on a P-deficient site in Maramarua Forest (A318) also indicated that superphosphate application at 52 kg/ha P was below the optimum rate (Mead, 1974b). This trial was designed to compare ordinary superphosphate applied at 0 and 52 kg/ha P with uncalcined ground Christmas Island "C" rock phosphate applied at 52 and 104 kg/ha P. None of the treatments completely corrected phosphate deficiency in the 7-year-old stand of radiata pine. To achieve the same response, about 67% more P was needed if rock phosphate was used instead of superphosphate. At age 16 years the total volumes were 34.9, 84.0, 181.5 and 146.8 m^3/ha for the control, 52 kg/ha P as rock phosphate, 104 kg/ha P as rock phosphate and 52 kg/ha P as ordinary superphosphate respectively.

These studies, together with experience from topdressing operations (Mead, 1968) and poor fertiliser distribution from aircraft (Ballard and Will, 1971), indicate that rates of about 55 kg/ha P are insufficient for optimum growth on the poorer sites. Foliage analyses confirm this conclusion.

Foliage Analysis

Research into the relationship between radiata pine growth and P concentration in the foliage has shown that a level of 0.13% indicates that growth is not being restricted due to a lack of soil P (Mead, 1972; Raupach *et al.*, 1969). This provides a useful criterion by which we can determine the adequacy of phosphate dressings.

Foliage analyses from the early Riverhead plots suggested that low rates (about 50 kg/ha P) only temporarily increased levels above this 0.13% P criterion. Table 6 illustrates this point. There was a large initial rise in foliar P concentration, but this was not maintained beyond the second year. An application rate of 220 kg/ha P was more effective since foliar P levels remained higher than 0.13% for at least 6 years.

TABLE 6—Foliage levels of P (% dry weight) in A159 Riverhead Forest. Intermediate site quality stand planted 1931, treated 1955 or 1966

Treatment	Year									
P (kg/ha)	1955	1957	1958	1959	1960	1961	1966	1968	1969	1971
0	0.08*	0.10	0.08	0.09	0.09	0.10	0.09	0.06	0.06	0.07
45 (1955)	0.09*	0.18	0.10	0.11	0.10	0.12	0.09	0.08	0.06	0.08
56 (1966)	†	†	†	†	†	†	0.08*	0.15	0.12	0.12
220 (1955)	†	†	0.15	0.14	0.14	0.16	0.12	0.12	0.10	0.10

* Before fertiliser application † Not sampled

In trial A286, where superphosphate was applied to 5- to 8-year-old stands, the effect on foliar P concentration varied with site (Fig. 2). At Riverhead, a very impoverished site, 56 kg/ha P raised the foliar P concentration to 0.12% only briefly and the 112 kg/ha rate did not increase levels above 0.13% for longer than 2 years. The response of foliar P levels to superphosphate application at Maramarua Forest was somewhat better: 56 kg/ha P was effective for at least 2 years and the higher rates for at least 5 years. At Whangapoua Forest (Blocks 1 and 2) a single dressing of 56 kg/ha P was adequate for 6 years and a single dressing of 112 kg/ha for at least 8 years. At the most fertile site, Glenbervie Forest, all P applications have maintained foliar levels above 0.13% P for 5 years. The effect of thinning in increasing foliar P levels at Whangapoua is also shown in Fig. 2.

A summary of the foliar P response to superphosphate application in trials throughout New Zealand is given in Table 7. This table illustrates the following points:

(1) Foliage P levels do not respond to superphosphate dressings when levels before

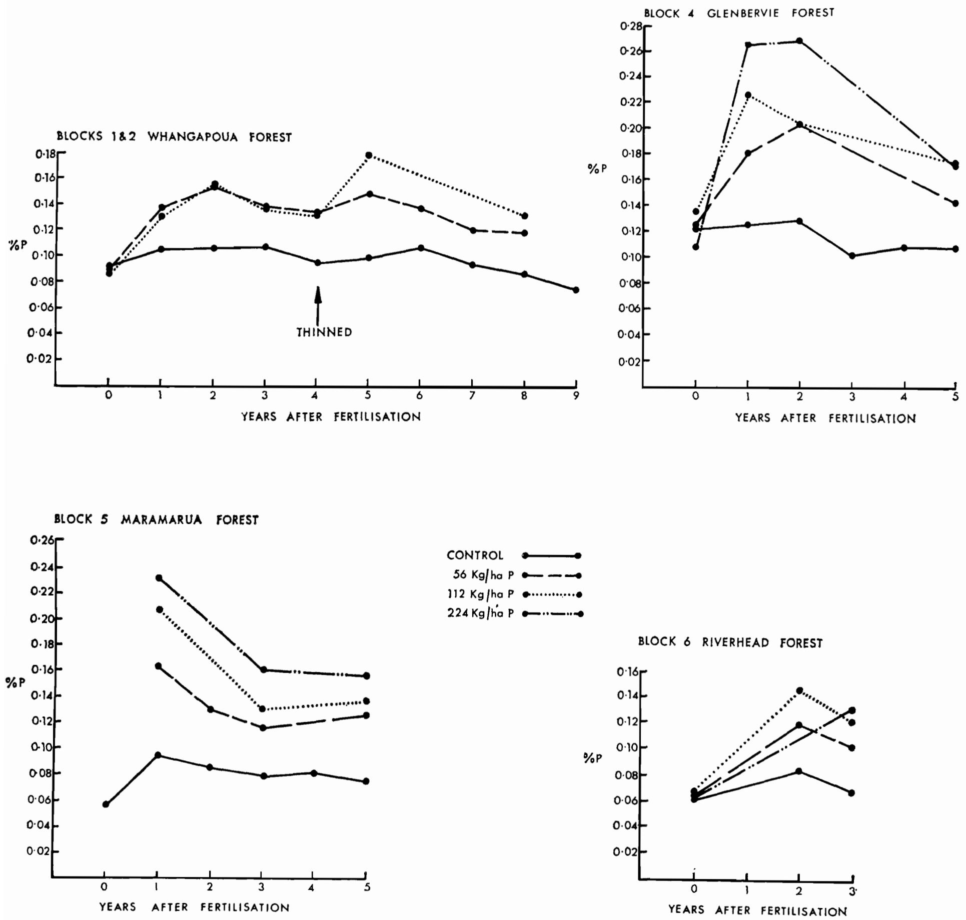

FIG. 2—Trends in foliage P concentration in Trial 286, Auckland Conservancy.

treatment are greater than 0.16%. This agrees with South Australian experience (Raupach *et al.,* 1969).

(2) The length of response varies with site.

(3) Within a trial the length of response is generally greater with the higher rates of phosphate.

Phosphorus Utilisation

Will (1965) studied P uptake in one of the early trials at Riverhead Forest (A90; A90C) and estimated that 15% of the applied phosphate was incorporated into the trees 8 years after application. Studies on the P content of healthy radiata pine stands (Will, 1968; Madgwick, 1977) indicate that the largest demand occurs prior to canopy closure. A healthy stand extracts about 40 kg/ha P from the soil during the first 10 years, but very small amounts are taken up thereafter. If we assume 20% utilisation of applied P (Will, 1965) then a very deficient site will require 200 kg/ha P during the first 10 years of the rotation.

TABLE 7—Response to various rates of P as judged by the duration in years with foliage P level being 0.13% or more

Trial	Forest	Age (Years)	Stand condition	Rate kg/ha P	% P in Control	Response
A90	Riverhead	20	V. unthrifty	225	0.07	10-14
A195	Riverhead	24	Mod. unthrifty	45	0.09	2
		24		220	0.09	7-11
		35		56	0.08	2
A160	Riverhead	27	Unthrifty	22 & 45	0.07	< 5
		27	Unthrifty	220	0.07	12
A286/1 & 2	Whangapoua	6	Mod. unthrifty	56	0.10	5
		6	Mod. unthrifty	112	0.10	> 8
		11		56	0.09	< 3
A286/3	Whangapoua	8	Mod. unthrifty	56	0.09	4
				112	0.09	> 5
A286/4	Glenbervie	5	Healthy	56, 112, & 225	0.12	> 5
A286/5	Maramarua	8	Mod. unthrifty	56	0.09	2
				112 & 225	0.09	> 5
A286/6	Riverhead	6	Unthrifty	56	0.06	< 2
				112	0.06	2
				225	0.06	> 3
A318	Maramarua	7	Unthrifty	52	0.08	< 2
A334	Woodhill	9	Healthy	112	0.18	V. slight
N281*	Tasman	7	Healthy	112	0.14	6
N277**	Tasman	5	Mod. unthrifty	226	0.09	> 4
N318*	Tasman	7	Mod. unthrifty	112	0.09	> 3
N151**	Golden Downs	7	Healthy	112	0.18	V. slight
N285*	Tasman	10	Healthy	112	0.09	> 3
N262**	Golden Downs	6	Healthy	112	0.21	None
N239**	Pigeon Valley	7	Mod. unhealthy	112	0.13	5
N125**	Tasman	8	Mod. unhealthy	112	0.11	> 5
N150**	Tasman	10	Mod. unhealthy	50	0.11	4
N191*[a]	Tasman	14	Mod. healthy	112	0.11	5
N191*[b]	Tasman	14	Mod. healthy	112	0.11	3-4
N263**	Waiwhero	29	Unthrifty	112	0.09	> 4
N238**	Pigeon Valley	23	Unthrifty	112	0.21	None
N190**	Braeburn	40	Mod. unthrifty	112	0.11	3-4
N261**	Golden Downs	46	Healthy	112	0.19	V. slight
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(2)	Tokoroa	14	Healthy	68	0.16	None
(4)**	Tokoroa	5	Healthy	68	0.15	Small
(7)**	Tokoroa	14	Healthy	68	0.16	None

