GROWTH AND NUTRITION OF PINUS RADIATA ON RHYOLITIC TEPHRA AS AFFECTED BY MAGNESIUM FERTILISER

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ABSTRACT

An area of **Pinus radiata** D. Don with extreme magnesium deficiency in southern Kaingaroa State Forest was treated with a mixture of ground dolomite ($CaCO_3.MgCO_3$) and Epsom salts to supply 100 kg Mg/ha. Recovery in tree appearance and growth was slow but by 2 years after treatment a strong response was noticeable. Over a 5-year period trees treated with dolomite (750 kg/ha) and Epsom salts (200 kg/ha) grew 66% more in height and 45% more in diameter than untreated trees.

Biomass determinations 5 years after fertiliser application showed that treated trees had taken up 29 kg Mg/ha more than untreated trees. Although magnesium was probably the major growth-limiting nutrient at this site, the particular amendments used to remedy the deficiency included other nutrients (calcium and sulphur) that may have been in short supply. The dolomite component may also have affected soil dynamics by its liming action. Slight boron deficiency was induced in the magnesium-treated pines.

Keywords: magnesium; fertiliser; dolomite; Epsom salts; pumice soil; **Pinus radiata.**

INTRODUCTION

New Zealand lies in a zone of crustal subduction. The predominantly acidic magmas which have resulted from melting of sinking crustal material have forced their way to the surface through the numerous volcanic vents of the central North Island. The most recent eruption of a major complex of vents near Lake Taupo occurred about 1900 years ago and deposited a great depth of acid rhyolitic pumice over much of the central part of the North Island (Pullar & Birrell 1973), called the Taupo Pumice formation. Approximately 35% of New Zealand's exotic forest is planted on soils derived from Taupo Pumice which thins out towards the north away from its sources. In northern Kaingaroa Forest the thinner deposit is friable and overlies older more weathered tephra but in southern Kaingaroa the Taupo Pumice is much thicker (up to 6 m). It consists of coarse, angular, often-compacted pumice called flow-tephra which locally has a thin capping of water-sorted pumice.

Tree planting in Kaingaroa Forest began in the 1920s and well over 100 000 ha had been planted by the late 1930s. The northern part of the forest was planted in *Pinus radiata* but the southern part, after failures due to frost, was planted in other species – *Pinus ponderosa* C. Lawson, *Pinus contorta* Loud., *Pinus nigra* Arn. The growth of these latter species was always disappointing and they were not managed or studied intensively. They may have avoided nutritional problems either because they were less demanding or because of their slow growth rate. On the other hand, because of the low intensity of management, undetected nutritional problems may have been present.

Magnesium deficiency symptoms were observed in northern Kaingaroa in the 1960s. Severe symptoms occurred in Kaingaroa nursery and were corrected by magnesium fertiliser (Will 1961). Slight symptoms (yellow tips to previous years' needles) occurred in young trees, particularly just after pruning. However, the trees were, with time, able to strike down through the rhyolitic material into the buried topsoils of older, slightly more weathered tephra which contained sufficient magnesium (Will 1966).

Advances in site preparation (Menzies *et al.* 1981) made it possible to plant *P. radiata* in the southern part of Kaingaroa as the other species were harvested from 1970 onwards. Despite the fact that the main soil type of southern Kaingaroa (Kaingaroa sand) had been shown to be extremely low in cation exchange capacity, exchangeable magnesium, and reserve magnesium (New Zealand Soil Bureau 1968), the young *P. radiata* crop grew satisfactorily without overt symptoms of magnesium deficiency for several years. Foliar analysis of several stands of young trees in that part of the forest between 1976 and 1980 showed widespread low concentrations of only 0.06% Mg compared with 0.10% Mg in northern Kaingaroa (Hunter *et al.* 1985). By 1980 patches of severe magnesium deficiency were noted in 6-year-old *P. radiata.* At this stage most of the affected area was aerially topdressed with dolomite. However, as the symptoms of magnesium deficiency were more severe than those previously observed in the field a small area (approximately 10 ha of trees) with extreme symptoms (depressed height growth, limited retention of brown-tipped yellow foliage, and dead lower branches) was left untreated and reserved for experimentation. The present study was subsequently established in the reserved area and was designed (1) to find out whether the disorder could be corrected by the application of magnesium compounds and (2) to measure tree growth responses to the fertiliser tested.

METHODS

Site Selection

An area of 6-year-old unpruned, unthinned *P. radiata* displaying severe symptoms was selected. The trees on the site were stunted, malformed, sparsely foliaged, and averaged only 2.2 m in height. The site was bare of any other vegetation, with rubbly pumice exposed on the surface.

