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Applying Boron by Fertigation or as a Foliar Fertilizer Is More Effective than Soil Applications in Northern Highbush Blueberry

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Abstract. **Boron (B) is often deficient in many fruit crops, including blueberry (*Vaccinium* sp.). The objective of the present study was to evaluate different methods for applying B fertilizers to two commercial cultivars of northern highbush blueberry (*V. corymbosum* Earliblue and Aurora) in western Oregon, USA. Treatments included soil application of sodium tetraborate in early April (before bloom), foliar application of boric acid in late April (during bloom or petal fall), weekly fertigation with boric acid from April through July, and a control with no B. The plants were irrigated by drip, and the fertilizers were applied for two consecutive seasons at a total rate of 1.5 kg·ha^{-1} B per year. Each method of fertilizer application increased the concentration of B in the soil solution relative to the control, but fertigation was the only treatment that increased extractable soil B to the recommended level of 0.5 to 1.0 mg·kg^{-1} B. In terms of plant nutrition, foliar application of B was the most effective method for increasing the concentration of B in the leaves, roots, and fruit, followed by fertigation. Soil application of B, on the other hand, was relatively ineffective and, after 2 years, only increased the concentration of B in the leaves of 'Earliblue'. Although leaf B levels were initially deficient at the site (<30 ppm B), none of the B application methods had any effect on yield, berry weight, fruit firmness, or titratable acidity of the fruit in either cultivar. However, foliar applied B resulted in higher concentrations of soluble solids in the fruit than no B or soil applied B in 'Earliblue', whereas B fertigation resulted in higher concentrations of soluble solids than soil applied B in 'Aurora'. On the basis of these results, applying B by fertigation or as a foliar spray is recommended over the use of soil applications of B fertilizer in northern highbush blueberry.**

Boron (B) is readily leached by rain or irrigation and is often deficient in many fruit crops, including northern highbush blueberry (*Vaccinium corymbosum* L.) (Broadley et al. 2012; Retamales and Hancock 2018). Common symptoms of B deficiency in blueberry include tip dieback, mottled chlorosis, leaf cupping, and short internodes (Polashock et al. 2017). When B is severely deficient in the plants, leaf and flower buds may fail to open, pollen tube growth is impaired, seeds are aborted, and fruit may become malformed (Dell and Huang 1997). Winter injury also tends to be greater with B deficiency, and low soil B is generally associated with Ca deficiency in fruit crops (Stiles and Reid 1991). However, too much B is toxic to plants. Concentrations >0.5 mg·L^{-1} B in soil solution can reduce growth and production in sensitive crops, such as blueberry, and concentrations >5.0 mg·L^{-1} B will negatively affect almost any crop (Sposito 2008).

The current recommendation for mature blueberry plantings is to apply 0.4 to 2.5 kg·ha^{-1} B when the concentration in recent fully expanded leaves in midsummer is ≤30 ppm B (Hart et al. 2006). Usually, B is applied using soil applications of sodium tetraborate (e.g., Borax and Granubor®) or foliar applications of sodium octaborate (e.g., Solubor®) or boric acid. Boron can also be applied by fertigation through the irrigation system using liquid or soluble fertilizers. Currently, many blueberry fields are irrigated by drip, which is well suited for fertigation (Bryla and Strik 2015). When managed properly, fertigation provides a continuous supply of nutrients required for plant growth and proper development of the flowers and fruit (Kafkafi and Tarchitzky 2011). Potential advantages of fertigation include lower delivery costs (no need for tractors or spreaders), direct placement of nutrients in the root zone, targeted applications of nutrients during certain stages of crop development, and less fertilizer loss when nutrients are supplied in small amounts as needed. However, there are also a few disadvantages to fertigation, including the need for higher fertilizer quality (i.e., purity and solubility) and the capital costs of the equipment required to inject the fertilizer through the irrigation system (Burt et al. 1998).

Fertigation with B fertilizers has been shown to be more effective and safer in terms of avoiding B toxicity than foliar sprays or soil applications of B in fruit crops, including apple [*Malus* ×*sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] (Wójcik and Treder 2006) and grape (*Vitis vinifera* L.) (Peacock and Christenson 2005). The present study was undertaken to determine whether fertigating with B was likewise more effective and less likely to cause toxicity than other methods of application in northern highbush blueberry.