* B applied with P
** Several nutrients applied with P
[a] With B but without N
[b] With B and with N

Silvicultural Considerations

The current practice of prescribing phosphate dressings to maintain foliar P levels above 0.12% is a convenient management technique to ensure that tree growth is not restricted by P deficiency (Mead, 1972). In areas of multiple deficiency it is important to supply all limiting nutrients to ensure a response.

Trial data suggest that on some sites (e.g., Riverhead and Maramarua Forests and some forests on the Moutere gravel soils) it is necessary to apply more than one dressing of at least 75 to 125 kg/ha during a rotation. On slightly better sites (e.g., Glenbervie Forest) a rate of between 50 and 75 kg/ha P seems sufficient. The influence of soil P-retention characteristics on the length of responses has still to be evaluated. Patterns of P uptake and results from trials where P has been applied at planting (Ballard, 1978) suggest that the first heavy aerial dressing should be made as soon as the trees are above the competing vegetation, probably at age 3 to 4 years. Further dressing may be required at first thinning (age 7 to 9 years), depending on soil type. Thinning debris will release P slowly to the crop trees (Will, 1968). If N is applied after thinning, growth rates could be stimulated to the extent that extra P may be required, and in this case a mixed N-P fertiliser should be used.

NITROGEN

Growth Responses

The first use of N in established stands in New Zealand was in the 1955 trials at Riverhead Forest. There was no obvious growth response since a low rate (50 kg/ha N) was used in stands where P deficiency had not been completely corrected.

Stone and Will (1965b), Appleton and Slow (1966), Jacks (1970), and Jacks *et al.* (1972) have reported basal area responses to N fertilisers in radiata pine stands on the more weathered Moutere gravel soils of the Nelson region. These early trials involved small, often unreplicated plots but they served to show that growth could be improved by thinning dense regeneration, and by application of N, P and, occasionally, Mg fertilisers. Boron was also needed to prevent dieback. One of these early trials (N143) consisted of three treatments—control, thinning, and thinning + 132 kg/ha—in dense 10- to 12-year-old regeneration. The 0.04-ha plots were assessed for basal area growth and volume using sectional measurement as described by Whyte (1971). The crop trees showed a dramatic response to thinning, plus an additional response to the N fertiliser (Table 8). The total basal area and volume increments were not increased by thinning but were increased by fertiliser in the thinned plots. Foliage analyses and annual basal area trends showed that the response to N was short-lived (Jacks, 1970). Foliage P levels in this stand were marginal (0.12%) and Mg, K, Ca, Zn, Cu and B levels adequate, while N levels were low (1.15%).

Results from early fertiliser trials in stands on the Moutere gravels led to the establishment of two large N × P factorial experiments in 1968 (Mead, 1974a; 1976a). Phosphorus was applied as superphosphate at 0 and 112 kg/ha P and nitrogen as calcium nitrate at 0, 69.5, 139 and 208.5 kg/ha N. A ninth treatment was included (N_3P_1+) in which K, Ca, Mg, Zn, Cu and Mn were added to the high rate of N and P treatment. All plots received a basal dressing of B. Each treatment was replicated six times. Both trials were situated on Mapua hill soils, the most infertile soils of the series formed from Moutere gravels. Trial N190 was in a 40-year-old first rotation radiata pine stand which had been thinned at age 33 years. Trial N191 was established in 14-year-old second rotation regeneration which had been thinned at age 9 years and again immediately prior to plot establishment. Details of the sites and experimental methods (Mead, 1974a; 1976a) have been reported.

In both trials growth was measured annually for 5 years. Plot volumes and volume increments before and after topdressing were determined by stem analysis in order to obtain precise data and to allow for changes in tree form (Mead, 1974a; 1976a; and Whyte and Mead, 1976).

In the older stand (trial N190) annual volume increments in the N_0P_0 and the N_3P_1+ plots were obtained for 5 years before and 5 years following topdressing (Mead, 1974a). In N191 volume data for all plots were obtained, by a double sampling procedure, for 3 years before and 5 years following topdressing (Mead, 1976a).

An analysis of covariance of the basal area data (using initial basal area as the covariate) from the 40-year-old stand (N190) showed a linear response to N but no response to P. There was no interaction between the two nutrients. Basal area was found to be an insensitive measure of fertiliser response because a greater proportion of the extra wood was in the upper portion of the stems (Mead, 1974a; Whyte and Mead, 1976). The trees were tall (predominant mean height ranging from 33 to 46 m) with relatively short crowns. In the N_3P_1 treatment a 12% basal area response was significant at $P \leq 0.05$.

TABLE 8—Summary of growth responses to thinning and 132 kg/ha N in 10- to 12-year-old **P. radiata** regeneration. Mapua hill soil, Nelson region (N143)

	Untreated	Thinned	Thinned + N
Stocking (stems/ha)	6250	790	760
B.A. (m^2/ha) all trees $\geq$ 6.5 cm			
At treatment	18.6	6.9	6.7
+ 3 years	28.2	15.2	17.7
+ 6 years	36.7	24.3	27.3
Incr./year	3.01	2.90	3.43
B.A. (m^2/ha) 247 largest stems			
At treatment	4.4	3.4	3.4
+ 3 years	6.7	7.8	9.0
+ 6 years	9.4	12.6	14.0
Incr/year	0.84	1.53	1.76
Vol (m^3/ha) all trees $\geq$ 6.5 cm*			
At treatment	29.2	5.3	2.1
+ 6 years	144.6	119.2	129.0
Incr/year	19.23	18.98	21.15
Wood density (kg/m^3)	534	486	469

* Based on stem analysis of 8 trees per plot.

Volume response was more marked. A covariance analysis, using pre-treatment volume increments as the covariate, showed that the N_3P_1+ treatment increased volumes over the 5-year period by 59.5 ± 23.34 m^3/ha (95% confidence level), a 62% increase in volume increment (Whyte and Mead, 1976). Stem analysis indicated that some 35% of this extra wood was present in the two bottom logs (0-12 m) and a further 47% in the 12-24 m zone. The response had been rapid (Fig. 3) with volume increments increasing to a maximum in the second and third growing seasons after fertiliser application; the current annual increments (adjusted by covariance analysis) increased from 19.6 m^3/ha in the controls to 35.6 m^3/ha in the complete fertiliser treatment.

The 5-year height increment for the untreated trees was 1.02 m while in the N_3P_1+ treatment the increment was 1.64 m (difference significant at $P \leq 0.05$). Two years after topdressing with the complete fertiliser, N and P levels in the foliage were significantly higher than the controls—N had increased from 1.13% to 1.30% and P from 0.113% to 0.130%. At the end of the fifth year only the P levels were significantly different ($P \leq 0.001$), the level of P in the controls being 0.097% and in the fertilised trees, 0.116%.

