MICRONUTRIENT AND MACRONUTRIENT UPTAKE BY *PINUS RADIATA*, AND SOIL BORON FRACTIONS, AS AFFECTED BY ADDED NITROGEN AND BORON

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(Received for publication 19 January 1993; revision 11 August 1994)

ABSTRACT

Changes in soil boron fractions, dry weights of biomass components (needles, branches, stem bark, stem wood) and uptake of nitrogen, phosphorus, potassium, calcium, magnesium, boron, copper, and zinc were studied in a 4-year-old *Pinus radiata* D.Don stand in Ashley Forest, North Canterbury, 1 year after application of urea at 0 and 400 kg N/ha and/or ulexite at 0 and 7.4 kg B/ha.

Significant responses to both the applied nitrogen and boron were measured in total above-ground tree biomass. The needle, branch, and stem components were significantly heavier in the trees fertilised with boron alone, but only the needle component was significantly heavier where nitrogen fertiliser had been added alone. Increased tree growth was associated with increased total uptake of all nutrients except phosphorus and potassium which increased only in trees treated with ulexite. Increased nutrient uptake was measured mainly in needles of trees treated with urea, but in needles and branches of those to which ulexite was applied. Nutrient concentrations of non-fertiliser elements remained similar or declined in trees to which fertiliser was applied. This was attributed to dilution effects and/or internal translocation between biomass components.

Boron application significantly increased boron concentrations in the current and 1-year-old needles whereas nitrogen application had no effect on nitrogen concentrations.

Some of the added boron was retained in plant-available fractions in the top 20 cm of the soil 1 year after application and this, together with the potential retranslocation of boron within the ulexite-treated trees, will provide a future supply of boron for tree growth.

The results confirmed that ulexite is a suitable long-term supplier of fertiliser boron to *P. radiata* growing in low rainfall areas.

Keywords: nitrogen; phosphorus; potassium; calcium; magnesium; boron; copper; zinc; biomass; nutrient uptake; soil boron fractions; *Pinus radiata.*

INTRODUCTION

Increased growth rates of *Pinus radiata* on farm sites in New Zealand (West & Dean 1988) have stimulated interest in farmland by forestry companies (Hawke & O'Connor 1993). Farm sites typically have a history of phosphorus fertiliser application and nitrogen accretion from fixation by clover. The available nitrogen is typically present as nitrate rather than the ammonium form commonly presumed to be the main nitrogen source in forest soils (Haynes & Goh 1978), although many acid forest soils do show significant nitrification (Adams 1986; Killham 1986). High nitrate levels have been implicated in the growth disorder known as "speed wobbles" (Toorour syndrome in Australia) which is typically observed in *P. radiata* growing on ex-pasture soils (Carlyle *et al.* 1989; Birk 1990).

This paper reports part of a wider study of the effects of high nitrogen availability on micronutrient uptake by *P. radiata* in the context of ex-pasture systems. Individual tree species may respond to an increase in nutrient supply in different ways—including increasing their photosynthetic activity and canopy growth, and changing the allocation of photosynthetic products (Binkley 1986). For instance, Nambiar & Fife (1987) found that application of nitrogen fertiliser to *P. radiata* increased the number and size of needles, rates of shoot production, stem volume, and tree biomass. Nutrient fluxes into and out of the needles increased, as did retranslocation of nitrogen, phosphorus, and potassium as a result of the increased needle weight. Thus, assessment of a tree response to increased nutrient supply requires the measurement of both physical and chemical changes.

The aim here was to study the effects of nitrogen and boron fertilisers on the above-ground biomass of young *P. radiata*, the macronutrient and micronutrient uptake, the distribution of nutrients into different biomass components, and the effect of ulexite on soil boron fractions 1 year after fertiliser application.

MATERIALS AND METHODS

The study was carried out in Compartment 15 of Ashley Forest, North Canterbury, where the soils are Makerikeri hill soils (yellow grey earths). This site was chosen because, in terms of *P. radiata* growth, soil boron status is marginal and the supply of other nutrients is regarded as low (Fox *et al.* 1964).