Materials and Methods

Study site. The study was conducted in a mature planting of 'Earliblue' and 'Aurora' blueberry located at Oregon State University's Lewis Brown Farm in Corvallis, OR, USA (lat. 44°33′ N, long. 123°13′ W, 68 m elevation). The planting was established in Oct 2009 on Malabon silty clay loam soil (fine, mixed, superactive, mesic Pachic Ultic Argixerolls). Plants were spaced 0.8 × 3.0 m apart on raised beds (0.4-m high × 0.9-m wide) and mulched every other year with an ≈5-cm-deep layer of Douglas fir [*Pseudotsuga menziesii* Mirb. (Franco)] sawdust. Grass alleyways were planted between the beds and mowed as needed. See Vargas et al. (2015) for complete details on establishment of the planting.

The planting was irrigated from April through September using two lines of drip tubing (Netafim, Fresno, CA, USA) per row. The tubing had integrated pressure-compensating emitters (1.9 L·h^{-1}) every 0.3 m and was located on each side of the row at ≈0.2 m from the base of the plants. Irrigation was applied three to seven times per week, as needed and was scheduled based on weather conditions and daily estimates of crop evapotranspiration obtained from a nearby AgriMet weather station (available at http://usbr.gov/pn/agrimet).

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Weeds were controlled by hand weeding on top of the beds and by applying glyphosate and dichlobenil herbicides along the base of the beds. No insecticides or fungicides were applied to the planting during the study.

An initial set of soil samples were collected from the field in Oct 2017 and sent to a commercial laboratory (Brookside Laboratories, New Bremen, OH, USA) for analysis of pH, organic matter content, and nutrients. Soil pH was determined using a 1:1 ratio with water (McLean 1982), and organic matter content was determined by loss-on-ignition at 360 °C (Shulte and Hopkins 1996). Available N (NH_4-N and NO_3-N) was extracted with 1 M KCl and determined using automated colorimetric methods (Dahnke and Johnson 1990). Other nutrients were extracted using the Bray 1 method for P (Bray and Kurtz 1945) and the Mehlich 3 method for K, Ca, Mg, B, and Zn (Mehlich 1984) and each was analyzed by inductively coupled plasma (ICP) spectrometry. The results indicated that the soil was low in B and contained 0.38 to 0.40 $mg·kg^{-1}$ B (Horneck et al. 2011). The field had not been fertilized with B for 2 years before the study. Consequently, leaf B was likewise low in the plants and, depending on the year and cultivar, ranged from 15 to 22 ppm in Aug 2016 and 2017. Initial analyses also indicated that the soil contained 3.6% to 3.9% organic matter, 4 to 8 $mg·kg^{-1}$ NO_3-N, 10 to 17 $mg·kg^{-1}$ NH_4-N, 27 to 32 $mg·kg^{-1}$ P, 99 to 128 $mg·kg^{-1}$ K, 1463 to 1745 $mg·kg^{-1}$ Ca, 684 to 754 $mg·kg^{-1}$ Mg, and 3.80 to 4.72 $mg·kg^{-1}$ Zn and had a pH (1 soil: 1 water) of 4.6 to 5.0 and a total exchange capacity of 32.4–34.9 $cmol(+)·kg^{-1}$. Soil and leaves were sampled and analyzed following the standard procedures for northern highbush blueberry in western Oregon (Hart et al. 2006).

Experimental design. Four B treatments were applied to both cultivars, including a control with no B fertilizer; granular applications of sodium tetraborate [Granubor (14.3% B); U.S. Borax, Inc., Boron, CA, USA]; foliar applications of boric acid (Foli-Gro Boron 10%; Wilber-Ellis Co, Yakima, WA, USA); and fertigation with boric acid. Each fertilizer was applied in 2018 and 2019 at a total rate of 1.5 $kg·ha^{-1}$ B per year. During both years, sodium tetraborate was broadcast uniformly on each side of the rows in early April (before bloom) for the granular treatment, whereas boric acid was applied in late April (petal fall in ‘Earliblue’ and early bloom in ‘Aurora’) using a 15-L backpack sprayer (Solo USA, Newport News, VA, USA) for the foliar treatment and in 15 equal weekly applications from April through July using positive displacement injectors (Dosatron, Clearwater, FL, USA) for the fertigation treatment. Treatments were arranged in a randomized complete block design with five replicated plots per treatment. Each plot consisted of eight consecutive plants in a row. The center six plants in the plots were used for measurements.

