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Effect of boron application on tree form and growth in young *Pseudotsuga menziesii* trees at montane sites in the South Island of New Zealand

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Abstract

Pseudotsuga menziesii (Mirbel) Franco (Douglas-fir) is a preferred timber species for sites in the South Island of New Zealand above about 500 m elevation where precipitation exceeds 800 mm. However young stands often exhibit leader tip death, leader break and stem distortion that result in poor tree form. These symptoms may be caused by chemical factors such as boron deficiency or by environmental factors such as frost, snow, wind, insects or disease. Trials were installed in two young Douglas-fir stands at Lake Hill in the Rakaia Valley (570 m elevation) and Balmoral Station in the Mackenzie Basin (870 m elevation) to determine if tree form could be improved by applying boron in the form of hydrated sodium calcium borate hydroxide (ulexite). Stem malformation (stem forking or multi-leadering) was 48% and 88% at Lake Hill and Balmoral respectively. Stem malformation was not reduced by boron application at Balmoral, and only reduced at Lake Hill by the highest boron application rate (32 kg B ha^{-1}), which also greatly reduced tree stem volume growth. These results indicate that stem malformation was not due to boron deficiency. Boron applied at 4 kg ha^{-1} significantly increased tree stem growth at Lake Hill, but reduced stem growth at Balmoral, and higher rates reduced stem growth at both sites. Boron rates of 1 – 2 kg ha^{-1} may be more appropriate for young Douglas-fir. This study indicates that a foliar boron concentration of 12 mg kg^{-1} may be adequate for good form of Douglas-fir, but may not be adequate for optimum growth. It is concluded that further studies are needed to better understand the link between climate and Douglas-fir tree form in montane environments, as well as to better understand relationships between rate of boron application, foliar boron concentration and growth and form of Douglas-fir in different environments.

Keywords: boron application; foliar boron concentration; growth response; malformation; *Pseudotsuga menziesii.*

Introduction

Pseudotsuga menziesii (Mirbel) Franco (Douglas-fir) is commonly planted in the South Island of New Zealand at elevations above 500 m where annual precipitation exceeds 800 mm (Ledgard, 1994). Douglas-fir grows well in these environments compared to other species and is often the preferred species because of its tolerance to wind, snow and low winter temperatures (Miller & Knowles, 1994). Young Douglas-fir plantations in these environments often show a high incidence of leader tip death or stem breakage, and stem and branch distortion. These symptoms are similar to those of boron deficiency in Douglas-fir as described by Carter et al. (1984, 1986), though such symptoms can result from other causes including frost, snow and wind damage, insects, disease, and heat and drought stress (Carter & Brockley, 1990; Lehto et al., 2010). In the South Island, boron deficiency in pine species occurs on a range of soils, particularly on free-draining coarse textured soils in low rainfall areas in the rain shadow of the Southern Alps (Will, 1990) where it may be exacerbated by low inputs of boron from either wet or dry atmospheric deposition (Herrmann, 2001).

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Nutrient requirements for Douglas-fir at establishment were investigated by Davis et al. (2001) in field trials at two South Island montane sites on well drained silt loam Tekapo soils where annual precipitation was 800 – 900 mm. In these trials, treatments consisted of omission of one nutrient at a time from an otherwise complete fertiliser application. Douglas-fir trees showed no growth response to omission of boron, but the effect on tree form was not assessed. In contrast, *Pinus radiata* D.Don (radiata pine) growing in a drier (i.e. 600 mm annual rainfall) environment on free-draining soils, showed both height growth and form responses to boron addition (Davis et al., 2001). In the Douglas-fir trials, fertiliser was applied in a spade slot beside tree roots, and there was insufficient spacing between treatments to allow longer-term effects of boron omission on tree growth or form to be studied. Boron deficiency is characterised by large inter-annual variation in expression of symptoms and is commonly expressed only in years of low rainfall (Stone, 1990; Will, 1985; Hunter et al., 1990). Thus, trials that encompass these long-term variations are necessary to confirm boron deficiency or adequacy.