Fertiliser Trial

Twelve 20 × 20-m plots were established. An inner measurement plot of 14 × 14 m was laid out, containing an average of 30 trees (1500 stems/ha). The plots were grouped into four blocks, each of three plots, and to these plots one of the following three fertiliser treatments was broadcast by hand in October 1980:

(1) Control – no fertiliser

(2) ED – 100 kg Mg/ha (25% as Epsom salts 13% Mg, 75% as dolomite ($MgCo_3.CaCO_3$ – 10% Mg and 25% Ca))

(3) ED+ – magnesium as in (2) plus a compound fertiliser, a mixture of diammonium phosphate and Hoechst Complesal, containing 90 kg N/ha, 100 kg P/ha, 50 kg K/ha, 8 kg Ca/ha, 8 kg Zn/ha, 20 kg Mn/ha, and 5 kg B/ha.

Tree Measurement

The trees were remeasured each winter. Because of the very high degree of malformation and multi-leadering and the small size of many of the trees we departed from the normal forestry practice of measuring breast height diameter and measured root collar diameter, in the interests of repeatability. Breast height diameter was measured only once, in 1985, at the conclusion of the experiment. All tree heights were also measured.

Foliage Sampling

Foliage samples were collected annually from the standard sampling point – upper crown current foliage on secondary branchlets – in late summer to early autumn and were analysed for nitrogen, phosphorus, potassium, calcium, magnesium, manganese, zinc, boron, and copper using the methods outlined by Nicholson (1984).

Biomass Determinations

In December 1984, three trees per plot from the control and the ED treatments, were selected by random tree numbers, felled, and divided into foliage age classes, live branches and dead branches, stemwood and bark. The root system of one tree in each plot was excavated to the limit of vertical root development. Horizontal roots were cut off 1 m from the stump. Roots and stumps were weighed separately. All components were oven dried; subsamples were ground and analysed for nitrogen, phosphorus, potassium, calcium, magnesium, and boron. Plot weights were estimated using the basal area ratio method (Madgwick 1981).

Mobility of Magnesium, Calcium, and Boron in Stem Sections

To study the mobility of magnesium, calcium, and boron in the stem of the tree, randomly selected bole sections, complete with bark, were cut from each biomass sample tree. A subsample was taken from one end for chemical analysis. The sections were approximately 15 cm in length and varied in diameter from 10 to 20 cm approximately. The volume of each section was calculated and each section was then sealed into a glass funnel. Firstly, distilled water was pulled through the section by vacuum to three times the section volume. A further subsample was cut off the end of the section. Then 1 N sodium nitrate was pulled through by vacuum until three times the stem section volume had passed through, and a final sample was taken.

Soil Sampling

Soil pits 50 × 50 cm were excavated down to the average maximum rooting depth (60 cm). The soil removed was weighed wet and separated into size fractions greater and less than 2 mm in order that the degree of stoniness could be calculated (after derivation of an air-dry : wet-weight ratio). Subsamples of each soil size fraction were analysed for total magnesium, calcium, silicon, aluminium, sodium, potassium, sulphur, phosphorus, manganese, and iron by X-ray fluorescence (XRF) and for available magnesium by the Bray-2 method, as described by Nicholson (1984), and by an acid digest. One gram of soil was boiled with 25 ml of 1 N HCl for 15 min, then filtered, and diluted to 50 ml.

Litter and Forest Floor Sampling

Five 0.5-m^2 litter traps were exposed in each control and ED plot in April 1984 and litter was collected regularly from them for 1 year. In addition, eight 0.25-m^2 forest floor samples were collected from each control and ED plot in autumn 1985. After oven-drying and chemical analysis, the amount of magnesium, calcium, and boron in the forest floor and litter collected in traps was calculated.

RESULTS

Foliar Nutrient Analysis

At the time the trial was laid out it was noticed that many trees had needles with green base sections, yellow mid sections, and necrotic brown tips. A collection of such needles was made and divided into the three differently coloured sections for analysis (Table 1).

All tested elements are at adequate levels except for magnesium and possibly calcium (Will 1985). Although necrotic tips associated with high micronutrient concentrations have been reported elsewhere (such as boron in excess of 40 ppm – Stone & Will 1965), the micronutrient levels shown above are not excessively high. Hence, the change from green through yellow to brown along the needle is probably caused by acute magnesium (possibly calcium) stress.