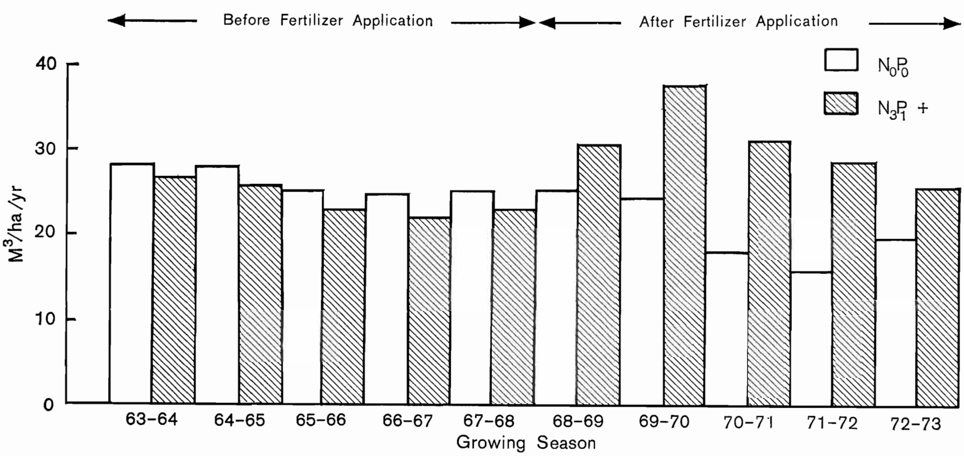

FIG. 3—Mean total volume increments for N_0P_0 and N_3P_1+ treatments applied to 40-year-old radiata pine at Braeburn, Nelson (N190).

In this old stand the response to the fertiliser was substantial. Furthermore a large change in stem form took place. The trial also illustrated that over-mature radiata pine will respond to fertiliser treatment.

In the younger stand the predominant mean height at age 14 years ranged from 15.5 to 23.5 m. Basal area response was more marked than that for the trial in the 40-year-old stand. In both volume and basal area there was a highly significant interaction between N and P as well as highly significant N and P main effects (Table 9). The response in basal area was only slightly less pronounced than the volume response (Fig. 4). Over the 5-year post-topdressing period, basal areas showed responses of 18, 10 and 62% over the N_0P_0 treatment for the N_3P_0, N_0P_1 and N_3P_1+ treatments respectively. Volume responses were 23, 14 and 67% respectively. The total volume

TABLE 9—Summary of the analysis of covariance† for basal area, height and volume data in a 14-year-old stand at Harakeke, Nelson (N191)

Source	df	B.A. (1973)	Height (1972)	Total stem vol. (1968-73 incr.)	Vol. to 6 m ht (1968-73 incr.)
Covariate	1	***	***	***	***
Block	11	*	NS	NS	NS
Treatment	8‡	***	NS	***	***
N	3	***	NS	***	***
P	1	***	*	***	***
N × P	3	***	NS	*	**

† For basal area and height the covariates were 1968 BA and height respectively. For volume the covariate was 1965-68 increment. Gross basal area and volume were used and three plots were excluded as they were windblown in 1970 (see Mead, 1976a).

‡ Analysis of covariance ignoring block effect but with all 9 treatments.

NS Not significant ** Significant at $P \leq 0.01$

* Significant at $P \leq 0.05$ *** Significant at $P \leq 0.001$

response to the highest rate of N + P was equivalent to $93 \pm 37.3\ m^3/ha$ over the 5-year period and almost 40% of this extra volume was in the bottom log (0-6 m). The response was equivalent to an increase in periodic mean annual increment from 28 to $43\ m^3/ha/year$.

The curves for volume response to increasing levels of N fertiliser (P not applied) had a significant quadratic component in the first 3 years after topdressing. By the fourth and fifth year the quadratic component was not significant at normal test levels, even though it was apparent in the means (Table 10, Fig. 4). If we assume that the quadratic component was real, then N_2 or about 140 kg/ha N should be applied to P deficient stands. This would produce a calculated extra $30\ m^3/ha$ of wood over a 5-year period. The application of 208 kg/ha N would produce little extra growth.

TABLE 10—Summary of the analysis of covariance of N response curves in a 14-year-old stand at Harakeke, Nelson (N191)

	Total Stem Volume — Increment period				
(1) Non-phosphate treated plots:					
Component	68-69	68-70	68-71	68-72	68-73
Linear	***	***	***	***	***
Quadratic	**	**	*	(10%)	NS
Cubic	NS	NS	NS	NS	NS
(2) Phosphate treated plots:					
Component	68-69	68-70	68-71	68-72	68-73
Linear	***	***	***	***	***
Quadratic	NS	NS	NS	NS	NS
Cubic	NS	NS	NS	NS	NS

NS Not significant ** Significant at $P \leq 0.01$

* Significant at $P \leq 0.05$ *** Significant at $P < 0.001$

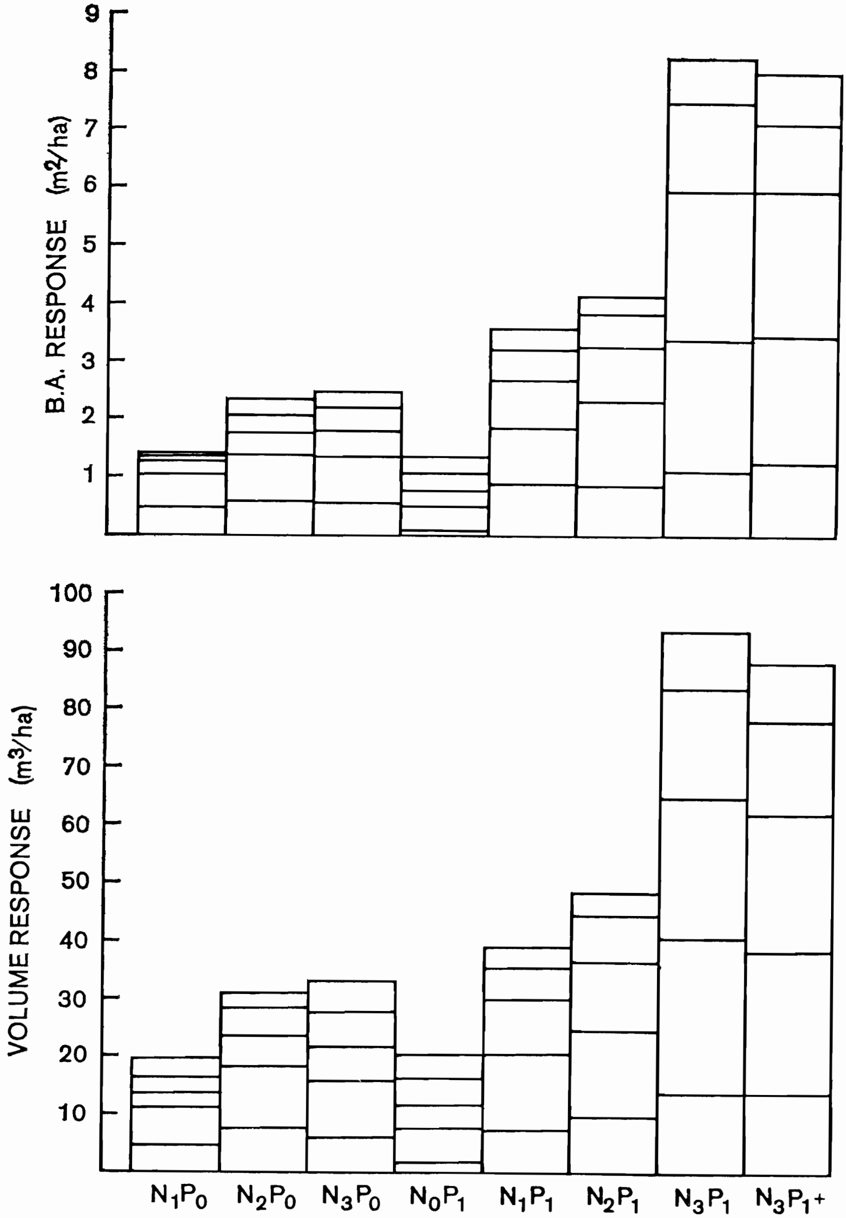

FIG. 4—Response, in terms of increase over control, in basal area and stem volume annual increments for 14-year-old radiata pine at Harakeke, Nelson (N191). Data adjusted by covariance analysis.

In contrast, where the P deficiency was corrected, there was a linear response to increasing N rate and no suggestion of a quadratic component (Table 10). Thus the optimum rate of application is probably in excess of 200 kg/ha N.

There was no height response to added N. Predominant mean height growth was increased by the superphosphate but the increase amounted to only 0.5 m over 4 years.

In the treatments where P was added the pattern of response with time was similar to that found in the older stand, the maximum response occurring in the second and third growing seasons after topdressing (Fig. 4). Foliar analyses indicated that the N levels were increased by the N fertiliser for two growing seasons but P levels were increased by the superphosphate for a longer period. It seems that in these stands N should be applied on a 3- to 5-year cycle, particularly if the crowns have free growing space.

