Use of boron in conifer and hardwood nurseries

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Abstract

Nursery seedlings with visual boron (**B**) deficiencies are rare, especially for broadleaf species but they may have occurred in conifer nurseries in Florida, Oregon and the UK. Factors favoring a deficiency include high soil pH, high soil calcium and low soil moisture (i.e. withholding irrigation). Symptoms of a boron deficiency in pine include dead terminals, resin exudation from buds, dark green foliage, and terminal needles with less than 3 µg g^{-1} **B**. Chlorosis is an iron deficiency symptom but is not a boron deficiency symptom. At some nurseries (with more than 2% organic matter and more than 0.05 µg g^{-1} **B** in irrigation water), seedlings do not have a hidden hunger for **B**. As a result, there are no published trials that demonstrate a positive growth response from adding boron to managed nursery soils (when seedbed density is not reduced by boron). This review highlights some of the past and current uses of **B** in nurseries with a focus on deficiency and toxicity effects.

Keywords

Nutrition; Foliar analysis; Soil testing; Hidden hunger; Toxicity

Contents

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1 Introduction

Boron (**B**) is an essential nutrient for normal growth of seedlings (Shuman 1998; Wimmer et al. 2015) but some question its involvement in plant metabolism (Lewis 2019). This review will focus on boron fertilization in nurseries and greenhouses and will include a few observations from tree plantations. Most citations involve conifers, since hardwood species rarely develop a boron deficiency in nurseries (Stone 1968; May et al. 2009; Landis 2001). For example, pine seedlings may have needles with 6 µg g^{-1} **B** but hardwoods rarely have foliar values below 20 µg g^{-1} **B** and the average may be 36 µg g^{-1} **B** (Smith 1979). Although many examples of boron deficient angiosperms exist (Shorrocks 1997; Wang et al. 2015), I could not find any photos in my files of hardwoods with **B** deficiency symptoms in nursery seedbeds.

2 Materials and methods

Early in the 20th century, boron was not considered necessary for plant growth but research flourished after boron was declared an essential element. When growing seedlings in sand in greenhouses, researchers used solutions containing 0.1 or 0.2 µg g^{-1} **B** (Hoagland and Snyder 1933; Addoms 1937) or 0.5 µg g^{-1} **B** (Ingestad and Jacobson 1962; Smith et al. 1983). Some attempts to induce a boron deficiency failed (e.g. Hobbs 1940) since sand and water contained trace amounts of boron. In Australia, researchers were able to produce deficiency symptoms when water contained 0.01 µg g^{-1} **B** (Ludbrook 1942; Smith 1943). Several other greenhouse trials were successful in producing symptoms of boron deficiency (Table 1). Since deficiency symptoms are rare in well irrigated nurseries, photos of seedlings with symptoms in nurseries are rare (Table 1).

Only a few boron trials were installed at operational nurseries during the 20th Century. In 1937, boric acid was included in a fertilizer trial at a bareroot nursery in Indiana (Auten 1945). A high rate of boron (67 kg ha^{-1} **B**) was applied before sowing *Pinus echinata* with no positive effect on growth. This rate reduced *Pinus echinata* height by 15% to 22% but variability was such that a 33% decrease in height was required before declaring treatments detrimental ($\alpha=0.05$). Wilde (1946) said "Information on the acute deficiency of trace elements in forest soils is far from complete. A number of trials, conducted in the past ten years in forest nurseries of the Lake States and Central States regions have given no indication of such deficiencies."

During the second half of the 20th Century, boron was tested at several nurseries with no beneficial effect on seedlings. In 1955 and 1956, fritted micronutrients (including 0.8 kg ha^{-1} **B**) were tested at the Wareham Nursery in the United Kingdom (Benzian 1965) and in 1957 tests were conducted in Minnesota (Lease and Duncan 1959). In British Columbia, borax was tested at a pine nursery using a stocking of about 540 m^{-2} (Schaedle 1959). In general, 1.2 kg ha^{-1} **B** had no positive effect on bareroot *Pseudotsuga menziesii* seedlings but, in one trial, shoots growing in borax treated soil were 21 mg heavier than controls which was likely due to boron-related mortality (van den Driessche 1963). Boron was applied to *Pseudotsuga menziesii* in nurseries at rates ranging from 1.1 to 2.7 kg ha^{-1} with no positive results (van den Driessche 1963; Oldenkamp and Smilde 1966). Prior to 1970, a large proportion of bareroot nurseries were not treated with boron likely because visual deficiency symptoms were not observed in operational nurseries (Wilde 1946; Wakeley 1954; Stoeckeler and Arneman 1960; van den Driessche 1963; Tanaka et al.

1967; Anderson 1968; Iyer and Wilde 1974; Will 1985). The need to apply boron on a regular basis "seldom arises in most nurseries" (Knight 1981).

Table 1. A selected list of photographs of boron deficiencies in trees.

Species	Location	Photo on page	Reference
Acacia mearnsii	Field	2055	Lehto et al. 2010
Eucalyptus globulus	Field	105	Dell et al. 2001
Picea abes	Field	2055	Lehto et al. 2010
Picea glauca	Greenhouse	15	van den Driessche 1989
Pinus elliottii	Field	111	Stone et al. 1982
Pinus elliottii	Field	13	South et al. 2018
Pinus patula	Field	146	Procter 1967
Pinus pinaster	Field	431	Stone and Will 1965
Pinus radiata	Field	194	Appleton and Slow 1966
Pinus radiata	Greenhouse	201	Lanuza 1966
Pinus radiata	Field	315	Bengtson 1968
Pinus radiata	Greenhouse	112	Snowdon 1973
Pinus radiata	Field	222	Snowdon 1982
Pinus radiata	Field	30	Will 1985
Pinus radiata	Field	25	Crane and Borough 1987
Pinus radiata	Field	51	Khan 2012
Populus deltoides	Greenhouse	28	Hacskaylo et al. 1969
Pseudotsuga menziesii	Greenhouse	15	van den Driessche 1989
Pseudotsuga menziesii	Field	49	Green and Carter 1993
Robinia pseudoacacia	Greenhouse	26	Hacskaylo et al. 1969
Tectona grandis	Greenhouse	17	Sujatha 2003
Tectona grandis	Greenhouse	194	Whittier 2018

Before 1980, most nursery managers were not fertilizing with borax due, in part, to experiments showing no benefit and because soil reports from state laboratories included only macronutrients and sometimes zinc (Marx et al. 1984; Youngberg 1984). For example, in 1979, 27.9 Mg of boron was used in New Zealand plantations but nurseries used 0.0% of that amount (Ballard and Will 1978). However, after a deficiency occurred in 1979 (Stone et al. 1982), consultants felt justified in recommending boron, even in the absence of soil tests. In December 1976, Dr. May (University of Georgia) suggested 33.6 kg ha^{-1} of Frit 503 (which provided 1 kg ha^{-1} **B**) be applied to soil before sowing. Although the W.W. Ashe Nursery had no evidence of a **B** deficiency (Maki and Henry 1951), the FRIT 503 slow-release treatment was adopted in 1964. It was likely the only nursery in the southern United States that was routinely applying fritted **B**, Cu and Mn to soil (Marx et al. 1984). However, trials were not conducted to determine if this treatment was beneficial or a waste of time. The fritted iron (2.6 kg ha^{-1} Fe) was not effective in preventing summer chlorosis and fritted copper increased soil copper in one field (3.8 µg g^{-1} Mehlich 1) to the highest recorded among 45 sampled nurseries (South and Davey 1983). Soil samples taken from the Ashe Nursery in 1983 indicated 0.4 to 0.5 µg g^{-1} **B** and the following year the nursery stopped the routine application of fritted micronutrients.

Ingestad published a paper entitled "Mineral nutrient requirements of *Pinus silvestris* and *Picea abies* seedlings" (Ingestad 1979) which increased use of boron in greenhouses. This paper provided "optimum" nutrient ratios for hydroponics even though the "optimum" nitrogen/**B** (N/B) ratio was never determined. As a result, Ingestad's generic 500 N/B ratio was adopted (Tinus and McDonald 1979; Landis 1997) and boron was subsequently applied to container-grown stock. However, managers realized that **B** did not need to be proportionally increased along with nitrogen. When boron in irrigation water is sufficient, seedlings can be grown without boric acid fertilization (Hobbs 1944; Walker et al. 1955; Marx et al. 1984; Dumroese and Wenny 1997; Iyer et al. 2002; Masullo et al. 2021). Fertilizers with N/B ratios of 735 to 3,670 have been used to grow seedlings in containers (Brissette et al. 1977; Landis et al. 1989; 2009; Wilkinson et al. 2014).

In 1982, Dr. Davey at NCSU began making region-wide fertilizer suggestions based on soil test data from a laboratory in Tennessee (South and Davey 1983). When soil tests indicated 0.3 µg g^{-1} **B**, Davey suggested a soluble source (20.5% **B**) be applied before sowing. Prior to 1983, many nursery managers were not aware of the boron levels in their soils and most did not apply boron fertilizer to nursery soils. Due, in part, to active pH management, appropriate irrigation practices, soil testing and fertilization, boron deficiencies in nurseries have not been reported since 1980.

3 Soil tests

Although soils contain both soluble and insoluble forms of boron, the insoluble portion typically contains the greatest proportion (ie. organic matter and minerals like tourmaline). The soluble portion can be estimated with various extraction methods: Mehlich 1, Mehlich 3, ammonium acetate (AA), hot water and others (Nable et al. 1997; Davey 2002). Extractions of identical soil samples might produce values of 0.22 (Mehlich 1) and 0.46 µg g^{-1} **B** (Mehlich 3) (Mylavarapu et al. 2002). Therefore, when using the identical "trigger value" for determining when to spray boron, a manager will likely apply more boron fertilizer when using the Mehlich 1 test. The highest solution extracted (Mehlich 3) from 200 soil samples from Maryland and Delaware was 1.9 µg g^{-1} **B** (Shuman et al. 1992).

