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ABSTRACT

Fertiliser requirements at establishment of pines and *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) were examined in field trials on four soils in low to medium (600- to 900-mm) rainfall environments in the high-country of the South Island, New Zealand. A combination of boron, nutrient omission, and factorial nitrogen-phosphorus-sulphur trials was used to examine potential responses to nitrogen, phosphorus, sulphur, potassium, magnesium, and boron. Tree form and height responses to boron application were obtained in *Pinus radiata* D. Don breeds growing on free-draining Fork and Pukaki soils in a low-rainfall environment. In the same trials *P. nigra* Arn. subsp. *laricio* (Poiret) Maire (Corsican pine) and *P. ponderosa* P. Lawson et Lawson (ponderosa pine) showed no response to boron. The form response to boron varied amongst *P. radiata* breeds and depended on soil type. Douglas-fir showed no response to omission of boron from an otherwise-complete fertiliser mixture on Tekapo soils in moister (800–900 mm) environments. No responses were demonstrated to nitrogen, phosphorus, sulphur, potassium, or magnesium fertilisers by either pines or Douglas-fir.

Keywords: boron; nutrient deficiency; fertiliser; genetic varieties; magnesium; nitrogen; phosphorus; potassium; sulphur; *Pinus radiata*; *Pinus nigra*; *Pinus ponderosa*; *Pseudotsuga menziesii*.

INTRODUCTION

Forestry is a potential alternative land-use to grazing in the area of land to the east of the Main Divide in the South Island commonly known as the high country (Nordmeyer 1979; Ledgard & Belton 1985a, b; O'Connor 1986; Belton 1991). The most favoured species are Douglas-fir for moister sites, and *Pinus nigra* for drier sites (Ledgard 1994). Fertiliser requirements for establishment of pasture in the region are well known (During 1984; Scott 1992; McIntosh & Hunter 1997), but there is little information on fertiliser requirements of tree species. Belton & Davis (1986) reported a response to phosphorus by Douglas-fir on an eroded high country soil. Davis (1997) showed that *P. radiata* seedlings responded similarly to pasture species to nitrogen, phosphorus, and sulphur in a glasshouse pot trial with an outwash gravel soil from the Mackenzie Basin, but suggested that the responses by pine occurred prior to mycorrhizal formation, and that the responses needed to be confirmed under field conditions with plants which possessed mycorrhizal root systems at the time of fertiliser application. This paper summarises results of field trials undertaken to determine potential fertiliser requirements of tree species at establishment in low-to-medium rainfall high-country sites where experimental or management-scale afforestation is occurring for soil conservation or production forestry purposes.

METHODS

Eight trials were established on flood plain, terrace, or moraine surfaces at Ribbonwood and Balmoral Stations in the Mackenzie Basin, upper Waitaki catchment, and one trial was located on a moraine surface at Mt Barker in the Rakaia catchment (Table 1). Vegetation at all sites was dominated by low stature and low productivity grassland species. With one exception (Trial 1) the sites had never been cultivated or treated with fertiliser, though sheep had grazed all sites. Trial 1 had been cultivated, sown with pasture species, and treated with superphosphate. The soils were derived from greywacke alluvium or from loess over alluvium or moraine till. Sawdon soil is a moderately leached stony soil from alluvium. Fork soil is a strongly leached stony soil from alluvium and is excessively drained and highly drought-prone. Pukaki and Tekapo soils are moderately leached soils from loess over alluvium and till respectively (Webb 1992). The soils were moderately acid and had medium carbon levels (except for Fork soil), and low to medium nitrogen levels (Table 2). Extractable

TABLE 1–Trial site location, characteristics, tree species, and type of fertiliser trial.

Trial	Location and grid reference*	Physiography	Precipitation (mm)	Soil†	Tree species	Trial type
1	Ribbonwood H39 576425	Flood plain	800	Sawdon	*P. nigra*	Boron
2	Balmoral I37 039825	Terrace	580	Fork	*P. radiata*, *P. nigra*, and *P. ponderosa*	Boron
3	Balmoral I37 025833	Terrace	580	Pukaki	*P. radiata*, *P. nigra*, and *P. ponderosa*	Boron
4	Balmoral I37 039827	Terrace	580	Fork	*P. nigra*	Nutrient omission
5	Balmoral I37 035826	Terrace	580	Pukaki	*P. nigra*	Nutrient omission
6	Mt. Barker K35 968597	Moraine	900	Tekapo	Douglas-fir	Nutrient omission
7	Balmoral I37 937885	Moraine	800	Tekapo	Douglas-fir	Nutrient omission
8	Balmoral I37 026828	Terrace	580	Pukaki	*P. nigra*	NPS
9	Balmoral I37 029839	Moraine	580	Tekapo	Douglas-fir	NPS

* *Department of Survey and Land Information Infomap Series 126.*
† Soil names follow Webb (1992)

TABLE 2–Chemical properties of soils (0–10 cm) at the trial sites. Phosphorus and cations extracted in Bray-2 reagent (0.1N HCl + 0.03N NH_4F).