In both stands the addition of N and P produced economically worthwhile results (Mead, 1974a; 1976a). Furthermore, the energy balance in terms of calorie input (fertiliser manufacture, transport and application) to calorie return in extra wood was good (Table 11) and compares well with agricultural data such as those of Pimentel *et al.* (1973). It was higher where P was added as well as N, especially in the younger stand.

TABLE 11—Energy budget for N191 Harakeke and N190 Braeburn, Nelson Conservancy

Experiment	Treatment	Cal return/cal input
N191 (Young stand)	69 kg/ha N	37
	139 kg/ha N	29
	208 kg/ha N	19
	0 kg/ha N + 112 kg/ha P	142
	69 kg/ha N + 112 kg/ha P	57
	139 kg/ha N + 112 kg/ha P	39
	208 kg/ha N + 112 kg/ha P	53
N190 (Old Stand)	208 kg/ha N + 112 kg/ha P	31

In conjunction with these two main trials a series of simpler trials was laid out in other parts of the Nelson Conservancy (Mead, 1976b). Each consisted of three replicates of a control and the "balanced" (N_3P_1+) fertiliser treatment used in N190 and N191; they were located in a wide variety of sites and age classes (Table 12). Similar trials were also established in Balmoral Forest, Canterbury Conservancy (C337) and in Berwick Forest, Southland Conservancy (S244). Volume responses were estimated by sectional measurements on individual trees and conversion of data to plot estimates (Mead, 1976b). Plot basal area and volume data were subjected to covariance analysis using pre-treatment basal area as the covariate. Foliage samples were analysed to determine which nutrients were limiting growth.

Positive basal area and, with the exception of S244 at Berwick, volume responses were obtained in all trials and most were significant at $P \leq 0.10$ (Table 12). This

TABLE 12—Summary of response to a balanced fertiliser mix in **P. radiata** stands in the South Island

Trial No.	Forest	Stand age years	Regen.	Soil type[a]	Rainfall mm/yr	Years of trial	Mean stems/ha	Response to fertiliser (by ANCOVA)[b] Net B.A. (m^2/ha/yr)	Gross B.A. (m^2/ha/yr)	Net Vol. (m^3/ha/yr)	Gross Vol. (m^3/ha/yr)
N262	Golden Downs	6	Yes	Korere h.s. (L.Y.B.E.)	1350	4	1483	1.61**	1.61**	5.9*	5.9*
N239	Pigeon Valley	7	Yes	Rosedale h.s. (L.Y.B.E.)	1200	4	1480	0.75*	0.75*	4.7*	4.7*
S244	Berwick	11	No	Waitahuna s. (Y.G. to Y.B.E.)	750	4	740	0.18†	0.17	—0.7	—0.8
N191	Harakeke	14	Yes	Mapua h.s. (Y.G. to Y.B.E.)	1150	5	698	—	1.59***	—	17.6***
C337	Balmoral	17	Yes	Balmoral s. (Y.G.E.)	650	3	295	0.55	0.74	3.4**	4.5**
N238	Pigeon Valley	23	No	Rosedale h.s. (L.Y.B.E.)	1200	4	494	0.52†	0.51*	14.5†	14.2†
N240	Rai Valley	25	No	Pelorus s.s. (P.Y.B.E.)	2000	4	413	0.38*	0.34†	8.1	8.0
N263	Waiwhero	29	Yes	Mapua h.s. (Y.G. to Y.B.E.)	1200	4	403	0.67†	0.83**	7.1	19.4*
N190	Braeburn	40	No	Mapua h.s. (Y.G. to Y.B.E.)	1150	5	333	—	0.29†	—	11.9***
N261	Golden Downs	44	No	Spooner h.s. (L.Y.B.E.)	1300	4	741	0.17	0.18†	—	12.7[c]

[a] Y.B.E. = Yellow Brown Earth
Y.G.E. = Yellow Grey Earth
L = Lowland
P = Podzolised
s = Soil, h.s. = Hill Soil, s.s. = Steepland Soil

[b] Significance levels
† Significant at $P \leq 0.10$
* Significant at $P \leq 0.05$
** Significant at $P \leq 0.01$
*** Significant at $P \leq .001$

[c] An estimate made by different methods is given in the text

result is important as it indicates that radiata pine will respond to fertilisers under a wide range of climatic, site and silvicultural conditions. Foliage analyses indicated that the responses were due to N or N + P fertilisers. A poor response noted at Rai Valley was consistent with the observation of Woollons and Will (1975) that on high site quality areas the response to N fertilisers is reduced if the fertilisers are not applied within 2 years of thinning. The 25-year-old Rai Valley stand had been thinned 6 years before the fertiliser was applied.

The trial at Balmoral Forest included an extra N + P treatment and this was as effective as the balanced fertiliser (Table 13). In both treatments 215 kg/ha N and 112 kg/ha P were applied. Although the response at Balmoral Forest was considerably smaller than that of intermediate-aged stands elsewhere it represented a considerable increase in increment (36%).

TABLE 13.—Basal area and volume response to N + P fertiliser and a balanced fertiliser at Balmoral Forest (C337)

Treatment	Gross BA 1975* m^2/ha	1972-75 Gross Vol. Inc.* m^3/ha
Control	14.16^a	40.69^a
N + P	16.10^b	56.63^b
N + P + Other Nutrients	16.37^b	54.21^b

* Adjusted means by covariance analysis using initial basal area in 1972 as covariate. Different superscript letters indicate significant differences at $P \leq 0.05$ (Duncan's test).

The response to N fertiliser by radiata pine plantations on yellow-brown pumice soils in the central region of the North Island has been discussed by Woollons and Will (1975). Their data, in contrast to those obtained on Moutere gravels soils and at Balmoral Forest, were taken from very high-producing stands (m.a.i. 25 to 30 m^3/ha) which did not show visual signs of nutrient deficiency. The main conclusions of Woollons and Will (1975) were:

(1) The response was to nitrogenous fertilisers; Mg sometimes produced a fleeting response but P and K were definitely not required (N.Z. Forest Products Limited, trial Nos. 2 and 3).

(2) The response in 13- to 14-year-old plantations was 61 m^3/ha over a 7-year period in a stand thinned to 540 stems/ha. The response was less (36 m^3/ha) when a heavier thinning to 320 stems/ha had been applied (N.Z. Forest Products Limited, trial No. 1).

(3) Two consecutive annual applications of at least 115 kg/ha N were required. One application of 115 kg/ha N was not enough (N.Z. Forest Products Limited, trial No. 5).

(4) Thinning before fertiliser application was essential. N.Z. Forest Products Limited trial No. 4 was in an unthinned stand and produced no response. Fertiliser should be applied within 2 years of thinning.

(5) Growth response was greatest during the first 2 or 3 years after application. However, growth increment in the fertilised plots was still greater than that of the controls after 7 years.

In Kaingaroa Forest an early trial (R246) was established in 6-year-old radiata pine regeneration which had been thinned to 1070 stems/ha. Biannual applications of 112 kg/ha N + 50 kg/ha P + 95 kg/ha K + 56 kg/ha Mg were applied to treated plots. At the fourth dressing only N was applied. Over the first 6 years basal area in the fertilised plots was 2.9 m^2/ha greater than in the controls (Ballard, 1971). This was equivalent to a response of 3.8 m^3/ha/year. Foliage analysis suggested that the response was to N, the foliar N levels being significantly higher in the treated plots.

A second trial at first thinning (age 7 years; height 6.5 m) was established in Kaingaroa in 1974 (R683). This involved four replications of five treatments. Individual plots were 0.08 ha with treated surrounds of 10 m width. Two thinning intensities were studied. In the heavily thinned plots (600 stems/ha), urea was applied at 0, 230 and 460 kg/ha N. In the lightly thinned plots (1000 stems/ha) only two rates of N, 0 and 230 kg/ha were used. An analysis of covariance of mean tree basal areas 2 years after fertiliser application showed (i) a highly significant response to N applied at 230 kg/ha, (ii) a highly significant difference due to thinning, average individual tree basal area growth being higher in the heavily thinned plots, (iii) no interaction between thinning and fertilisation. The very heavy rate of N (460 kg/ha) gave a response which was twice as great as that of 230 kg/ha N in the lower stocked plots (Table 14).