TABLE 1—Chemical analysis of needle sections

Section	N	P	K	Ca	Mg	B	Mn	Zn	Cu
	(% d.w.)					(ppm d.w.)			
Green base	1.37	0.13	0.94	0.05	0.03	9	180	38	26
Yellow middle	1.39	0.12	0.75	0.03	0.02	12	137	23	9
Brown tip	1.83	0.15	0.71	0.04	0.02	15	164	26	11

The change in foliar magnesium over time for all three treatments is shown in Fig. 1. In the controls foliar magnesium remained fairly constant at 0.03–0.04%. Foliar magnesium in the treated plots rose only slowly, taking 2 years before it exceeded the critical deficiency level of 0.08%. This result is surprising considering that 25 kg Mg/ha were applied as very water-soluble Epsom salts. Foliar magnesium continued to rise

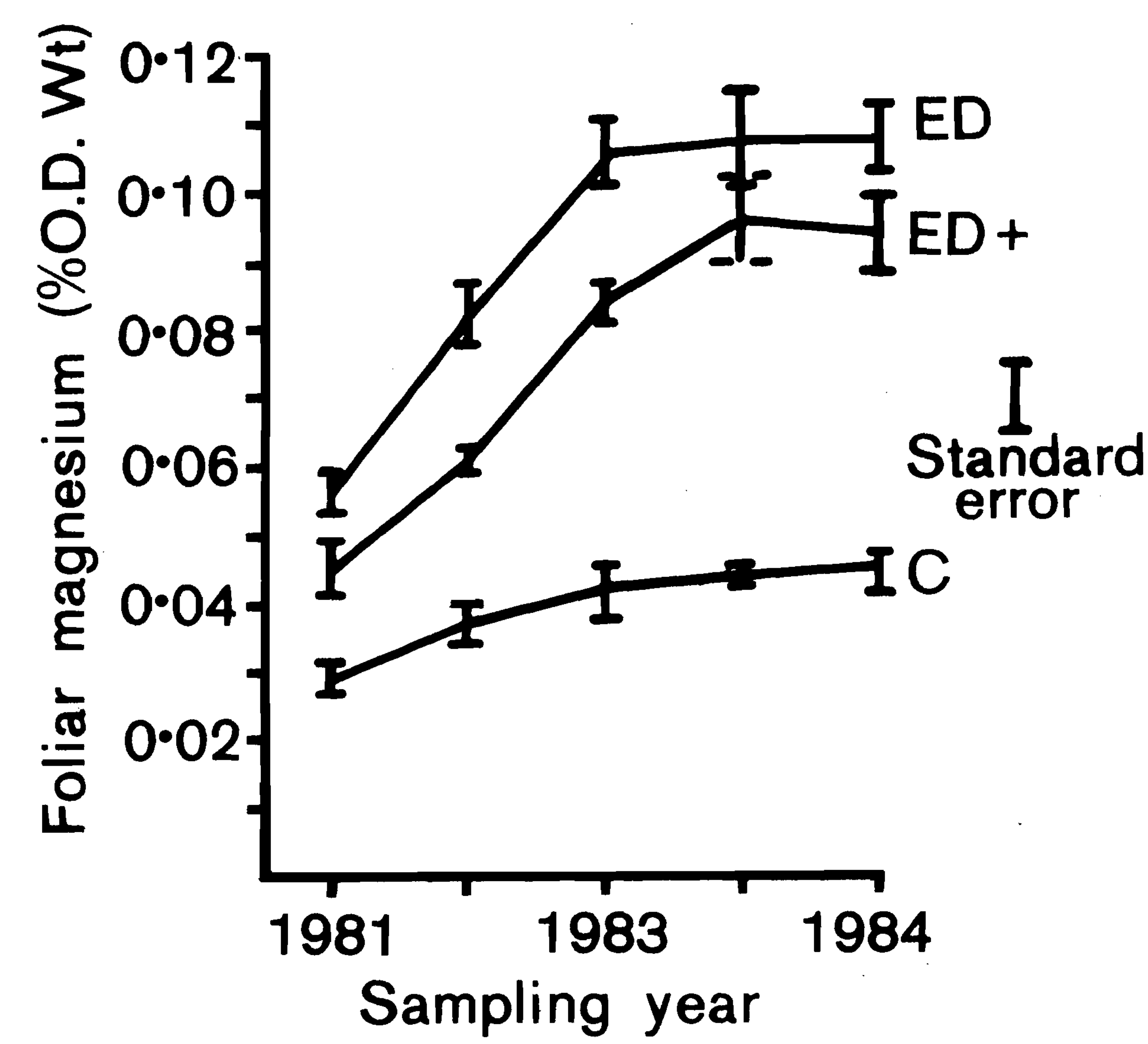

FIG. 1—Change of foliar magnesium concentration (% oven-dry weight) with time.

until 1984 reaching a peak of 0.11% in the ED treatment but only 0.095% in the ED+. It is not clear why the two treatments differed in this respect, although it may have been because of interaction with other nutrients.