Mean annual rainfall at forest headquarters (4 km from the study area) was 808 mm, with summer droughts being common. The site carried a 3-year-old stand of *P. radiata* (833 stems/ha) and had been root-raked after the felling of the previous Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand. Stand management had not included weed control and in 1990 a mixture of gorse (*Ulex europaeus* L.), broom (*Cytisus scoparius* L.), Yorkshire fog (*Holcus lanatus* L.), wildling *P. radiata*, and wildling Douglas-fir was present.

The basis of the study was a nitrogen plus boron fertiliser trial which had a randomised block design (Olykan 1993). Four of the treatments were used, namely the control (N_0 B_0), 7.4 kg B/ha as ulexite (sodium calcium borate, 2- to 5-mm chips, 14% B) (N_0 $B_{7.4}$), 400 kg N/ha as urea (N_{400} B_0), and 400 kg N/ha plus 7.4 kg B/ha (N_{400} $B_{7.4}$). The $B_{7.4}$ rate was that currently used in forest management at Ashley, and a high rate of nitrogen was used to try to maximise any interaction effects with other nutrients. All plots had a basal dressing of 14 kg P/ha as North Carolina rock phosphate. The fertilisers were broadcast by hand on 1 November 1989.

One year after fertiliser application, three trees were randomly selected from each of the four treatments in Block 1 of the field trial for biomass measurement. Trees were divided into needles, branches, stem bark, and stem wood for four age-classes (1, 2, 3, and 4 years old) plus the current season's growth. The method used for separating the age-classes of the woody components (stems and branches) is shown diagrammatically in Fig. 1. Bark was not removed from the current season's growth but was separated from the other age-classes of stem.

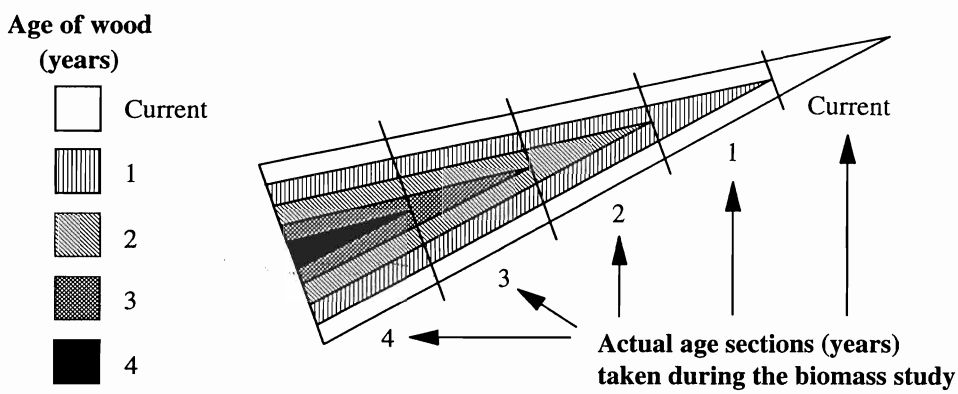

FIG. 1–Nomenclature used in describing the different age-classes of wood present in *P. radiata* stems or branches taken during the biomass study at Ashley Forest.

Dry weight of each component and nutrient contents of ground sub-samples were determined. Concentrations of nitrogen, phosphorus, potassium, calcium, and magnesium were determined after a H_2SO_4/H_2O_2 digestion, nitrogen and phosphorus being measured autoanalytically and potassium, calcium, and magnesium by atomic absorption spectrophotometry (Nicholson 1984). Concentrations of the micronutrients copper, zinc, and boron were determined in a dry-ashed extract by atomic absorption for copper and zinc and using azomethine-H for boron (Wolf 1974; Gaines & Mitchell 1979).