Because of the widespread occurrence of deformity in young Douglas-fir plantations at montane sites in the South Island, an additional study of the influence of boron on Douglas-fir growth and form was considered warranted. To investigate potential responses of Douglas-fir to boron application, two trials were established in locations where nearby plantings exhibited typical stem deformity symptoms. This paper presents results of the effect of boron application on the early growth, form and foliar boron concentrations of Douglas-fir in these trials. The present trials extend the work of Olykan et al. (2008), who examined boron response in radiata pine over the same range of application rates at lower elevation North and South Island sites.

Methods

The trials were installed in two young stands of Douglas-fir in the central South Island of New Zealand. Characteristics of each site are provided in Table 1. Both trials were located on Tekapo soil formed in loess on moraine surfaces. This is an Acidic Firm Brown soil in the New Zealand soil classification (Hewitt, 1992) and is a well-drained silt loam. Both stands were planted in 1999 with the same strain of Douglas-fir ("Ashley" from Eyrewell Forest), which is believed to have been introduced to New Zealand from coastal Oregon, USA in 1875 (Miller & Knowles, 1994). The trees were machine planted into grassland which had been previously grazed.

Trial Sites

One trial was installed in a one-year-old stand of Douglas-fir at Lake Hill near the southern end of Lake Coleridge in the Rakaia Valley. Herbicide was applied around trees after planting to reduce competition from pasture vegetation.

The other trial was installed in a two-year-old stand of Douglas-fir at Balmoral Station to the east of Lake Pukaki in the Mackenzie Basin. No herbicide was used at this site where the grassland was dominated by the flatweed *Hieracium pilosella* L.

Trial Design

Plots were 32 x 32 m with a 20 x 20 m internal measurement plot. Ulexite ($NaCaB_5O_6(OH)_6{\bullet}5(H_2O)$, hydrated sodium calcium borate hydroxide) (Ravensdown, Christchurch, New Zealand), was applied at Lake Hill to give rates of 0, 4, 8, 16 or 32 kg B ha^{-1} in December 2000 in a randomised block

TABLE 1: Trial site characteristics and timing and rates of boron application.

Characteristic	**Site**	
	Lake Hill	**Balmoral**
Latitude (°S)	43° 21'	43° 58'
Longitude (°E)	171° 33'	170° 18'
Elevation (m)	570	870
Slope (°)	2 (west facing)	7 (south-east facing)
Soil	Tekapo silt loam	Tekapo silt loam
Annual precipitation (mm)[1]	878	887
Year of planting	1999	1999
Tree stocking (trees ha^{-1})	1600	1200
Date of boron application	5 December 2000	11 December 2001
Rates of boron (kg ha^{-1})	0, 4, 8, 16, 32	0, 4, 8, 16

[1] Mean annual (July-June) precipitation from 1999 to 2004. For Lake Hill, data for the first two years after planting were from Lake Coleridge Homestead (520 m a.s.l.), 3 km north-east of the trial site. For the following three years precipitation data were obtained from the mean of three rain gauges installed at Lake Hill Forest, within 1.8 km of trial site. Precipitation data for the Balmoral site were from Guide Hill Station (740 m a.s.l.), 4 km south-west of the trial site.

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design. At Balmoral rates of 0, 4, 8 or 16 kg B ha^{-1} were applied in December 2001 in a completely randomised design as plot location did not allow effective blocking. There were four replicates at each site.