Each treatment was also fertilized with granular monoammonium phosphate (11N–23P–0K) at a rate of 30 $kg·ha^{-1}$ P in April each year and were fertigated weekly from April through July with liquid ammonium sulfate (9N–0P–0K–10S) at a total rate of 224 $kg·ha^{-1}$ N per year.

Measurements. Soil solution was collected weekly in 2018 and every other week in 2019 using soil moisture samplers (Rhizon SMS 10 cm; Rhizosphere Research Products, Wageningen, The Netherlands). The samplers were installed vertically to a depth of 5 to 15 cm and located beneath a drip emitter and at 7.5 and 15 cm from an emitter in each plot of ‘Earliblue’. Samplers were not installed in ‘Aurora’ due to cost and logistics. Suction on the samplers was created using a 10-mL syringe at ≈1 h after the plants were fertigated, and solution was collected from the syringes the following morning. The solution was then analyzed for B using an ICP optical emission spectrometer (Optima 8300; Perkin Elmer, Waltham, MA, USA).

Soil samples were also collected from each plot in October each year. The samples were taken to a depth of 20 cm (under a drip emitter) using a 1.75-cm-diameter soil corer (JMC Soil Samplers, Newton, IA, USA) and then sent to a commercial laboratory (Brookside Laboratories, New Bremen, OH, USA) for analysis of pH and soil nutrients. Sawdust mulch was removed before taking the cores and returned immediately afterward.

Ripe fruit was handpicked on 27 Jun and 10 Jul 2018 and 1 and 22 Jul 2019 from ‘Earliblue’ and on 22 Aug and 4 Sep 2018 and 6 Aug, 19 Aug, and 11 Sep 2019 from ‘Aurora’. Once picked, the fruit was weighed to determine the total yield of each plant. A subsample of 100 berries was also weighed on each date to calculate the average berry weight of each treatment. The subsamples were then oven-dried at 70 °C, ground with a porcelain mortar and pestle, and analyzed for B using the ICP. Each sample was digested in a microwave (Multiwave Pro; Anton Parr USA, Ashland, VA, USA) with 70% (v/v) nitric acid before running them on the ICP (Gavlak et al. 2005). A reference standard of apple [*Malus ×sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] leaves (no. 151, National Institute of Standards and Technology) was included with each run to ensure the accuracy of the ICP and digestion procedure.

Additional samples of the berries were analyzed for firmness, total soluble solids, and titratable acidity on each harvest date. To determine the firmness, 25 berries were randomly selected from each plot and placed on their sides (calyx facing inward) on the turntable of a firmness tester (FirmTech 2; BioWorks Inc., Wamego, KS, USA). Reference size and deflection thresholds were set at 18.87 mm and 0.51 to 1.47 mm, respectively, and the mean of each replicate was recorded as g of force per mm of deflection. Approximately 150 g of berries were frozen from each plot for the remaining analyses. These berries were later thawed and pureed in a blender. Six grams of each was then diluted with 50 mL of deionized CO_2-free water and titrated with 0.1 $mol·L^{-1}$ NaOH to an endpoint pH of 8.1 using an autotitrator (DL12; Mettler-Toledo LCC, Columbus, OH, USA). Titratable acidity was calculated as a percentage of citric acid. Another 5 to 10 g of puree was centrifuged for 10 to 15 min, and drops of the supernatant were measured for soluble solids using a temperature-compensating digital refractometer (HI96801; Hanna Instruments, Smithfield, RI, USA).

Thirty recent, fully expanded leaves were sampled randomly from each plot in early August each year and analyzed for N using a combustion analyzer (TruSpec CN; Leco Corp., St. Paul, MN, USA) and for B and other nutrients using the microwave and ICP, as described earlier. Roots were also collected from each plot in Oct 2019. In this case, a set of 1.75-cm-diameter soil cores were taken to a depth of 0–20 cm beneath each drip emitter located next to a plant (four emitters/plant) in each plot, washed to remove the roots, and likewise analyzed for B. Each leaf and root sample was oven-dried at 70 °C before analysis and ground to pass through a 20-mesh screen using a Wiley mill (No. 3379-K41; Thomas Scientific, Logan Township, NJ, USA).

