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Chemigation with Micronized Sulfur Rapidly Reduces Soil pH in a New Planting of Northern Highbush Blueberry

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Abstract**. Northern highbush blueberry (*Vaccinium corymbosum* L.) is adapted to acidic soil conditions and often grows poorly when soil pH is greater than 5.5. When soil pH is high, growers will usually mix prilled elemental sulfur (S°) into the soil before planting (converted to sulfuric acid by soil bacteria) and, if needed, inject acid into the irrigation water after planting. These practices are effective but often expensive, time consuming, and, in the case of acid, potentially hazardous. Here, we examined the potential of applying micronized S° by chemigation through a drip system as an alternative to reduce soil pH in a new planting of 'Duke' blueberry. The planting was located in western Oregon and established on raised beds mulched with sawdust in Oct. 2010. The S° product was mixed with water and injected weekly for a period of ≈2 months before planting and again for period of ≈2 months in late summer of the second year after planting (to assess its value for reducing soil pH once the field was established), at a total rate of 0, 50, 100, and 150 kg·ha^{-1} S° on both occasions. Each treatment was compared with the conventional practice of incorporating prilled S° into the soil before planting (two applications of 750 kg·ha^{-1} S° each in July and Oct. 2010). Within a month of the first application of S°, chemigation reduced soil pH (0–10 cm depth) from an average of 6.6 with no S° to 6.1 with 50 kg·ha^{-1} S° and 5.8 with 100 or 150 kg·ha^{-1} S°. However, the reductions in pH were short term, and by May of the following year (2011), soil pH averaged 6.7, 6.5, 6.2, and 6.1 with each increasing rate of S° chemigation, respectively. Soil pH in the conventional treatment, in comparison, averaged 6.6 a month after the first application and 6.3 by the following May. In July 2012, soil pH ranged from an average of 6.4 with no S° to 6.2 with 150 kg·ha^{-1} S° and 5.5 with prilled S°. Soil pH declined to as low as 5.9 following postplanting S° chemigation and, at lower depths (10–30 cm), was similar between the treatment chemigated with 150 kg·ha^{-1} S° and the conventional treatment. None of the treatments had any effect on winter pruning weight in year 1 or on yield, berry weight, or total dry weight of the plants in year 2. Concentration of P, K, Ca, Mg, S, and Mn in the leaves, on the other hand, was lower with S° chemigation than with prilled S° during the first year after planting, whereas concentration of N, P, and S in the leaves were lower with S° chemigation during the second year. The findings indicate that S° chemigation can be used to quickly reduce soil pH after planting and therefore may be a useful practice to correct high pH problems in established northern highbush blueberry fields; however, it was less effective and more time consuming than applying prilled S° before planting.**

Northern highbush blueberry (*Vaccinium corymbosum* L.) is adapted to acidic soil conditions and is often most productive at soil pH between 4.5 and 5.5 (Retamales and Hancock, 2012). To grow blueberry at sites with a higher initial soil pH, elemental sulfur (S°), which oxidizes to sulfuric acid by chemotrophic soil bacteria such as *Thiobacillius* species, is often mixed into soil before planting (Chapman, 1990; Germida and Janzen, 1993). In many soils, large amounts of S° (>1500 kg·ha^{-1}) are needed for the process, and in some cases, such as in soils with high amounts of calcium carbonate, S° acidification is unfeasible (Horneck et al., 2006; Modaihsh et al., 1989; Neilsen et al., 1993). Soil incorporation of S° is also limited after planting because blueberry has a fine, shallow root system (<0.3-m deep) that is easily damaged by cultivation (Bryla and Strik, 2007). Therefore, when soil pH is too high after planting, growers must either apply S° on the soil surface or inject acid (e.g., sulfuric acid) into the irrigation water (chemigation). However, surface application of S° is ineffective in dry environments and difficult to do in fields mulched with geotextile fabric (''weed mat''), while acid chemigation is hazardous and requires expensive, non-corrosive irrigation equipment (Burt et al., 1998).