Even when using the same extraction procedure, different laboratories will report different boron values for the same soil sample. As a result, managers who use laboratory X will apply less boron to their seedbeds than managers who send samples to laboratory Y (Table 2). This might help to explain why some soil laboratories do not routinely test for boron (Gilliam and Smith 1980; Vitosh et al. 2000). "Actual levels of boron in soil are not measured due to the nutrient's high mobility in sandy soils, where many of the crops that require **B** are grown" (Hardy et al. 2013). Another reason is that for sensitive crops, it may cost less to apply low rates of borax than to test soils for boron (Vitosh et al. 2000).

In many sandy soils, organic matter contains most of the total boron. When 1 million kg of soil contains 2% organic matter, the organic fraction may contain 0.4 kg **B**. After time, some of the boron in the organic matter becomes available to bareroot seedlings. One nursery soil with 1.7% organic matter had a soil solution test reading of 0.1 µg g^{-1} **B** (dos Santos 2006). In theory, this soil contained a total of 0.44 µg g^{-1} **B** (0.34 µg g^{-1} in organic matter and 0.1 µg g^{-1} in soil solution). Most soil laboratories attempt to estimate the level of soluble boron without quantifying the total amount. In some soils, the soluble boron may represent 10% of the total boron (Whetstone et al. 1942).

Typically, there is a poor correlation between soil solution boron and uptake of boron by seedlings. A surface soil with low soluble boron, therefore, does not mean leaves will be deficient in boron. For example, soil tests from one acid soil (pH 3.5 to 3.8) indicated no soluble boron in the topsoil (South et al. 2004), but needles sampled from pines at that location contained more than 16 µg g^{-1} **B**. Likewise, at a hardwood nursery soil contained 0.2 µg g^{-1} **B** and leaves of *Quercus nuttallii* contained 21 µg g^{-1} **B** (dos Santos 2006).

Table 2. Examples of boron soil test results (Mehlich 3) using three soil samples. All three laboratories agreed that soil C was low in boron. However, laboratory X indicated that soil A was low (L) while the other two laboratories indicated soil A was medium (M) in boron.

	Laboratory		
Sample	X µg g^{-1}	Y µg g^{-1}	Z µg g^{-1}
Soil A	0.16 (L)	0.5 (M)	0.7 (M)
Soil B	0.10 (L)	0.6 (M)	0.0 (L)
Soil C	0.10 (L)	0.2 (L)	0.0 (L)

4 Tissue analysis

For *Pinus taeda* plantations (NCSFNC 1992), foliar boron concentrations were positively related to soil organic matter (r= 0.43), soil nitrogen (r= 0.36) and negatively related to soil pH (r= -0.42). Since foliar nutrient concentrations provide a better understanding of seedling nutrient status, tissue analysis is the preferred sampling method once nursery plants have developed true leaves.

In Australia and New Zealand, foliage of bareroot pine seedlings contained less than 23 µg g^{-1} **B** (Knight 1978b; Flinn et al. 1980) and the maximum value for 1-0 bareroot *Pinus taeda* (sampled in February, 2010) was 25 µg g^{-1} **B** (Figure 1). Foliage samples from 2-year-old *Pseudotsuga* (Krueger 1967) and *Pinus resinosa* (Iyer and Wilde 1974) seedlings ranged from 2 to 14 µg g^{-1} **B**. Bareroot pine seedlings (sampled December to February without surface residues) usually have less than 30 µg g^{-1} **B** in needles. As a comparison, foliage samples from 42 unfertilized plantations of *Pinus taeda* (age 9 to 19 years) revealed that all samples were below 18 µg g^{-1} **B** (NCSFNC 1992).

When needles contain more than 30 µg g^{-1} **B**, they might have been sampled from newly emerged seedlings that are growing in boron-fertilized soil. For example, 37% of bareroot pine seedlings sampled in July (3-months after sowing) had foliage exceeding 30 µg g^{-1} **B** (Figure 1). Likewise, container-grown pine seedlings sampled in May and June had foliage ranging from 28 to 35 µg g^{-1} **B** (Rey 1997) and in December the range was from 32 to 62 µg g^{-1} **B** (Fan et al. 2004). Attempts to stimulate growth of stunted seedlings with micronutrient fertilizers could explain why needles sampled in July from one Alabama bareroot nursery exceeded 85 µg g^{-1} **B.**

Other reasons for high boron tests include: irrigation with water containing high levels of boron (Truvey et al. 1992); sampling soon after application of boron fertilizers; or seedlings growing in soil containing high levels of boron. On a mine spoil with high soil boron (3 µg g^{-1}), pine foliage had 15-20 µg g^{-1} **B** at planting but after 8 months, needles contained over 150 µg g^{-1} **B** (Wood 1985). When grown in water containing 500 µg g^{-1} **B**, pine needles can exceed 3,000 µg g^{-1} **B** (Lanuza 1966).

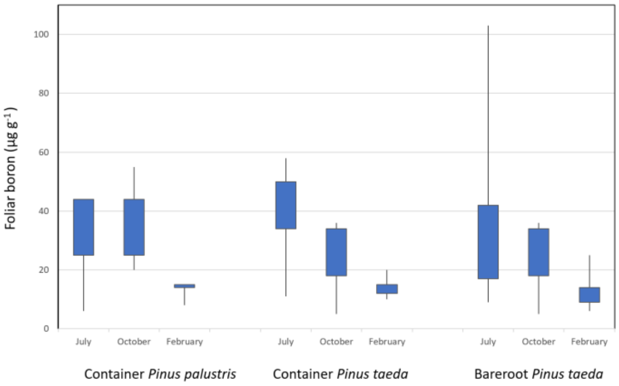

Figure 1. Foliar boron can vary by sampling month (2010-2011), species, and stock type (Starkey and Enebek 2012). Plots are based on 19 bareroot nurseries and 6 to 7 container nurseries. Box represents 10 values for bareroot seedlings and 5 values for container-grown seedlings. The lowest boron values were 6 µg g^{-1} for seedlings sampled in July and February.

Sometimes there is a trend in lower boron concentrations over time for pine needles (Schmidtling 1995; Iyer et al. 2002; Figure 1; Figure 2). There are several theories to explain this decline. First, the decline in µg g^{-1}could be due an increase in needle dry mass with no change in boron content over time (a.k.a. carbohydrate dilution). Second, as soil boron levels decline, perhaps a portion of the boron in needles becomes phloem mobile and the decline in concentration is due to retranslocation to other tissues (Aphalo et al. 2002). Third, if nursery sprays cease in August, then a decline might occur if rainfall and sprinkler irrigation remove residual traces of boron fertilizer from needles. Research can be conducted to test these hypotheses, but the carbohydrate dilution theory does not explain the decline observed for pine cuttings (Figure 2). Most likely this decline is due to a retranslocation effect.

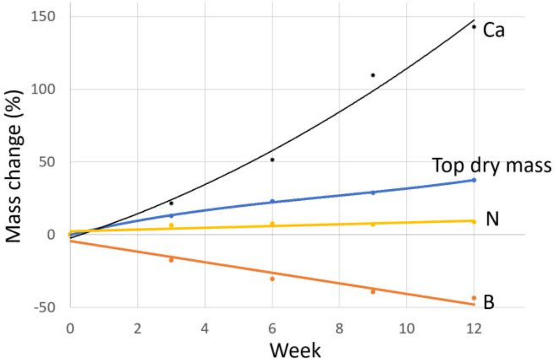

Figure 2. As *Pinus taeda* cuttings grow (9 cm; unrooted at week 0; top dry mass at week 0 = 0.38 g; week 12 = 0.52 g), the mass and foliar concentrations of calcium can increase while decreases occur for mass and foliar concentration of boron; week 0 = 23 µg g^{-1}, week 12 = 13 µg g^{-1} (Rowe 1996; Rowe et al. 1999). The decline in boron content can be explained if some of the boron is translocated from old needles to new adventitious roots (15.4 mg root dry mass at week 12). Mass of nitrogen in cuttings increased from 7.04 mg (week 0) to 7.86 mg (week 12).

5 Soils

Many soils in the United States are not deficient in boron but many sandy nursery soils have topsoil with less than 0.4 µg g^{-1} **B** (Figure 3). Approximately half the mineral soils in Florida contain less than 0.32 µg g^{-1} **B** (Mehlich 3) (Mylavarapu et al. 2002) but loam and silt loam nursery soils may average more than 1 µg g^{-1} **B** (Mehlich 1) (Tanaka et al. 1967; South and Davey 1983). Therefore, there is a negative correlation (r = -0.66) between **B** and sand content (South and Davey 1983).

The lowest soil test value for boron at a bareroot nursery is 0.0 µg g^{-1} (Mehlich 3) but 0.1 µg g^{-1} is expected at a few nurseries with sandy soils (Figure 3). Boron leaches rapidly in sand which explains why boron is low in topsoil at most bareroot nurseries. Pine trees in plantations typically do not exhibit boron deficiency symptoms when growing in non-fertilized soils in lower Coastal Plain soils of the United States (Albaugh et al. 2010). As a result, some researchers do not even test forest soils for boron.

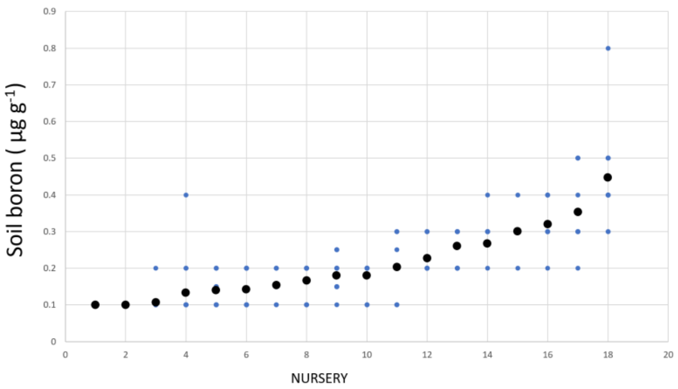

Figure 3. Soil boron (Mehlich 3) from 18 southern nurseries in the United States varies from 0.1 to 0.8 µg g^{-1}. Each nursery is represented by a mean (black dot) of 15 soil samples (i.e. 270 points on graph with many hidden points). Boron fertilizer was applied to fields (in March) when < 0.4 µg g^{-1}. Since pH levels were adequate (South 2017) and calcium levels were less than 600 µg g^{-1}, there were no reports of pine seedlings with black, aborted or dead terminals.