Data collection

Tree heights and ground level diameters were measured annually in spring (October) for four years after the start of the Lake Hill trial and for three years after the start of the Balmoral trial. Tree stem volume (V) index was calculated from tree height (h) and ground level diameter (d) as:

$$V = (\pi\ (d/2)^2\ h) \times 0.40$$

Tree form assessments were made in March (autumn) of each year for three years after fertiliser application. Sinuosity was assessed by measurement of stem displacement from vertical (Adams & Howe, 1985, Spicer et al., 2000), and tree form (stem forking or multi-leadering) and leader status were scored using assessment categories (Table 2). Leader bud death was frequently observed and occasionally part of the stem below the bud was also observed to be dead. Under leader status, both conditions were categorised as "leader tip dead" (Table 2).

Foliage samples were collected from fully expanded current-year needles from the lower part of second order branches in March 2003 (Lake Hill) and March 2004 (Balmoral), approximately 2.5 years after boron application. Needles were collected from approximately 30 trees per plot and composited by plot. Foliar boron concentrations were determined by inductively coupled plasma-optical emission spectroscopy (Perkin Elmer, Toronto, Canada) after digestion in concentrated nitric acid and 30% hydrogen peroxide (modified after Kovacs et al. 1996, using 0.25 g of sample material, 5 mL of concentrated nitric acid and 1.5 mL of 30% hydrogen peroxide).

Statistical analysis

Because of differences in trial design and timing of boron application, statistical analysis was undertaken separately for the two sites. Average annual tree height, diameter and volume increments were determined for the three years after boron application at Balmoral and for the four years at Lake Hill. These data were then subjected to analysis of variance. The Newman-Keuls test was used to test for differences between application rates where analysis of variance indicated that means differed significantly at $P < 0.05$. Statistical analyses of growth data were carried out using SAS (SAS Institute, 1996).

The effect of boron application on tree sinuosity over the entire measurement period at each site was assessed using linear mixed-effects models. The models contained error structures that accounted for temporal pseudo-replication as each individual tree was measured three times. The effect of boron application on sinuosity in individual years and the difference between years was also examined using analysis of variance (ANOVA), using an appropriate error structure to account for pseudo-replication in the latter case. The data were transformed when necessary to meet assumptions of normality. The effect of boron on tree form and leader status was determined by calculating the proportion of each category (refer Table 2) in each plot and then assessing variation in proportions using linear mixed models with an error structure to account for pseudo-replication. Where analysis indicated that treatment means differed significantly at $P < 0.05$, Tukey's Honest Significant Difference test (for ANOVA) and the Wald test or the general linear hypothesis test (for linear models) were used to perform the post-hoc examination of treatment means. The analyses described for sinuosity, tree form and leader status were carried out in R version 2.14.1 (R Development Core Team, 2011).

TABLE 2: Tree-form attribute score definitions.

Attribute	Score	Definition
Sinuosity	-	For the 2nd internode from the top of the tree, the largest distance (mm) the stem is offset from the position it would occupy if there was no sinuosity.
Tree form	0	No malformation
	1	Leader forked, or multi-leadered, or no well defined leader
Leader status	0	Leader intact
	1	Leader tip dead
	2	Leader stem broken

Results

Tree growth

Tree growth was assessed as a combination of tree height, diameter and volume increments. Boron application significantly ($P < 0.01$) affected tree height, diameter and volume increments at both sites. Compared to control trees, boron application at 4 kg ha^{-1} significantly increased increments of all measured parameters in trees at the Lake Hill site. However, higher rates significantly reduced increments relative to either the control or the 4 kg ha^{-1} treatment (Figure 1). In contrast to Lake Hill, boron application at 4 kg ha^{-1} reduced height and volume increments of trees at the Balmoral site but did not affect diameter increment (Figure 1). Higher boron applications progressively reduced stem height, diameter and volume increments of trees at Balmoral (Figure 1). At the highest boron application rates (32 kg h^{-1} or 16 kg h^{-1} respectively), stem volume increment was reduced to 54% of the control at Lake Hill and 50% of the control at Balmoral (Figure 1c).