Soil acidification with S° usually takes several months or more to change soil pH from 6.0 or higher to a desired level for northern highbush blueberry (Gough, 1994; Hart et al., 2006). The rate of the process is largely dependent on soil temperature, moisture, and aeration (Germida and Janzen, 1993), soil organic matter content (Cifuentes and Lindermann, 1993; Wainwright et al., 1986), and the size of the S° particles (Germida and Janzen, 1993; Lee et al., 1988; Sholeh and Blair, 1997; Zhao et al., 2016). Generally, smaller S° particles are oxidized faster than larger particles because of the greater surface area to volume ratio (Lawrence and Germida, 1988; Li and Caldwell, 1966). Currently, there are several micronized S° products on the market labeled for chemigation that can be easily injected and applied through an irrigation system. These products contain micropropogules of S° (<10 µm) that readily dissolve in water. Although micronized S° is primarily intended for use as a foliar fungicide, it could also be used to reduce soil pH.

The objective of the present study was to determine the potential of applying micronized S° by chemigation through a drip irrigation system to quickly reduce soil pH in a new planting of northern highbush blueberry. Micronized S° was applied before planting, to evaluate its use as a preplant amendment, and after planting, to assess its value for reducing soil pH, once the field was established. We expected that applying S° through a drip system would reduce soil pH faster and require less product than conventional applications of prilled S° because the former would concentrate S° directly beneath the drip emitters in a zone where many roots are located (Bryla et al., 2017), and where soil conditions remain moist (Bryla et al., 2011) and are favorable for rapid bacterial transformation of S° to sulfuric acid (Konopka et al., 1986).

Material and Methods

Study site. The study was conducted at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, OR in a field of 'Duke' northern highbush blueberry planted on 21 Oct. 2010. Soil at the site is a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerolls) (Parsons and Herriman, 1970). The soil had an initial pH of 6.6 before any treatment and contained 2.4% organic matter. Plants were obtained from a commercial nursery as 2-year-old container stock and spaced 0.76 × 3.05 m apart on raised beds (0.4-m high and 0.9-m wide). The beds were shaped 3 months before planting to initiate the S^o treatments. A 5-cm-deep layer of douglas fir (*Pseudotsuga menziesii* Franco) sawdust was rototilled ≈20-cm deep into each row just before making the beds, and a bed shaper (Kennco Manufacturing, Inc., Ruskin, FL) was used to raise the beds. A 5-cm-deep layer of sawdust mulch was also applied on top of the beds after planting and reapplied in May 2012.

Sulfur treatments. Micronized wettable S^o (0N–0P–0K–80S; Nufarm Americas Inc., Burr Ridge, IL) was mixed with irrigation water [pH 6.9, electrical conductivity (EC) of 0.13 $dS \cdot m^{-1}$, and 42 $mg \cdot L^{-1}$ $CaCO_3$ (alkalinity)] and applied once or twice weekly by chemigation at a total rate of 0, 50, 100, and 150 $kg \cdot ha^{-1}$ S^o before planting (28 July to 27 Sept. 2010) and again during the second year after planting (3 Aug. to 12 Oct. 2012) (Fig. 1). Each treatment was compared with the conventional practice of incorporating a prilled S^o (0–0–0–90S; Tiger-Sul Products LLC, Atmore, AL) into the soil before planting. Prilled S^o was applied in two applications of 750 $kg \cdot ha^{-1}$ each on 28 July and 10 Oct. 2010. The first application of prilled S^o was rototilled into the plots along with the sawdust before shaping the beds, and the second application was incorporated using a hand rake.

The treatments were arranged in a randomized complete block design with five plots of four plants each per treatment. Drip tubing (Netafim USA, Fresno, CA) was installed on each side of the row at a distance of ≈20 cm from the base of the plants. The tubing had 2-$L \cdot h^{-1}$ in-line emitters every 0.3 m and was installed immediately after the beds were shaped. The wettable S^o solution was injected through the drip system using water-powered proportional chemical injectors (Model D25F1; Dosatron, Clearwater, FL). Five injectors were installed in a manifold located at the head of each treatment. Irrigation was initiated ≈10 min before each injection to fully pressurize the system, and run for at least 10 min after injection to flush the lines. Water only was applied to treatments with prilled or no S^o. There was no evidence of emitter plugging during the study.