5.1 pH - Calcium

Soil pH affects the availability of boron in both bareroot and container nurseries. When soil pH is below 7.0, about 99% of the soil solution boron is boric acid which is readily available to seedlings (Wimmer et al. 2015). In alkaline soils, however, the borate ion is adsorbed on organic matter and clay which makes it less available to seedlings. On basic soils, many agronomic crops become deficient in boron but this type of deficiency is rare at bareroot nurseries with pH < 7.0. Seedlings growing in basic soils are more likely to experience deficiencies in iron and zinc.

Wilde (1954) said some foresters were inclined to interpret soil fertility problems in terms of pH and to ignore the effect of other factors such as calcium (Ca). Applying too much lime increases the chance of a boron deficiency (Wear 1957; Braekke 1983; Stone 1990; Lehto and Mälkönen 1994) but is this is likely due to calcium? Although increasing soil pH with lime can reduce growth of conifer seedlings (Hathaway and Witcomb 1985; Rikala and Jozefek 1990; Lamhamedi et al. 2011; South 2017), it is not clear how much calcium is required to induce a boron deficiency. Boron deficiencies were not observed on pines when nursery soil pH was high and calcium exceeded 2,000 µg g^{-1} (Landis 1979; 1988; Mexal and Fisher 1987).

To test this hypothesis, data from plots at a pine nursery in Texas were examined. An application of 3,252 kg ha^{-1} of dolomitic lime increased soluble calcium but foliar boron levels were not affected (South et al. 2017). A subsequent, non-replicated trial was established in 2018. An application of 6,776 kg ha^{-1} of dolomitic lime (881 µg g^{-1} Ca) resulted in "summer chlorosis" but necrosis of terminal buds was not observed. However, a combination of lime and gypsum (each at 6,776 kg ha^{-1}) increased soil calcium to 1,251 µg g^{-1} and some terminals turned black and died (Figure 4). Death of the shoot tip is a symptom of a boron deficiency and symptoms vary "markedly from one seedling to the next" (Stone et al. 1982). Apparently, at this location, boron deficiency symptoms can occur under high levels of soil calcium when soil temperatures exceed 40°C.

Figure 4. When 1-0 *Pinus taeda* seedlings were grown in soil (pH 6.7) with 1,251 µg g^{-1} of calcium (Mehlich 3), needles were chlorotic (iron deficiency) and a small percentage of seedlings had dead terminals (July 16). Dead terminals with resin exudation are signs of a boron deficiency (Stone et al. 1982; Stone 1990). At this location, the symptoms varied markedly from one seedling to the next. "The most characteristic symptom of boron deficiency is death of the apical meristems" (Snowdon 1982).

In one greenhouse trial, conifer seedlings were grown in unlimed peat (pH 3.8) with a water-soluble concentration of 0.2 µg g^{-1} **B** (Rikala and Jozefek 1990). Adding dolomitic lime (16 kg m^{-3}) increased pH to > 7.0 and decreased foliar boron of *Pinus sylvestris* seedlings from 35 µg g^{-1} to 12 µg g^{-1}. A similar response occurred with *Pinus banksiana* where increasing pH to 8.5 (with KOH) reduced the foliage concentration by 10 µg g^{-1} **B** (Zhang et al. 2015).

In *Pinus taeda* plantations, there is a negative correlation between soil pH and foliar boron concentration (NCSFNC 1992). However, this correlation might not exist at nurseries where seedbeds are irrigated with water that contains > 0.005 µg g^{-1} **B**. Even when $CaCO_3$ levels are high in alkaline soils (pH >7.1), pine needles may contain 14-27 µg g^{-1} **B** (Mexal and Fisher 1987).

In greenhouse trials with *Quercus rubra* seedlings, adding $CaCO_3$ to soil reduced the growth of seedlings. This treatment also increased the uptake of calcium and reduced the uptake of boron (Table 3). Since the seedlings were irrigated, there were no symptoms of boron deficiency. Although it is relatively easy to induce micronutrient deficiencies with lime in container nurseries (Dumroese et al. 1990), low foliar boron levels have not been reported after liming.

Table 3. The effect of lime (4,480 kg ha^{-1}) on total dry mass of *Quercus rubra* seedlings (g) in greenhouse trials (Phares 1964). Seedlings in the 1962 trial were smaller than those grown in the 1963 trial. Overall, the lime ($CaCO_3$) reduced seedling mass and foliar boron concentration by 17% and 33%, respectively. Soil acidity before liming was pH 5.5-5.8. N=nitrogen; P=phosphorus; K=potassium; LSD = least significant difference; C.V. = coefficient of variation.

	Seedling mass		Foliar boron		Foliar calcium	
Year-Fertilizer	No lime	Lime	No lime	Lime	No lime	Lime
	g	g	µg g^{-1}	µg g^{-1}	mg g^{-1}	mg g^{-1}
1962-NP	13.86	10.12	40.4	29.5	11.8	15.4
1962-NPK	12.70	11.06	38.0	24.8	10.6	13.1
1962-NP	15.60	9.30	33.0	30.7	9.8	17.2
1962-NPK	13.59	10.81	35.6	33.0	11.4	14.9
1963-NP	14.57	17.00	56.6	27.2	11.8	13.5
1963-NPK	15.16	14.88	55.2	28.3	10.2	12.2
1963-NP	17.86	12.85	48.2	34.3	7.7	12.6
1963-NPK	16.13	12.22	51.0	33.0	6.7	13.1
Mean	14.9	12.3	44.7	30.1	10.0	14.0
Lime; P > F	0.005		0.0002		0.0001	
LSD α=0.05	1.69		6.02		1.55	
C.V.	11.4		14.75		11.88	

5.2 Organic matter

The likelihood of a boron deficiency is increased when soils have low levels of organic matter (Stone 1990) and deficiencies have occurred on soils with less than 1.3% organic matter (Stone et al. 1982; Mahler 2004). Although significant correlations may not exist at several bareroot nurseries, positive correlations between organic matter and soil boron do occur (Shuman et al. 1992; South et al. 2018; Table 4). When examining data from 45 bareroot nurseries, the correlation coefficient was r = 0.34 (South and Davey 1983). Similar organic matter-boron correlations were reported for soils in Georgia, Maryland and South Carolina (Shuman et al. 1992).

In theory, one might assume the amount of boron in soil solution increases after adding organic matter to the soil. This assumption, however, is flawed. Although adding organic matter does increase the total amount of soil boron, it can simultaneously, decrease the amount of soluble boron (Yermiyahu et al. 2001). Therefore, when 67 Mg ha^{-1} of pine bark (ie. 40 g **B**) is added to the soil, the boron taken up in pine foliage might decrease by 10 µg g^{-1}.

Container nurseries use various media (peat, pine bark, compost) and some irrigate with water containing 0.06 µg g^{-1} **B**. Therefore, adding additional micronutrients to media might not benefit growth or color at some nurseries (Kalmowitz 1987; Smith 1992; Rose and Wang 1999). However, when boron in irrigation water is near zero and when lime is added to media, boron deficiencies have occurred in horticultural crops (Krug et al. 2009).

Table 4. Examples of simple correlation coefficients between independent variables organic matter (OM) and soil acidity (pH) and dependent variable boron (B) for eleven bareroot nurseries. Pearson correlation coefficients (r) in bold are significant (α = 0.06).

Nursery	State	pH	pH (r)	Soil boron ($\mu g\ g^{-1}$)	Organic matter (r)	Organic matter (%)
A	AL	5.1-6.3	**0.721**	0.1-0.2	0.173	0.8-1.6
B	MS	4.7-5.6	**0.539**	0.1-0.2	-0.010	0.9-1.2
C	AR	4.8-6.1	**0.405**	0.2-0.4	0.382	0.7-1.5
D	TN	4.5-5.5	0.292	0.1-0.2	**0.478**	1.6-3.3
E	GA	4.2-5.8	-0.103	0.1-0.15	**0.425**	0.5-1.2
F	TX	4.6-5.8	0.291	0.1-0.6	**0.405**	0.3-0.8
G	GA	4.8-6.6	0.048	0.3-0.8	0.206	2.1-5.1
H	SC	5.0-5.7	0.045	0.2-0.45	-0.225	0.3-0.8
I	TX	4.7-5.9	-0.201	0.1-0.2	-0.174	0.6-1.2
J	SC	4.6-5.9	-0.358	0.1-0.3	0.182	0.4-1.1
K	VA	4.3-5.6	-0.362	0.1-0.2	0.272	0.9-2.2

5.3 Water

Moisture levels affect boron availability more than any other micronutrient (Krug et al. 2009). “Sites expected of being boron deficient commonly have surplus soil moisture through most of the growing season, followed by a short but possibly severe period of summer moisture deficit” (Ballard and Carter 1985). In coastal regions with more or less than 1 m of rainfall, aquafers may contain boron at <0.6 mg L^{-1} and >2.0 mg L^{-1}, respectively (Glenn and Lester 2010). At nurseries with historically low rainfall in the summer or fall (Hopmans and Clerehan 1991; South and Nadel 2020), irrigation will reduce the risk of seedlings exhibiting a boron deficiency (Landis 2001).

The boron in irrigation water often determines the boron status of seedlings (Eaton 1935; Brown 2008) and trees (Möller 1983). At some container nurseries, growers fertilize seedlings using solutions with 0.2 to 0.5 mg L^{-1} **B** (Landis et al. 2009; Copes et al. 2017). Additional boron fertilization is not required at nurseries that irrigate sufficiently using water with 0.2 mg L^{-1} **B** since 3 L per seedling will provide 0.6 mg **B** (equivalent to 0.6 kg per million seedlings). However, irrigation water may contain less than 0.1 mg L^{-1} **B** (Figure 5) and some nurseries have little or no boron in irrigation water (Komor 1997; Altland et al. 2008; Landis et al. 2009). When water contains 0.02 mg L^{-1}, applying 1 m of irrigation would add 0.2 kg ha^{-1} **B** to a nursery soil. When irrigation rates are high, too much boron in irrigation water can be harmful. For example, 0.9 mg L^{-1} **B** injured pines when 1700 mm of irrigation was applied (Neary et al. 1975) while 100 mm of irrigation at the same location would likely not be harmful.