Soil*	Location	Trial	pH	C	N	C/N	P	K	Ca	Mg
				--- g/100 g ---			μg/g	------ c mol+/kg ------		
Sawdon	Ribbonwood	1	5.28	5.99	0.44	13.6	28	0.50	8.94	0.81
Fork	Balmoral	2, 4	5.50	2.89	0.25	11.5	73	0.32	3.20	0.66
Pukaki	Balmoral	3	5.52	5.03	0.28	18.0	19	0.49	4.98	0.89
Pukaki	Balmoral	5	5.29	4.06	0.33	12.3	25	0.36	6.90	1.25
Tekapo	Mt Barker	6	5.39	5.51	0.33	16.7	35	0.51	8.89	1.23
Tekapo	Balmoral	7	5.53	4.47	0.24	18.6	21	0.37	4.10	0.66
Pukaki	Balmoral	8	5.48	4.55	0.27	16.8	23	0.47	5.01	0.79
Tekapo	Balmoral	9	5.56	5.00	0.30	16.7	14	0.59	5.62	1.01

* Soil names follow Webb (1992)

cation levels were low in Fork soil, and low to medium in other soils. Bray-extractable phosphorus levels were substantially higher in Fork soil than in other soils (Table 2).

Three types of trial were used to test for nutrient responses:

(1) Single-element boron trials were used to test for response to boron, as deficiency symptoms of this element have been observed by the authors on some high-country soils. Trial 1 tested the response of *P. nigra* to three rates of boron applied as colemanite (10% B) on Sawdon soil. Trials 2 and 3 compared the responses of three pine species, and of five different "breeds" within one species (*P. radiata*) to two rates of boron applied as ulexite (13% B) on Fork and Pukaki soils. The breeds of *P. radiata* were GF17, GF25, GF28, a Guadalupe origin, and a hybrid between *P. radiata* and *P. attenuata* Lemmon. GF25 plants were grown from cuttings and the other breeds were grown from seed.

(2) A nutrient omission design was used to test for deficiencies of major nutrients and boron in *P. nigra* and Douglas-fir on Fork, Pukaki, and Tekapo soils (Trials 4–7). In this design complete fertiliser was applied in one treatment, while the remaining treatments consisted of omitting each of the nutrients, one at a time, from the otherwise-complete mixture. Trials 6 and 7 on Tekapo soils included a treatment where no fertiliser was added (control), to give a total of eight treatments. In the nutrient omission trials nitrogen was applied as calcium ammonium nitrate (27% N), phosphorus was applied as North Carolina rock phosphate (13% P), sulphur was applied as gypsum (17% S), potassium was applied as potassium chloride (52% K), magnesium was applied as calcined magnesite (50% Mg), and boron was applied as ulexite.

(3) Nitrogen-phosphorus-sulphur factorial trials (2^3) were used to test for responses to these nutrients, which are the major deficient nutrients for pasture species in the high country. These trials (Trials 8 and 9) examined responses in *P. nigra* and Douglas-fir on Pukaki and Tekapo soils respectively. For these trials nitrogen was applied as urea (46% N), phosphorus was applied as North Carolina rock phosphate, and sulphur was applied in elemental form.

Rates of nutrient elements applied in all trials are presented in Table 3. With the exception of the boron trials, fertilisers were applied in a spade slot centred approximately 15 cm from

TABLE 3–Year of planting, nutrient application rate, timing of fertiliser application, and method of weed control.

Trial type (and number)	Year of planting	Nutrient	Nutrient rate (g/tree)	Time of fertiliser application	Method of weed control
Boron (1)	1985	B	0, 5, 10	2 years after planting	Herbicide prior to planting (Simazine 12.1 kg/ha Delapon 7.8 kg/ha Amitrole 3.7 kg/ha)
Boron (2, 3)	1993	B	0, 1.3	1 year after planting	Herbicide after planting (Terbuthylazine 15 *l*/ha)
Nutrient omission (4, 5)	1993	N P S K Mg B	20* 10 10 15 10 1.7	At planting	Herbicide in second year (Terbuthylazine 15 *l*/ha Haloxyfop 3 *l*/ha Clopyralid 4 *l*/ha)
Nutrient omission (6)	1996	as above	as above	1 year after planting	Herbicide after planting (Terbuthylazine 15 *l*/ha Haloxyfop 3 *l*/ha)
Nutrient omission (7)	1997	as above	as above	At planting	Mechanical at planting
NPS (8, 9)	1995	N† P S	0, 20 0, 10 0, 10	1 year after planting	Mechanical at planting, herbicide at beginning of third year (Terbuthylazine 15 *l*/ha Haloxyfop 3 *l*/ha)

* For Trials 4–7, nutrient rates are presented for the "complete" treatment. Individual nutrients were omitted, one at a time, from the otherwise "complete" treatment to give a total of seven treatments in Trials 4 and 5. For Trials 6 and 7, an additional treatment ("control", no nutrients) was included.