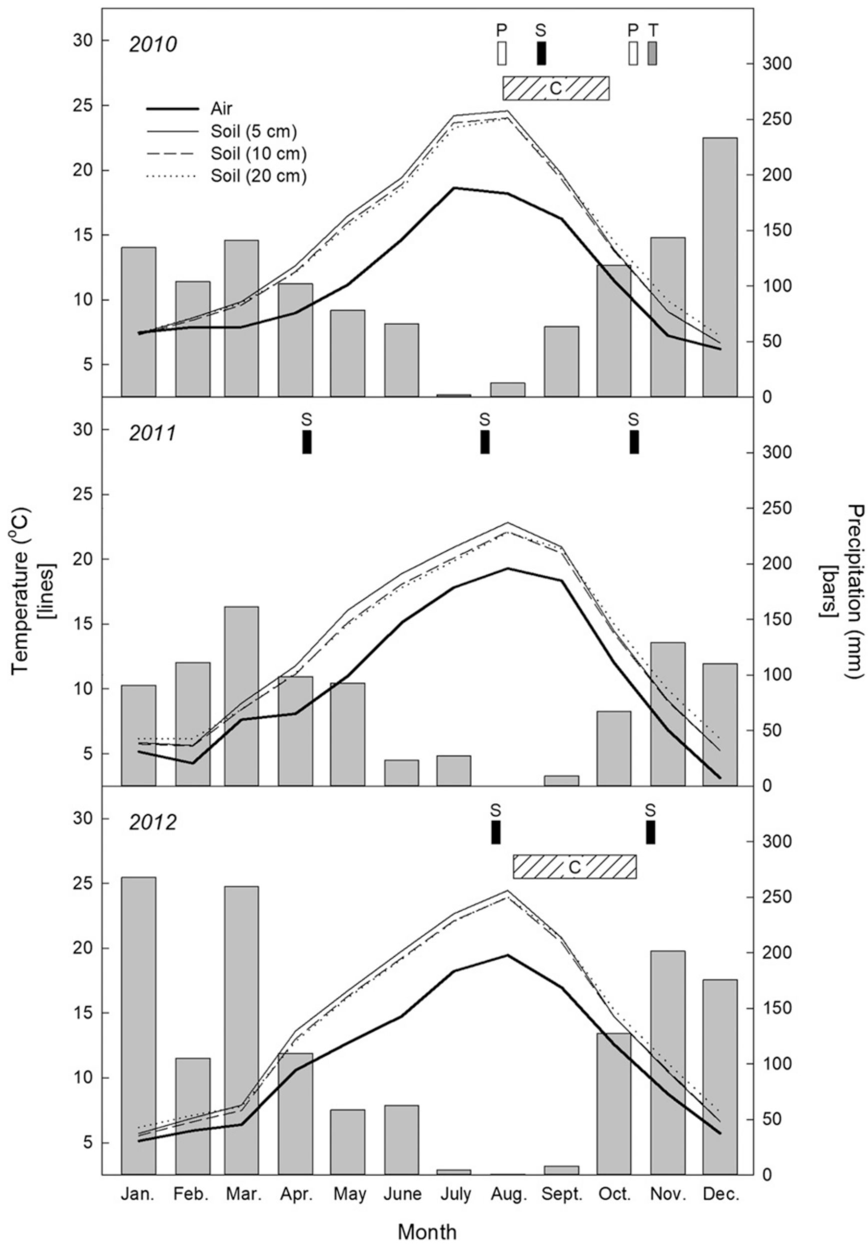

Fig. 1. Temperature (air and soil; lines) and precipitation (bars) in a new planting of 'Duke' blueberry that was either chemigated or treated conventionally with elemental sulfur (S^o). Hashed bars with a "C" indicate the dates on which S^o was applied by chemigation; white bars with a "P" indicate the dates on which prilled S^o was applied conventionally; the gray bar with a "T" indicates the date on which the plants were transplanted (planted in the field); and black bars with an "S" indicate the dates on which soil was sampled and analyzed for pH and EC. Data were obtained from a local Pacific Northwest Cooperative Agricultural Weather Network AgriMet weather station (http://usbr.gov/pn/agrimet).