Areas with high boron in water are found in volcanic regions and arid zones (Eaton 1935). Irrigating with 2 mg L^{-1} **B** is considered to be the upper limit (Robbins 2010), 0.75 mg L^{-1} **B** is of marginal quality (Landis et al. 1989) and 0.3 mg L^{-1} **B** might cause problems for sensitive species (Baudoin et al. 2013). For soilless media, 0.05 to 0.3 mg L^{-1} **B** is considered slight to moderate risk.

Pine roots grow normally when hydroponics contains 0.05 or 0.4 mg L^{-1} but they do not grow well when boron is near zero (Ludbrook 1943; Goslin 1959; Lyle 1969). Since most irrigation water contains some boron, pine and oak foliage in greenhouses contained at least 24 µg g^{-1} (Walker and Huntt 1992; McLeod and Ciravolo 1998). In these greenhouse trials, the boron originated from both water and peat. When 140 L of water (at 0.02 mg L^{-1} **B**) is used to irrigate 10 L of peat, approximately half the soluble boron is supplied by water and the remainder is supplied by peat (Dumroese et al. 2018).

The likelihood of a boron deficiency at a bareroot nursery is increased when soils become dry. Even when irrigation water contains only 0.003 mg L^{-1} **B**, irrigation can keep soil moist which decreases the chance of a boron deficiency. According to Bryson and Mills (2014), calcium and boron "move into the new growth of the plant primarily by transpiration of water from the leaf, pulling water containing calcium and boron up to the growing points of the plant. Under conditions of moisture stress, low moisture or high relative humidity, transpiration from the leaf is reduced, and so is the movement of these essential nutrients into the new growth areas of the plant. Though a soil test may confirm adequate levels of these two nutrients in the soil, a deficiency in the plant may occur due to factors such as low soil moisture and high relative humidity."

At some locations, foliar concentration in pines is positively related to the amount of rainfall (Turner and Lambert 1986; Hopmans and Clerehan 1991). At one bareroot pine nursery (Stone et al. 1982), no irrigation and less than 6 mm of rainfall in October (Madison County, FL - 1979) contributed to a boron deficiency. The practice of ceasing all irrigation after the fall equinox (South et al. 1989; South and Nadel 2020) is now an outdated practice, in part, because it increases the risk of a boron deficiency which can decrease outplanting performance.

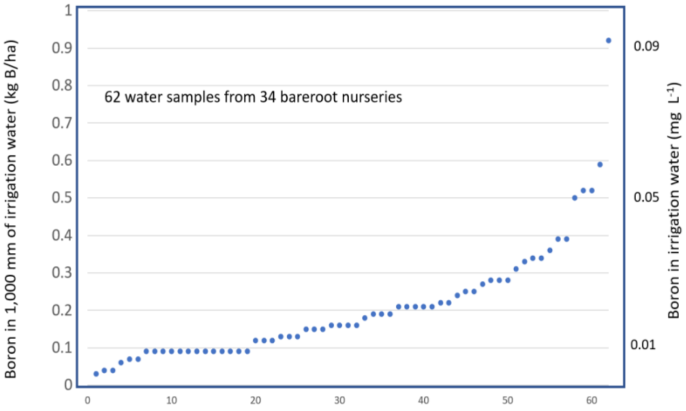

Figure 5. The amount of boron in irrigation water at 34 nurseries ranged from 0.003 to 0.09 mg L^{-1} (McNabb and Heidbreder-Olson 1998). When the level of boron in irrigation water is 0.01 mg L^{-1}, then 60 cm of irrigation would add approximately 60 g ha^{-1} yr^{-1} or 12 µg B per seedling (at a container tray density of 500 cells per m^2). About 40% of irrigation water samples from southern nurseries contain less than 0.015 mg L^{-1} but 19% contain more than 0.03 mg L^{-1} B.

5.4 Mycorrhiza

In moist soils, non-mycorrhizal roots can take up a sufficient amount of boron so seedlings do not become B-deficient. For example, stunted, non-mycorrhizal *Pinus taeda* seedlings exhibited P deficiency symptoms and yet had >40 µg g^{-1}**B** in shoots (Table 5). Similar foliar boron concentrations were observed for ectomycorrhizal and non-mycorrhizal pine seedlings (Cumming and Weinstein 1990; Walker and McLaughlin 1997; South et al. 2018). Inoculation with vegetative inoculum *Pisolithus tinctorius* increased growth of seedlings in greenhouses, which either decreased foliar concentrations of boron in pine seedlings (Mitchell et al. 1990) or increased boron concentrations in *Populus tremuloides* (Quoreshi and Khasa 2008). In contrast, applying spores of *Pisolithus tinctorius* (before or after transplanting) had no effect on uptake of boron by pine seedlings (Wood 1985; Walker 1999). Other species of ectomycorrhiza had little effect on uptake of boron by *Betula pendula* (Ruuhola and Lehto 2014).

Table 5. The presence of ectomycorrhiza at a nursery in Alabama increased the uptake of phosphorus but did not increase boron concentrations in shoots and roots of *Pinus taeda* seedlings. Normal seedlings (0.68 g dry mass) were mycorrhizal while stunted seedlings (0.20 g dry mass) were non-mycorrhizal. Seeds were sown on fumigated "new ground" on April 9th (South et al. 1988) and foliage was sampled on July 29, 1986. LSD = least significant difference; C.V. = coefficient of variation.

Sample location	Boron normal shoot	Boron stunted shoot	Boron normal root	Boron stunted root	Phosphorus normal shoot	Phosphorus stunted shoot
	µg g^{-1}	µg g^{-1}	µg g^{-1}	µg g^{-1}	µg g^{-1}	µg g^{-1}
1	208	133	27	19	1,500	900
2	76	99	18	16	1,600	600
3	53	150	17	21	1,500	600
4	60	78	18	26	1,500	600
5	45	67	16	22	1,400	700
Mean	88.4	105.4	19.2	20.8	1,500	680
P > F	0.567		0.613		0.001	
LSD $\alpha=0.05$	75.8		8.1		200	
C.V.	44.6		23.1		10.7	

5.5 Nitrogen

Although some say the likelihood of B deficiency will increase with nitrogen (N) applications (Stone 1968; Aronsson and Elowson 1980; Möller 1983; Willett et al. 1985; Bunt 1988; Brockley 2003), supporting evidence from nurseries is lacking. Applying more than 300 kg ha^{-1} of N did not induce boron deficiencies at bareroot nurseries (Dierauf et al. 1991; Birchler et al. 2001; South and Cross 2020). Likewise, in greenhouse trials, N fertilization increased boron uptake by *Juniperus virginiana*, *Cercis canadensis* and *Pinus taeda* (Henry et al. 1992; Rowe et al. 1999; Wooldridge et al. 2009).

In a pot trial with *Quercus rubra*, applying 360 kg ha^{-1} of N reduced seedling growth and also reduced the boron concentration in leaves (Phares 1964). However, seedlings were not deficient since the lowest foliar value from the high N treatment was 25 µg g^{-1} **B**. In another pot study with pine, added N increased the uptake of boron, but, due to carbohydrate dilution, the boron in needles was reduced to a level of 36 to 50 µg g^{-1} (Warren and Adams 2002). Likewise, in a hydroponic trial, adding N increased growth and reduced boron concentrations but did not result in a boron deficiency (Figure 6).

Fertilizing four-year-old *Pinus radiata* trees with 400 kg ha^{-1} of N had no effect on boron concentrations in needles (Olykan et al. 1995). With older pines in seed orchards and plantations, N fertilization increased boron concentration in needles (McCall and Kellison 1981; Schmidtling 1995). In *Pinus taeda* plantations, a positive correlation (r= 0.36) existed between soil N and foliar boron concentrations (NCSFNC 1991). Perhaps claims that N fertilization of conifers will cause boron deficiencies are based on observations where extra growth in plantations resulted in freeze injury of the terminals (South et al. 2002) and dieback of shoots was assumed to be due to a boron deficiency.

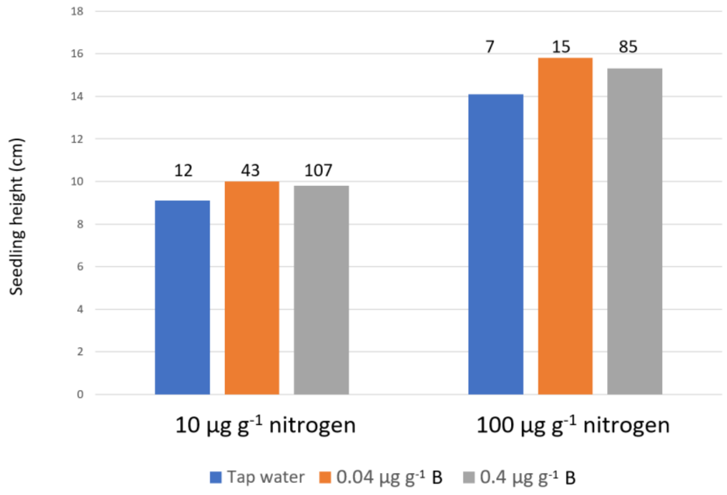

Figure 6. *Pinus contorta* seedlings grew taller when hydroponics contained 100 µg g^{-1} of N (Majid 1984). Tap water from Vancouver, BC (Capilano system) contained an unknown amount of boron and numbers above bars represent foliar concentrations of **B** (µg g^{-1}). Boron in needles were highest when solutions contained 0.4 µg g^{-1}. Due to carbohydrate dilution, boron concentrations in foliage were reduced when the extra nitrogen increased growth. When needles contained less than 13 µg g^{-1}**B,** stems were thin and crooked with terminal needles forming a cluster with resin. Needle twisting and discoloration were more severe when solutions contained 100 µg g^{-1} N plus 0.4 µg g^{-1} **B**.