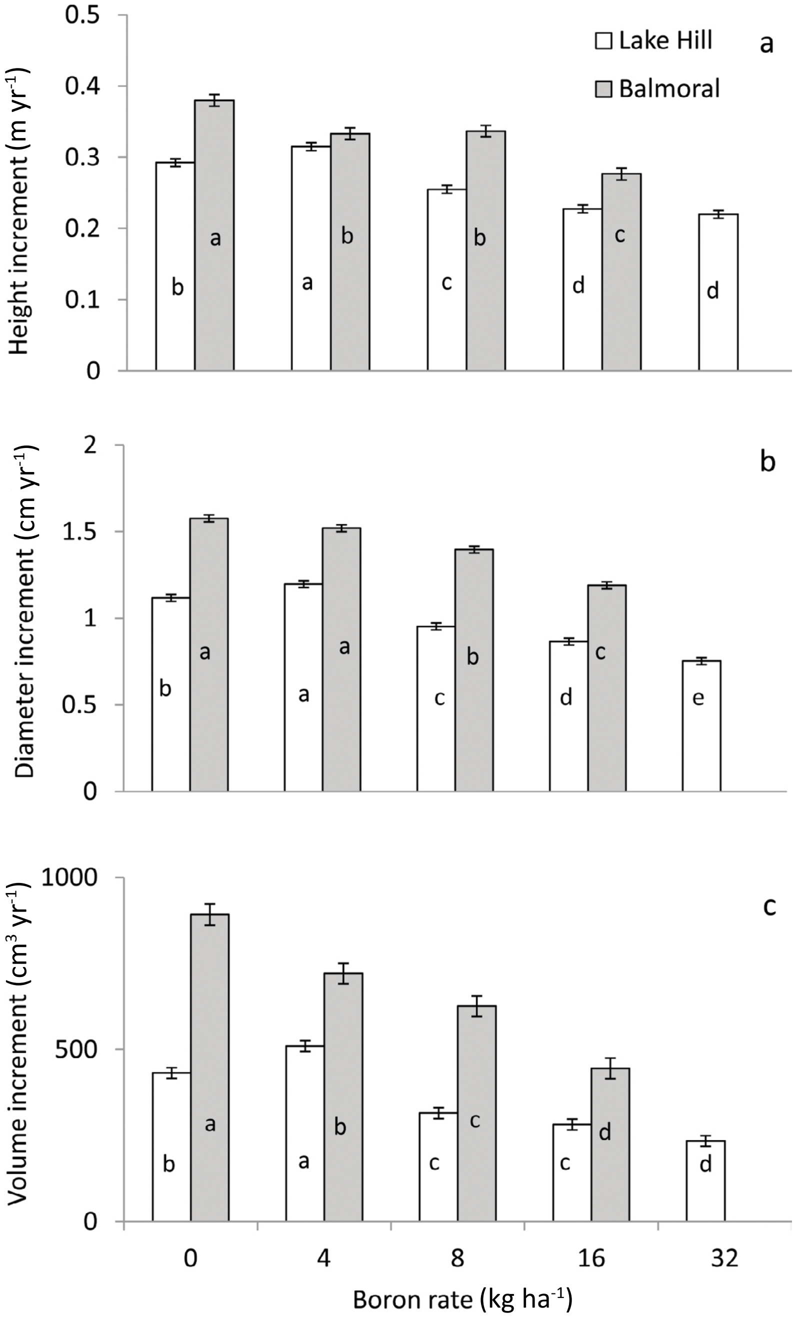

FIGURE 1: Mean annual (a) tree height; (b) diameter; and (c) stem volume increments for the first three years following boron application at Balmoral and for the first four years following boron application at Lake Hill. Within sites, histograms without a letter in common are significantly different ($P < 0.05$). Bars show standard errors.