Crop management. Weeds were controlled by cultivating between rows, as needed and were removed by hand at least once a month from the planting beds. Irrigation was scheduled up to 7 d/week, as needed, to meet crop water demands over each growing season (Bryla et al., 2011). Granular urea (46N–0P–0K) was applied by hand around the base of the plants at rate of 10 $kg \cdot ha^{-1}$ N each on 27 April and 11 May 2011, and liquid urea (20N–0P–0K) was injected weekly through the drip system at a rate of 8 $kg \cdot ha^{-1}$ N per application from 25 May to 27 July 2011 and 15 June to 27 July 2012. Overall, the plants received a total of 100 $kg \cdot ha^{-1}$ N in 2011 and 56 $kg \cdot ha^{-1}$ N in 2012. No other nutrients were applied to the plants, which is common in the region for northern highbush blueberry. There was no evidence of insect or disease problems in the plants, and therefore, no chemicals were used for pest control.

Measurements. Plant growth occurred primarily from May to October each year. Plants were pruned immediately after planting in Oct. 2010 and before the second

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growing season on 18 Feb. 2012. To encourage vegetative growth, flower buds were completely removed from the plants during the first pruning and were limited to 40–80 buds/plant during the second pruning to avoid over-cropping. Prunings were weighed fresh from each plot when the plants were pruned the second time.

Soil samples were collected in each plot using a 2-cm-diameter soil probe (Clements Associates Inc., Newton, IA). The soil was cored 3 cm from a single drip emitter to a depth of 10 cm in each plot on 18 Aug. 2010 (before planting) and 18 May 2011 (beginning of first growing season) and was cored under a single drip emitter and at 5, 10, and 15 cm on each side of the emitter (perpendicular to row) to a depth 0–10, 10–20, and 20–30 cm in each plot on 18 July and 11 Oct. 2011 and 23 July and 21 Oct. 2012. The cores were collected near a different emitter in each plot on each date. The samples were oven-dried at 38 °C, ground to pass through a 2-mm sieve, mixed with two parts water (v/v), and analyzed for pH using a calibrated pH/ion meter (model S220 SevenCompact; Mettler-Toledo, LCC, Columbus, OH) and for EC using a calibrated conductivity meter (Omega Engineering, Inc., Stamford, CT).

Five recent fully expanded leaves per plot were collected for nutrient analysis on 3 Aug. 2011 and 10 Aug. 2012. The leaves were oven-dried at 80 °C for 3 d, ground to pass through a 40-mesh screen (0.42-mm openings) and analyzed for N using a combustion analyzer (CN-2000; Leco Inc., St. Louis, MO) and for P, K, Ca, Mg, S, Fe, B, Cu, Mn, and Zn using ICP-OES (Optima 3000DV; Perkin Elmer, Wellesley, MA) after wet ashing in nitric acid (Gavlak et al., 2005).

Ripe fruit were handpicked and weighed from each plot on 9 July, 18 July, and 3 Aug. 2012, and total yield was calculated. A random sample of 100 berries/plot was also weighed on each date and used to calculate the yield-based weighted average of mean berry weight.

One representative plant per plot was harvested destructively on 14 Dec. 2012. The plants were excavated with a shovel and washed with a hose to remove soil from the roots. Care was taken to obtain both coarse and fine roots from the plants. Each plant was then separated into whips, new branches, woody canes (1- and 2-year-old wood), and roots (including the crown), oven-dried for 3 weeks at 70 °C, and weighed.

Statistical analysis. Pruning weights, yield, berry weights, shoot and root dry weights, and the concentration of nutrients in the leaves were analyzed by one-way analysis of variance using R v. 3.4.0 (Oregon State University, Corvallis, OR). Normality of the data was validated using the Shapiro–Wilk test and homogeneity of variance was checked using Lavine's test. Means were separated at the 0.05 level using Tukey's honestly significant difference test. Parameters for nonlinear relationships between soil pH and the rate of S° chemigation were calculated using SigmaPlot v. 12.3 (SysStat Software, Inc., San Jose, CA).

Results and Discussion

Soil pH. Chemigation quickly reduced soil pH (0–10 cm) within a month of the first application of S° from an average of 6.6 with no S° to 5.8 with 100–150 kg·ha^{-1} S° (Fig. 2). The change in pH was short-term, however, and by May of the following year ranged from 6.7 with no S° to 6.1 with 150 kg·ha^{-1} S°. Conventional application of prilled S°, by contrast, reduced soil pH gradually and only to 6.3 by May (Fig. 2). Despite plenty of precipitation before May, soil acidification was likely inhibited by the large size of the prilled S° granules and by low soil temperatures during the first few months after planting (Fig. 1). Oxidation of S° by soil bacteria is slow or null at temperatures below 5 °C (Wainwright, 1984), but it increases exponentially with higher temperatures, until an optimum is reached at 30 to 40 °C (Germida and Janzen, 1993; Janzen and Bettany, 1987).