Soil samples were collected at 10-cm increments from a depth of 0 to 30 cm, from a soil profile dug beside each biomassed tree. This represented the fine earth part of the soil profile above the underlying gravels. The samples were air-dried and sieved (2 mm). At the time of soil collection, there was no consistent forest litter layer and no residual ulexite was observed on the soil surface.

The soil samples were analysed for pH, organic calcium, total nitrogen, and Bray 2 phosphorus according to Nicholson (1984). Hot 0.02 M calcium chloride-extractable boron was determined using the method of Parker & Gardner (1981) as modified by Hamzah (1987). Samples were also analysed for soil boron fractions using a fractionation scheme based on those of Jin *et al.* (1987) and Hogg (1988). This involved sequential extraction of (i) non-specifically adsorbed boron with 0.02 M calcium chloride, (ii) specifically adsorbed boron with 0.02 M calcium chloride + 0.01 M mannitol, (iii) amorphous iron and aluminium oxide-bound boron with cold 0.2 M ammonium oxalate + 0.2 M oxalic acid at pH 3, and (iv) crystalline iron and aluminium oxide-bound boron with hot 0.2 M ammonium oxalate + 0.2 M oxalic acid + 0.1 M ascorbic acid at pH 3.

Data were subjected to analysis of variance using the computer program GENSTAT. The following were examined: (i) the effect of nitrogen and boron addition on the weight of the above-ground tree components, the total amount of nutrients in the above-ground tree, the amount of nutrients in each of the above-ground tree components, and the concentrations of nutrients in the current and 1-year-old needles and branches; and (ii) the effect of boron fertiliser addition on soil boron fractions.

The least significant difference (LSD) test was used to compare mean values at the 5% level ($p<0.05$).

RESULTS AND DISCUSSION

Soil Properties

The Makerikeri hill soils in the study area are strongly acid with low Bray 2 phosphorus and hot calcium chloride-soluble boron concentrations (Table 1). The mean Bray 2 phosphorus first extraction value of 7.2 μg/g was below the 12 μg/g regarded as being adequate for *P. radiata* establishment (Ballard 1974) even though a basal dressing of rock phosphate had been added. However, the soils have appreciable phosphate buffering capacity as shown by the second and third Bray extractions and fall into Category 2 of the classification described by Skinner *et al.* (1991). This may explain the adequate foliar phosphorus concentrations typically measured at Ashley.

TABLE 1–Chemical properties of the Makerikeri hill soils, Ashley Forest. Values are means from three soil profiles in the control plot.

Depth (cm)	pH	Organic carbon (%)	Total nitrogen (%)	Bray 2 P* (μg/g) 1†	2	3	Hot 0.02 M $CaCl_2$-soluble B (μg/g)
0–10	5.0	2.23	0.14	7.2	4.8	3.5	0.9
10–20	5.0	1.83	0.13	4.1	2.5	2.1	0.9
20–30	5.0	2.45	0.11	4.8	2.5	1.9	0.8

* Control plots received a basal dressing of phosphorus at 14 kg/ha (*see* Methods).
† Sequential extractions after Skinner *et al.* (1991).

Soil organic carbon and total nitrogen were low and in individual profiles the amounts increased or fluctuated down the profile, most likely as a result of soil disturbance during site clearing after felling of the previous stand. Some profiles appeared to have been either partially or completely inverted with consequent mixing of the soil horizons.

Bray cations were also analysed (Olykan 1993) and results indicated that Bray magnesium rated medium while Bray calcium and potassium were both very low.

Effects of Fertiliser Nitrogen and Boron on Biomass

The mean total above-ground dry weight of trees from each of the fertiliser treatments was significantly greater than that of the control trees (Fig. 2). The average control tree had a dry weight of 1.6 kg compared to an average of 3.5 kg where $B_{7.4}$ and/or N_{400} had been added.