† In Trials 8 and 9, nitrogen, phosphorus, and sulphur were added in all combinations to give eight treatments (control, N, P, S, NP, NS, PS, and NPS).

the base of the stem, and the slot opening was covered after application. In the boron trials fertiliser was spread on the ground around the base of the trees. Fertiliser was applied in spring, either at planting or 1 or 2 years after planting (Table 3). Trials 2, 3, and 6 were planted by hand and all other trials were machine planted. Weed control was achieved by spot spraying with herbicide in Trials 1–6 (Table 3). In Trials 7–9, initial weed control was provided by mechanical removal of turf by the coulter on the machine planter; in Trials 8 and 9 herbicide was applied subsequently to control herbaceous species which responded to the fertiliser.

In all except the boron trials, individual plots consisted of 10 trees planted at 2-m intervals in rows spaced 2.5 or 3 m apart. These trials were arranged as randomised blocks with either four (Trial 6) or five replicates. Trial 1 used a randomised block design with six replicates. Individual plots consisted of five trees/row planted at 2-m intervals in rows spaced 3 m apart. Trials 2 and 3 used a split plot design with five replicates. The main plots consisted of fertiliser treatment (presence or absence of boron), within which there were sub-plots consisting of rows of seven or eight trees of an individual species or breed. The sub-plots were randomly arranged and trees were spaced at 2-m intervals within the rows which were 2 m apart. Buffer rows were not installed between the fertiliser treatments in any of the trials.

In the boron trials tree heights were measured and tree form was assessed to determine fertiliser response. In Trial 1 form was assessed by simply noting the presence or absence of malformation (stems with double or multiple leaders or broken tops). In Trials 2 and 3 form was assessed by rating trees on a 3-point scale where 1 = severe malformation (unlikely to be a crop tree), 2 = fork or ramicorn present (tree judged to require corrective pruning), 3 = no malformation. A note was also made of trees showing shoot die-back symptoms of boron deficiency. In Trials 4–9 tree heights and stem base diameters were measured periodically using height poles and callipers respectively, and tree volume was calculated (diameter^2 × height) to assess fertiliser response.

Nutrient concentrations were determined in current-season foliage samples of fully expanded needles collected from Trials 1, 2, 3, 8, and 9. In Trials 2 and 3 foliage of only one of the *P. radiata* breeds (GF17) was sampled, foliage being collected in spring. In the other trials foliage was collected in late summer or autumn. In Trial 1 foliage was sampled at the end of the second, third, and fourth growing seasons after the fertiliser was applied. In Trials 2 and 3 foliage was sampled after two growing seasons, and in Trials 8 and 9 it was sampled at the end of the first growing season. Foliage was sampled from all trees and bulked by plot or sub-plot. Samples were oven-dried at 70°C and ground for analysis. Samples from Trials 1–3 were analysed for all nutrients except sulphur and iron (Trial 1), while samples from Trials 8 and 9 were analysed for nitrogen, phosphorus, and sulphur only. Nitrogen, phosphorus, potassium, calcium, and magnesium were determined after sulphuric-acid/hydrogen-peroxide digestion, and micronutrients were determined after dry ashing, using methods described by Nicholson (1984). Sulphur was determined as described by Quinn & Woods (1976).

All data were subjected to analysis of variance, with the analysis performed on plot means. For Trials 2 and 3, the analysis of variance compared the fertiliser response of pine species and breeds across the two soils. Where analyses indicated significant differences existed, statistical differences between treatment means were sought using the least significant difference (LSD) method.

RESULTS

Boron Trials

Boron application had no effect on height growth ($p = 0.80$) or malformation ($p = 0.93$) of *P. nigra* at age 8 (6 years after boron application) on Sawdon soil (Trial 1). The site for this trial was particularly stony and trees averaged only 3 m in height, and 23% of all stems had some degree of malformation. Boron application increased foliar boron levels at all three sampling dates, the increase being greatest at the first sampling (Table 4). Foliar boron concentrations in untreated trees were higher at the third measurement than at previous measurements, possibly indicating extension of roots of untreated trees into the plots with boron addition, as the trial progressed. Precipitation at Ribbonwood homestead (1.5 km from the trial site) over the summer (December–February) prior to the third sampling (1990–91)

TABLE 4–Effect of boron fertiliser on foliar boron levels (µg/g) in *Pinus nigra*, Sawdon soil, at three sampling dates (Trial 1). Boron was applied in November 1987, approximately 2 years after planting.

Boron rate (g/tree)	Sampling date		
	March1989	March1990	May1991
0	8 a	6 a	13 a
5	41 b	23 b	23 b
10	53 b	34 b	35 c
SE mean	7.1	5.8	2.8
LSD	15	14	7

Within columns, values without a letter in common are significantly different at $p < 0.05$ (LSD test).

was intermediate between those of the two previous years, indicating that the elevated foliar boron concentrations at the third measurement were unlikely to be due to differences in seasonal precipitation. In contrast to the untreated trees, concentrations in treated trees were higher at the initial measurement. Boron application had no effect ($p = 0.19$) on the concentrations of other nutrients in foliage of *P. nigra*. Nutrient concentrations in foliage from untreated trees were (s.e. in parentheses): N 1.45% (0.023); P 0.14% (0.003); K 0.76% (0.026); Ca 0.12% (0.020); Mg 0.04% (0.006); Mn 23 µg/g (3.6); Zn 17 µg/g (2.1); Cu 3.2 µg/g (0.13).