TABLE 14—Basal areas 2 years after topdressing with N in R683 Kaingaroa forest. Data analysed by covariance analysis on a mean tree basis using initial mean basal area as covariate

Treatment	Adj. mean tree BA* (cm^2)	S.E.	Basal area/ha (m^2)
600 stems/ha, 0 kg/ha N	171^c	3.9	10.26
600 stems/ha, 230 kg/ha N	187^b	4.4	11.23
600 stems/ha, 460 kg/ha N	204^a	5.9	12.25
1000 stems/ha, 0 kg/ha N	147^d	2.3	14.75
1000 stems/ha, 230 kg/ha N	169^c	1.4	16.90

* Different superscript letters indicate significant differences at $P \leq 0.05$ using Duncan's test.

Response to fertiliser treatment was also studied in an 11-year-old naturally regenerated stand in Kaingaroa Forest (Will and Woollons, 1975). The stand had been thinned to 620 stems/ha at age 8 years. Mean top height at age 11 years was 16.9 m. The trial (R689) was a 2 × 2 factorial with two stocking rates (620 and 370 stems/ha) and two levels of fertiliser (with and without) replicated four times. A balanced fertiliser was applied in the first spring and urea was applied one year later. Each dressing provided 125 kg/ha N.

Results at the end of the third growing season indicated significant differences in individual tree volumes, but there was no change in tree form (Will and Woollons, 1975). The response to fertiliser was 3.6 m^3/ha/year in the 620 stems/ha plots, while at the lower stocking rate (370 stems/ha) the response was 4.8 m^3/ha/year.

The results of an analysis of covariance of mean tree basal areas 5 years after the initial fertiliser dressing also indicated highly significant responses to fertiliser and stocking. The interaction between the two factors was almost significant at $P \leq 0.10$. These results (Table 15) are very similar to those of the earlier analysis of plot volumes, the response to fertiliser being greater at the lower stocking level. If all plots had been thinned at the same time, the results of Woollons and Will (1975) suggest that the greater response would have been observed in plots with the higher stocking rate. Will and Woollons (1975) concluded from trial R689 that the nature of the response from plots with different stocking rates had been changed by the superimposed difference of interval between thinning and fertiliser application.

TABLE 15—Basal areas at age 16 years in R689 Kaingaroa Forest. Data analysed by covariance analysis on a mean tree basis, using initial mean basal area as covariate

Treatment	Adj. mean tree BA (cm^2)	Basal area/ha (m^2)
370 stems/ha — no fertiliser	689.6	25.56
370 stems/ha — fertiliser	806.5	29.90
620 stems/ha — no fertiliser	587.7	36.31
620 stems/ha — fertiliser	612.2	37.82

Foliage analysis

Optimum foliar N levels cannot be specified from available New Zealand data. Raupach *et al.* (1969) have suggested from Australian studies that 1.70% N is an adequate level for radiata pine but if foliar N levels are higher than 1.4% the chances of a response to N fertiliser are less than 20%. In areas of known N deficiency in New Zealand, such as the Mapua hill soils, foliar N levels are usually lower than 1.3%. In high-producing stands on the pumice plateau where responses to N are obtained, foliar N values are about 1.3-1.4% (Leonard and Wheeler, 1974; Mead and Will, 1976). Foliar N concentrations in some South Island stands which later responded to a balanced fertiliser were sometimes higher than 1.4%. The highest recorded level was 1.70% in trial N262 at Golden Downs (Mead, 1976b). Similarly, a growth response to N was observed in a trial (A334) at Woodhill Forest where foliar N concentration was 1.6% (Mead *et al.,* 1969). Concentrations greater than 1.7% have not been encountered in trial areas in New Zealand.

Silvicultural Considerations and Research Needs

The use of N fertiliser should take into account the demand for N as the stand develops, the length of time over which an application of N is effective, the relationship of the response to silvicultural operations, the influence of N on stand stability and disease and, of course, the economic advisability of fertiliser application.

Nitrogen accumulation by developing pine stands has been studied by Will (1968) and Madgwick (1977). Rate of accumulation is greatest during canopy development, a good stand requiring some 500 kg/ha during the first 10 years. The rate decreases during the second decade, but after thinning, when the crown mass of the remaining trees is expanding, there is again a net accumulation of N in the trees.

The proportion of fertiliser N absorbed by the trees is likely to be low. Studies with other pine species indicate a 10-20% utilisation rate (Nommik, 1966; Baker *et al.*, 1974; Mead and Pritchett, 1975a). In a small study with radiata pine in Nelson Conservancy, Oliver (pers. comm.) accounted for 9.7% of a 300 kg/ha N application in the above-ground parts of the trees (Table 16).

TABLE 16—Nitrogen uptake by 6-year-old radiata pine regeneration at Pigeon Valley (N392)*

Component	Treatment	
	No N	300 kg/ha N
	— — N kg/ha — —	
Current foliage	25.7	41.8
1-year-old foliage	10.4	7.2
Older foliage	1.3	1.7
Branches	5.5	11.9
Stem	8.4	17.9
Total above ground	51.3	80.5

* Study by G. Oliver based on three trees per plot, 8 months after fertiliser application.

The low utilisation rate does not mean that added N is necessarily lost from the ecosystem. More probably it reaches an equilibrium with native soil N and becomes less available to plants (Mead and Pritchett, 1975b). Many soils contain large quantities of total N: for example a yellow-brown pumice soil at Kaingaroa Forest may have 8400 kg/ha N in the total rooting zone, most of it unavailable to trees (Knight and Will, 1970). Thus it is not surprising that a single dressing of N fertiliser will have short-term effects on foliar N levels and tree growth. To sustain higher growth rates, N additions would need to be repeated. Applications should be timed to coincide with periods of rapid tree-crown expansion. Optimum application rates can be determined by relatively simple, long-term management trials (Mead, 1976c) and nitrogen rates trials are currently being established throughout the country for this purpose (Mead, 1974c).

Studies on the economics of fertiliser application indicate that total compounded costs are similar for the same quantity of fertiliser, whether this is applied in infrequent large dressings or in more frequent small dressings (Tustin and Mead, 1974). For a given application interval, compounded costs alter with the total quantity applied over a rotation, with the source of nitrogen and with interest rate.

The current recommendation for established stands is to apply 150-250 kg/ha N within 2 years of thinning. It is also very important to supply other nutrients where these are or are likely to become limiting.

In areas where there is no obvious nitrogen deficiency, priority for topdressing can be given to those stands grown for high value produce (e.g. pruned saw-logs) and areas likely to command an extra premium due to such factors as location or anticipated wood deficit. Management decisions should take into account the change in tree form which occurs with N fertilisers as this will change log assortments.

To optimise N use in forests, research is needed on the following:

1. Definition of the N response curve for different levels of N fertiliser over a wide range of site conditions. This can be achieved by increasing the number of standard N rates trials (Mead, 1974c).
2. The use of N in 3- to 4-year-old stands. The pattern of N accumulation by trees suggests that a first post-planting fertiliser application earlier than at first thinning might be advantageous.
3. The interaction of N fertiliser application with thinning and pruning.
4. The improvement of N fertiliser utilisation by the trees. Multiple dressings (Baker *et al.,* 1974) and foliar application (Bengtson, 1976) show promise in this regard.
5. Criteria for the selection of N fertiliser type with due consideration for alternatives to artificial fertilisers.
6. Investigation of the influence that N application at first thinning may have on N requirement at second thinning.

Legumes (lupins) as an Alternative to N Fertiliser

The yellow-brown sands which occur principally on the West Coast of the North Island have received little attention in the form of fertiliser trials even though inherently they are among the most nitrogen-deficient soils in the country. The reason is that trees planted on these sands benefit from association with marram grass (*Ammophila arenaria* L.) and perennial tree lupin (*Lupinus arboreus* Sims), plants which are used to stabilise the sand before forest establishment.

It is now apparent that the bulk of the N used in tree growth on these sands is fixed from the atmosphere by lupin plants through their symbiotic association with the bacterium *Rhizobium lupini.* Vigorous plants growing amongst marram can fix at least 160 kg/ha N during the first year of growth from seed (Gadgil, 1971a) and while it is unlikely that this rate is maintained, the presence of lupin plants implies a continuing input of fixed nitrogen to the forest ecosystem (Sprent and Silvester, 1973). Fertiliser additions to aid marram establishment (a total of 20 kg/ha N) and additions in rainfall (no more than 10 kg/ha annually—Miller, 1963; Egunjobi, 1971) could not supply the requirements of a forest, and there is no evidence that free-living or rhizosphere organisms fix significant amounts of atmospheric nitrogen (Carter, 1974).

The decomposition products of lupin litter and seedling exudates are known to provide N compounds which radiata pine can use (Gadgil, 1971b). Lupins subjected to stress by shading and insect attack are likely to release N compounds into the soil through root decay, and death of whole plants releases more substantial amounts of N (Gadgil, 1971c).