By the time soil temperature exceeded 15 °C in July 2011, soil pH averaged 5.6 in the top 10 cm of the soil profile with conventional S° application (Fig. 3A). The chemigated treatments, on the other hand, appeared to be impacted largely by hydrolysis of the urea fertilizer, which increases soil pH (Broadbent et al., 1958). Without S°, soil pH was 6.7 under the drip emitter and declined with distance and depth from the emitter. Soil pH was only <6.0 at the highest rate of S° chemigation and, in this case, only near the drip emitter.

By Oct. 2011, soil pH increased in each of the chemigated treatments and, at that point, was only slightly lower than without S° chemigation (Fig. 3B). Soil pH was also higher in October than in July in the conventional S° treatment. Normally, soil pH declines over the growing season in western Oregon (Horneck et al., 2004). However, nearly 55 mm of rain fell during the week before soil sampling in Oct. 2011, which probably leached H^+ and diluted the pH of the soil.

Soil pH declined in each treatment from 2011 to 2012, including in the control with no S° (Fig. 3). Soil pH commonly declines over time in blueberry fields, due primarily to nitrification of excess ammonium-N from the fertilizer (Bryla et al., 2010). Blueberry plants mainly acquire the ammonium form of N and, therefore, are usually fertilized with ammonium sulfate or urea (Hart et al., 2006). Young plants accumulate <20 kg·ha^{-1} N during the first year after planting (Bañados et al., 2012), and therefore, much of the remaining 80 kg·ha^{-1} N applied in year 1 in the present study would have likely nitrified into nitrate-N by the following year. Despite low N requirements in new plantings, extra N is commonly added at this stage to compensate for low fertilizer use efficiency (Bryla and Strik, 2015). In July 2012, soil pH averaged 6.2–6.4 at 0–10 cm with increasing rates of S° chemigation and 5.5 with conventional prilled S° (Fig. 3C). In general, soil pH declined with horizontal distance from the drip emitter and increased with depth in all but the no S° treatment.

As with the preplant application of S°, adding S° by chemigation after planting (i.e., in Aug. to Oct. 2012) also reduced soil pH quickly (Fig. 3D). Even with 67 mm of rain before sampling, soil pH in Oct. 2012 was 5.9–6.1 in the top 10 cm of the soil in the treatments chemigated with 100–150 kg·ha^{-1} S°; and at the higher rate of S°, soil pH was similar, on average, to the prilled S° treatment at both the 10–20 and 20–30 cm depths. Thus, chemigation with S° rapidly reduced soil pH both before and after planting in the present study, and when chemigation was done after