In the boron trials with different pine species and breeds on Fork and Pukaki soils (Trials 2 and 3), mean tree height on Pukaki soil exceeded that on Fork soil, while mean tree form was better on Fork soil (Table 5). However, the form difference between soils was much more pronounced in the *P. radiata* breeds than in *P. nigra*, and not evident in *P. ponderosa* (Fig. 1). Boron application improved mean tree form on both soils (Table 5), though there was a weak interaction between soil type, boron application, and species/breed ($p = 0.07$). On Fork soil, the improvement in form in the presence of boron was most pronounced in the *P. radiata* breeds GF28 and Guadalupe and the *P. radiata* × *attenuata* hybrid, while *P. nigra* and *P. ponderosa* showed no improvement in form with boron application (Fig. 1). In contrast, on Pukaki soil the improvement in form with boron application was evident mainly in the *P. radiata* breeds GF25 and Guadalupe. Boron also increased mean tree height; however, the increase was greater on Fork soil (0.30 m) than on Pukaki soil (0.05 m), and was apparent only in the *P. radiata* breeds (Fig 2). Within the *P. radiata* breeds boron application increased the proportion of trees of good form more on Fork soil than on Pukaki soil (21% and 6% respectively, Table 6), despite there being a higher proportion of good form trees on Fork soil.

Boron application substantially increased foliar boron concentrations in trees on Fork and Pukaki soils, the increase being greatest in *P. ponderosa* on both soils (Fig. 3). In the presence of added boron the foliar boron concentration of *P. radiata* was lower on Pukaki soil than on Fork soil, whereas concentrations in the other two species did not differ significantly between the two soils. Boron application slightly depressed mean foliar zinc concentrations (from 18 to 15 µg/g, $p = 0.06$), but had no effect on concentrations of other nutrients. Mean concentrations of nutrients other than boron in foliage of the three pine species are recorded in Table 7.

TABLE 5–Tree form and height (m) response to boron on Fork and Pukaki soils (Trials 2 and 3)

	Form	Height
Probability from analysis of variance		
Soil	<0.01	<0.01
Boron	≤0.01	0.02
Species/breed	<0.01	<0.01
Soil × boron	0.72	0.01
Soil × species/breed	<0.01	0.10
Boron × species/breed	0.08	<0.01
Soil × boron × species/breed	0.07	0.53
Main effect means		
Soil		
Fork	2.55 a	2.28 a
Pukaki	2.23 b	3.16 b
s.e.	0.014	0.032
Boron		
–B	2.30 a	2.63 a
+B	2.47 b	2.81 b
s.e.	0.033	0.048
Species/breed		
GF17	2.22 bc	2.94 bc
GF25	2.34 b	2.96 bc
GF28	2.10 c	2.88 c
Guadalupe	2.18 bc	3.31 a
P. radiata × attenuata	2.29 b	3.10 b
P. nigra	2.72 a	1.91 d
P. ponderosa	2.88 a	1.95 d
s.e.	0.089	0.092

TABLE 6–The effect of boron on the percentage of *P. radiata* trees in each of three form scores in Trial 2 (Fork soil) and Trial 3 (Pukaki soil).

Soil		Form score*		
		1	2	3
Fork	–B	12	48	40
	+B	3	36	61
Pukaki	–B	24	58	17
	+B	13	63	23

* 1 = severe malformation; 2 = tree forked or with ramicorn branch; 3 = no malformation

Nutrient Omission Trials

Pinus nigra: Fork and Pukaki soils

Growth of *P. nigra* on Fork soil (Trial 4) after 5 years was not significantly ($p = 0.64$) reduced by omission of nutrients compared to addition of complete fertiliser.

No effect of nutrient omission on the height of *P. nigra* was observed at the end of the first growing season on Pukaki soil (Trial 5). No further growth measurements of this trial are

