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Growth and Fruit Production of Highbush Blueberry Fertilized with Ammonium Sulfate and Urea Applied by Fertigation or as Granular Fertilizer

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***Abstract*. Fertigation with liquid sources of nitrogen (N) fertilizers, including ammonium sulfate and urea, were compared with granular applications of the fertilizers in northern highbush blueberry (*Vaccinium corymbosum* L. 'Bluecrop') during the first 5 years of fruit production (2008–12). The planting was established in Apr. 2006 at a field site located in western Oregon. The plants were grown on raised beds and mulched every 2 years with sawdust. Liquid fertilizers were injected through a drip system in equal weekly applications from mid-April to early August. Granular fertilizers were applied on each side of the plants, in three split applications from mid-April to mid-June, and washed into the soil using microsprinklers. Each fertilizer was applied at three N rates, which were increased each year as the plants matured (63 to 93, 133 to 187, and 200 to 280 kg·ha^{-1} N) and compared with non-fertilized treatments (0 kg·ha^{-1} N). Canopy cover, which was measured in 2008 only, and fresh pruning weight were greater with fertigation than with granular fertilizer and often increased with N rate when the plants were fertigated but decreased at the highest rate when granular fertilizer was applied. Yield also increased with N fertilizer and was 12% to 40% greater with fertigation than with granular fertilizer each year as well as 17% greater with ammonium sulfate than with urea in 2011. The response of berry weight to the treatments was variable but decreased with higher N rates during the first 3 years of fruit production. Leaf N concentration was greater with fertigation in 4 of 5 years and averaged 1.68% with fertigation and 1.61% with granular fertilizer. Leaf N was also often greater with ammonium sulfate than with urea and increased as more N was applied. Soil pH declined with increasing N rates and was lower with granular fertilizer than with fertigation during the first 3 years of fruit production and lower with ammonium sulfate than with urea in every year but 2010. Soil electrical conductivity (EC) was less than 1 dS·m^{-1} in each treatment but was an average of two to three times greater with granular fertilizer than with fertigation and 1.4 to 1.8 times greater with ammonium sulfate than with urea. Overall, total yield averaged 32 to 63 t·ha^{-1} in each treatment over the first 5 years of fruit production and was greatest when plants were fertigated with ammonium sulfate or urea at rates of at least 63 to 93 kg·ha^{-1} N per year.**

Northern highbush blueberry is well adapted to acidic soil conditions and often grows best in a pH range of 4.0 to 5.5 (Retamales and Hancock, 2012). Blueberry has low nutrient requirements compared with many other fruit crops (Hancock and Hanson, 1986) but typically needs regular applications of N fertilizer to maximize growth and fruit production (Bañados et al., 2012; Hanson and Hancock, 1996). The plants acquire primarily the ammonium form of N (Claussen and Lenz, 1999) and, therefore, the most common N fertilizers applied to blueberry are ammonium sulfate and urea. Both are excellent sources of ammonium-N but the latter requires soil temperatures greater than 20 °C for complete breakdown and is only half as acidifying as ammonium sulfate (Havlin et al., 2005). Hart et al. (2006) suggest applying ammonium sulfate to blueberry when soil pH is greater than 5.5 and urea or a mix of urea and ammonium sulfate when soil pH is less than 5.0.

Current N recommendations for blueberry range from 20 to 140 kg·ha^{-1} N per season, varying with the age of the planting, plant vigor, location (region), soil type, soil management (e.g., mulch applications), and inherent soil fertility (British Columbia Ministry of Agriculture, 2012; Hanson, 2006; Hart et al., 2006). Nitrogen is either applied as granular fertilizers or by fertigation. Granular fertilizers are typically spread along the rows and washed into the soil by rain or sprinkler irrigation. Two or three equal applications of granular N fertilizer are recommended each spring, which is when N uptake in blueberry is considered most active (Bañados et al., 2012; Throop and Hanson, 1997). Liquid fertilizers are usually injected and applied in small and frequent applications (e.g., once a week) through an irrigation system such as drip, starting at leaf emergence (and finishing 2 months before the end of the growing season) or beginning in May when irrigation is required on a regular basis (D.R. Bryla, personal observations). In the latter case, an initial application of granular fertilizer is often applied before fertigation, in March or April.

Current nutrient management guidelines for blueberry were developed based on granular fertilizers and may not be optimized for plants fertilized by fertigation. Bryla and Machado (2011) compared fertigation to granular applications of N fertilizer in a new planting of highbush blueberry and determined that fertigation was less efficient (i.e., less plant growth per unit of N applied) but safer (i.e., less salt damage and plant death) than granular fertilizer during the first 2 years of establishment. The objective of the present study was to extend this original study and compare the effects of fertigation with granular fertilizer during the first 5 years of fruit production (Years 3 to 7). Both methods of fertilizer application were evaluated using ammonium sulfate or urea.