A significant response to added boron ($N_0\,B_{7.4}$) occurred in the dry weight of all biomass components except the stem bark (Fig. 2). Trees also responded to nitrogen but only in the needle biomass. Although mean values for the other three biomass components were twice as great where nitrogen had been applied, individual observations were too variable for the increases to be regarded as significant.

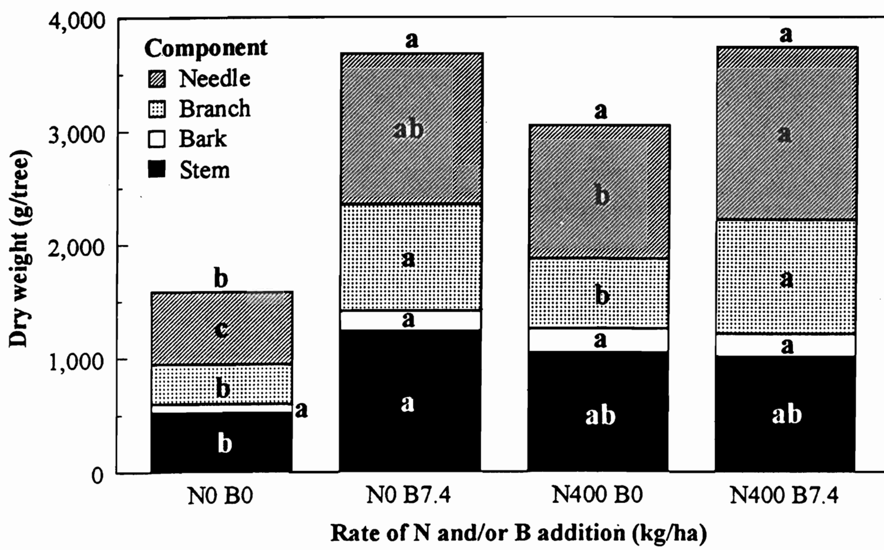

FIG. 2–Effect of added nitrogen and boron fertilisers on *P. radiata* components and total biomass 1 year after application at Ashley Forest. For the total above-ground tree dry weight (letters on top of bars) and for each biomass component, means with the same letter were not significantly different ($p < 0.05$).

Addition of both nutrients together ($N_{400}\,B_{7.4}$) gave no greater response than that obtained from boron alone, either in total biomass or in the biomass components. A comparison of the $N_{400}\,B_{7.4}$ with nitrogen alone ($N_{400}\,B_0$) revealed no significant difference in total biomass but the mean dry weights of the needle and branch components were significantly heavier for the $N_{400}\,B_{7.4}$ treatment.

The extent of the biomass response to boron (Fig. 2) was considerable, given that there were no visual symptoms of boron deficiency in the control plots. Correction of potential or marginal boron deficiency in *P. radiata* in New Zealand has typically been followed through foliar analysis (Knight *et al.* 1983; Will 1985) although Knight *et al.* showed no effects of applied boron on height or diameter measures in Harakeke Forest near Nelson where foliar boron values in the control trees were satisfactory (>12 ppm). In our trial at Ashley Forest, measurements of tree height 6 months after fertiliser addition and tree height and diameter 3 years after fertiliser addition showed no significant effects of nitrogen and/or boron application (Olykan 1993).

Although there were large differences in biomass between the control and fertiliser-treated tree stems, the difference was significant only for the N_0 $B_{7.4}$ treatment because of the considerable variation associated with weights of the individual age-classes of stem. For example, the 4-year-old portions of the tree stem, which were not significantly affected by fertiliser addition, ranged in weight from an average of 213 g to an average 372 g, with the smaller weight being recorded for the control treatment (Olykan 1993).

Effects of Fertiliser Nitrogen and Boron on Nutrient Uptake

Nutrient uptake into the different biomass components is presented in Table 2. Application of boron (alone or with added nitrogen) resulted in significantly increased uptake of macronutrients into the needles and branches compared with that in the untreated trees. There was also significantly greater uptake of calcium into the stem wood and bark for the N_{400} $B_{7.4}$ treatment and greater calcium and phosphorus uptake into the stem for the N_0 $B_{7.4}$ treatment. Application of nitrogen alone resulted in increased uptake of calcium into the needles, branches, and stem bark but increased uptake of nitrogen and magnesium into the needles only. There were no significant changes for phosphorus or potassium.