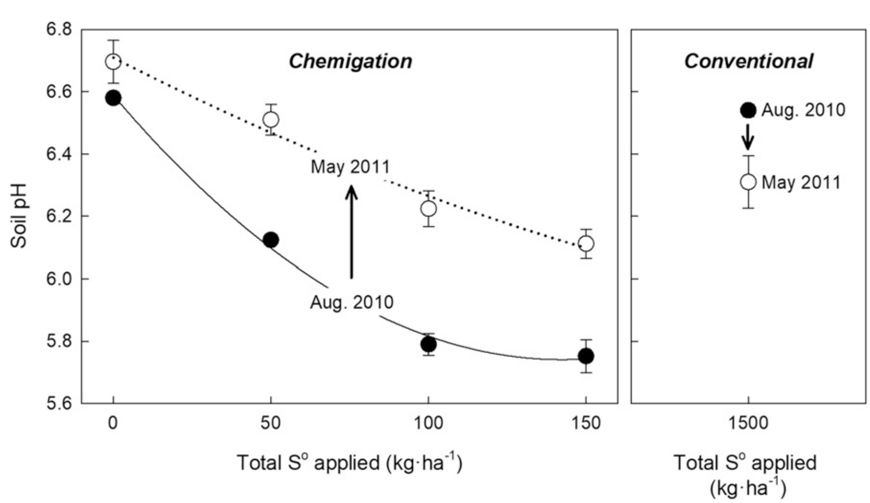

Fig. 2. Soil pH during (Aug. 2010; ●) and at ≈7 months after (May 2010; ○) either chemigation or conventional applications of elemental sulfur (S°) in a new planting of 'Duke' blueberry. The dates of S° application are illustrated in Fig. 1. Soil was sampled near a drip emitter at a depth of 0–10 cm. Error bars indicate ±1 SE (n = 5). The response of soil pH to the rate of S° chemigation was fit using quadratic polynomials [Aug. 2010: $y = 4.18\text{E–}05x^2 - 0.0119x + 6.5887$ ($r^2 = 0.9564$, $P < 0.0001$); May 2011: $y = 7.40\text{E–}06x^2 - 0.0052x + 6.7097$ ($r^2 = 0.7936$, $P < 0.0001$)].