Materials and Methods

Study site. The study was conducted from 2008 to 2012 in a planting of 'Bluecrop' blueberry established in Apr. 2006 at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, OR (lat. 44°33′10″ N, long. 123°13′9″ W, 68 m elevation). Soil at the site was a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerolls) that had 2.4% organic matter content and an initial pH of 6.2 (Nov. 2005). Two applications of 670 kg·ha^{-1} of elemental sulfur were incorporated into the field at 6 and 10 months before planting, which reduced soil pH to 5.5 by planting (Horneck et al., 2004). Plants were obtained from a commercial nursery (Fall Creek Farm & Nursery, Jasper, OR) as 18-month-old container stock. The plants were transplanted onto 0.4-m high × 0.9-m wide raised planting beds at an in-row spacing of

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0.76 m. Raised beds were formed using a tractor-powered bed shaper and were centered 3.0 m apart. A 7.5-cm deep × 1-m wide layer of aged (greater than 6 months) Douglas fir (*Pseudotsuga menziesii* Franco) sawdust was spread and rototilled into each row before shaping the beds (to increase soil organic matter content and improve drainage in the beds), and a 9-cm layer of the sawdust was applied as mulch on top of beds immediately after planting (primarily for weed control). The sawdust mulch was reapplied every 2 years. Grass alleyways (1.5 m wide) were planted between the beds and mowed every 1 to 2 weeks during the growing season. Weeds were controlled as needed using glyphosate herbicide at the base of beds and hand-weeding on the top of beds. No insecticides or fungicides were applied to the field.

Experimental design. An irrigation system was installed before planting and designed with a manifold to accommodate 16 different fertilizer treatments. The treatments were arranged in a split-plot design with a combination of two N sources (ammonium sulfate and urea) and two methods of fertilizer application (weekly fertigation and dry granular fertilizer applications) as main plots and four N rates as subplots. Each subplot consisted of one row of eight plants and was replicated six times. Only the middle six plants in each subplot were used for measurements. The planting contained a total of 952 plants and included 12 rows of treatment plots with two border plants on each end and two border rows on each side of the planting.

Liquid ammonium sulfate (9N–0P–0K–10S) and urea (20N–0P–0K) were applied by fertigation through a drip system. One line of drip tubing (GeoFlow, Charlotte, NC) was installed initially near the base of the plants during the first 3 years after planting (2006–08), and a second line was added in Apr. 2009. When the second line was added, the lines were repositioned on each side of the row at a distance of ≈0.2 m from the base of the plants. The lines had 1.9 $L \cdot h^{-1}$ integrated pressure-compensating emitters located every 0.30 m and were covered with sawdust mulch after installation. The liquid fertilizers were injected at the manifold using Venturi-type injectors (Mazzei Model 584 Injector Corp., Bakersfield, CA). Plants were fertigated weekly beginning in mid-April each year and continuing until early August. Fertigation was not applied during the latter part of the growing season (i.e., mid-August to late September) because N applications in late summer reduce fruit bud set in blueberry and increase the potential for winter freeze damage (Hart et al., 2006).

Granular ammonium sulfate (21N–0P–0K–24S) and urea (46N–0P–0K) were applied by hand once a month from April to June in three equal applications per year. The fertilizers were spread along the row in a 20-cm-wide band on each side of the plants and then immediately washed into the soil using 22.7-$L \cdot h^{-1}$ hanging fan-jet microsprinklers (DC Series; Bowsmith, Exeter, CA). The microsprinklers were attached to a trellis wire (suspended in the middle of the row at a height of 1.5 m) and located directly between each plant in the treatment plot (i.e., six microsprinklers per plot). The system was operated at a pressure of 100 to 140 kPa. Each microsprinkler produced an ≈2.3-m diameter, circular wetting pattern.

Both the liquid and granular fertilizers were applied at initial rates of 0, 50, 100, and 150 $kg \cdot ha^{-1}$ N during the first 2 years after planting (2006–07) and increased (as the plants matured) to 0, 67, 133, and 200 $kg \cdot ha^{-1}$ N in Year 3 (2008); 0, 75, 150, and 225 $kg \cdot ha^{-1}$ N in Year 4 (2009); 0, 83, 167, and 250 $kg \cdot ha^{-1}$ N in Year 5 (2010); and 0, 93, 187, and 280 $kg \cdot ha^{-1}$ N in Years 6 and 7 (2011–12). Because treatments with no N (0 $kg \cdot ha^{-1}$ N) were identical within the two fertilizer methods (fertigation and granular fertilizer), only one of each was used for measurements in the present study; the others were used to test additional N sources (unpublished results).