Tree-form attributes

Sinuosity

Across the three-year measurement period, the linear mixed effect model demonstrated that sinuosity at Balmoral was significantly lower in trees that received 16 kg ha^{-1} boron than trees that received 0 or 4 kg ha^{-1} boron ($P < 0.05$). No significant effects were observed at Lake Hill over the entire measurement period. However, in year four, significantly less sinuosity was observed in trees treated with 32 kg ha^{-1} boron than trees treated with 4 kg ha^{-1} ($P < 0.01$, Figure 2a). At both sites, sinuosity differed significantly between years for a given application rate (both $P < 0.001$, Figures 2a & 2b). Mean sinuosity over all years and boron treatments at Balmoral (7.2 mm) was about double that at Lake Hill (3.9 mm).

Leader status

At the Balmoral site, neither leader stem breakage nor leader tip death varied significantly with boron application over the measured period (Figures 2d & 2f respectively). The number of broken leaders was substantially lower in year four than years two and three ($P > 0.01$, Figure 2d), while more leader tip death was observed in year three than either years two or four ($P < 0.001$, Figure 2f) regardless of boron application rate. At Lake Hill, boron did not have a significant effect on the number of broken leaders in any individual year, but when the whole measured period was taken into account, significantly fewer broken leaders were measured in the plots treated with 32 kg ha^{-1} boron than in plots receiving 0, 4 or 8 kg ha^{-1} boron (all $P < 0.01$, Figure 2c). There were fewer broken leaders in year four than either years two or three