The mean nitrogen concentrations for all treatments fluctuated from 1.5 to 1.7% during the trial. Phosphorus concentrations increased from an average 0.11% at the start of the trial to 0.15% at the end; they were unaffected by treatment and seem unlikely to have been growth limiting. Potassium concentrations declined from an average of 0.8% in the controls to 0.5% in the ED plots. The ED+ plots (which had received potassium fertiliser) averaged 0.7%. The lowest potassium of 0.43% in one ED plot was marginal but unlikely to be growth limiting. Manganese, copper, and zinc concentrations averaged 420, 7, and 35 ppm respectively and appear to be unaffected by treatment.

Foliar calcium was markedly affected by the fertiliser, being increased from an average of 0.09% in the controls to 0.13% and 0.12% respectively in the ED and ED+ plots in the first year. These results are not unexpected since dolomite contains 25% calcium. Foliar calcium in the treated plots remained higher than in the controls throughout the experiment although it declined on average in these plots to 0.11% by 1985. Two of the four controls regularly had very low calcium concentrations averaging 0.07% to 0.08%. The marginal concentration of foliar calcium for *P. radiata* is thought to be about 0.1% but there appears to be little field evidence of fertiliser response in *P. radiata* crops below this concentration. Very recently Nys (1984) reported an unprecedented calcium fertiliser response in *Picea abies* (L.) Karst. with a foliar calcium level of 0.23% in the untreated plots.

By 1981 foliar boron was markedly affected by treatment, being reduced from 13 ppm in the controls to 9 ppm in the ED plots while increasing to 21 ppm in the ED+ treatments. In 1983 foliar boron averaged 7 ppm in the ED plots as against 12 ppm in the controls and 21 ppm in the ED+ treatments. By 1985 the boron concentration had decreased further to 5 ppm in the ED plots and dieback of the type usually associated with boron deficiency was fairly frequent.

Tree Growth

Tree growth effects were slow to emerge, probably because of the slow rise in foliar magnesium and the need to replace the inefficient chlorotic and necrotic foliage of the crown with fully functioning green needles.

Over the 5 years of the trial the magnesium-treated trees grew 66% more in height (Table 2) and 45% more in root-collar basal area (Table 3) than the controls. Since there was little difference in growth between the ED and ED+ treatments, the ED+ was omitted from the nutrient cycling and nutrient uptake studies (in order to reduce the workload to a manageable level).

TABLE 2—Mean tree height (m)

Treatment	Year					
	1980	1981	1982	1983	1984	1985
Control	2.18	2.68	3.29	3.58	4.05	4.44
ED	2.18	2.73	3.68	4.36	5.09	5.94
ED+	2.18	2.69	3.59	4.31	5.03	5.68
Significance	Covariate	ns	*	**	*	*

ns Not significant
* Difference significant at $p < 0.05$
** Difference significant at $p < 0.01$

TABLE 3—Basal area (m^2/ha)

Treatment	Root collar						Breast height
	1980	1981	1982	1983	1984	1985	1985
Control	6.6	10.0	14.0	17.7	21.8	24.2	9.7
ED	6.6	10.0	15.3	22.5	28.9	32.2	14.4
ED+	6.6	10.3	15.9	22.9	29.9	33.4	14.9
Significance	Covariate	ns	<0.1	*	*	*	*

ns Not significant
* Difference significant at $p < 0.05$

1985 Biomass Estimation

Dry weight

The dry weight data (Table 4) show the effect of magnesium on the length of time that live needles are retained on the tree. Immature foliage in the treated plots weighed just less than twice that in the control plots while the 2+ year foliage was 10 times greater in the treated plots. Dead foliage weight was greater in the control plots, although not significantly so.

There were significantly more live branches in the magnesium-treated plots and more dead ones in the controls.

The dry weight of the forest floor was 5400 kg/ha in the controls and 6520 kg/ha in the ED (difference not significant). There was an aggregate of 1980 kg litter/ha collected in traps in the control plots and 4260 kg/ha in the ED plots ($p = 0.09$).