6 Mobility of boron

Misconceptions regarding the mobility of boron in seedlings are the result of incorrect assumptions and poor terminology. Although boron easily moves from the root to uppermost leaves in the xylem, claims that “boron is immobile in plants” persist. What authors likely meant to say is that once boron compounds reach leaves in the top of a 30 m tree, boron rarely enters the phloem and moves back down to roots. However, this statement is not true for pines, eucalyptus, and Malus (Helmisaari 1990; Aphalo et al. 2002; Lehto et al. 2004; Ruuhola et al. 2011; Reid 2014). Boron is “highly phloem mobile” in several species that translocate polyols (Brown et al. 1998; Boaretto et al. 2008; José et al. 2009; Viera and Schumacher 2009; Wimmer et al. 2015). For example, in one study, boron was detected in roots one day after shoots were immersed in a solution containing $H_3{}^{10}BO_3$ (Lehto et al. 2000). Also, in a study with pine cuttings, calcium levels in foliage increased by more than 140%, while boron levels decreased by more than 40% (Figure 2). This indicates boron was phloem mobile while calcium continued to move in the xylem and accumulate in leaves.

7 Amount removed at harvest

The amount of boron removed by harvesting bareroot seedlings depends on species, cultural practices, and seedling age. A million pine seedlings may contain 80 to 230 g **B** (Knight 1978b; Stone et al. 1982; South 2018) while hardwoods contain about 200 to 800 g **B** per million (Arnold and Struve 1993; dos Santos 2006). In comparison, harvesting *Zea mays* grain removes about 55 g ha^{-1} (Heckman et al. 2003). Total B levels in topsoil (top 15 cm) will decline over time at sites where harvest rates exceed inputs from irrigation, rainfall, and fertilizers (Figure 7).

The distribution of boron in seedlings is not uniform and the concentration in shoots can be 200% higher than the concentration in roots (Knight 1978b; Boyer and South 1985; Kalmowitz 1987; Arnold and Struve 1993). Therefore, an overestimation in removals may occur if one assumes the entire seedling has the same boron concentration as foliage.

Some soil boron is replaced during calcium and phosphorus fertilization. For example, boronated gypsum may contain 1 kg **B** per 100 kg while regular gypsum may provide 14 g **B** per 100 kg and triple superphosphate might provide 328 g **B** per 1,000 kg (Gilliam and Smith 1980). In addition, in some regions, inputs from 1,000 mm of rainfall may exceed 20 g ha^{-1} (Martens and Harriss 1976; Wikner 1983; Turner et al. 2021). If a manager applies 1,000 kg ha of regular gypsum and irrigates using 1,000 mm of water (plus an additional 1,000 mm of rain), then 310 g ha^{-1}**B** (140+150+20) might be added to the nursery. As a comparison, 10 Mg ha^{-1} of seedlings (dry mass) may contain 200 g **B**.

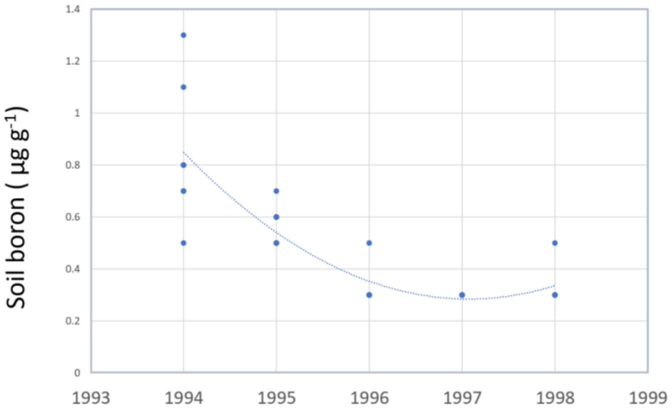

Figure 7. At some nurseries, the level of soluble boron (Mehlich 3) declines over time as harvesting seedling crops removes nutrients. At one loamy sand nursery the decline was about 0.2 µg g^{-1} year^{-1}. The decline typically ceases and soluble boron stabilizes at about 0.1 - 0.2 µg g^{-1}. At this level, inputs from irrigation, rainfall, organic matter and fertilizer might offset removals.

8 Boron deficiency

8.1 Visual symptoms

Six bareroot nurseries might have had boron deficiencies in the past (Krueger 1967; Aldhous and Mason 1994; Barnard 1997). A visual deficiency occurred at one nursery in Florida due to high pH soil, alkaline irrigation water containing calcium (Stone et al. 1982), low soil boron, low organic matter and low soil moisture due to the practice of ceasing all irrigation after the fall equinox. An infrequent occurrence in Florida might be explained because Octobers with less than 6 mm of rain may occur about once every two decades and managers now irrigate seedlings during autumn droughts. Although deep wells in Florida tend to have alkaline water with more than 100 ppm bicarbonates (Morgan and Graham 2019), managers now apply sulfur to increase soil acidity. Thus far, bareroot nurseries in other states have not reported any visual deficiencies in pine seedbeds. Although photos have been taken of deficiency symptoms in plantations (Table 1) and in growth chambers (Figure 8), similar photos from irrigated tree nurseries are very rare because managers tend to prevent boron deficiencies by applying irrigation during dry seasons.

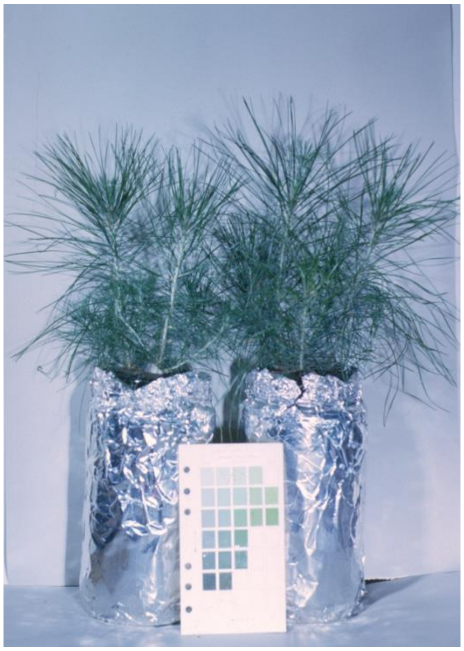

Figure 8. The glass container on the right contains three *Pinus taeda* seedlings (normal color Munsell 7.5 GY 5/6) growing in nutrient solutions that contain boric acid (Lyle 1969). The nutrient solution in the left container did not contain boron and resin exuded from the terminal buds. Foliage color was 7.5 GY 4/4 or 3/4 and was darker green than normal.

Visually deficient pine seedlings in bareroot nurseries have boron ranges of 1.8 to 4.2 µg g^{-1}(Stone et al. 1982) and in greenhouses the range can be 3 to 5 µg g^{-1} (Snowdon 1982). *Pseudotsuga* seedlings with short needles (< 2.7 cm) ranged from 2 to 6 µg g^{-1} **B** (Krueger 1967). Estimates for the minimum "adequate" boron foliar value for conifers include: 30 (Lanuza 1966), 20 (Maxwell 1988; Landis et al. 2005; Hawkins 2011; Turner and Lambert 2017), 16 (Walker et al. 1955), 12 (Green and Carter 1993), 9 (van den Driessche 1984); 8 (Knight 1978b; Braekke 1983; Sypert 2006), 7 (Majid

1984), 6 (Sayer et al. 2009), 5 (Riikonen et al. 2013) and 4 µg g^{-1} (Powers 1974; Jokela 2004; Albaugh et al. 2010). Although several authors suggest container-grown conifer seedlings are more sensitive to boron deficiency than bareroot seedlings, empirical data do not exist to support this hypothesis.

When there is too much calcium in pine nurseries, then terminals may turn black and die (Figure 4). At one nursery (pH > 6.0), terminals of pine seedling terminals turned black and some died when very dry soil contained >600 µg g^{-1} Ca (Stone et al. 1982). Fortunately, many nurseries have less than 400 µg g^{-1} Ca (South and Davey 1983). In greenhouses, needles on deficient seedlings may be darker green with some resin exudation from terminal buds (Figure 8). Symptoms of boron deficiency in tree plantations (Table 1) can occur after dry spells have stressed trees which reduces the uptake of boron (Stone 1990; Turner et al. 2021).

8.2 Hidden hunger

A hidden hunger exists when there are no visual deficiency symptoms but growth is increased when the supply of nutrients is increased (Landis et al. 2005). To demonstrate a hidden hunger exists, multiple rates of boron are used to develop a growth response curve. Once a curve has been produced (e.g. Lanuza 1966), then the “critical point” (Landis et al. 2005) for optimum growth can be determined and points where visual symptoms occur can be plotted on the curve. The critical point separates the deficient zone from the “adequate” zone. The “hidden hunger” zone is the area where no visible deficient symptoms are present but growth is less than maximum. Fertilization may improve seedling growth when a hidden hunger exists but it will not be cost effective when seedlings have no hidden hunger (e.g.*Picea glauca* Figure 9).

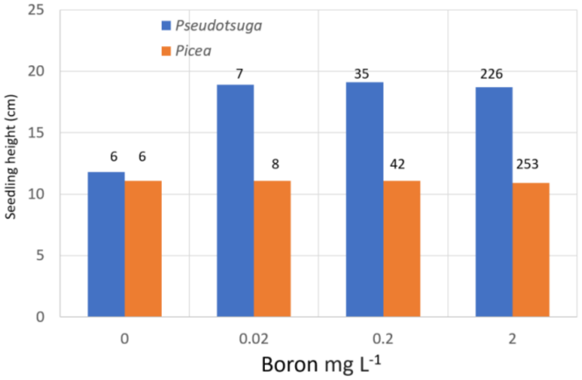

Figure 9. The effect of a boric acid solution on the growth of *Pseudotsuga menziesii* and *Picea glauca* in a growth chamber (van den Driessche 1989). Numbers above bars represent the foliar boron level (µg g^{-1}) 7 months after sowing. Deionized water was used for irrigation and for preparing nutrient solutions. Seedling heights on October 12, 1987 were significantly different for *Pseudotsuga* (P =0.001) but not for *Picea* (P =0.70).