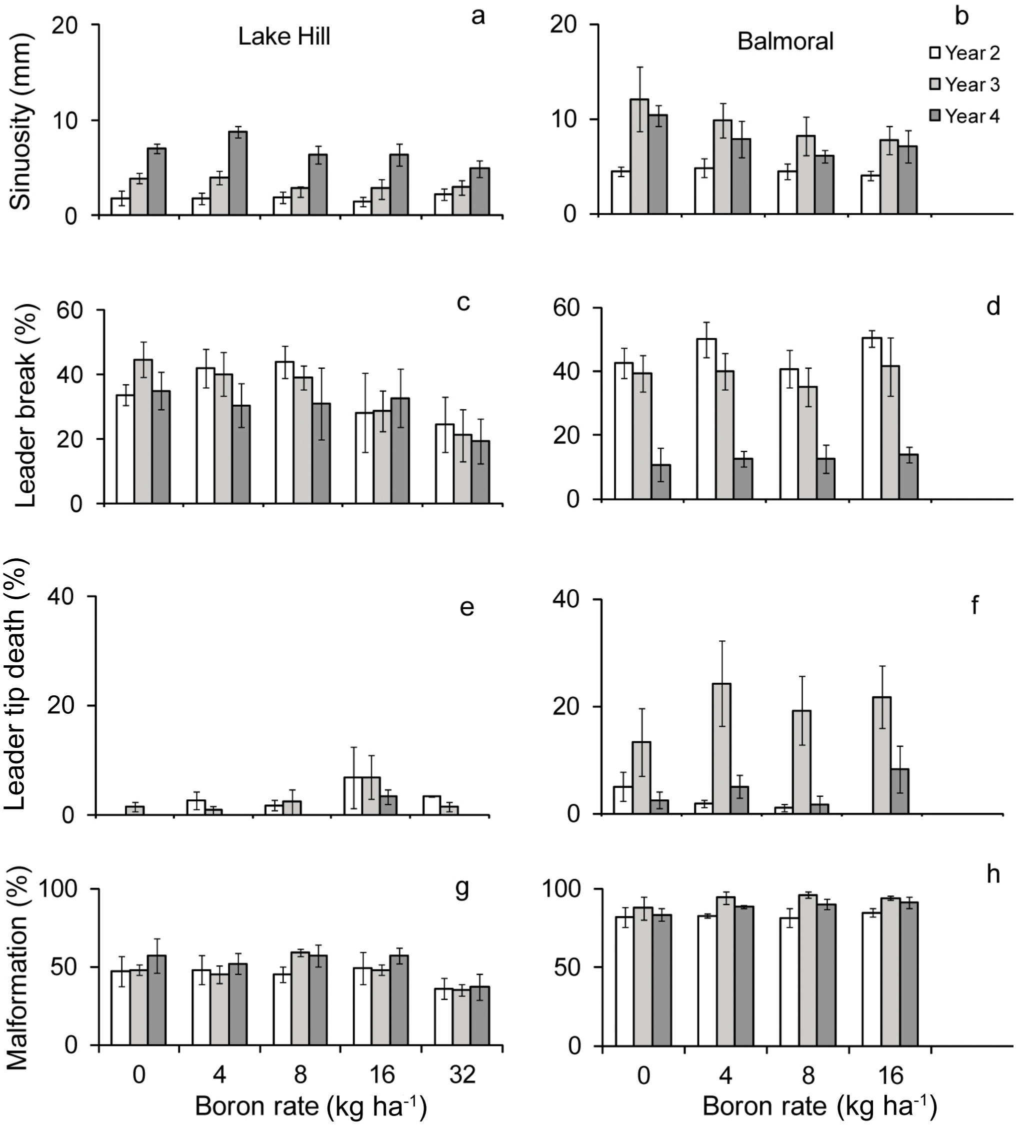

FIGURE 2: The effect of boron application on tree form for years 2 – 4 after treatment; (a) mean stem sinuosity; (b) mean % leader stem break; (c) mean % leader tip death; and (d) mean % tree malformation. Within years, boron rates increase from left to right at 0, 4, 8, 16 and 32 kg ha^{-1} for Lake Hill and at 0, 4, 8 and 16 kg ha^{-1} for Balmoral. Bars show standard errors.

(both $P < 0.05$), again regardless of boron application rate. Similarly, boron did not have a significant effect on leader tip death in any individual year, but when considered over the whole measured period leader tip death was observed significantly more often in plots treated with 16 kg ha^{-1} of boron than plots receiving 0, 4 or 8 kg ha^{-1} (all $P < 0.05$, Figure 2e).

Tree form

Tree form did not vary with boron application rate at Balmoral over the measured period (Figure 2h), although the malformation rate did vary significantly between years (the year-three malformation rate was greater than that for either year two or year four, $P < 0.01$; the year-four rate was greater than that for year two, $P < 0.05$). At Lake Hill, rates of malformation were significantly lower in the plots receiving 32 kg ha^{-1} boron than in plots either receiving 8 kg ha^{-1} ($P < 0.01$) or in plots receiving 0 or 16 kg ha^{-1} boron (both $P < 0.05$) over the measured period (Figure 2g). Rates of malformation at Lake Hill did not vary significantly between years. Malformation at Balmoral was about twice that at Lake Hill (Figures 2h & 2g respectively).

Foliar boron

Foliar boron concentrations in the untreated control plots three years after boron application were 12.5 and 20 mg kg^{-1} at Balmoral and Lake Hill respectively. Foliar boron concentrations increased to 102 and 61 mg kg^{-1} at Balmoral and Lake Hill respectively at the lowest boron application rate of 4 kg ha^{-1}, and increased progressively thereafter ($P < 0.01$ and $P = 0.03$ for Lake Hill and Balmoral respectively) (Figure 3).

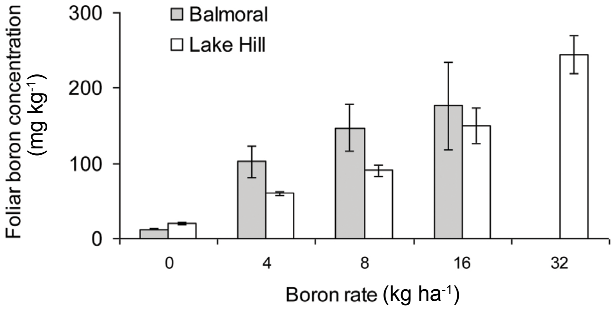

FIGURE 3: Effect of boron application on foliar boron concentrations at Balmoral and Lake Hill, two and a half years later. Bars show standard errors.