Compared with the untreated trees there was increased uptake of copper and zinc into needles and branches after application of boron either alone or with added nitrogen, whereas adding nitrogen alone resulted in increased uptake into the needles only (Table 2). Boron uptake was not significantly affected by application of nitrogen alone, but increased more than four-fold after boron application. Significant increases in boron uptake occurred in all four biomass components in nearly all age-classes, but most markedly into current and 1-year-old growth (Olykan 1993).

Effects of Fertiliser Nitrogen and Boron on Nutrient Concentrations

The effect of fertiliser nitrogen and boron additions on nutrient concentrations in the current and 1-year-old needles and branches is summarised in Table 3. Nitrogen addition alone caused a significant decline in phosphorus concentrations in the current needles compared to the control. Interestingly, nitrogen application 1 year previously had no effect on nitrogen concentrations in the needles or branches. Knight *et al.* (1983) noted a similarly short-lived foliar response of barely 1 year after nitrogen application to *P. radiata*. They ascribed this to a growth dilution effect.

Boron application alone resulted in a decline in nitrogen concentrations in the 1-year-old needles and current branches. The addition of nitrogen plus boron (N_{400} $B_{7.4}$) significantly reduced the concentrations of phosphorus in the current needles and branches and magnesium in the current needles and 1-year-old branches.

The application of boron resulted in large increases in boron concentrations in both the current and 1-year-old needles and in the 1-year-old branches. The increases were largest in the needles and stem bark (not included in Table 3) and occurred in all age-classes of these two biomass components (Olykan 1993).

Overall, any response to application of boron and/or nitrogen took the form of a reduction in concentration of nitrogen, phosphorus, potassium, copper, zinc, and particularly magnesium in above-ground tree components (Olykan 1993). This may have represented a dilution

TABLE 2–Effect of fertiliser nitrogen and boron on nutrient uptake into four biomass components of *P. radiata* at Ashley Forest. For each nutrient in each biomass component, means followed by the same letter were not significantly different ($p < 0.05$).