Plants were irrigated from early May to late September each year using the drip system for the fertigated treatments and the microsprinklers for the granular treatments. Irrigation was scheduled three to seven times per week based on weather and daily estimates of crop evapotranspiration (Bryla, 2011a). Precipitation and crop evapotranspiration were obtained at least weekly from a nearby AgriMet Cooperative Agricultural Weather Network weather station (http://www.usbr.gov/pn/agrimet/agrimetmap/crvoda.html). Water application was monitored using water meters (Model SRII; Sensus, Raleigh, NC) installed at the inflow of each treatment. Additional water (≈5 mm/week) was also applied for fertigation in April each year, and all treatments, including those with no N or with microsprinklers, were irrigated using the same amount of water. The pH of the irrigation water was 6.9 to 7.0 over the course of the growing season, and EC was less than 0.1 $dS \cdot m^{-1}$.

Measurements. Canopy cover was estimated on 28 Aug. 2008 from digital images captured using an ADC multispectral camera (TetraCam Inc., Chatsworth, CA). The camera was suspended from a marked trellis wire located ≈2.5 m above the planting bed. Images were collected from every other plant of the center six plants in each treatment plot for a total of 288 images. Percent live cover in each image was determined using software provided by the camera manufacturer (Pixelwrench and Briv32; TetraCam Inc., Chatsworth, CA). Care was taken to ensure that the image area always exceeded canopy width in each image. Any cover by weeds or the grass alleyway was cleaned from the images before analysis using Adobe Photoshop Version 5.0 (Adobe Systems Inc., San Jose, CA). Live cover was converted to total percent canopy cover based on the proportion of the field covered by each image (1.2 m × 1.5 m). By 2009, differences in plant size were no longer discernible by measuring canopy cover. At this point, the branches overlapped between adjacent plants within each row, and the measurements were discontinued.

Plants were pruned in January or February each year. To encourage vegetative growth during establishment, all fruit buds were removed during the first 2 years of pruning, delaying fruit production until the third year after planting in 2008 (Strik and Buller, 2005). The prunings were weighed fresh in each plot every winter. Fruit were hand-picked three or four times per year from mid-July to early-August and weighed each time to determine the total yield in each treatment plot. A random sample of 100 berries was also weighed at each harvest to calculate the average berry weight in each plot.

Leaf samples were collected for N analysis during the first week of August each year (Hart et al., 2006). Six recently mature leaves were sampled and pooled from the center six plants in each plot, oven-dried at 70 °C, ground, and analyzed for total N using a combustion analyzer (Model CNS-2000; LECO Corp., St. Joseph, MI). Each sample was also analyzed for phosphorus, potassium, calcium, magnesium, sulfur, iron, boron, copper, manganese, and zinc using an inductively coupled plasma optical emission spectrometer (Optima 3000DV; Perkin Elmer, Wellesley, MA) following microwave digestion in 70% (v/v) nitric acid (Gavlak et al., 2005). Each year, the concentration of these additional nutrients was similar among the treatments and always within the range recommended for highbush blueberry (Hart et al., 2006)

Soil samples were collected during the third week of July each year and analyzed for pH and EC. A 30-cm long × 2-cm diameter soil probe (JMC Backsaver; N-2 Handle, Newton, IA) was used to collect the soil samples to a depth of 0 to 20 cm. Each plot was sampled on each side of the planting bed at a distance of ≈30 cm from the center of the row (i.e., directly near a drip emitter in the fertigated plots and where the fertilizer was banded in the granular plots). Holes created by sampling were immediately refilled using soil collected from the border rows, and care was taken to sample a different location each year. Soil samples were air-dried, ground to pass through a 2-mm sieve, and measured for pH and EC following a 1:2 soil:water (w/w) method (Jackson, 1958; Jones, 2001).

Data analysis. Data were analyzed by analysis of variance (ANOVA) using the PROC MIXED procedure in SAS (Version 9.3 software; SAS Institute, Cary, NC). To create a balanced factorial treatment structure, the non-fertilized plants (0 $kg \cdot ha^{-1}$ N) irrigated by drip and microsprinklers were excluded from the ANOVA. Orthogonal contrasts were used to make independent linear comparisons between the two non-fertilized treatments and factorial comparisons among N rates and two-way interactions with N rate (Gomez and Gomez, 1984). To achieve homogeneity of variance in the data, soil EC was log-transformed before analysis and back-transformed for presentation. Means were separated at the 0.05 level using the Tukey-Kramer honestly significant difference test.