TABLE 4—Dry weight (kg/ha) by tree biomass component

Component	Treatment				Probability of significant difference
	Control		ED		
Immature foliage	910		1 725		0.04
1 yr foliage	1 099		3 647		0.01
2+ yr foliage	173		1 732		0.09
Total live		2 182		7 104	
Live branches	5 516		15 848		0.02
Stem wood	10 695		15 782		0.16
Stem bark	2 018		3 325		0.08
Total live		18 229		34 955	
Dead foliage	854		689		0.55
Dead branches	3 216		1 199		0.06
Total		4 070		1 888	
Stump	3 040		5 119		0.14
Roots	2 646		4 247		0.08
Total		5 686		9 366	
Total biomass		23 915		44 321	

Biomass nutrient content

There was more than five times as much magnesium in the total foliage component of the treated plots (7.9 kg/ha in the ED as against 1.5 kg/ha in the control), and nearly three times as much magnesium in the woody component (25.5 kg/ha as against 8.8 kg/ha) (Fig. 2). In the total tree component there was 33.4 kg Mg/ha in ED plots and 10.2 kg Mg/ha in the controls. The forest floor contained 8.4 kg Mg/ha in the ED plots as against 2.6 kg/ha in the controls. Thus the magnesium fertiliser utilisation (by difference) was 29 kg/ha, equivalent to 29% of the amount applied.

Calcium content was increased by dolomite fertiliser from 4.5 kg/ha to 14.8 kg/ha in the foliage component and from 33.5 kg/ha to 43.2 kg/ha in the woody component. Among the individual components only the difference in calcium content of 1-year foliage was significant. On the forest floor there was an extra 7.3 kg Ca/ha in the treated plots (12.6 kg/ha as against 19.9 kg/ha). The over-all difference in calcium content was 27.3 kg/ha, equivalent to 14.6% of the 187 kg Ca applied in the dolomite.

Boron content in the total tree component increased from 0.18 kg/ha in the control plots to 0.27 kg/ha in the ED plots. Only the 1-year foliage and branch boron contents were significantly different.