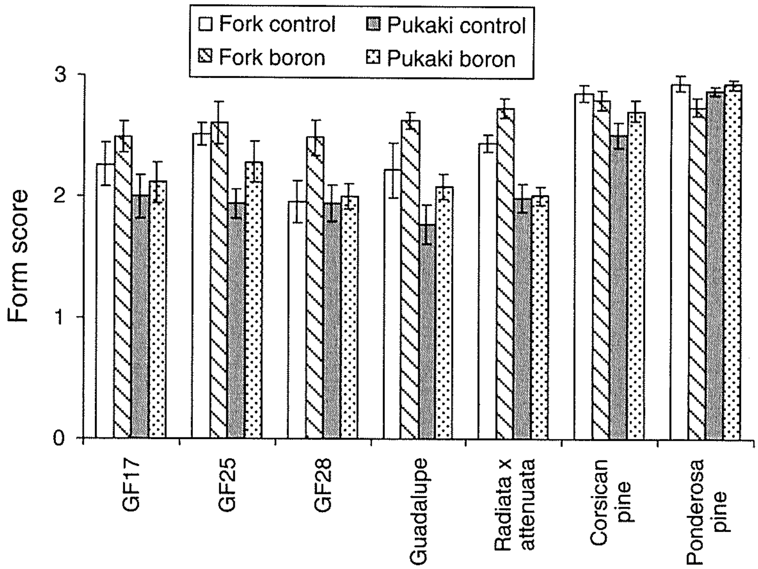

FIG. 1–Form response by *P. radiata* breeds, *P. nigra*, and *P. ponderosa* to boron application at age 7 on Fork and Pukaki soils, Trials 2 and 3. Bars show standard errors.

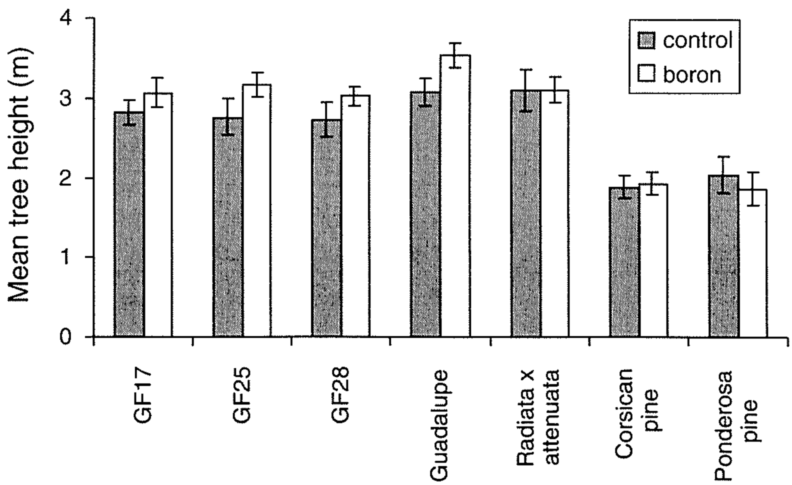

FIG. 2–Height responses by *P. radiata* breeds, *P. nigra*, and *P. ponderosa* to boron application at age 7, Trials 2 and 3. Values are means of Fork and Pukaki soils. Bars show standard errors.

TABLE 7–Foliar nutrient concentrations in three pine species in boron trials on Fork and Pukaki soils (Trials 2 and 3 respectively). Values are means of boron treatments.

	N	P	S	K	Ca	Mg	Zn	Cu	Mn	Fe	Al
	%						µg/g				
Fork soil (Trial 2)											
P. radiata	1.40b	0.14b	0.08b	0.46	0.38a	0.10a	29a	3.3a	134a	58	534a
P. nigra	1.26c	0.12c	0.08b	0.46	0.20b	0.09b	16b	2.3b	101b	59	577a
P. ponderosa	1.56a	0.15a	0.09a	0.45	0.17b	0.08b	25a	2.6b	117ab	55	305b
s.e. mean	0.042	0.004	0.004	0.022	0.024	0.005	2.9	0.18	15.0	7.5	30.6
Pukaki soil (Trial 3)											
P. radiata	1.36b	0.14a	0.08	0.53	0.28a	0.09	12a	3.1a	71b	45	565a
P. nigra	1.30c	0.12b	0.08	0.50	0.22b	0.09	10b	2.3c	92a	49	614a
P. ponderosa	1.49a	0.14a	0.09	0.50	0.19b	0.09	11ab	2.6b	76ab	45	326b
s.e. mean	0.027	0.003	0.005	0.019	0.014	0.004	0.7	0.07	8.4	3.6	23.6

Within columns, values without a letter in common are significantly different at $p<0.05$ (LSD test)

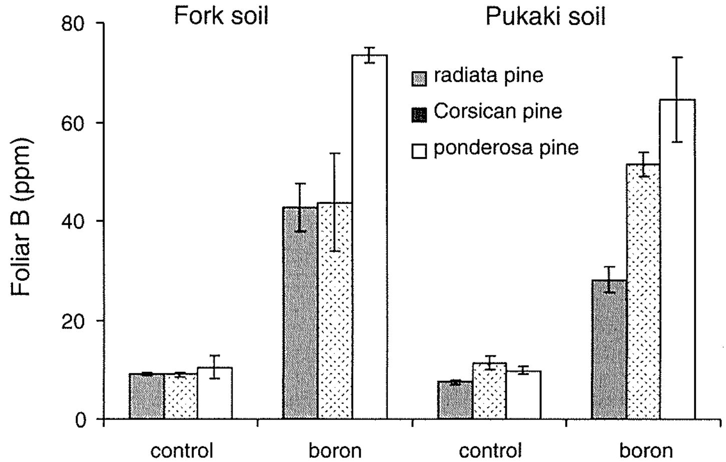

FIG. 3–Effect of boron fertiliser on tree foliar boron concentrations at age 3 on Fork and Pukaki soils, Trials 2 and 3. Foliage was sampled 2 years after boron application. The *P. radiata* breed is GF17. Bars show standard errors.

reported as the trees developed distortion from herbicide applied in mid-December 1994 to remove competition from herbaceous species.