Discussion

At both sites, trees exhibited a high degree of malformation and symptoms (including sinuous stems, leader tip death and leader stem break) that appeared consistent with boron deficiency (Carter et al., 1984, 1986). With one exception (leader break, year four), the symptoms were more pronounced at Balmoral than at Lake Hill. This result is consistent with the lower foliar boron concentrations in the control treatment at Balmoral. However, stem malformation was not reduced by boron application at Balmoral and was only reduced at Lake Hill when boron was applied at a rate sufficient to severely limit tree growth. Thus, stem malformation evident in this study was not caused by boron deficiency. The key contributors to stem malformation include leader tip death and stem break, neither of which were reduced by boron application at Balmoral. At Lake Hill, leader stem break was reduced by boron application, but again only at the highest rate, which was sufficient to greatly reduce tree growth. Thus, neither of the conditions contributing to malformation appeared to be attributable to boron deficiency. Symptoms similar to those caused by boron deficiency can result from wind, snow and frost damage (Carter & Brockley, 1990) and it is possible that the weather experienced over the duration of the trial may have contributed to the stem sinuosity, leader tip death, leader stem break and consequent high degree of malformation evident in the trials. New Zealand montane environments are characterised by the occurrence of high wind speeds, snow and frosts. Such events can occur in any month of the year, and the incidence of these phenomena increases with elevation (e.g. Coulter, 1967; McCracken, 1980). The greater expression of malformation in trees at Balmoral is consistent with the higher elevation of this site than Lake Hill. It is not uncommon for Douglas-fir in New Zealand to suffer leader stem breakage or tip death and malformation as a result of damage by strong winds (Miller & Knowles, 1994). Further work is required to explore the link between climate and malformation in Douglas-fir.

While boron is an essential nutrient it can be toxic to plants if its supply is excessive (Lehto et al., 2010). In this study, both tree stem height and volume increment were reduced at the boron application rate of 4 kg ha^{-1} at Balmoral while stem height, diameter and volume increment were all reduced at the rate of 8 kg ha^{-1} at Lake Hill. These effects are attributed to boron toxicity. At the lowest rate of boron application, there were significant positive stem height, diameter and volume responses at Lake Hill. Differences in initial sapling size and grassland vegetation may have contributed to these different response patterns. The trees at Balmoral were one year older and were larger than those at Lake Hill when treated, thus larger root systems may have facilitated greater uptake of boron at Balmoral. Further, the grassland vegetation at Lake Hill was substantially more vigorous and productive than at Balmoral and would have competed more strongly for boron outside of the zone where weeds were controlled with herbicide. Olykan et al. (2008) reported increased uptake of boron in radiata pine where competing vegetation was controlled with herbicide, especially where boron was applied at higher rates. Greater uptake of boron at Balmoral is supported by the greater foliar boron concentrations in treated plots than at Lake Hill. While Olykan et al. (2008) concluded that application of 8 kg ha^{-1} of boron was safe for radiata pine, the present study showed that this is not the case for young Douglas-fir, and rates as low as 4 kg ha^{-1} may reduce growth in some situations. Lower rates (1 – 2 kg ha^{-1}) may be more appropriate for young Douglas-fir stands. The growth reductions in the present study were associated with foliar boron concentrations of 90 and 102 mg kg^{-1} at Lake Hill and Balmoral respectively. These concentrations are slightly higher than those associated with growth reductions in radiata pine in response to high boron application rates in New Zealand (Olykan et al., 2008), and than those associated with toxicity symptoms in *Eucalyptus* species (Lehto et al., 2010), but lower than those observed in other studies with pines (Lehto et al., 2010).