Nutrient	Biomass component	Fertiliser treatments			
		N_0 B_0	N_0 $B_{7.4}$	N_{400} B_0	N_{400} $B_{7.4}$
N (g/tree)	Needles	10.9 c	18.9 b	20.0 ab	23.3 a
	Branches	2.2 b	4.6 a	4.1 ab	6.1 a
	Stem bark	0.5 a	0.9 a	1.5 a	1.3 a
	Stem wood	1.1 a	1.8 a	1.6 a	1.7 a
	TOTAL	14.7 b	26.2 a	27.2 a	32.4 a
P (g/tree)	Needles	1.36 b	2.75 a	2.09 ab	2.44 a
	Branches	0.41 b	0.99 a	0.56 b	0.90 a
	Stem bark	0.09 a	0.19 a	0.21 a	0.25 a
	Stem wood	0.26 b	0.54 a	0.42 ab	0.37 ab
	TOTAL	2.12 b	4.47 a	3.28 ab	3.96 b
K (g/tree)	Needles	5.4 b	11.6 a	6.9 b	11.4 a
	Branches	2.6 b	6.3 a	3.9 b	5.7 a
	Stem bark	0.3 a	0.6 a	0.6 a	0.5 a
	Stem wood	1.2 a	2.1 a	1.4 a	1.3 a
	TOTAL	9.5 b	20.6 a	12.8 b	18.9 a
Ca (g/tree)	Needles	2.09 b	5.14 a	4.16 a	5.23 a
	Branches	0.48 c	1.55 ab	1.12 b	1.96 a
	Stem bark	0.14 b	0.33 ab	0.39 a	0.45 a
	Stem wood	0.31 b	0.72 a	0.61 ab	0.73 a
	TOTAL	3.02 c	7.74 ab	6.28 b	8.37 a
Mg (g/tree)	Needles	1.11 b	2.07 a	1.92 a	2.03 a
	Branches	0.49 b	1.05 a	0.83 ab	1.16 a
	Stem bark	0.10 a	0.15 a	0.21 a	0.19 a
	Stem wood	0.28 a	0.46 a	0.41 a	0.44 a
	TOTAL	1.98 b	3.73 a	3.37 a	3.82 a
B (mg/tree)	Needles	6.1 b	38.5 a	10.5 b	38.8 a
	Branches	3.7 b	11.9 a	6.1 ab	13.3 a
	Stem bark	1.4 b	5.3 a	3.7 ab	4.5 a
	Stem wood	2.2 b	4.6 a	2.9 ab	4.4 ab
	TOTAL	13.4 b	60.3 a	23.2 b	61.0 a
Cu (mg/tree)	Needles	3.27 b	5.61 a	6.31 a	6.51 a
	Branches	1.61 b	3.85 a	3.22 ab	4.96 a
	Stem bark	0.33 a	0.59 a	0.91 a	0.83 a
	Stem wood	1.68 b	2.82 a	2.66 ab	2.29 ab
	TOTAL	6.89 b	12.87 a	13.1 a	14.59 a
Zn (mg/tree)	Needles	19.6 b	43.4 a	35.3 a	37.7 a
	Branches	10.2 b	22.6 a	17.8 ab	25.2 a
	Stem bark	2.8 a	4.2 a	5.6 a	5.4 a
	Stem wood	6.2 a	10.7 a	10.8 a	9.9 a
	TOTAL	38.8 b	80.9 a	69.5 a	78.2 a

TABLE 3–Effect of fertiliser nitrogen and boron additions on nutrient concentrations in current and 1-year-old needles and branches in *P. radiata* at Ashley Forest. For each nutrient in each aged biomass component, means followed by the same letter were not significantly different ($p < 0.05$).

Nutrient	Biomass component	Age class	Fertiliser treatments			
			N_0 B_0	N_0 $B_{7.4}$	N_{400} B_0	N_{400} $B_{7.4}$
N (g/kg)	Needles	Current	19.2 ab	16.9 b	20.0 a	18.2 ab
		1-year	16.3 a	14.0 b	16.7 a	14.9 ab
	Branches	Current	10.7 a	8.8 b	11.9 a	10.6 a
		1-year	5.0 a	4.8 a	5.8 a	4.7 a
P (g/kg)	Needles	Current	3.1 a	3.1 a	2.3 b	1.9 b
		1-year	1.7 a	1.7 a	1.7 a	1.6 a
	Branches	Current	1.9 ab	2.1 a	1.5 bc	1.3 c
		1-year	1.0 a	0.9 a	0.8 a	0.8 a
K (g/kg)	Needles	Current	11.8 a	11.2 a	10.7 a	10.4 a
		1-year	6.7 a	7.6 a	4.9 a	6.8 a
	Branches	Current	14.1 a	13.4 a	11.1 a	10.2 a
		1-year	5.6 a	6.0 a	5.6 a	4.6 a
Ca (g/kg)	Needles	Current	2.0 a	2.4 a	2.5 a	2.1 a
		1-year	3.8 a	4.2 a	3.5 a	3.6 a
	Branches	Current	1.1 a	1.2a	1.5 a	1.5 a
		1-year	1.5 a	1.9 a	1.9 a	2.0 a
Mg (g/kg)	Needles	Current	1.7 a	1.5 ab	1.7 a	1.3 b
		1-year	1.8 a	1.5 a	1.6 a	1.3 a
	Branches	Current	1.4 a	1.1 a	1.3 a	1.0 a
		1-year	1.5 a	1.3 ab	1.5 a	1.2 b
B (µg/g)	Needles	Current	11 b	23 a	10 b	22 a
		1-year	8 c	31 a	9 c	27 b
	Branches	Current	12 ab	15 a	11 b	15 a
		1-year	10 b	14 a	10 b	13 a
Cu (µg/g)	Needles	Current	6.0 ab	5.4 b	7.6 a	5.6 b
		1-year	4.9 a	4.1 a	5.1 a	4.0 a
	Branches	Current	6.1 ab	5.1 b	7.2 a	5.9 ab
		1-year	4.7 a	4.6 a	5.2 a	4.3 a
Zn (µg/g)	Needles	Current	30 a	28 a	34 a	26 a
		1-year	30 ab	32 a	28 ab	23 b
	Branches	Current	29 a	25 a	27 a	26 a
		1-year	29 a	25 a	31 a	24 a