Douglas-fir: Tekapo soils

Douglas-fir showed no growth response to omission of nutrients in the two nutrient omission trials at Mt Barker (Trial 6) and Balmoral (Trial 7) established on Tekapo soils in 1997. Any potential responses at Balmoral in the first season may have been limited by drought, as rainfall for the growing period September–April at Tekapo, 11 km east of the trial site, was only 292 mm (75% of normal), and height growth averaged only 5 cm. However, this cannot be argued for Trial 6, where height growth averaged 40 cm. Height growth in the second season averaged 21 and 59 cm for the two sites respectively.

Nitrogen-Phosphorus-Sulphur Factorial Trials

Nitrogen application reduced the growth of *P. nigra* on Pukaki soil by 39% ($p < 0.01$) after 3 years (Trial 8). Sulphur application reduced growth by a smaller amount (22%, $p = 0.06$), and phosphorus application had no effect on growth. There was no interaction between nitrogen, phosphorus, and sulphur in their effect on tree growth. Nitrogen application marginally depressed the foliar phosphorus concentration in *P. nigra* from 0.14% to 0.13% ($p = 0.07$), and the nitrogen concentration when applied alone (1.35%), but not in the presence of phosphorus (1.45%; N × P interaction = 0.06). Mean values were (s.e. in parentheses) 1.40% (0.033), 0.14% (0.004), and 0.07% (0.004) for nitrogen, phosphorus, and sulphur respectively.

There were no significant main effects of nitrogen, phosphorus, or sulphur on the growth of Douglas-fir on Tekapo soil (Trial 9), but there was a significant interaction ($p = 0.03$) between nitrogen and sulphur. Tree growth was greatest where nitrogen and sulphur were applied alone, and least when they were applied together (Fig. 4). As in *P. nigra*, nitrogen

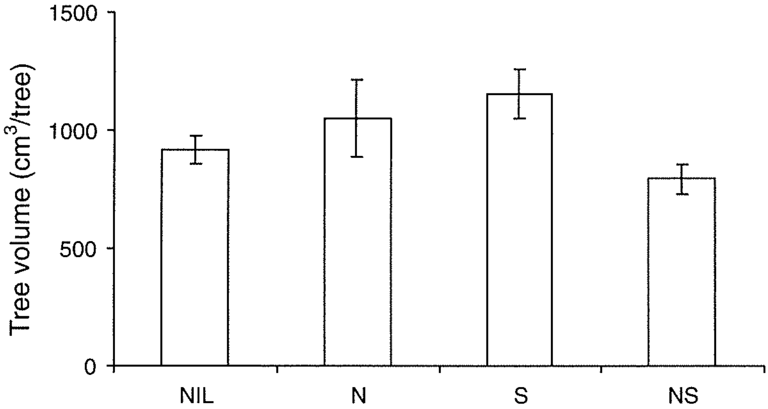

FIG. 4—Effect of nitrogen and sulphur fertiliser on the growth of 5-year-old Douglas-fir on Tekapo soil, Trial 9. Values are means of phosphorus treatments. Bars show standard errors.

application decreased the foliar phosphorus concentration in Douglas-fir from 0.16% to 0.14% ($p < 0.01$). Phosphorus application depressed phosphorus and sulphur concentrations in foliage ($p = 0.05$), but only by small amounts (0.01%). Mean values were (s.e. in parentheses) 1.58% (0.040), 0.15% (0.004), and 0.09% (0.003) for nitrogen, phosphorus, and sulphur respectively.

DISCUSSION

The only significant positive response to fertiliser in the present series of trials was to boron, for which form and height responses were recorded in *P. radiata* breeds on Fork and Pukaki soils (Trials 2 and 3). In the treatments without fertiliser in these trials, foliar boron concentrations were marginal for *P. radiata* (9 and 8 μg/g respectively) according to Will (1985). Although foliar concentrations were similar in the treatments without fertiliser, form and height responses amongst the *P. radiata* breeds were mostly greater on the highly drought-prone Fork soil, consistent with the common association of boron deficiency symptoms with the occurrence of droughty, coarse-textured soils in low-rainfall environments (Hunter *et al.* 1990; Stone 1990).