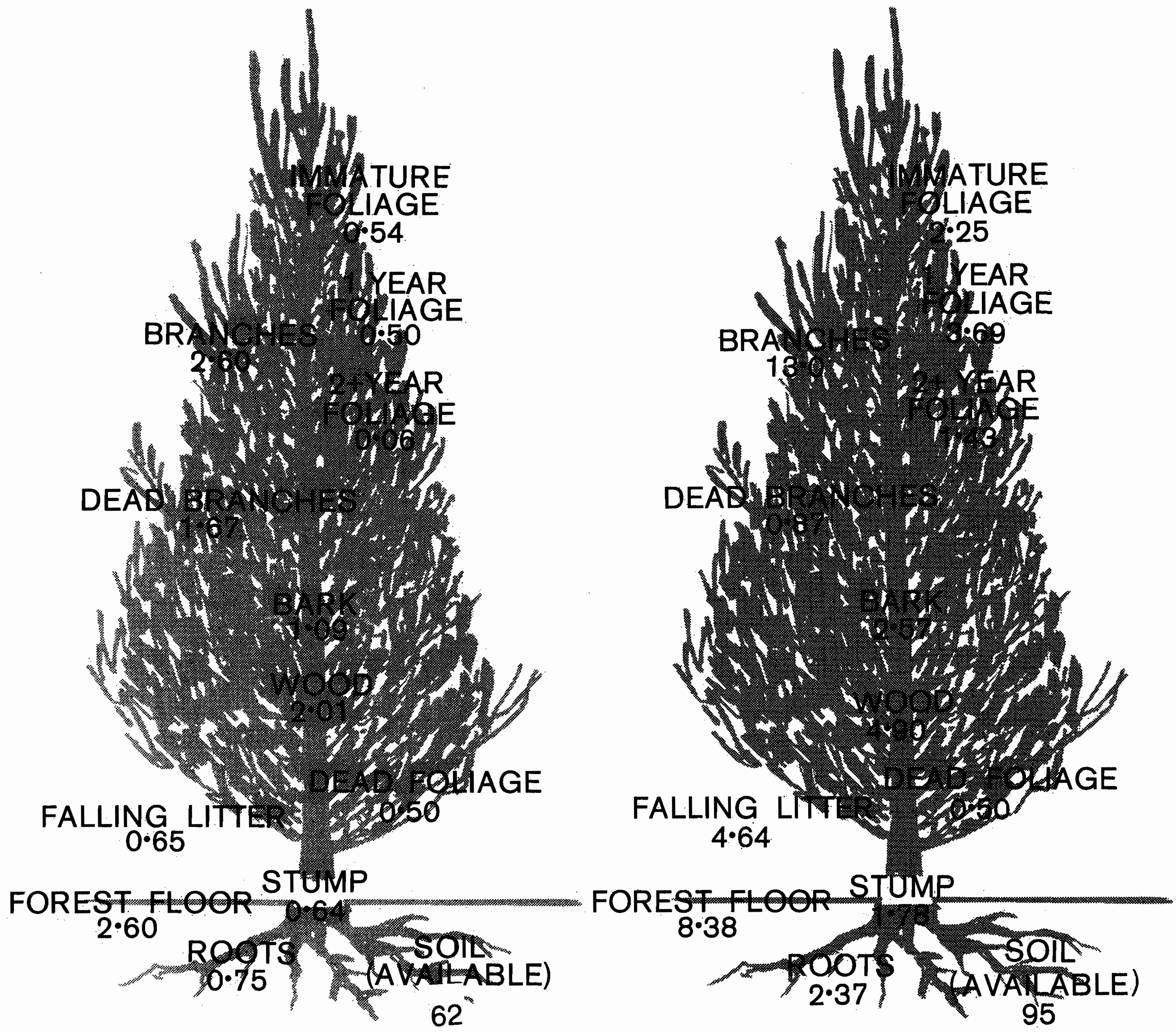

FIG. 2—Magnesium content (kg Mg/ha) of 11-year-old trees. Left: control plots. Right: ED plots.

Nutrient Mobility

Pulling water through stem sections by vacuum reduced the magnesium concentrations in the combined wood and bark sample only slightly – from 0.027% to 0.023% in untreated trees and from 0.047% to 0.038% in the magnesium-treated trees. There was a marked reduction, however, after further leaching with sodium nitrate – to 0.012% in untreated trees and 0.024% in treated trees.

Water leaching had almost no effect on calcium content. Sodium nitrate leaching reduced the average stem section concentration markedly from 0.09% Ca (regardless of treatment) to 0.05%. Neither form of leaching reduced boron content.

Litter collected in traps contained 4.64 kg Mg/ha in the treated plots but only 0.85 kg Mg/ha in the controls. The difference for calcium was less marked – 10.9 kg/ha in treated plots as against 3.6 kg/ha in the untreated.

Soil

The soils have the high concentrations of silicon and aluminium typical of an intermediate/acid rock (Harmsen & Vlek 1985) and an only slightly elevated (but non-significant) concentration of calcium and magnesium in the treated plots. The highest concentration of calcium and magnesium was in the finer (< 2 mm) soil fraction (Table 5).

TABLE 5—Soil elemental composition (%)

Element	Treated plots (ED)			Untreated plots (control)		
	A horizon	B	Mean*	A horizon	B	Mean*
< 2 mm fraction						
Mg	0.63	0.33	0.43	0.61	0.31	0.42
Ca	1.75	1.48	1.58	1.73	1.43	1.54
Si	30.8	35.5	33.8	30.8	35.4	33.7
Al	8.2	8.1	8.1	8.1	8.1	8.1
Na	1.2	1.4	1.3	1.2	1.4	1.3
K	1.4	1.6	1.5	1.4	1.7	1.6
S	0.07	0.03	0.04	0.07	0.03	0.04
P	0.05	0.03	0.04	0.06	0.03	0.04
Mn	0.05	0.05	0.05	0.05	0.05	0.05
Fe	2.6	2.0	2.3	2.5	2.0	2.2
> 2 mm fraction						
Mg	–	–	0.24	–	–	0.24
Ca	–	–	1.23	–	–	1.24
Si	–	–	35.2	–	–	35.5
Al	–	–	7.9	–	–	7.9
Na	–	–	1.4	–	–	1.4
K	–	–	1.7	–	–	1.7
S	–	–	0.04	–	–	0.04
P	–	–	0.04	–	–	0.03
Mn	–	–	0.05	–	–	0.05
Fe	–	–	1.8	–	–	1.9

* The means of the < 2 mm fraction are weighted by horizon proportions.
The values for the > 2 mm fraction are from a bulked sample.

Over all sample pits the > 2 mm fraction represented 46% by weight of the dry soil.

An acid extraction technique indicated that 256 kg Mg/ha might be available from the whole soil volume (to 60 cm) in the treated plots and only 199 kg Mg/ha in the untreated plots. The Bray extraction technique indicated 95 kg Mg/ha (treated) as against 62 kg Mg/ha (untreated). However, for both the extractions a proportion (between 25% and 40%) of the available magnesium was made "available" only after fine grinding of the > 2-mm rhyolite pumice fraction.

Total magnesium in the tree rooting zone averaged 12 930 kg/ha. Attempts to find the remaining 71 kg of the applied magnesium that was unaccounted for by the crop foundered on the variability of the large amounts of soil total-magnesium relative to the tiny amount sought. There was no significant difference in soil total-magnesium content between treated and untreated plots, although the means differed by 1268 kg/ha.