Statistical analysis. Data were analyzed by analysis of variance using a mixed model procedure when appropriate in R (R Core Team 2019). Fixed effects included the B treatments, distance from the drip emitters (B in soil solution), time (soil solution sampling dates) or harvest (yield, fruit quality characteristics, fruit nutrients), and their interactions, and random effects included block. All measurements differed between years and, therefore, were analyzed independently in 2018 and 2019. Data were assessed for normality and homogeneity of variance using the Shapiro–Wilk and Levene test, respectively, and were transformed as needed. Transformed data were back transformed after analysis to represent actual means. Means were separated at the 0.05 level using Tukey’s honestly significant difference test.

Results and Discussion

Boron in soil solution. Concentration of B in the soil solution varied over time and was significantly affected by an interaction between B treatment and distance from the drip emitters during both years of the study ($P < 0.05$); however, it was unaffected by other interactions, including time × distance, time × B treatment, and time × distance × B treatment. During the first year of the study (2018), B levels measured directly under the drip emitters (0 cm) were higher with fertigation than with any other treatment (Fig. 1A). At 7.5 cm from the emitters, B levels were still higher with fertigation than with no B or granular B. This pattern changed at 15 cm from the emitters where B was highest with foliar B, intermediate with granular B, and lowest with no B or fertigation. Apparently, a substantial amount of B applied as a foliar spray dripped off the plants and leached into the soil after it rained. The response was similar the following year, although in this case, B levels were alike between fertigation and foliar B directly under the emitters (0 cm); greater with foliar B than with no B at 7.5 cm from the emitters; and the same between granular and foliar B at 15 cm from the

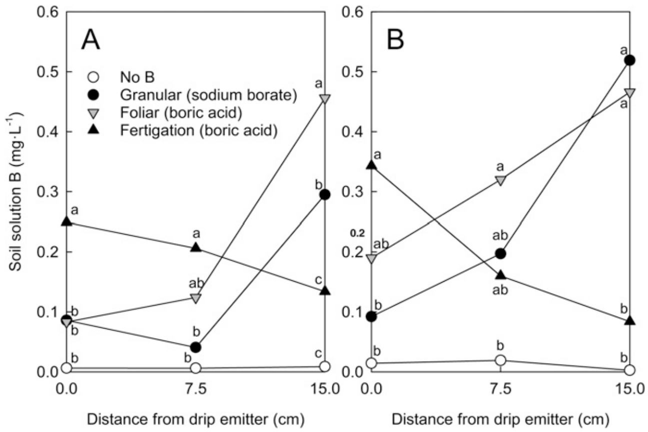

Fig. 1. Concentration of boron (B) in the soil solution in plots of 'Earliblue' blueberry treated with no B (control), granular applications of sodium borate, foliar applications of boric acid, and fertigation with boric acid in 2018 (**A**) and 2019 (**B**) in western Oregon, USA. Each fertilizer was applied at a total rate of 1.5 kg·ha^{-1} B per year. Means (n = 5) were separated at each distance by Tukey's test ($P \leq 0.05$). Data are pooled across 15 dates (28 Apr to 1 Aug) in 2018 and seven dates (1 May to 25 Jul) in 2019.

emitters (Fig. 1B). Levels were also higher, on average, the second year than the first year when plants were treated with granular or foliar B ($P < 0.05$). In this latter case, precipitation in the spring was heavier the second year (27 vs. 82 mm in 2018 and 2019, respectively), which may have leached more of the B from these two treatments into the soil (Parker and Gardner 1982).

In most cases, the concentration of B in the soil solution was <0.5 mg·L^{-1}, which is below the level considered toxic to sensitive crops such as blueberry (Sposito 2008). However, concentration was slightly >0.5 mg·L^{-1} B at 15 cm from the emitter when the plants were fertilized with granular B in 2019 (Fig. 1B).

Extractable soil B. Concentration of extractable soil B under the emitters was affected by B treatment in 2018 ($P < 0.001$) and 2019 ($P = 0.023$) but was unaffected by cultivar or interactions between cultivar and B treatment in either year ($P > 0.05$). Relative to the treatment with no B, soil B increased when B was applied as a granular fertilizer in the first year and by fertigation in both years (Fig. 2). Only fertigation reached what is considered an adequate soil test level for B (i.e., 0.5 to 1.0 mg·kg^{-1} B; Horneck et al. 2011). On the basis of the soil solution measurements, extractable soil B concentrations might have been higher with granular and foliar B if the soil had been sampled between the drip emitters rather than under them (Fig. 1). However, Arrington and DeVetter (2017) found no differences in soil B after applying various doses of foliar B to northern highbush blueberry in Washington State, USA.