In sand dune forestry radiata pine is planted into the lupin/marram stand and is released from lupin competition by aerial herbicide application about 6 months later.

Further lupin growth from seed continues unchecked until the year before tree canopy closure (age 4 years) when the trees suppress and kill the lupins. When the trees are thinned a lupin understorey develops from buried seed and persists for about four years. A lupin understorey of similar longevity will also develop after a second thinning (Gadgil, 1971d).

Proof of the importance of lupins as a source of tree N supply came from lupin exclusion trials at Woodhill Forest. In experiment A287, lupins were killed soon after tree planting and further growth from seed was removed. This treatment (0) was compared with others where lupin growth was controlled only by necessary releasing of the trees (L) and where regular fertiliser dressings including 50 kg/ha N twice a year, were applied to plots with (LF) and without (F) lupins. The fertiliser prescription is given in Table 17.

TABLE 17—Fertiliser application rates in Experiment A287, Woodhill Forest in each 2-year period

		Total (kg/ha)	N (kg/ha)
February (Year 1)	Urea	122	51
August (Year 1)	Magamp with K	336	24
	Diammonium phosphate	180	32
	Potassium sulphate	71	—
	Dolomite	207	—
February (Year 2)	Urea	122	51
August (Year 2)	Urea	122	51
	Potassium sulphate	112	—

Regular analysis of radiata pine foliage and visual observations showed that symptoms of N stress occurred only where lupin had been excluded and no fertiliser added (0). The fact that these symptoms did not appear until the sixth year of the trial suggests that all trees were adequately supplied with N up to this point. The residual effect of the lupins in the 0 treatment evidently persisted for 5 years but was not sufficient to meet the demands of the trees when the rate of foliage devlopment was at its greatest and the volume of soil left available for root exploitation was limited (Gadgil, 1976a). Although foliar N levels in the L and F treatments were similar during years 5-7 of the trial (Table 18), growth measurements have indicated that the effect of the F treatment was superior to that of L over this period. However, the LF treatment produced the greatest response, increasing basal area increment of the largest 741 stems/ha by 66% compared with 28% (L) and 38% (F) (D. S. Jackson, pers. comm.). This suggests that neither of the single treatments satisfied the nutritional requirements of the trees at this stage.

Marram grass plays an important role in regulating the N supply to the trees. The avidity of marram for N and its physical ability for sand exploitation are well known

(Willis, 1965). Marram in a 4-year-old radiata pine stand has been shown to contain 50 kg/ha N, almost twice the amount retained by marram in a stand where lupin had failed to develop after aerial herbicide application (Gadgil, 1976b). In the trial already described (A287), marram height measurements and foliar analysis showed that considerable amounts of the N supplied by both lupins and fertiliser were absorbed by the marram. It is almost certain that the treatment differences observed among tree measurements after canopy closure were related to the N released by the decomposing marram plants (Gadgil, 1976a). In this way marram acts as a reservoir for N when tree demand is low, and as a major source of supply when tree demand increases. At this point tree root systems are well developed and are able to exploit the whole area for N.

TABLE 18—Nitrogen Status of **P. radiata** Foliage, Experiment A287, Woodhill Forest

	Year 5 (1972-3)				Year 6 (1973-4)				Year 7 (1974-5)			
	Nitrogen concentration (% oven-dry weight)											
	Aug.	Nov.	Feb.	May	Aug.	Nov.	Feb.	May	Aug.	Nov.	Feb.	May
Lupin and fertiliser (LF)	1.77	1.29	1.52	1.81	1.67	1.56	1.41	1.60	1.54	1.28	1.29	1.28
Lupin (L)	1.65	1.24	1.58	1.67	1.47	1.48	1.36	1.30	1.42	1.15	1.13	1.12
Fertiliser (F)	1.49	1.29	1.52	1.65	1.47	1.43	1.35	1.45	1.47	1.26	1.19	1.31
Lupins excluded (0)	1.59	1.22	1.45	1.53	1.21	1.30	1.22	1.18	1.05	0.90	0.91	1.01
L.S.D. (P = 0.05)	0.56	0.21	0.12	0.15	0.33	0.51	0.20	0.16	0.17	0.10	0.21	0.23

In a further trial at Woodhill Forest (A334), the response to lupins was compared with the response to various rates of N fertiliser (Mead *et al.*, 1969). The experiment was laid out in a relatively high site quality stand thinned to 370 stems/ha at age 9 years. An analysis of covariance of basal area 4 years after the start of the trial (using initial basal area as the covariate) revealed a small but significant response to N and lupins (Table 19). The relatively good N status of the site (foliar N concentrations being 1.6% in the controls) probably accounted for the relatively small response.

Experience with tree lupins or indeed with any other legume in soils other than the

TABLE 19—Treatment means (adjusted by covariance analysis) and standard errors for basal areas at age 13 years (4 years after the start of the trial) in A334, Woodhill Forest

	BA (m^2/ha)	SE
No lupins	18.73^{b}	0.159
Lupins	19.67^{ba}	0.249
56 × 2 kg/ha N*	19.45^{ba}	0.343
112 × 2 kg/ha N*	19.39^{ba}	0.381
213 kg/ha N	20.46^{a}	0.352

* Split dressings; the first dressing was applied as uramite and the second, a year later, as urea. Means followed by the same superscript letters do not differ at P ≤ 0.05 using Duncan's test.

coastal sands is limited. A pilot trial (N150) on N and P deficient Mapua hill soils has indicated that lupins have some potential on these sites (Table 20). Details of the plot are given by Jacks *et al.* (1972).

The use of legumes as a source of N in forestry depends on the maintenance of a fine ecological balance. The legume must be successful, and may require artificial fertiliser to achieve this success. On the other hand it must not be allowed to compete with the tree crop. In soils where leaching or denitrification losses are likely, it is important that the fixed N should be retained until it can be utilised by the trees. In young stands retention might be achieved by the introduction of a third suitable but non-competing plant species. The trees, by assuming total dominance at the time of maximum demand and maximum soil exploitation, would manipulate this source of N supply to advantage.

TABLE 20—Average d.b.h. and basal area 9 years after establishment in N150, Tasman Forest, showing the response to lupins compared to N fertiliser*

Treatment**	Mean d.b.h. (cm)	SE	% BA increase between age 10 and 18***
Control	22.9[b]	0.46	239
PKB	21.8[b]	0.41	248
NPKB	24.1[a]	0.56	319
Lupins + PKB	24.4[a]	0.51	307
Lupins + NPKB	24.1[a]	0.61	300

* Treatments unreplicated; as ANCOVA is based on individual trees within plots, results should be treated with caution.

** 115 kg/ha N, 50 kg/ha P and 50 kg/ha K applied at age 10 and 112 kg/ha P and 9 kg/ha B applied at age 16 years.

*** From Jacks **et al.** (1972).

Means followed by the same superscript letters do not differ at $P \leq 0.05$ using Duncan's test.

OTHER NUTRIENTS

Potassium

Potassium deficiency in radiata pine stands in New Zealand has been recorded on the soils derived from serpentine near Nelson. These soils are very high in magnesium and this produces a K/Mg imbalance in the trees. A trial where K fertiliser was added at planting showed that the imbalance could be corrected (Jacks *et al.,* 1972).

Foliage analyses and visual evidence from conifers growing on some of the impoverished gley podzols (pakihis) on the West Coast of the South Island indicate a possible K deficiency, but there is no experimental evidence of a growth response to K fertiliser. The critical level of K in radiata pine foliage is about 0.4% (Will, 1966).

Magnesium

A transient Mg deficiency in 3- to 12-year-old stands growing on the yellow brown pumice soils at Kaingaroa Forest has been described by Will (1966). The most severe chlorosis occurred in a dry spring after heavy pruning and was corrected by Mg spray.

A small response to K + Mg fertiliser applied to a 14-year-old thinned radiata pine stand in N.Z. Forest Products Limited plantations near Tokoroa has been ascribed to the Mg component (Woollons and Will, 1975). However, in another N, P, K, Mg factorial trial the response was only to N.

Appleton and Slow (1966) have described responses to Mg on Mapua hill soils in Tasman Forest near Nelson. These appeared to be more marked where N was also added. As reported elsewhere in this paper, the balanced fertiliser in two large factorial trials on this soil type (N190, N191) did not show faster growth rates than the N_3P_1+ treatment.

The critical level of Mg in foliage is 0.06 to 0.08% (Will, 1966). Levels in or below this range have been found in some Westland forests but there is no record of a response to Mg fertiliser. When these stands are being topdressed with other nutrients, Mg is sometimes added to the fertiliser mix at the rate of 30 to 50 kg/ha.