DISCUSSION

Over the 5 years of the experiment we gradually gained a greater, although by no means complete, understanding of the circumstances in which severe magnesium deficiency is to be expected in southern Kaingaroa. Low in magnesium throughout southern Kaingaroa, trees appear to become severely deficient if one of three extra conditions apply: there is substantial pasture grass competition; there has been topsoil disturbance or removal; there is an appreciable depth (greater than 30 cm) of water-sorted tephra in the soil profile. After the most recent Taupo eruption many very shallow lakes formed in natural depressions in a confused landscape where relief was minimal. These gradually infilled and are now difficult to locate by eye. The resultant localised areas of water-sorted tephra are difficult to manage because they occur in a pattern which is hard to detect.

Areas with substantial grass competition are very limited since pasture grasses do not flourish in those soils without large fertiliser amendments.

Aerial photographs showed that at one time the trial area had been on the forest boundary and had been cleared for a firebreak, possibly by discing. The trial might therefore be representative of the second site type – induced by management practice. This site type is currently limited to other old firebreak areas and several windrowed compartments. However, it is the site type which is most likely to increase. Management does not have to be particularly harsh, considering the background of already low magnesium levels, to induce severe deficiency.

Despite the large total magnesium content of these soils (enough for several hundred rotations) the amount that is truly available to the trees is only a minute fraction of the total since untreated trees are able to take up only approximately 2 kg/ha/yr (approximately 0.02% of the total magnesium). At normal logging approximately 65% of the 100 kg Mg/ha in the biomass is removed in the wood and bark (Webber & Madgwick 1983). Normal logging therefore further depletes a site already low in magnesium. As would be expected, the small younger trees sampled from this trial had a much lower percentage of the total magnesium in their stems than those sampled by Webber & Madgwick. However, it is important to note that in the deficient trees the percentage of magnesium in the stem was higher than in the treated trees (35% as against 26%). If this represents a shift in allocation and is not a function of size, and were to persist to clearfelling, it would mean that normal logging of deficient trees would remove an even higher percentage of available magnesium from poor sites.

The initially slow growth response to the applied fertiliser was surprising. In all our previous experience with rapidly soluble and somewhat insoluble fertilisers (such as rock phosphate), response in *P. radiata* crops deficient in that element has been rapid. Since a quarter of the applied magnesium was as very soluble Epsom salts and since the soil type is sufficiently acid (pH 5.0 – New Zealand Soil Bureau 1968) to slowly dissolve dolomite, we would have expected a more rapid increase in foliar magnesium. However, the base saturation of the soil type is extremely low (3% – New Zealand Soil Bureau 1968) and it has been suggested that a period of soil retention of magnesium might be expected before the applied magnesium becomes available to tree roots. The delayed response is undesirable to a forest manager since it means that even after remedial action has been taken, tree increment will continue to be lost for several years.

A sustained and strong response was achieved from the second year after application. There was an increasing degree of uptake until 1984 since foliar magnesium increased from year to year. Uptake may now have reached a plateau since 1985 foliar magnesium concentrations show no increase over 1984 levels. Height and diameter increments for treated trees were consistently at least 50% better than the control between 1982 and 1985. The growth differences show no evidence of decreasing so the response has not yet culminated. Strong height responses to fertiliser are thought to be unusual. However, we have now documented similar height responses to nitrogen and phosphorus when those nutrients are strongly deficient (Hunter & Hoy 1983; Hunter & Graham 1982) and have come to expect it in most areas of acute nutrient deficiency.

When we made the biomass determination the treated trees were larger than the untreated ones and it is not surprising to find this differential reflected in the weight of almost every measured component. Trees from this study were compared with trees from the age-class sequence of Madgwick *et al.* (1977) (Table 6). The treated trees at age 11 had an average diameter intermediate between normal 6- and 8-year-old trees, which gives an indication of the increment lost to the initial magnesium deficiency and slow recovery. The control trees' average diameter was intermediate between normal 4- and 6-year-old trees. The treated trees appeared to be fairly "normal" for their size, except that their stemwood was less than expected – probably because total height was still less than normal for trees of their diameter. The control trees were clearly abnormal in two respects: they had very little foliage and, although their total branch weight (live and dead) was average, they were unusual in that a much higher proportion (37%) of that total was dead. This branch death must be associated with the magnesium nutrient deficiency since in a healthy stand of this age and stocking there would normally be little if any death of lower branches caused by shading.