effect arising from the increased biomass production. However, some internal translocation from older biomass components to the current season's growth in order to meet the nutrient requirements of the extra biomass arising from the fertiliser application may also have occurred. Such a mechanism would explain the observed decline in nutrient concentrations in the older biomass components, such as the 3- and 4-year-old stem wood, where the component weight was not affected by the fertiliser treatments.

In contrast, the concentrations of boron increased significantly, particularly in the needles, branches, and stem bark of those trees to which boron fertiliser had been applied. The greater uptake of both macronutrients and micronutrients associated with boron application (Table 2) was therefore mainly a result of the increased biomass, except for boron uptake where increased concentrations also contributed.

The application of ulexite resulted in substantial accumulation of boron throughout the tree. Boron has often been considered to be immobile in trees, with little or no capacity for biochemical cycling through future internal translocation (Hunter *et al.* 1990; Stone 1990). However, Hopmans & Clerehan (1991) found that boron redistribution will occur down to a limit of 5 µg/g in *P. radiata* needles. In an earlier study at this Ashley Forest site, retranslocation of boron from *P. radiata* needle fascicles was observed during the summer, even when the trees had received boron fertiliser (Olykan 1993). This suggests that accumulated fertiliser boron in the trees, particularly in the needles, may be available for future translocation and that the overall response to the added boron may take place over a longer period.

Previous research has shown that the slow-release properties of ulexite can increase foliar boron concentrations in *P. radiata* for at least 4 years after application (Hunter *et al.* 1990). The results from our trial at Ashley Forest confirmed that ulexite is an effective boron source for *P. radiata* in this low-rainfall environment. Although recovery of boron in the above-ground biomass was low (less than 0.5% of the 7.4 kg/ha added), ulexite treatment resulted in boron concentrations in the 1-year-old needles (*see* Table 3) well in excess of the standard values considered adequate for *P. radiata* (Will 1985) while the boron status of the untreated trees was marginal to low. It is likely that the trees treated with boron will have satisfactory foliar boron concentrations for at least 5 years.

Soil Boron Fractions

In both the plots without and the plots with boron fertiliser (B_0 and $B_{7.4}$ respectively), the largest part of the soil boron was bound in the amorphous and crystalline iron and aluminium oxide fractions which are considered to be relatively unavailable to plants (Table 4). Ulexite application resulted in a significant increase in the amount of boron associated with the non-specifically and specifically adsorbed fractions, which approximately doubled in the top

TABLE 4–Effect of boron fertiliser, as ulexite, on soil boron fractions 1 year after addition at Ashley Forest. For each boron fraction, means followed by the same letter were not significantly different (p <0.05).