Calcium

As with K and Mg good experimental evidence for calcium deficiency in New Zealand forests does not exist. Symptoms usually associated with Ca deficiency in pines are common in some of the forests in North Auckland which have been described as severely P deficient. Superphosphate contains appreciable quantities of Ca and use of this fertiliser would correct both deficiencies.

Copper

Copper deficiency has been found in radiata pine forests on sand-dunes at Mangawhai (Will, 1972) and Aupouri Forests in North Auckland. The application of 5 kg/ha Cu has corrected this deficiency. A level of 2.5 to 3 ppm Cu in the foliage is required to prevent leader twisting.

Boron

Boron deficiency results in repeated leader dieback and thus reduced height growth and malformation. In areas of severe deficiency the trees may be unmerchantable. On less deficient sites the number of malformed trees can make selection at thinning difficult. Lower yields and poorer-grade returns may result. No attempt has been made to quantify these losses although cost-benefit analyses are required.

The correction of B deficiency by the application of B fertilisers is simple, and trees quickly regain their normal pattern of apical growth (Stone and Will, 1965a; Appleton and Slow, 1966). A single application may be effective for a number of years. An unreplicated pilot trial (N209) laid out in 7-year-old B-deficient radiata pine growing on Rosedale hill soils at Waiwhero, Nelson, and the results of a more comprehensive trial (N228) laid out at age 9 years in the same compartment, illustrate the results that can be obtained (Tables 21 and 22).

In both trials the various B fertilisers reduced the incidence of dieback for 5 years. The higher rates of B usually resulted in higher foliar B levels and the application of other nutrients (N and P) also increased B uptake (Table 22). The best growth responses were observed where P and B were applied together. Both trials consisted of very small plots without treated surrounds. Cost-benefit evaluation was therefore impossible.

A current trial (N305) has been designed to study the influence of N, P and B fertilisers on foliar B level. Initial results confirm that N fertiliser enhances B fertiliser

TABLE 21—Results of applying B and other fertilisers to 7-year-old radiata pine at Waiwhero Forest (N209)

Treatment	Dieback age 12 (%)	Ht. (m) age 7	Ht. (m) age 12	Foliar B age 14 (ppm)
Control	100	3.4	7.3	5
224 kg/ha N	50	3.4	7.9	11
112 kg/ha Mg	100	2.1	4.9	9
112 kg/ha P	75	2.1	7.0	11
4.3 kg/ha B*	10	2.7	8.2	14
13.0 kg/ha B**	10	2.1	8.2	22

* Applied as a spray, borax solution being applied at 1350 litres/ha.
** Applied as borax powder.

TABLE 22—Results of applying B fertilisers to 9-year-old radiata pine at Waiwhero, Nelson (N228)

Treatment	Dieback age 14 (%)	3 year diam. incr (mm)*	Foliar B (ppm) age 13	Foliar B (ppm) age 14
Control	57	33.0^{d}	7	9
Timbor — 2.5 kg/ha B**	3	34.8^{d}	14	26
Timbor — 5 kg/ha B**	9	42.7^{c}	24	29
Timbor — 10 kg/ha B**	5	46.5^{b}	26	30
Boronated superphosphate (3 kg/ha B + 112 kg/ha P)	0	53.0^{a}	29	34
B. super + Timbor** (8 kg/ha B + 112 kg/ha P)	0	54.6^{a}	38	30
B. super + urea (3 kg/ha B + 112 kg/ha P + 220 kg/ha N)	8	53.0^{a}	27	35
Weed control	35	40.4^{c}	10	14

* Data analysed by covariance analysis; different superscript letters indicate significant differences at $P \leq 0.05$.
** Applied in 1350 litres/ha water.

uptake (Knight, pers. comm.). Other trials investigating optimum application rates and foliage levels have also been established recently.

Boron deficiency is widespread in the South Island and B fertiliser is currently being applied in all South Island Conservancies. Current management application rates vary from 4 to 12 kg/ha B and P is also applied if it limits growth. Although B was sometimes applied as a spray in the 1960s, solid forms are now invariably used. In areas of severe B deficiency the first broadcast applications may be made as early as 2 or 3 years of age.

Foliage analyses are used to decide which forest areas should be topdressed with B. A level of 9-12 ppm is considered to be marginal particularly in dry regions.

Other Minor Elements

Trials with Zn were established in the early 1950s as a result of Australian experience. There were no indications of a response to this nutrient, and subsequent needle analyses from many parts of New Zealand have indicated adequate Zn levels.

Deficiencies of S, Mn, and Fe have not been recorded in established stands in New Zealand.

GENERAL CONCLUSIONS

In the preceding sections an attempt has been made to present a detailed description of the results of fertiliser trials in established stands and to describe current management practices. Outstanding features are:

1. Fertilisers have been effective in allowing the forest industry to produce fast-growing radiata pine plantations in nutrient deficient areas. Use of N, P and B fertilisers is widespread but there is still considerable room for expansion, particularly in the use of nitrogenous fertilisers.
2. Where P is the main limiting nutrient the practice of basing P applications on periodic foliage tests is well founded. The technique is flexible in that it may be used for all site and silvicultural conditions.
3. Good economic evaluation of management alternatives with phosphate fertilisers must await growth data from current trials.
4. It is apparent that on some P deficient sites a single dressing of P at 55 to 110 kg/ha will be sufficient for a rotation. On other sites several dressings may be required in the first rotation.
5. The need to correct N deficiency on soils derived from the Moutere gravels in the Nelson region has now been established beyond doubt.
6. Current foliage analysis methods do not provide a sound basis for N fertiliser application. A programme testing N fertiliser regimes to determine optimum application rates for a wide range of sites has been started.
7. Fertilisers, particularly N, are now being used to increase production on stands which do not show obvious signs of a deficiency (e.g., N.Z. Forest Products Limited forests on yellow-brown pumice soils). The results from trials on a wide range of sites indicate that N responses are likely in many situations.
8. To obtain the maximum benefit from fertiliser N it is important to apply it during periods of canopy development. Thus on fertile sites it is important to apply N fertilisers within 2 years of thinning.
9. The importance of perennial tree lupin in increasing the N status of trees in sand dune forests is now well established.
10. The use of B fertilisers to correct malformation resulting from dieback of the terminal leader is now accepted in many forests in the South Island. Current practice is to recommend fertiliser treatment when foliar B levels are low and deficiency symptoms are present. Trials have been started to evaluate the effectiveness of different rates of this nutrient.
11. The recommended application rates for various nutrients are:
    N — 150 to 250 kg/ha applied when the tree canopy is developing. Repeat applications may be required after 3 to 5 years.
    P — 55-75 kg/ha on sites which are marginally P deficient: 75-125 kg/ha on severely P deficient areas. Soil characteristics should be taken into account.
    Foliar P concentration should be kept above 0.12%.
    K — 50 to 100 kg/ha.
    Mg — 30 to 50 kg/ha.
    B — 4 to 12 kg/ha.
    Cu — 5 kg/ha.
12. The main requirements for research on the use of fertilisers in established stands are the continuation of current foliage nutrient surveys and the use of fertiliser trials of standard

design. Information from these investigations will be used to define areas of similar nutrient status. Subsequent studies in these areas will be designed to produce fertilisation programmes integrated with management requirements and silviculture. Good growth data are required from these studies so that satisfactory economic evaluations can be made. Trials will also provide a basis for further development and calibration of foliage and soil analysis techniques.

13. Research into methods of increasing fertiliser effectiveness is needed. The wider use of legumes as an alternative to nitrogenous fertilisers should also be investigated.

14. The use of broadcast N and P fertiliser dressings at age 3 to 4 years is in need of investigation. Heavy dressings at this age have not been studied although nutrient uptake studies suggest that they could be important.

REFERENCES

APPLETON, E. J. and SLOW, L. J. 1966: Nutritional disorders and fertiliser trials in **Pinus radiata** stands in Waimea county, Nelson. **N.Z. J. For. 11:** 185-201.

BALLARD, R. 1971: Complete fertiliser trials—Kaingaroa Forest (R246, R914). **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 21** (unpubl.).

——— 1978: Use of fertilisers at establishment of exotic forest plantations in New Zealand. **N.Z. J. For. Sci. 8(1):** (In press).

BALLARD, R. and WILL, G. M. 1971: Distribution of aerially applied fertiliser in New Zealand forests. **N.Z. J. For. Sci. 1:** 50-59.