In contrast to *P. radiata*, neither *P. nigra* nor *P. ponderosa* responded to boron. Differences between pine species in susceptibility to boron deficiency have been observed elsewhere (Stone 1990). Wikner (1985) suggested that species or genotypes developed in coastal regions (*P. radiata*) would be more susceptible to boron deficiency than those from inland areas (*P. nigra* and *P. ponderosa*) because of higher atmospheric inputs of boron in coastal regions. This explanation implies differences in susceptibility to boron deficiency that are associated with differences in efficiency of absorption or use of boron within the plant. Clonal differences in foliar boron concentration (Knight 1978) and uptake and utilisation of boron (Beets & Jokela 1994) have been shown previously for *P. radiata*. The higher foliar boron concentrations of *P. ponderosa* than of *P. radiata* in the boron fertiliser treatment on Fork soil, and of both *P. ponderosa* and *P. nigra* than *P. radiata* on Pukaki soil (Trials 2 and 3) are supportive of differences between the species in boron uptake efficiency.

On the other hand, the lower foliar boron concentrations in *P. radiata* may be due to growth dilution, as the *P. radiata* breeds all had significantly higher growth rates than *P. ponderosa* and *P. nigra*. The slower growth rates of the latter species may have contributed to their lack of form and height response to boron. Differences in phenology might also have contributed to the differing boron responses observed. Both *P. nigra* and *P. ponderosa* complete shoot extension during the late spring to early summer period, prior to the onset of drought conditions which commonly occur from mid-summer through to autumn. Thus, both species may avoid the period of most severe boron stress, in contrast to *P. radiata* which does not have a determinate period for shoot extension.

The form response to boron varied amongst *P. radiata* breeds and depended on soil type. The breed GF28 had the poorest form overall and showed the strongest response to boron on Fork soil. Die-back symptoms of boron deficiency were also more common ($p = 0.01$) in GF28 than in all other breeds (data not presented). However, on Pukaki soil GF28 showed no response to boron, in contrast to GF25 and the Guadalupe origin. These results suggest that, while it may be possible to select breeds that are more tolerant of boron deficiency for use on boron-deficient soils, the value of such selection may be site-dependent.

Although form responses to boron were recorded on Fork and Pukaki soils, considerable malformation was evident in *P. radiata* breeds, especially on Pukaki soil, in the presence of boron fertiliser where foliar boron levels were well above deficiency levels. Malformation was also evident in Trial 1 where no form response to boron was recorded. Such malformation was likely to be due to factors other than boron deficiency, including animal or wind damage. Most malformation occurred too high up the stem to be attributed to rabbits or hares which were common in the vicinity of the trial sites, while possums, which are a major cause of stem damage in *P. radiata* elsewhere in New Zealand, were absent from the trial site area. Wind damage was the most likely cause of this malformation as strong nor'-west winds are a feature of the local climate. Wind damage may have contributed to the poorer form of *P. radiata* in Trial 3 than in Trial 2, as the latter site is sheltered from westerly winds by the presence of a 20-m-high scarp about 50 m to the west of the trial site. Although the occurrence of total malformation was high, the proportion of severely malformed stems (judged to be unlikely to make final crop trees) was only 3% and 12% on Fork and Pukaki soils respectively, where boron was applied. While *P. radiata* breeds showed both height and form responses to boron, longer-term study using new trials with larger plots than those used here (to allow for thinning) are required to determine if lasting and economic responses to boron fertiliser can be obtained.

Douglas-fir showed no growth response to omission of boron from otherwise-complete fertiliser applications on Tekapo soils. Although tree form was not scored in these trials, observations indicated no difference in tree form between treatments. It may be premature to conclude that boron addition is not required by Douglas-fir on Tekapo soils, as measurements of these trials have been made for only 2 years after fertiliser application. Both years were drier than normal, however, and if boron was deficient then responses to boron application should have been apparent.

Nitrogen, phosphorus, and sulphur are key deficient nutrients for pasture species in the South Island high-country (e.g., Scott 1992). Under glasshouse conditions *P. radiata* seedlings were found to respond to these nutrients in a similar manner to pasture species on Fork soil (Davis 1997), but in that study it was suggested that the responses observed may have occurred before the seedlings became mycorrhizal. In the present field trials no statistically significant positive responses were obtained to any of these nutrients.

"Deficient" and "optimum" concentrations of macronutrients in foliage of *P. radiata*, *P. nigra*, and Douglas-fir are listed in Appendix 1. For the pines, foliar cation concentrations in Trials 1–3 on Sawdon, Fork, and Pukaki soils were either optimum or close to optimum. Nitrogen and phosphorus were close to optimum in *P. radiata* on Fork and Pukaki soils in Trials 2 and 3, but below optimum in *P. nigra*, possibly because samples were collected in spring rather than autumn. Nitrogen and phosphorus were higher in autumn-collected samples in *P. nigra* in Trial 1 on Sawdon soil, and Trial 8 on Pukaki soil, though phosphorus was still below optimum. These below-optimum foliar phosphorus levels in *P. nigra* were not consistent with soil Bray-phosphorus levels (Table 2), all of which exceeded the critical value for normal growth of 12 μg/g proposed by Ballard (1974) for *P. radiata*. Less information is available for sulphur, but concentrations appeared either low or deficient in all trials when compared to the calculated levels given in Appendix 1. The indication of deficiency on Fork soil is consistent with tree growth in Trial 4. Although there were no significant effects of fertiliser on growth, poorest growth was recorded where sulphur was omitted from the otherwise-complete fertiliser mix. This result is, however, in conflict with that recorded on Pukaki soil (Trial 8), where sulphur application reduced the growth of *P. nigra*.