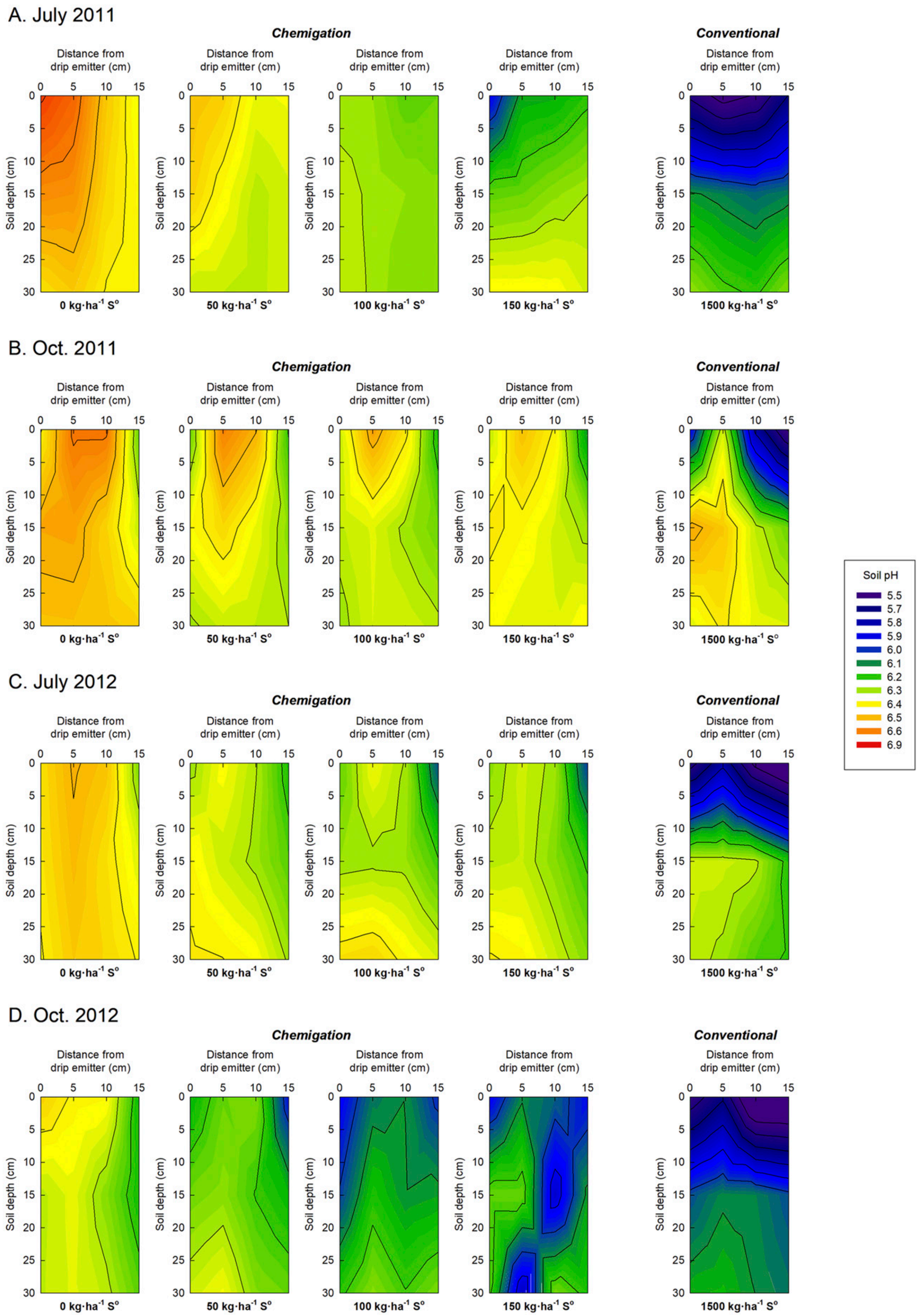

Fig. 3. Soil pH in relation to soil depth and distance from a drip emitter following chemigation or conventional applications of elemental sulfur (S^o) in a new planting of 'Duke' blueberry. Soil was sampled in (**A**, **C**) July and (**B**, **D**) October during the (**A**, **B**) first and (**C**, **D**) second year after planting (2011–12). The dates of S^o application are illustrated in Fig. 1; note that S^o was reapplied to the chemigated treatments before the last sampling date in 2012.

planting, it resulted in deeper soil acidification (i.e., up to 30-cm deep within a month or two) than what would be typically expected from a surface application of prilled S° (Wen et al., 2001).

Soil EC. A potential side effect of S° acidification is high levels of salinity in the soil (Turan et al., 2013). Acidification with S° increases soil salinity by releasing sulfate (SO_4^{2-}) and other soluble ions (e.g., PO_4^{2-}, Mn^{2+}, and Zn^{2+}) (Spiers and Braswell, 1992; Yang et al., 2010). Indeed, soil salinity, which is measured as EC, increased with S° application in the present study and, consequently, was negatively correlated to soil pH on each sampling date (r^2 = 0.94–0.99; $P \leq$ 0.01). In general, soil EC was lower with S° chemigation than with conventional prilled S°, but the readings never exceeded 0.6 dS·m^{-1} in either treatment on any of the sampling dates (data not shown). Soil EC < 2.0 dS·m^{-1} is considered safe for salt-sensitive crops such as northern highbush blueberry (Grieve et al., 2012). Thus, it is unlikely that plants in any of the treatments were adversely affected by salinity in the present study.

Plant growth and early fruit production. The S° treatments had no effect on pruning weight, yield, berry weight, or plant dry weight during the first 2 years after planting (Table 1). In general, yield at this stage was normal for 'Duke' in Oregon, whereas plant dry weight was somewhat lower than expected based on previous reports (e.g., Larco et al., 2013a; Strik and Buller, 2005; Strik et al., 2017). It is unclear why growth was unaffected by any of the treatments, including no S°, given that soil pH at the site was above the recommended range for northern highbush blueberry. 'Duke' often performs poorly and usually worse than most other cultivars when soil pH is too high (Strik et al., 2014; 2017). However, none of the plants in the study exhibited interveinal Fe chlorosis commonly associated with high soil pH in northern highbush blueberry (Polashock et al., 2016). This suggests that bulk soil pH measurements may be less important when the plants are irrigated and fertigated with ammonium sources of N by drip. As mentioned, blueberry roots tend to concentrate near the drip emitters and, therefore, may be more affected by pH of the rhizosphere than of the bulk soil. More work is needed to understand pH dynamics of drip-irrigated plants.

Leaf nutrients. Chemigation with S° resulted in lower concentrations of P, K, Mg, S, and Mn in the leaves than the conventional application of prilled S° in year 1, as well as lower concentrations of N, P, and S in the leaves than prilled S° in year 2 (Table 2). Most of the leaf nutrient concentrations were within the recommended range for northern highbush blueberry in Oregon; however, leaf Mg, S, and Mn were above and leaf Cu was below recommendations in year 1, while leaf Fe was above and leaf N and P were below recommendations in year 2 (Hart et al., 2006). Low leaf Cu in not unusual when Cu-containing fungicides are omitted from the pest management program (Strik and Vance, 2015). Leaf Fe may have been high in year 2 because of dust on the leaves (not washed before analysis). Leaf N was likely low because N fertilization was late and lower than recommended the second year (Bryla and Strik, 2015). Consequently, the plants were slightly chlorotic that spring but recovered quickly once fertigation was initiated and one or two applications of urea were applied. Strik and Vance (2015) also reported low leaf P in various cultivars of northern highbush blueberry in western Oregon, but the concentrations measured in the present study in year 2 were below those reported previously for 'Duke' (Larco et al., 2013b; Strik and Vance, 2015). Phosphorus uptake is sometimes limited in fertigated plants

Table 1. Effects of chemigation and conventional applications of elemental sulfur (S°) on growth and early fruit production during the first 2 years after planting in 'Duke' blueberry.