In a greenhouse trial, deficiency symptoms occurred with 6 µg g^{-1} **B** in shoots of *Pseudotsuga menziesii* while seedlings grew well and had no symptoms at 7 µg g^{-1} **B** (Figure 9). If visual symptoms appear at the same time as growth starts to decline, then a hidden hunger zone for boron is very small or it simply does not exist when seedlings are grown in hydroponics (Figure 10). In contrast, a hidden hunger occurred where pine cuttings grew better in a greenhouse when soil was fertilized with 120 kg ha^{-1} of ulexite (Figure 11). Although a growth response from ulexite might be related to calcium, many studies in tree plantations show a hidden hunger for boron (Vail et al. 1961; Savory 1962; Shorrocks 1997; Brockley 2003; Turner et al. 2021).

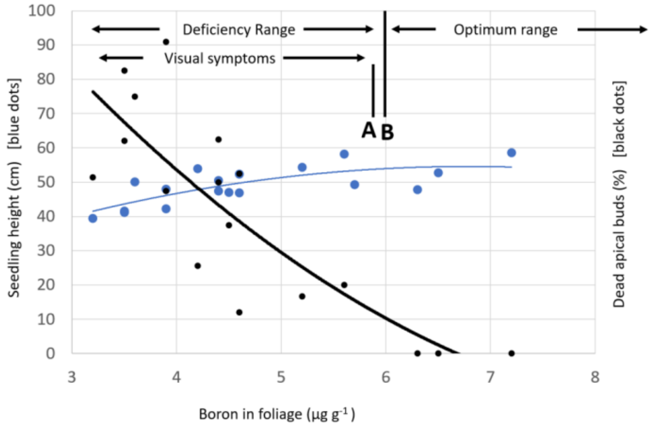

Figure 10. After 11 months in a greenhouse, fertilized *Pinus radiata* seedlings had dead terminals when needles contained less than 6 µg g^{-1}**B** (Snowdon 1982). The "critical point" for height growth (point B) is very close to the beginning of visual symptoms (point A). The "hidden hunger" zone is the gap between A and B which, in this example, is essentially zero. Each dot represents a different soil and seedlings were fertilized with all nutrients except boron.

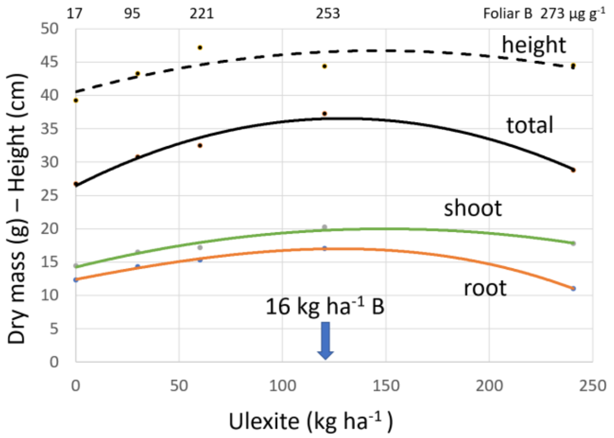

Figure 11. After 7 months in a greenhouse, *Pinus radiata* cuttings had brown needles and less total mass when soil was treated with 241 kg ha^{-1} of ulexite (Khan 2012). This slow-release, treatment contained 32 kg ha^{-1}**B,** 24 kg ha^{-1} Ca, and 14 kg ha^{-1} Na. Cuttings growing in untreated soils (0.3 µg g^{-1}**B**) had no deficiency symptoms and foliage contained 17 µg g^{-1}**B.** Each dot represents the mean of five seedlings; one seedling per pot.

Although boron might be applied to seedbeds under the belief that it will increase root growth more than shoot growth, data do not support this hypothesis. In four greenhouse trials, boron treatments did not increase root mass (Goslin 1959; Van Lear and Smith 1972; Kalmowitz 1988; Khan et al. 2012) and where an increased was reported, the effect was apparently due to a reduction in stand density (Schaedle 1959; van den Driessche 1963; Kalmowitz 1987). Just because withholding boron can reduce root growth in hydroponic trials, this does not mean applying boron to seedbeds will increase the root-weight-ratio of seedlings (Möttönen et al. 2001). In one greenhouse trial, applying 120 kg ha^{-1} of ulexite did not increase the root-weight-ratio of pine cuttings (Figure 11).

9 Toxicity

The toxic effects of boron on plants were recognized during the 19th Century (Eaton 1935). Although some say boron complexes found in cell walls is proof that boron is an essential element, others contend this is the result of a detoxifying mechanism (Lewis 2019). What is clear is that boron is more toxic to pine seedlings than copper, manganese, iron, or zinc (Lanuza 1966; van Lear and Smith 1972; Buchler 2002).

Many boron fertilizers contain sodium which can also be toxic to seedlings (Egorov et al. 2021). Therefore, seedling injury might due to a combination of two toxic elements. Toxicity trials with boric acid do not contain sodium but trials with borax contain 12% sodium.

Often toxic effects are missed because root growth is affected before shoots and some researchers do not examine or report root mass. In one nursery trial there was “no evidence of damage” even though root mass was reduced by 55% (Auten 1945). Likewise, in another pot trial, a 16% reduction in root mass (5 µg g^{-1} **B**)was viewed as not toxic (Figure 12). The toxic effects of boron on seed germination may be overlooked due to a lack of published research on tree seeds. At two nurseries, density in *Pseudotsuga menziesii* seedbeds was reduced when 1.1 kg ha^{-1} **B** was applied to soil before sowing (van den Driessche 1963) and density of *Liquidambar styraciflua* was reduced when sand was treated in a greenhouse with perhaps 2.7 kg ha^{-1}(Kalmowitz 1987).

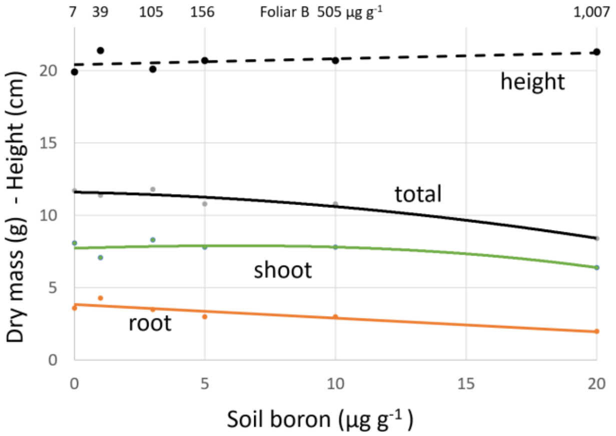

Figure 12. The effect of boric acid treatments (applied 4 months after sowing) on height and dry mass of 12 *Pinus taeda* seedlings in a greenhouse (Kalmowitz 1988). Adding boron to in a loamy fine sand resulted in a significant (α = 0.05) reduction in total seedling mass. Seedlings growing in soil with no boric acid were 3.8 mm diameter at the root-collar and the dry mass averaged 975 mg. Numbers at the top of the graph represent the respective foliar boron levels (µg g^{-1}) 15 weeks after treatment. No visual deficiency symptoms were noted since soil without added boric acid received irrigation and therefore the soil contained 0.1 µg g^{-1} **B** at week 31.

Due to different species, different methods of application, different soil types, and different compound solubilities, tests in nurseries and plantations have produced toxicity symptoms over a wide range of rates (Table 6). Labels for disodium octaborate tetrahydrate typically suggest higher rates for soil application (2X or 4X) than for foliar application (1X). At high rates, foliar applications of soluble products are more toxic than soil rates (Ben-Gal 2007) and in one pot trial with *Pinus elliottii*, applying 1.1 kg ha^{-1} **B** (11 weeks after sowing) caused needle tips to turn brown (Westveld 1946). Certain soil properties (e.g. high levels of soil calcium), can lower the risk of injury and slow-release fertilizers may be less toxic. For example, with a very soluble source, root growth was reduced at 5 µg g^{-1} **B** (Figure 12) but root injury occurred at perhaps 16 µg g^{-1} **B** with less soluble ulexite (Figure 11). Detailed information about how plants react to boron toxicity have been published (Nable et al. 1997; Landi et al. 2019).

For some sources, irrigation will leach boron away from the roots soon after application. When 2.2 kg ha^{-1} **B** (disodium octaborate tetrahydrate) is applied 4 weeks before sowing, it is likely much of the boron is gone from the topsoil by the time germination begins. Therefore, for pre-sow treatments, the time between treatment and sowing will determine the level of toxicity. Applying boron just before sowing reduce germination of *Pinus taeda* while seedling mortality did not occur when boron was applied 16 weeks after sowing (Kalmowitz 1988).

The method of application can affect the degree of injury (Appleton and Slow 1966). In one trial, a spray applied to foliage increased mortality while a soil application had no effect on newly planted pine seedlings (Buchler 2002). When boron comes in direct contact with roots, this can injure seedlings and increase mortality. In one trial (Walker 1999), applying a complete fertilizer in the planting hole (0.45 kg ha^{-1} **B** plus 21 kg ha^{-1} N) increased concentration in needles to above 1,000 µg g^{-1} **B** which might explain why survival of pine seedlings was lower than expected. Due to many years of toxicity caused by overdoses of sodium borate, foresters in New Zealand switched to using ulexite chips (Will 1985).

Managers should be careful when applying boron because the difference between operational and toxic rates is small (van den Driessche 1963; Degryse 2017). A target for irrigation water may be 0.5 mg L^{-1} **B** while a toxic rate may be 2 mg L^{-1} (Neary et al. 1975; Robbins 2010). Boron at 1 µg g^{-1} (before sowing) may be desired for a nursery soil while 4 µg g^{-1} might reduce root growth (Figure 13). For this reason, uniformity of application is important.