In a study in which boron application eliminated deficiency symptoms of swollen leading shoots and rosetting and curling of needles in Douglas-fir, Green and Carter (1993) found that foliar boron concentrations were satisfactory above 12 mg kg^{-1}, but deficient at 10 mg kg^{-1}. From North American literature, Boardman et al. (1997) proposed a deficient level of boron for Douglas-fir as 12 mg kg^{-1} and adequate levels to be in the range of 15 – 20 mg kg^{-1}. These values are currently used for diagnosis of boron deficiency in New Zealand. More recently, Moore et al. (2004) suggested using 20 mg kg^{-1} as the upper limit for deficiency until better estimates are developed. In the present study, no positive tree form response to boron was obtained except where boron application rates were sufficient to stunt tree growth. Thus, the concentration of 12 mg kg^{-1} in mature current-year foliage sampled in autumn, as found in control plots at Balmoral, appeared adequate for good form of Douglas-fir, supporting the value of Green and Carter (1993). This concentration is also considered satisfactory for radiata pine in New Zealand (Will, 1985). While 12 mg kg^{-1} boron may be satisfactory for good form of Douglas-fir, it may not be adequate for optimum growth, as there was a strong positive growth response to boron application at Lake Hill where the foliar concentration in control plots was 20 mg kg^{-1}. Height growth responses to boron in the absence of visible deficiency symptoms have been reported in Douglas-fir where the foliar concentration in control plots was 15 mg kg^{-1} (Green & Carter, 1993), and also in *Picea mariana* (Mill.) Britton, Sterns & Poggenb. (White & Krause, 2001), *Picea abies* (L.) H. Karst. (Saarsalmi & Tamminen, 2005) and radiata pine (Olykan et al., 2008). Further work is needed to better understand relationships between rates of boron application, foliar boron concentrations and growth and form responses in Douglas-fir in different environments.

Foliar boron concentrations in Douglas-fir measured 2.5 years after application of boron at a rate of 4 kg ha^{-1} remained well above the equivalent concentrations in the control treatments at both Balmoral and Lake Hill (respectively 100 and 60 mg kg^{-1} after the 4 kg ha^{-1} boron treatment compared to 12 and 20 mg kg^{-1} for control plots). This result indicates that ulexite has good long-term effectiveness for Douglas-fir in Tekapo silt loam soils. In contrast, Olykan et al. (2008) found much lower boron concentrations in radiata pine needles in their 3 – 4 year-old trees (~ 20 mg kg^{-1} in their 4 kg ha^{-1} treatment compared to ~ 10 mg kg^{-1} in the control). The higher foliar concentrations of boron in Douglas-fir than radiata pine foliage 3.5 years after similar rates of boron application may be due to greater growth, and hence dilution of boron, in plant tissue of radiata pine than in Douglas-fir.

Conclusions

The Douglas-fir trees in the two trials in this study exhibited high stem malformation typical of young stands in montane environments. Boron application had beneficial effects on leader stem break and stem malformation, but only at rates high enough to severely stunt tree growth. Thus, stem malformation at the sites in this study was not caused by boron deficiency. Stem sinuosity, leader stem break, leader tip death and stem malformation were all greater at the higher elevation site (Balmoral), consistent with greater exposure to damaging weather events. Further work is required to explore the link between climate and Douglas-fir tree form in montane environments. Although a low rate of boron application (4 kg ha^{-1}) resulted in increased growth of trees at Lake Hill, it decreased tree growth at Balmoral. This result indicates that Douglas-fir may be particularly sensitive to boron toxicity and that lower application rates (1 – 2 kg ha^{-1} borate) may be more appropriate for young Douglas-fir trees growing in montane environments. This study indicates that a foliar boron concentration of 12 mg kg^{-1} may be sufficient for good tree form in Douglas-fir, but may not be sufficient for optimum tree growth. Further work is required to better understand relationships between rate of boron application, foliar concentrations and growth and form of Douglas-fir in different environments.

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