Method and rate of S° application	Pruning wt (g/plant)[y]	Yield (kg/plant)[x]	Berry wt (g)[x]	Plant dry wt (kg/plant)[z]	
				Aboveground	Belowground
Chemigation					
0 kg·ha^{-1} S°	40	0.77	2.62	0.24	0.32
50 kg·ha^{-1} S°	35	0.89	2.59	0.23	0.30
100 kg·ha^{-1} S°	38	0.77	2.62	0.21	0.29
150 kg·ha^{-1} S°	35	0.65	2.63	0.23	0.30
Conventional (1,500 kg·ha^{-1} S°)	33	0.64	2.73	0.25	0.33
P value	0.869	0.069	0.517	0.502	0.630

[z]Measured after the second growing season. The aboveground portion of the plants included the whips, new branches, and woody canes, and the belowground portion included the roots and crown.
[y]Measured after the first growing season.
[x]Measured during the second growing season.

Table 2. Effects of chemigation and conventional applications of elemental sulfur (S°) on the concentration of nutrients in recent fully expanded leaves sampled in early August during the first 2 years after planting in 'Duke' blueberry.

Method and rate of S° application	Leaf macronutrients (mg·g^{-1})						Leaf micronutrients (µg·g^{-1})				
	N	P	K	Ca	Mg	S	Fe	B	Cu	Mn	Zn
Year 1											
Chemigation											
0 kg·ha^{-1} S°	2.07	0.11 b[z]	0.60 b	0.66	0.24 b	0.52 b	189	34	3	371 b	21
50 kg·ha^{-1} S°	1.95	0.10 b	0.60 b	0.67	0.25 b	0.51 b	191	33	3	381 b	20
100 kg·ha^{-1} S°	2.00	0.10 b	0.64 b	0.68	0.27 b	0.55 b	188	34	3	373 b	20
150 kg·ha^{-1} S°	1.95	0.11 b	0.61 b	0.70	0.27 b	0.55 b	197	36	2	393 b	24
Conventional (1,500 kg·ha^{-1} S°)	1.94	0.13 a	0.89 a	0.83	0.38 a	1.00 a	188	40	3	570 a	24
P value	0.533	<0.001	<0.001	0.083	<0.001	<0.001	0.978	0.569	0.570	0.050	0.574
Year 2											
Chemigation											
0 kg·ha^{-1} S°	1.19 b	0.07 b	0.50	0.56	0.19	0.10 b	410	49	6	178	12
50 kg·ha^{-1} S°	1.23 b	0.07 b	0.52	0.55	0.19	0.11 b	414	51	7	146	11
100 kg·ha^{-1} S°	1.24 b	0.07 b	0.50	0.51	0.18	0.10 b	475	48	6	154	11
150 kg·ha^{-1} S°	1.22 b	0.07 b	0.51	0.55	0.19	0.10 b	368	54	6	157	11
Conventional (1,500 kg·ha^{-1} S°)	1.38 a	0.08 a	0.50	0.54	0.19	0.16 a	428	55	5	185	10
P value	0.031	0.032	0.973	0.795	0.839	<0.001	0.465	0.774	0.851	0.384	0.132
Recommended range[y]	1.76–2.00	>0.10	0.41–0.70	0.41–0.80	0.13–0.25	0.11–0.16	61–200	31–80	5–15	30–350	8–30

[z]Means followed by the same letter within a year are not significantly different at $P \leq 0.05$.
[y]From Hart et al. (2006).

because of the smaller size of the root system (Bryla, 2011).

Conclusions

The findings indicate that S° chemigation can be used to quickly reduce soil pH in northern highbush blueberry. However, it was less effective and more time consuming than conventional application of prilled S° before planting. Therefore, S° chemigation may be most useful when soil pH is too high after planting. The practice is less expensive and safer than using acid to correct high soil pH problems and is a convenient alternative for both conventional and organic blueberry production.

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