At one nursery in Alabama, a calculation mistake resulted in a toxic application in July. To reduce injury, irrigation was applied for a 12-hr period in hopes of leaching the material to below the rooting zone. This was apparently successful except for one portion of the treated zone.

Some toxicity trials are unclear since a solution concentration is provided but not the total rate applied (e.g. Silveira et al. 2004). As a result, a kg ha^{-1} value could not be calculated for several studies listed in Table 6. Applying 16 L of a 2 µg g^{-1} **B** solution to one pot will apply twice as much boron as 2 L at 8 µg g^{-1}. For this reason, it is wrong to assume solution concentration is the only factor that should be documented. When researchers plan on repeating a published study correctly, they must know both the solution concentration and the volume of solution applied to the seedling or pot.

Table 6. A list of boron treatments that produced toxicity symptoms on seedlings in field and greenhouse trials (either grown in pots or in water). Boron concentrations in spray solution (mg L^{-1}) can be converted to kg ha^{-1}**B** when the application rate (L ha^{-1}) is known. Values in **bold** are estimates. In some cases, the statistical power of the test was too low to declare toxic effects significant (α=0.05)t injury occurred at 10 μg g^{-1} and all seedlings were dead at 40μg g^{-1}**B** (Ludbrook 1942).

Species	Study	B kg ha^{-1}	B mg L^{-1}	$P<0.05$	Reference
Pinus patula	Planting hole	0.33	-	yes	Buchler 2002
Pinus radiata	Planting hole	0.5	-	-	Appleton and Slow 1966
Pinus radiata	Planting hole	0.9	-	-	Ballard 1978
Pinus elliottii	Pot	1.1	-	-	Westveld 1946
Pseudotsuga menziesii	Nursery	1.1	-	yes	van den Driessche 1963
Pinus strobus	Field	1.2	-	-	Stone and Baird 1956
Acer macrophyllum	Pot	**2**	1	-	Glaubig and Bingham 1985
Nyssa aquatica	Pot	**2.4**	2	yes	McLeod and Ciravolo 1998
Liquidambar styraciflua	Pot	**2.7**	3	-	Kalmowitz 1987
Thuja plicata	Pot	3.9	-	-	Walker et al. 1955
Carya illinoinensis	Pot	4	2	-	Haas 1929
Pinus elliottii	Pot	4	2	no	Van Lear and Smith 1972
Picea glauca	Nursery	4	-	-	Ensing 1986
Pinus sylvestris	Nursery	5.2	-	-	Chernobrovkina et al. 2008
Pinus patula	Field	5.4	-	-	Procter 1967
Pinus resinosa	Field	7.6	0.9	-	Neary et al 1975
Taxodium distichum	Pot	**9.5**	**8**	yes	McLeod and Ciravolo 1998
Pseudotsuga menziesii	Pot	**12**	-	-	Radwan and Brix 1986
Pinus taeda	Pot	**16**	8	no	Kaplan et al. 1988
Peltophorum dassyrachis	Pot	**17.8**	20	yes	Rose et al. 1999
Quercus nigra	Pot	**19**	16	yes	McLeod and Ciravolo 1998
Populus nigra	Pot	**20**	10	no	Yıldırım and Uylaş 2016
Populus russkii	Pot	**20**	**10**	yes	Ou et al. 2019
Pinus radiata	Pot	32	-	no	Khan 2012
Pinus radiata	Field	32	-	yes	Olykan et al. 2008
Pinus echinata	Nursery	67.2	-	no	Auten 1945
Salix viminalis	Pot	**90**	45	-	Rees et al. 2011
Eucalyptus saligna	Field	?	1.3	yes	Silveira et al. 2004
Diospyrus kaki	Pot	?	1.8	-	Bar-Tal et al. 2008
Sequoia sempervirens	Pot	?	2	yes	Wu and Guo 2006
Juniperus chinensis	Pot	?	2.5	-	Francois and Clark 1979
Pinus radiata	Water	?	5	-	Lanzua 1966
Pinus radiata	Water	?	5	no	Snowdon 1973
Carya illinoinensis	Pot	?	5	yes	Picchioni et al. 1991
Eucalyptus camaldulensis	Lysimeter	?	8	yes	Grattan et al. 1997
Pinus radiata	Water	?	10	-	Ludbrook 1942
Pinus taeda	Pot	?	10	yes	Kalmowitz 1988
Pinus banksiana	Pot	?	22	no	Apostol and Zwiazek 2004
Pinus patula	Field	?	410	yes	Buchler 2002

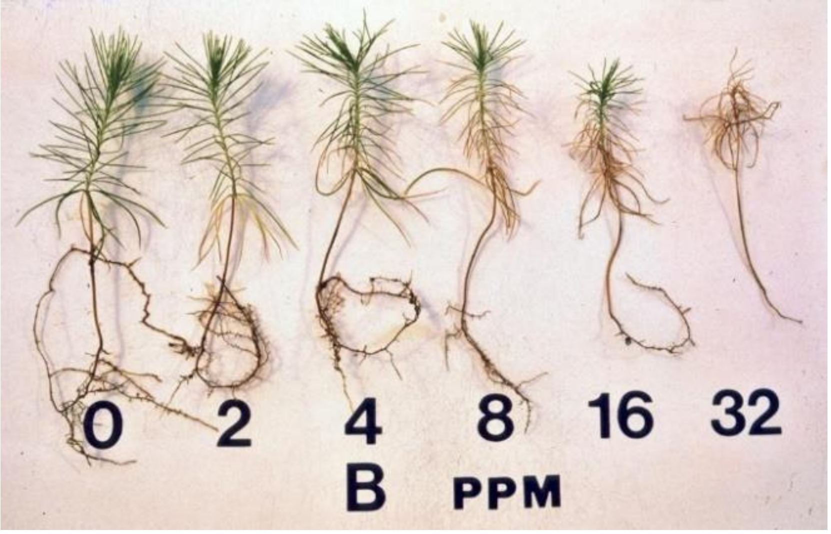

Figure 13. Effect of boron applied before sowing on *Pinus taeda* seedlings in a growth chamber. Numbers indicate the number of grams of boron incorporated into one million grams of soil prior to sowing. Seedling mortality occurred at 32 µg g^{-1} **B** and growth was reduced at 4 µg g^{-1} **B**. In a hydroponic study with *Pinus radiata,* slight injury occurred at 10 µg g^{-1} and all seedlings were dead at 40 µg g^{-1} **B** (Ludbrook 1942).

10 Operational Use

The amount of boron applied at bareroot nurseries depends on solubility which decreases in the order: borax > kernite > ulexite > colemanite > calcium and magnesium borate. In New Zealand, an insoluble hydroboracite (calcium-magnesium borate - 10% **B**) was used before sowing at one nursery while another spayed a liquid product (10.9% B) over seedlings in the summer. In the United States disodium octaborate tetrahydrate is used which leaches rapidly from the topsoil. As a result, more **B** is used to produce a million pine seedlings in Alabama than to produce a million pine seedlings in New Zealand.

Use of **B** in sandy bareroot soils is typically greater than the amount applied to emerged seedlings at container nurseries. For example, a million bareroot seedlings may be fertilized with 1.2 kg **B** while an equal number of container-grown seedlings may receive less than 60 g (Riikonenu et al. 2013; Zhu et al. 2020). Tradition, growing media and boron source help explain this difference. Generally, managers of container nurseries are concerned about boron toxicity (Gilliam and Smith 1980; Landis et al. 1989) while at sandy nurseries the concern is over low boron levels in the soil. In the first half of the 20th Century, managers of bareroot and container nurseries did not see a need to apply boron fertilizers to grow tree seedlings but now fertilization with boron as insurance is an accepted practice.

10.1 Bareroot

There are six approaches to fertilizing bareroot nurseries with boron: (1) rely on boron in irrigation water and rainfall and apply boron when visual deficiency symptoms appear; (2) apply an insoluble boron fertilizer to soil (e.g. 2 kg ha^{-1} **B**) approximately once every four to eight seedling harvests; (3) apply soluble boron before sowing when soil tests indicate low boron (Stone et al. 1982; Dumas and Patterson 2005); (4) test soil a month after sowing and apply soluble boron to areas with < 0.4 µg g^{-1} **B**; (5) test foliage in July and apply soluble boron to seed lots with < 8 µg g^{-1} **B** in foliage; and (6) routinely apply soluble boron to seedlings in July or after the summer equinox (Hopmans and Flinn 1983; Landis et al. 1989; Rodríguez-Trejo and Duryea 2003).

Billions of bareroot seedlings have been produced using method #1 without reports of deficiency symptoms. Method #3 is a common approach and may involve applying about 1 to 2.2 kg ha^{-1}**B** when soil is <0.4 µg g^{-1}. The time interval between application and sowing, for this method, is important. When disodium octaborate tetrahydrate is applied a month before sowing, rainfall may leach enough **B** so levels in topsoil are non-toxic. However, when applied just prior to sowing, a rate of 1.1 kg ha^{-1}**B** may reduce density of some species (van den Driessche 1963; Ashagre et al. 2014). Method #4 helps managers realize how quickly some products (applied in March) are leached from topsoil while method #5 can also be used to check on the status of other foliar nutrients. On coarse-textured soils, method #6 is occasionally used by managers who determine that it is cheaper to apply boron than to spend time and money on foliage sampling. The cost of soil analysis for micronutrients might be US$7 per sample while a 13-element foliar analysis might cost US$26.

Several approaches are used when boron is applied after the summer equinox. Some managers apply a 13-13-13 fertilizer (Table 7) at 100 kg ha^{-1} in July to provide about 0.1 kg ha^{-1} **B**. A second approach is to apply a liquid product (0.02% **B**) that contains several other micronutrients but a rate of 10 L ha^{-1} would provide only 2.5 g ha^{-1} **B**. In contrast, when a 20.5% **B** product is applied (Table 7), the rate for pines might be 0.5 kg ha^{-1} **B** (Knight 1978a) or 1 kg ha^{-1} (Maxwell 1988; Dumas and Patterson 2005) or 2.2 kg ha^{-1} for tolerant hardwoods (McLeod and Ciravolo 1998; Davey and McNabb 2019). *Pinus elliottii* may show injury symptoms at 1.1 kg ha^{-1} (Westerveld 1946). To reduce the risk of injury, some managers irrigate immediately after application. Managers concerned about applying 1.2 kg ha^{-1} **B** in a single application in July might apply two applications of 0.6 kg ha^{-1} spaced three or four weeks apart (Marx et al. 1989).