B rate (kg/ha)	Soil depth (cm)	Soil boron fractions (µg/g)			
		Non-specifically adsorbed	Specifically adsorbed	Amorphous Fe and Al oxide	Crystalline Fe and Al oxide
B_0	0–10	0.33 bc	0.35 b	3.5 ab	4.3 a
	10–20	0.22 c	0.22 b	2.9 bc	4.6 a
	20–30	0.20 c	0.23 b	2.5 c	4.1 a
$B_{7.4}$	0–10	0.65 a	0.69 a	3.9 a	3.7 a
	10–20	0.45 b	0.61 a	3.7 ab	4.2 a
	20–30	0.22 c	0.23 b	3.0 abc	4.2 a

20 cm of the profile, but there was no change in the iron and aluminium oxide-bound fractions.

Non-specifically and specifically adsorbed fractions are somewhat arbitrary separations which are perhaps best regarded as representing sequential desorption of boron adsorbed on the soil clays or organic matter (Hamzah 1987). They represent plant-available forms of boron (Adams *et al.* 1991) and taken together are approximately equivalent to the hot 0.02 M calcium chloride-soluble boron which showed a significant increase ($p < 0.05$) in the 0 to 10 cm increment from 0.8 μg/g in the untreated plot to 1.5 μg/g in the $B_{7.4}$ plots but did not significantly increase in the 10 to 20 cm increment (0.8 and 0.9 μg/g respectively).

Soils treated with 7.4 kg B/ha contained 1.3 μg/g more boron than the untreated soils (Table 4). This residual fertiliser boron was associated with the surface-absorbed fractions in the top 20 cm of the profile and, on a per hectare basis, represented approximately 3 kg (assuming a soil bulk density of 1.2 g/cm^3) or 40% of the fertiliser boron added. These results show that after 1 year a large proportion of the applied boron remained in the soil in a plant-available form and confirm ulexite as a suitable long-term source of boron where the boron status of the soil is considered to be marginal for *P. radiata* growth.

General

The increased needle biomass measured for the trees treated with fertiliser could have led to further biomass responses in the following years. In New Zealand, increases in the basal area of young *P. radiata* trees have been detected 4 to 5 years after nitrogen fertiliser addition (Mead *et al.* 1984; Hunter *et al.* 1986). However, when the entire trial at Ashley was remeasured 3 years after fertiliser addition, there was no significant increase in diameter growth (Olykan 1993).

CONCLUSIONS

Chemical analysis confirmed the low nutrient status of the soils in Cpt 15 of Ashley Forest.

One year after fertiliser application, there was a significant biomass response in the needle, branch, and stem wood components to added boron (ulexite at 7.4 kg B/ha) and a significant biomass response in the needle component to added nitrogen (urea at 400 kg N/ha) by a young *P. radiata* stand at Ashley Forest.

Fertiliser boron application caused significant increases in boron concentrations in the current and 1-year-old needles and branches, 1 year after application, whereas nitrogen application had no effect on nitrogen concentrations. The increases in biomass of the fertilised trees were accompanied by either no change or some reduction in nutrient concentrations in the biomass of non-fertiliser elements. This is considered to result from dilution effects and/or internal translocation from older biomass components to new growth. Nutrient uptake significantly increased as a result of the increase in biomass of the treated trees. For boron uptake, increased concentrations also contributed where boron fertiliser had been added.

Ulexite appears to be an effective long-term supplier of boron to *P. radiata* plantations growing in low rainfall areas when added at 7.4 kg B/ha. Although only 0.5% of the added boron was found in the above-ground tree biomass, approximately 40% of the added boron was retained in plant-available forms in the top 20 cm of the soils 1 year after application. This, together with the internal retranslocation of boron within the treated trees, will provide a future supply of boron for growth.

Future research should include an investigation into the effect of added boron on wood quality and a reassessment of foliar and soil boron levels to determine the longevity of the fertiliser response.

ACKNOWLEDGMENTS

Financial assistance from the New Zealand Vice Chancellors' Committee Postgraduate Scholarship Fund, the Ministry of Forestry, the Lincoln University Research Fund, and the New Zealand Federation of University Women is gratefully acknowledged. We also thank Peter Clinton and Murray Lang for field assistance and Carter Holt Harvey Forests Ltd for their support of the field trial.

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