Soil pH and other extractable nutrients were similar among the treatments and, apart from soil P, were within the range recommended for northern highbush blueberry and other fruit crops in the region (Hart et al. 2006; Horneck et al. 2011). When pooled across the two cultivars, soil pH averaged 5.5 in both years, and soil P averaged 28 and 29 mg·kg^{-1} in 2018 and 2019, respectively.

Concentration of B in the leaves, roots, and fruit. During both years of the study, the concentration of B in the leaves was significantly affected by cultivar, B treatment, and the interaction between cultivar and B treatment (Table 1). In 2018, leaf B in the foliar treatment was above the recommended range (31–80 ppm; Hart et al. 2006) in 'Earliblue' and was sufficient and similar to the control in 'Aurora'. Leaf B was also sufficient with fertigation in both cultivars in 2018 but was low and close to the control in the granular treatments. Clearly, granular B applications were less effective at correcting deficient leaf B levels than foliar B applications or fertigation with B. In the first year of their study, Arrington and DeVetter (2017) were also able to increase blueberry leaf B with foliar applications of B.

By the following year, leaf B remained low and was similar among the treatments in 'Aurora' but was sufficient or above the sufficiency range when B was applied by any method, including granular application of sodium borate, in 'Earliblue' (Table 1). Arrington and DeVetter (2017) also increased leaf B with foliar applications in the second year of their study. In their case, leaf B was above the sufficiency range during both years of a 2-year study in 'Draper' and during the second year of the study in 'Bluecrop'. Strik and Vance (2015) examined leaf nutrient concentrations in six cultivars of highbush blueberry at a commercial farm in western Oregon and found that leaf B was generally lower in late-season cultivars, including Aurora, than in early season cultivars such as Duke. The results of their and the present study suggest that late-season cultivars are less responsive to B fertilizers. The question remains whether late-season cultivars have lower requirements for B than early season cultivars. If not, they may require higher rates of B than is currently recommended for northern highbush blueberry. Like many plant species, movement of B in blueberry occurs primarily in the transpiration stream and is restricted in the phloem (Brown and Shelp 1997). Daily transpiration rates tend to be higher, on average, in early-season than late-season blueberry cultivars, which could explain why late-season cultivars accumulate less B in the leaves (Bryla and Strik 2007). Other possibilities include differences among blueberry genotypes in cell wall pectin content (Hu et al. 1996), boric acid channels (Takano et al. 2006), and borate transporters (Diehn et al. 2019).

Most other nutrients in the leaves, including N, P, Ca, Mg, S, Cu, Mn, and Zn, were within the recommended range for blueberry in western Oregon (Hart et al. 2006). Leaf N and P, however, were low both years in 'Aurora' and averaged 1.73% and 0.09%, respectively. Leaf K was also slightly low during the second year in 'Aurora' and averaged 0.39%. Previously, we determined that leaf P was likewise low in 'Duke' and 'Bluecrop' at the site and was unaffected by P fertilizer due to heavy clay in the soil (Leon-