Although soluble sources are ideal for treating deficient plants, seedlings with visible symptoms almost never occur in irrigated nurseries. Very soluble products leach quickly which is an advantage for avoiding toxicity but is a disadvantage for nutrient use efficiency. Depending upon the amount of rainfall, disodium octaborate tetrahydrate may be gone after six weeks while sodium tetraborate pentahydrate is gone after 16 weeks (Broschat 2008). Slow-release fertilizers include fritted boron, ulexite and colemanite (Degryse 2017). Colemanite has been used to correct boron deficiencies in pine plantations in New Zealand (Hunter et al. 1990). Wear (1957) said "Colemanite (Ca_2B_60-$5H_20$) contains 10.1 per cent boron and is equivalent to about 89 per cent borax. This material is less soluble in soil solution than borax and does not leach out of coarse-textured soils as rapidly. This property makes Colemanite a better source of boron for sensitive crops on coarse-textured soils." In some soils, colemanite persists for more than 80 weeks (Broschat 2008). If colemanite (which currently costs about US$8.30 kg^{-1} of **B**) could be applied uniformly, this product might reduce the frequency of boron treatments.

Table 7. A partial list of boron (**B**) fertilizer products sold as a soluble powders (SP), dry flowables (DF), dry dispersible powder (DDP), granules (G) or liquids (L).

Tradename	Ingredient	Form	% B	% N
Solubor®	disodium octaborate tetrahydrate	SP	20.5	
Boron DDP®	boric acid, Na-tetraborate and K-tetraborate	DDP	18.5	
Solubor® DF	boric acid, borax pentahydrate, sodium pentaborate	DF	17.2	
Brant® boric acid	boric acid	SP	17	
Boron 15%	sodium borate	G	15	
Boron 15	sodium borate and calcium borate	G	15	
Frit™ FB-48 G	ulexite and sodium borate	G	15	
Granubor®	di-sodium tetraborate pentahydrate	G	15	
Colemanite	di-calcium hexaborate pentahydrate	G	12	
Borax	sodium tetraborate decahydrate	G	11.3	
Bortrac™	ethanolamine chelated boron	L	10.9	4
Borates Plus	hydroboracite	G	10.5	
Ulexite	sodium calcium penta-borate octahydrate	G	10.5	
OrganiBOR®	calcium magnesium borate	G	10	
Borosol® 10	boric acid	L	10	
Brant® liquid boron	ethanolamine chelated boron	L	10	13
AgriGuardian Boron™	ethanolamine chelated boron	L	10	13
Tracite®	ethanolamine chelated boron	L	10	13
Max-In® boron	boric acid	L	8	
CoBo®	boric acid	L	5	12
Boron 10	boric acid	L	4	
N-boron™	boric acid	L	3.3	5
Biomin® boron	sodium tetraborate	L	3	1
SBC Boron 1.5%	boric acid	L	1.5	
13-13-13 + micros	blended fertilizer	G	0.1	13
Maxigreen II®	boron glucoheptonate, K, S, Mg, Fe, Mn, Zn	L	0.02	
(Several)	slow-release product	G	0.0125	20
20-20-20 + micros	blended fertilizer	SP	0.0068	20

10.2 Container

Documented cases of boron deficiencies in container nurseries are rare (Stone 1990; Sword and Garrett 1991; Riikonen et al. 2013). This is mainly because some nurseries irrigate frequently with water containing more than 0.05 µg g^{-1} B (e.g. Rose and Wang 1999). In fact, researchers have a difficult time producing boron deficiencies when irrigating container stock using tap water or deionized water containing boron (Schroeder et al. 1946; Snowdon 1973). For example, use of deionized water in one greenhouse produced pine foliage with a boron concentration of more than 100 µg g^{-1} (Mitchell et al. 1990). Many tropical nurseries only use organic media and see no need to apply boron fertilizers. To reduce the risk of iron deficiencies, managers often keep media below pH 6.0 which also lowers the risk of a boron deficiency.

In the middle of the 20th century, production nurseries did not add boron to container media. “The fact that they are required in such minute amounts and are natural components of peat, soil, fertilizers, and water makes it improbable that a soil mix will have a deficiency of a minor element” (Baker 1957). This may explain why boron fertilizer recommendations are not found in several container manuals (Baker 1957; Carlson 1979) and some laboratories do not analyze media for boron levels

(Chong 2005). Container-grown seedlings growing in peat-vermiculite mix (without added boron) can have more than 20 µg g^{-1} **B** in foliage (van den Driessche 1989; Walker and Huntt 1992; McLeod and Ciravolo 1998). Therefore, many managers do not fertilize with products that contain more than 1% **B.**

Several managers incorporate no fertilizers to media and begin fertilization about 2 to 3 weeks after sowing (Dumroese and Wenny 1997; Rodríguez-Trejo and Duryea 2003; Dumroese et al. 2005). Although researchers may purchase elements individually and formulate stock solutions using boric acid, nursery managers may purchase convenient, pre-mixed fertilizers (Dumroese and Wenny 1997; Wilkinson et al. 2014). For example, pine seedlings may be treated with a soluble fertilizer containing 15% N and 0.02% boron (i.e. 750 N/B ratio). When a million seedlings are fertilized with 105 kg N using this product, then each seedling would be treated with 0.14 mg **B**. Assuming every seedling received a total of 3 L of irrigation water (@ 0.05 mg L^{-1} **B**), then this would supply an additional 0.15 mg. With a seedling dry mass of 3 g, and only one-third of the 0.29 mg is taken up by the seedling, then the predicted boron concentration for the total seedling would equal 32 µg g^{-1} **B**. This might explain why deficiency photos from operational container nurseries are not listed in Table 1.

Some managers add a slow-release fertilizer into media before filling containers (Barnett and McGilvray 2000; Haase et al. 2008; Wilkinson et al. 2014; Starkey et al. 2015; Altland 2019; Madrid-Aispuro et al. 2020). For the slow-release product in Table 7, approximately 62.5 g **B** would be used to grow a million seedlings (using a target N rate of 100 mg per seedling). When a slow-release boron source is applied before sowing, additional boron treatments are not required (Fu et al. 2017; Altland 2019).

11 Cost

The cost of 1 kg of boron varies but may range from US$8 to $65 depending on the source. Assuming a price of US$0.50 $seedling^{-1}$ and a cost of $22 kg^{-1} **B**, then 44 seedlings would equal the cost of 1 kg **B**. Therefore, boron fertilization might be economically justified when seedling production is increased by >44 seedlings ha^{-1}. Unfortunately, researchers are unable to declare such a small increase as statistically significant (α=0.1). Instead of using economics, managers consider the cost of boron fertilization as insurance against a deficiency. At nurseries with > 1% organic matter and sufficient boron in soil (van den Driessche 1963, Tanaka et al. 1967; South and Boyer 1983), the need for this type of insurance is low. In contrast, boron insurance is purchased at sandy nurseries with less than 0.3 µg g^{-1} soil **B** (Figure 3). Some managers say it is better to apply boron and not need it, than to lose a good reputation. In some regions, boron fertilization in the nursery might even increase initial height growth (α=0.13) in the field (Riikonen et al. 2013) or increase freeze tolerance after outplanting (Räisänen et al. 2009).

Managers prefer to apply boron as a spray instead of dry granules. However, a granular source (50% sodium borate and 50% calcium borate) may cost half as much to purchase as a soluble source of B (disodium octaborate tetrahydrate). Since calcium borate leaches at a slower rate, additional cost savings might occur if the time interval between applications could be lengthened without reducing seed germination.

12 Conclusions

Although boron deficiency is common in tree plantations (Stone 1990), it is rarely occurs in nurseries. Boron deficiencies were not reported in nurseries before 1960 when soil test results did not include boron. The occurrence in nurseries is rare because seedlings are irrigated with water containing trace amounts of boron. Most tree plantations are not irrigated during dry spells which is when boron deficiencies are noticed.

For irrigated container-stock, visual boron deficiency symptoms do not occur when organic media is less than pH 6 and when the water contains more than 0.05 µg g^{-1} **B**. Some managers, therefore, see no need to add boron before or after sowing seed in containers.

Boron fertilizers are usually not applied at bareroot nurseries with less than 50% sand but they are used in seedbeds that contain more than 75% sand. Researchers who test boron in nurseries should consider the following.

(1) At sandy nurseries with more than 1,000 mm yr^{-1} of rainfall, it is difficult to increase Mehlich 3 boron by applying soluble sources of boron.
(2) When irrigation water contains >0.05 µg g^{-1}**B**, applying 500 mm of water will reduce the chance of a boron deficiency.
(3) Foliar values of 8 to 25 µg g^{-1}**B** are normal for pine in either bareroot or container nurseries and stock type does not affect the "adequate" range. The 100 µg g^{-1}**B** upper limit for the "adequate range" is meaningless.
(4) In pines and eucalyptus, boron can move in the phloem.
(5) For greenhouse trials, a good correlation can exist between boron treatments in the soil and foliar boron content but in non-fertilized pine stands the correlation is rarely significant (α=0.05).
(6) A "hidden hunger" for boron exists in plantations and hydroponic trials, but the zone was very small for some trials using containers.
(7) Data from nurseries do not support the theory that fertilization with N results in a **B** deficiency. Published "optimum" N/**B** ratios are subjective and were proposed without supporting response-curve data.
(8) Applying too much calcium to the soil can induce a boron deficiency.
(9) The benefit/cost ratio for boron fertilization in nurseries has not been determined and for most irrigated seedbeds it probably is less than 1.0.

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