Foliage analyses for Douglas-fir are available only for the nitrogen-phosphorus-sulphur trial on Tekapo soil (Trial 9), and only for those elements. Nitrogen and phosphorus concentrations were close to optimum, whereas sulphur was close to being deficient. The indication of sulphur deficiency is consistent with tree growth in Trial 9, where growth was greatest in treatments where sulphur was applied in the absence of nitrogen (Fig. 4).

In the nitrogen-phosphorus-sulphur trial on Pukaki soil, growth reductions in *P. nigra* resulted when nitrogen and sulphur were applied. The reduced growth associated with nitrogen application most likely resulted from increased competition for water from resident herbaceous species which responded to the fertiliser. Mean ground cover of herbaceous species within a 0.5-m radius around stems (estimated in November 1998) increased from 36% in plots without nitrogen to 68% in plots with nitrogen applied ($p < 0.01$). Herbaceous cover was not affected by sulphur application, however, indicating that the growth reduction in *P. nigra* in the presence of sulphur was not due to increased competition. Nitrogen application also increased herbaceous cover around Douglas-fir in the nitrogen-phosphorus-sulphur trial on Tekapo soil (from 29 to 46%, $p < 0.01$), but this had no impact on tree growth. The smaller cover increase compared to that in the trial with *P. nigra*, and the larger size of Douglas-fir when fertiliser was applied (mean height = 46 cm, compared to 23 cm for *P. nigra*), may have contributed to the differing responses of the two species to nitrogen application. As with *P. nigra*, sulphur alone had no effect on herbaceous cover around Douglas-fir trees on Tekapo soil, either in the presence or absence of nitrogen, and so the reduced growth in the nitrogen-sulphur treatment cannot be attributed to increased competition from herbaceous species.

There were some consistent differences between the pine species in foliar nutrient concentrations on the Fork and Pukaki soils in Trials 2 and 3—notably for nitrogen (high in *P. ponderosa*, low in *P. nigra*), calcium (high in *P. radiata*), copper (high in *P. radiata*, low in *P. nigra*), and aluminium (low in *P. ponderosa*). While copper concentrations were highest in *P. radiata*, they were marginal for that species on both soils, as was zinc on Pukaki soil (Will 1985), though deficiency symptoms of these nutrients were not observed. The low aluminium concentrations in *P. ponderosa* relative to other species have been reported previously (Nordmeyer & Ledgard 1993). The higher nitrogen, phosphorus, and zinc concentrations in *P. ponderosa* relative to *P. nigra* were also consistent with their results.

CONCLUSIONS

The results from the present series of trials indicate that form and growth responses to boron application by *P. radiata* may be obtained at establishment on free-draining soils in low-rainfall high-country sites. The trial results indicate that boron could be applied at 1–2 g/tree on well-drained soils to reduce stem malformation. There are indications that there may be scope to select breeds less susceptible to boron deficiency, but longer term study is required to determine if boron application results in lasting responses and can be justified economically. In contrast to *P. radiata*, no form or growth response to boron by the slower growing *P. nigra* or *P. ponderosa* was observed. Despite sometimes-low foliar nitrogen and phosphorus concentrations in *P. nigra*, and consistently low and sometimes apparently deficient foliar concentrations of sulphur in pines and Douglas-fir, no statistically significant responses to these nutrients were obtained. Foliar potassium and magnesium concentrations were generally close to optimum and no response to these nutrients was obtained. Consequently, use of nitrogen, phosphorus, sulphur, potassium, or magnesium fertilisers at establishment is not warranted.

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APPENDIX 1

"DEFICIENT" AND "OPTIMUM" CONCENTRATIONS IN FOLIAGE OF *PINUS RADIATA*, *P. NIGRA*, AND DOUGLAS-FIR. DATA ARE FOR UPPER CROWN FOLIAGE COLLECTED IN AUTUMN.

	Nitrogen		Phosphorus		Sulphur*		Potassium		Calcium		Magnesium	
	Def.	Opt.	Def.	Opt.	Def.	Opt.	Def.	Opt.	Def.	Opt.	Def.	Opt.
Pinus radiata †	<1.2	>1.5	<0.12	>0.14	<0.08	>0.10	<0.3	>0.5	<0.10	>0.10	<0.07	>0.10
P. nigra ‡	<1.2	>1.5	<0.12	>0.16	<0.08	>0.10	<0.3	>0.5	–	–	<0.03	>0.05
Douglas-fir §	<1.2	>1.45	0.08	0.15	<0.08	>0.10	0.35	0.80	0.10	0.25	0.06	0.12

* Calculated from foliar nitrogen levels, assuming that for every 1% N, 0.068% S is required (Turner & Lambert 1986)
† From Will (1985)
‡ From Binns *et al.* (1980) and Mead (1984)
§ From Boardman *et al.* (1997)