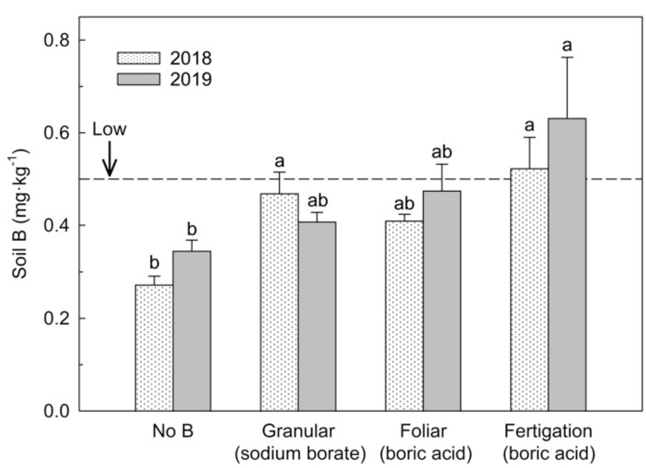

Fig. 2. Extractable soil boron (B) in plots of northern highbush blueberry treated with no B (control), granular applications of sodium borate, foliar applications of boric acid, and fertigation with boric acid in 2018 and 2019 in western Oregon, USA. Each fertilizer was applied at a total rate of 1.5 kg·ha^{-1} B per year. Means (n = 5) were separated each year by Tukey's test ($P \leq 0.05$), error bars represent one standard error of the mean, and the dashed line indicates "low" soil B, according to Horneck et al. (2011). Data are pooled across two cultivars, Earliblue and Aurora.

Table 1. Effects of method of boron (B) fertilizer application on the concentration of B in the leaves and roots of ‘Earliblue’ and ‘Aurora’ blueberry in western Oregon, USA.

	Leaf B (ppm)[ii]				
	2018		2019		
Fertilizer treatment[i]	Earliblue	Aurora	Earliblue	Aurora	Root B (ppm)[iii]
No B (control)	12 c[iv]	17 b	28 c	15 a	5.4 b
Granular (sodium borate)	26 c	18 b	52 b	22 a	9.2 b
Foliar (boric acid)	88 a	31 ab	91 a	32 a	22.5 a
Fertigation (boric acid)	50 b	32 a	73 a	29 a	6.0 b
Significance					
Cultivar	<0.001		<0.001		0.297
B fertilizer	<0.001		<0.001		<0.001
Cultivar × B fertilizer	<0.001		0.006		0.694

[i] Each fertilizer was applied at a total rate of 1.5 $kg \cdot ha^{-1}$ B per year.

[ii] Leaf samples were collected in Aug 2018 and 2019.

[iii] Data are pooled across the two cultivars. Root samples were collected in Oct 2019 but were not collected in 2018.

[iv] Means followed by a different letter within a column are significantly different at $P \leq 0.05$ (Tukey’s test).

Chang et al. 2023). Strik and Davis (2023) recently revised the leaf nutrient sufficiency standards for northern highbush blueberry in western Oregon and suggested reducing the lower limits of leaf N, P, and K to 1.40%, 0.08%, and 0.40%, respectively. On the basis of these standards, leaf N and P was not limited in the present study. Leaf K, on the other hand, was still considered low in ‘Aurora’ and suggests that K fertilizer may have been needed in this cultivar (Leon-Chang et al. 2022).

The concentration of B in the roots was also affected by the B treatments in 2019; however, in this case, the concentration was similar between the cultivars and was unaffected by interactions between cultivar and B treatment (Table 1). On average, root B was 1.4 to 4 times higher with foliar B than with any other treatment, including fertigation with B. This coupled with the high concentrations of B in the soil solution (Fig. 1) suggests that the roots absorbed much of the B applied as a foliar fertilizer. As mentioned earlier, B moves primarily in the xylem of the plants, and therefore, very little, if any, of the foliar-applied B would have been translocated from the leaves to the roots. In our study, the planting beds were mulched with sawdust, which allowed any B that dripped off the plants after a foliar spray to reach the roots. However, many new plantings of northern highbush blueberry are mulched with polyethylene or polypropylene woven landscape groundcover, often referred to as “weed mat” (Strik 2016). The fabric reduces water penetration and would likewise limit any fertilizers that are applied as a foliar spray from reaching the roots. Future studies with foliar B sprays should consider the impacts of weed mat. Such studies should also address the use of surfactants in the spray. Although it was not used in the present study, adding a surfactant to the mix increases retention of foliar applied nutrients on the surface of the leaves and fruit (Gerbrandt et al. 2019).

The concentration of B in the fruit was significantly affected by B treatment in both cultivars during both years of the study, as well as by an interaction between harvest date and B fertilizer during the first year in ‘Earliblue’ (Table 2). In most cases, fruit B was higher with foliar B than with any other treatment; however, it was similar when B was applied by a foliar application or fertigation in ‘Aurora’ during the second year. Arrington and DeVetter (2017) found that foliar B applications increased the concentration of B in the leaves but not in the fruit. Although they used a higher dose in their study, their results support the supposition that B is immobile and not readily reallocated to other tissues in northern highbush blueberry. In that study, the total dose of B was split from early pink bud stage through petal fall, whereas in the current study, only one foliar application was performed in late April, which coincided with petal fall in ‘Earliblue’ and early bloom in ‘Aurora’.