Dolomite fertiliser contains both calcium and magnesium. In two of the control plots calcium concentrations were below 0.1%. In the dolomite fertiliser plots calcium concentrations were improved by fertiliser application. Therefore we must consider to what extent the growth response could have been due to calcium. Resin bleeding

TABLE 6—Comparison between this trial (11-year-old trees) and Kaingaroa 4-, 6-, 8-, and 10-year-old trees, showing oven-dry weights of individual tree components per unit of squared diameter

	This trial		Kaingaroa trees*			
	Control	ED	4 yr	6 yr	8 yr	10 yr
Average square of diameter (cm)	59.30	127.7	36.0	90.2	176.9	479.6
Diameter at breast height (cm)	7.7	11.3	6.0	9.5	13.3	21.9
	Weight (g) per unit of squared diameter					
Immature foliage	6.5	9.4	-	-	-	-
1-yr foliage	8.5	19.3	57.1	23.7	21.2	17.4
2-yr+ foliage	1.1	8.0	-	-	-	-
Total live foliage	16.1	36.7	113.0	47.0	21.0	23.9
Dead foliage (attached or suspended)	7.4	3.6	-	-	-	-
Dead branches	27.7	6.4	0.0	1.1	6.7	0.1
Live branches	38.4	80.4	63.9	67.2	47.6Pr	44.0Pr
Stem wood	80.9	82.6	78.2	95.5	136.1	182.9
Stem bark	16.8	17.4	13.7	12.6	16.5	17.6
Stump	10.5	12.5	-	-	-	-
Roots	8.2	11.0	-	-	-	-

Pr = pruned
* Source: Madgwick et al. 1977

and apical meristem death have been produced easily by calcium deficiency in young *P. radiata* seedlings raised in greenhouse experiments (Will 1985), so the height response in this trial is not entirely inconsistent with a calcium response. Three reasons, however, lead us to believe that the role of calcium may be small or non-existent in the growth response in this trial: there was no difference in height growth or diameter growth between these plots with a calcium level below 0.1% and those with a higher concentration; uptake of calcium was lower than for magnesium, being only 15% of that applied; calcium concentrations doubled with needle age even in the plots with very low calcium concentration in the young foliage. But none of these reasons is sufficiently conclusive to completely exclude the role of calcium.

The calcium in the dolomite may, however, have helped to overcome the very low base saturation of this soil type and so make the magnesium available to the trees more rapidly. Moreover, sufficient doubt still exists over the role of calcium to limit practical advice to one fertiliser material only – dolomite – and this is undesirable from the forest manager's viewpoint since he is tied to very few suppliers and is hence a price taker. In 1984 therefore, as a follow up, a Ca × Mg factorial trial was established in an adjacent area using pure compounds as fertilisers, and will be reported on in due course. Also in 1984, trials testing different rates and types of magnesium fertiliser were established.

From the data available to us we can only estimate the annual magnesium demand of the trees. They demand magnesium for the fresh foliage (approximately 4 kg/ha/yr in the treated plots, 0.5 kg/ha/yr in the controls) and the wood, branch, and root increment (approximately 5 kg/ha/yr in treated plots growing at 10 dry tonnes/ha/yr). Thus the total magnesium uptake by trees in the ED-treated plots may amount to 9 kg/ha/yr. Our stem leaching experiment demonstrated that some of the magnesium is held on exchange sites in the wood and, by analogy with wood of other species, is possibly available for remobilisation (Ferguson & Turner 1981). The demand on the soil would be reduced by the amount of recycling from needles before they fall as litter and by release of magnesium from the forest floor. Rainfall supplies about 0.8 kg Mg/ha/yr in Kaingaroa (in the centre of the island) as against 4.9 kg Mg/ha/yr in a western coastal forest (P. Hodgkiss pers. comm.; Baker *et al.* 1985). If we accept a figure of 9 kg Mg/ha/yr as the upper limit (the maximum gross demand of the treated trees) and approximately 2 kg Mg/ha/yr as the lower limit (the uptake that the controls have been able to achieve), it can be seen that both the Bray and acid-extractable soil magnesium tests grossly overpredict what is available to the trees. In two separate unpublished studies, R. Ballard and the senior author found no correlation between soil exchangeable magnesium or Bray magnesium and *P. radiata* foliar magnesium. This inability to calibrate a soil test severely limits our ability to predict magnesium deficiency and clearly requires further work.

CONCLUSIONS

Severe magnesium deficiency in *P. radiata* growing on rhyolitic tephra can probably be corrected by fertiliser which can conveniently be applied as ground dolomite at approximately 1 tonne/ha. Alleviation of symptoms and recurrence of vigorous growth are slow but promise to be long-lasting.

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