BAKER, J. B., SWITZER, C. L. and NELSON, L. E. 1974: Biomass production and nitrogen recovery after fertilisation of young loblolly pines. **Soil Sci. Soc. Amer. Proc. 38:** 958-61.

BEEKHUIS, J. 1966: Predictions of yield and increment in **Pinus radiata** stands in New Zealand. **N.Z. For. Serv., Technical Paper 49:** 40 pp.

BENGTSON, G. W. 1976: Fertilisers in use and under evaluation in silviculture: A status report. Paper presented to IUFRO Congress, Norway.

CARTER, D. A. 1974: Factors affecting nitrogenase activity of yellow lupin (**Lupinus arboreus**) over an annual cycle at Woodhill State Forest. M. Sc. Thesis, University of Auckland, New Zealand.

CONWAY, M. J. 1962: Aerial application of phosphate fertilisers to radiata pine forests in New Zealand. **Comm. For. Rev. 41:** 234-45.

EGUNJOBI, J. K. 1971: Ecosystem processes in a stand of **Ulex europaeus** L. II. The cycling of chemical elements in the ecosystem. **J. Ecol. 59:** 669-78.

GADGIL, R. L. 1971a: The nutritional role of **Lupinus arboreus** in coastal sand dune forestry. III. Nitrogen distribution in the ecosystem before tree planting. **Plant & Soil 35:** 113-26.

——— 1971b: The nutritional role of **Lupinus arboreus** in coastal sand dune forestry. I. The potential influence of undamaged lupin plants on nitrogen uptake by **Pinus radiata**. **Plant & Soil 34:** 357-67.

——— 1971c: The nutritional role of **Lupinus arboreus** in coastal sand dune forestry. II. The potential influence of damaged lupin plants on nitrogen uptake by **Pinus radiata**. **Plant & Soil 34:** 575-93.

——— 1971d: Lupin productivity in **Pinus radiata** stands at Woodhill. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 26** (unpubl.).

——— 1976a: The influence of lupins, fertiliser application and stocking reduction on the nitrogen nutrition of **Pinus radiata** in Plot A287, Woodhill. 3. 4-6 years. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 71** (unpubl.).

——— 1976b: Nitrogen distribution in stands of **Pinus radiata** with and without lupin in the understorey. **N.Z. J. For. Sci. 6(1):** 33-9.

JACKS, H. 1970: Guide to current soils and nutrition experiments in the province of Nelson. **N.Z. For. Serv., For. Res. Inst., Soils and Nutrition Rep. 16** (unpubl.).

JACKS, H., FITZGERALD, R. E., KEIZER, R. and PHIBBS, S. B. 1972: Results of soils and nutrition experiments in Nelson for 1972. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 41** (unpubl.).

KNIGHT, P. J. and WILL, G. M. 1970: An appraisal of nutrient supplies available for tree growth in a pumice soil. **Earth Science Journal 4:** 1-16.

LEONARD, J. H. and WHEELER, P. J. 1974: Foliage analysis associated with forest fertilisation trials. pp. 3-13. **In** "Fertilising Forests". A. S. Edmonds and B. J. Allison (Eds). University of Waikato, Hamilton.

MADGWICK, H. A. I. 1977: Nutrient uptake in an age series of radiata pine plantations. **In** Use of fertilisers in New Zealand Forestry. **N.Z. For. Serv., For. Res. Inst. Sympos. 19.**

MEAD, D. J. 1968: A growth study in an aerially topdressed **Pinus radiata** stand at Riverhead Forest. **N.Z. J. For. 13(2):** 229-38.

——— 1972: Foliage analysis 2. A review of its use in management. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 40.** (unpubl.).

——— 1974a: Fertiliser response in a mature stand of radiata pine at Braeburn, Nelson. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 55** (unpubl.).

——— 1974b: Response of radiata pine to superphosphate and Christmas Island "C" phosphate fertilisers. **N.Z. J. For. Sci. 4(1):** 35-38.

——— 1974c: Standardised methods for forest fertiliser trials. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 50** (unpubl.).

——— 1976a: Fertiliser response in 14-year-old radiata pine at Harakeke, Nelson (N191). **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 69** (unpubl.).

——— 1976b: Trials with a balanced "complete" fertiliser in established radiata pine stands in the South Island. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 76** (unpubl.).

——— 1976c: Design of fertiliser trials for management decisions. Paper presented at IUFRO Congress, Norway.

MEAD, D. J., GADGIL, RUTH L., RENNIE, P. J. and WILL, G. M. 1969: The response of radiata pine to thinning and the presence of lupins. **N.Z. For. Serv., For. Res. Inst., Silviculture Rep. 119** (unpubl.).

MEAD, D. J. and PRITCHETT, W. L. 1975a: Fertiliser movement in a slash pine ecosystem. I. Uptake of N and P and N movement in the soil. **Plant & Soil 43:** 451-65.

——— 1975b: Fertiliser movement in a slash pine ecosystem. II. N distribution after two growing seasons. **Plant & Soil 43:** 467-78.

MEAD, D. J. and WILL, G. M. 1976: Seasonal and between-tree variation in the nutrient levels in **Pinus radiata** foliage. **N.Z. J. For. Sci. 6(1):** 3-13.

MILLER, R. B. 1963: Plant nutrients in hard beech. III. The cycle of nutrients. **N.Z. J. Sci. 6:** 388-413.

NOMMIK, H. 1966: The uptake and translocation of fertiliser N^{15} in young trees of Scots pine and Norway spruce. **Studia For. Suecia 35** 18 pp.

PIMENTEL, D., HURD, L. E., BELLOTTI, A. C., FORSTER, M. J., OKA, I. N. SHOLES, O. D. and WHITMAN, R. J. 1973: Food production and the energy crisis. **Science 182:** 443-9.

RAUPACH, M., BOARDMAN, R. and CLARKE, A. R. P. 1969: Growth rates of **Pinus radiata** D. Don in relation to foliar levels of nitrogen and phosphorus for plantations in the South-east of South Australia. **CSIRO Soil Public. 26.** 28 pp.

SPRENT, J. I. and SILVESTER, W. B. 1973: Nitrogen fixation by **Lupinus arboreus** grown in the open under different aged stands of **Pinus radiata**. **New Phytologist 72:** 991-1003.

STONE, E. L. and WILL, G. M. 1965a: Boron deficiency in **Pinus radiata** and **P. pinaster**. **For. Sci. 11:** 425-33.

——— 1965b: Nitrogen deficiency of second generation radiata pine in New Zealand. pp. 117-39. **In** "Forest-soil relationships in North America". C. T. Youngberg (Ed.). Oregon State Univ. Press, Corvallis, Oregon.

TUSTIN, J. R. and MEAD, D. J. 1974: Fertilisation as a management tool in Bay of Plenty radiata pine plantations. pp. 123-35. **In** "Fertilising Forests". Edmonds A. S. and Allison, B. J. (Eds.). University of Waikato, Hamilton.

WESTON, G. C. 1956: Fertiliser trials in unthrifty pine plantations at Riverhead Forest. **N.Z. J. For. 7:** 35-46.

——— 1958: The response of radiata pine to fertilisers. **N.Z. Soc. Soil Sci. Proc. 3:** 13-19.

WHYTE, A. G. D. 1971: Sectional measurement of trees: A rationalised method. **N.Z. J. For. Sci. 1:** 74-79.

WHYTE, A. G. D. and MEAD, D. J. 1976: Quantifying responses to fertiliser in the growth of radiata pine. **N.Z. J. For. Sci. 6(3):** 431-42.

WOOLLONS, R. C. and WILL, G. M. 1975: Increasing growth in high production radiata pine stands by nitrogenous fertilisers. **N.Z. J. For. 20(2):** 243-53.

WILL, G. M. 1965: Increased phosphorus uptake by radiata pine in Riverhead Forest following superphosphate applications. **N.Z. J. For. 10(1):** 33-42

——— 1966: Magnesium deficiency: the cause of spring needle-tip chlorosis in young pines on pumice soils. **N.Z. J. For. 11:** 88-94.

——— 1968: The uptake, cycling and removal of mineral nutrients by crops of **Pinus radiata. Proc. N.Z. Ecol. Soc. 15:** 20-4.

——— 1972: Copper deficiency in radiata pine planted on sands at Mangawhai Forest. **N.Z. J. For. Sci. 2:** 217-21.

WILL, G. M. and WOOLLONS, R. C. 1975: Fertiliser trials in forests on pumice soils: A position report, February 1975. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 63** (unpubl.).

WILLIS, A. J. 1965: The influence of mineral nutrients on the growth of **Ammophila arenaria. J. Ecol. 53:** 735-45.