Table 2. Interactive effects of harvest date and method of boron (B) fertilizer application on the concentration of B in the fruit of ‘Earliblue’ and ‘Aurora’ blueberry in western Oregon, USA.

	Fruit B (ppm)				
	2018			2019	
Main effect	Earliblue		Aurora	Earliblue	Aurora
Harvest[i]					
First	8.8 a[ii]		4.1 a	3.5 b	2.9 b
Second	2.3 b		4.6 a	6.0 a	10.6 a
Third	—		—	—	10.7 a
Fertilizer treatment[iii]	First harvest	Second harvest			
No B (control)	6.1 b	0.4 b	3.6 b	2.7 b	6.6 c
Granular (sodium borate)	6.4 b	1.4 b	3.0 b	3.9 b	7.4 bc
Foliar (boric acid)	16.7 a	5.7 a	6.9 a	7.8 a	10.2 a
Fertigation (boric acid)	6.1 b	1.9 b	4.0 b	4.6 b	8.0 ab
Significance					
Harvest	<0.001		0.213	<0.001	<0.001
B fertilizer	<0.001		<0.001	<0.001	<0.001
Harvest × B fertilizer	0.001		0.523	0.830	0.086

[i] Fruit were harvested twice per year in ‘Earliblue’ and harvested twice in 2018 and three times in 2019 in ‘Aurora’.

[ii] Means followed by a different letter are significantly different at $P \leq 0.05$ (Tukey’s test).

[iii] Each fertilizer was applied at a total rate of 1.5 $kg \cdot ha^{-1}$ B per year.

Fruit B also differed in most cases with harvest date (Table 2). For example, in ‘Earliblue’, fruit B was nearly 4 times higher during the first harvest than during the second harvest in 2018; however, the opposite occurred the following year, where fruit B was nearly twice as high during the second harvest than during the first. That same year, fruit B was also nearly 4 times higher during the latter two harvests than during the first harvest in ‘Aurora’. Much like in the leaves, these differences in B between harvest dates were likely driven by fruit transpiration, weather conditions, and the timing of B applications. Strik and Vance (2015) observed similar levels of B in the fruit of ‘Aurora’ at the commercial farm in western Oregon.

As mentioned previously, low soil B is generally associated with Ca deficiency in fruit crops (Stiles and Reid 1991). However, the concentration of Ca in the fruit was unaffected by any method of B application in ‘Earliblue’ or ‘Aurora’ (data not shown). Pooled across B treatments and harvest dates, fruit Ca averaged 0.033% to 0.026% in 2018 and 2019, respectively, in ‘Earliblue’ and 0.054% to 0.074%, respectively, in ‘Aurora’. Other nutrients in the fruit were also similar among the B treatments.

Yield and fruit quality. The B treatments had no effect on yield, berry weight, berry firmness, or titratable acidity at any harvest in either cultivar (data not shown). However, foliar B resulted in higher concentrations of soluble solids in the berries than either granular B during the first year or no B during both years in ‘Earliblue’, whereas fertigation with B resulted in higher concentrations of soluble solids than granular B during the second year in ‘Aurora’ (Table 3). Wójcik (2005b) found that both soil and foliar applications of boric acid increased soluble solids in ‘Bluecrop’ blueberries in Poland, but much like in the present study, it had no effect on yield, berry weight, or berry firmness. In their case, the soil application was applied at budbreak at a rate of 2 $kg \cdot ha^{-1}$ B, and the foliar applications were applied four times, including at the beginning of flowering, petal fall, and 3 and 6 weeks after flowering, at a split rate of 0.2 $kg \cdot ha^{-1}$ B each. In southern Chile, Meriño-Gergichevich et al. (2016) found that 200 $mg \cdot L^{-1}$ of foliar B was sufficient to increase soluble solids and fruit set in ‘Brigitta’ blueberry, whereas a

Table 3. Interactive effects of harvest date and method of boron (B) fertilizer application on the concentration of soluble solids in the fruit of 'Earliblue' and 'Aurora' blueberry in western Oregon, USA.

	Soluble solids (%)			
	2018		2019	
Main effect	Earliblue	Aurora	Earliblue	Aurora
Harvest[i]				
First	14.0 a[ii]	12.8 a	13.4 b	12.6 a
Second	13.6 a	10.8 b	14.6 a	11.4 b
Third	—	—	—	10.2 c
Fertilizer treatment[iii]				
No B (control)	13.5 b	11.6 a	13.3 b	11.5 ab
Granular (sodium borate)	13.5 b	11.6 a	14.2 ab	10.9 b
Foliar (boric acid)	14.2 a	12.0 a	14.6 a	11.6 ab
Fertigation (boric acid)	13.9 ab	12.0 a	13.9 ab	11.7 a
Significance				
Harvest	0.075	<0.001	<0.001	<0.001
B fertilizer	0.046	0.101	0.039	0.016
Harvest × B fertilizer	0.930	0.912	0.167	0.456

[i] Fruit were harvested twice per year in 'Earliblue' and harvested twice in 2018 and three times in 2019 in 'Aurora'.

[ii] Means followed by a different letter are significantly different at $P \leq 0.05$ (Tukey's test).

[iii] Each fertilizer was applied at a total rate of 1.5 $kg \cdot ha^{-1}$ B per year.

higher concentration (400–800 mg L^{-1} B) was needed to do the same in 'Legacy' blueberry.

According to Brown et al. (2002), B deficiency reduces membrane stability in the plant cells and consequently affects photosynthesis negatively. Therefore, adequate levels of leaf B may lead to higher rates of photosynthesis in blueberry and increase accumulation of sugars in the fruit. Different methods of B application have led to diverse effects on fruit soluble solids in various crops. For example, soil applications of B have been shown to increase soluble solids in tart cherry (*Prunus cerasus* L.) (Wójcik 2006), apples [*Malus ×sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] (Wójcik et al. 2008), and gooseberries (*Ribes grossularia* L.) (Wójcik and Filipczak 2015); however, unlike in the present study, fruit soluble solids were unaffected by foliar applications of B in these studies. In contrast, Ibrahim and Al-Wasfy (2014) found that foliar B led to higher concentrations of soluble solids than the control in Valencia oranges [*Citrus sinensis* (L.) Osbeck]. Fertigation with B has also been shown to be effective at increasing fruit soluble solids in apples (Wójcik and Treder 2006) and tart cherries (Wójcik 2007).

Several studies have indicated that B application has no effect on fruit soluble solids but increase fruit production. For example, granular and foliar applications of B increased yield of chestnuts (*Castanea sativa* Mill.) (Portela et al. 2011) and black currants (*Ribes nigrum* L.) (Wójcik 2005a), respectively, but had no effect on soluble solids in the fruit of either crop. The fact that B applications did not increase yield in the present study suggests that B levels in the control treatments were sufficient to maintain fruit production in both cultivars but was perhaps inadequate for maximizing the concentration of soluble solids in the fruit. Yield at the site was comparable to commercial fields in the region (Sutton and Sterns 2020) and averaged 4.4 to 5.6 kg/plant in 'Earliblue' and 4.9 to 5.8 kg/plant in 'Aurora'.

Conclusions

Each method of B application evaluated in this 2-year study, including granular applications, foliar sprays, and fertigation, increased the concentration of B in the soil solution, but only fertigation, which was applied weekly from April through July, increased extractable soil B to what is considered an adequate soil test level for the nutrient. In terms of plant nutrition, foliar B, which was applied during bloom or petal fall, was the most effective method for increasing the concentration of B in the leaves, roots, and fruit, followed by fertigation with B. Granular application of B, on the other hand, which was applied 2 or more weeks before bloom, was relatively ineffective and after 2 years only increased the concentration of B in the leaves of the early season cultivar, 'Earliblue'. Although leaf B levels were initially deficient at the site, none of the methods of B application had any effect on yield, berry weight, berry firmness, or titratable acidity in either cultivar. However, foliar B applications resulted in higher concentrations of soluble solids in the berries than granular B and no B fertilizer in 'Earliblue', and fertigation with B resulted in higher concentrations of soluble solids in the berries than granular B in 'Aurora'. At this point, applying B by fertigation or as a foliar fertilizer is recommended over the use of granular B fertilizers in northern highbush blueberry. Economically, foliar application of B is likely less expensive than fertigation and a good choice for fields without drip irrigation or fertilizer injectors.

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