Results

Plant growth. Analysis of the canopy cover images revealed that the plants were significantly larger with fertigation than with granular fertilizer during the first year of fruit production in 2008 ($P < 0.0001$; Fig. 1). A significant difference between the non-fertilized plants ($P = 0.0073$) suggests that at least some of the difference between the two fertilizer methods may have been the result of how the plants were irrigated. Even without N (0 kg·ha^{-1} N), plants irrigated by drip (used for fertigation) had more canopy cover than those irrigated by microsprinklers (used for granular fertilizers). The interaction between the method of fertilizer application and N rate was also significant ($P = 0.0199$) attributable to the fact that canopy cover increased slightly with N rate when the plants were fertigated but decreased at the highest N rate (200 kg·ha^{-1} N) when granular fertilizer was applied. Canopy cover was unaffected by N source (ammonium sulfate and urea) or any interactions with N source in 2008.

Analysis of the pruning weights suggested that plant growth continued to be greater with fertigation than with granular fertilizer each year and in, 3 of 5 years (2008, 2011, and 2012), increased linearly with N rate when plants were fertigated but decreased at the highest N rate when granular fertilizer was applied (Table 1). Pruning weight was also affected by N rate in 2009, but in this case, the increase was quadratic, regardless of the fertilizer method ($P = 0.0260$).

Fruit production. Yield was similar between non-fertilized plants irrigated by drip or microsprinklers each year but was always greater by 12% to 40% with fertigation than with granular fertilizer (Table 2). Significant interactions with method indicated that yield was also lower with ammonium sulfate than with urea when granular fertilizer was applied in 2008 and was similar among N rates with fertigation but decreased at the highest N rate when granular fertilizer was applied in 2009. Yield also decreased linearly with N rate in 2010 and was 17% greater with ammonium sulfate than with urea in 2011. After 5 years, total yield was 8.2 t·ha^{-1} greater with fertigation than with granular fertilizer but was similar between the fertilizer sources and among the N rates (Table 2).

Berry weight was greater with fertigation than with granular fertilizer in 2008 but was either similar between the methods or lower with fertigation the following years (Table 2). Berry weight also decreased linearly with N rate in 2008–10 (Table 2). In 2010, berry weights were below average in all treatments (1.3 to 1.5 g/berry), indicating the plants were overcropped and perhaps explaining why treatments with the highest yields such as the fertigated plants had the lowest berry weights. However, berry weight was also lower with drip than with microsprinklers in the non-fertilized plants in 2010, suggesting that irrigation could have also affected the berry weights that year (Table 2).

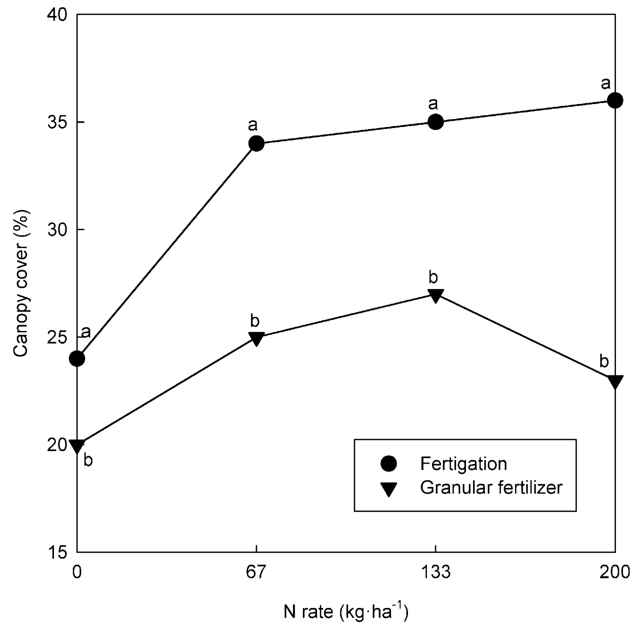

Fig. 1. Canopy cover of 'Bluecrop' blueberry during the first year of fruit production (2008) in Oregon. Plants were non-fertilized or fertilized with three rates of nitrogen (N) applied by fertigation or as granular fertilizer each year. Each symbol represents the mean of six replicates. Means with the same letter within each N rate are not significantly different, according to Tukey's honestly significant difference test ($P \leq 0.05$).

Table 1. Effects of different methods, sources, and rates of nitrogen (N) fertilizer on fresh pruning weight of 'Bluecrop' blueberry during the first 5 years of fruit production (2008–12) in Oregon.

	Pruning wt (kg/plant)							
Treatment	2008		2009	2010	2011		2012	
Non-fertilized plants								
Drip	0.12		0.08	0.26	0.15		0.12	
Microsprinklers	0.11		0.09	0.27	0.15		0.15	
Significance	NS		NS	NS	NS		NS	
Fertilized plants[z]								
Method (M)								
Fertigation	0.29		0.17	0.50	0.28		0.44	
Granular fertilizer	0.17		0.13	0.34	0.21		0.32	
Significance	***		***	***	***		***	
Source (S)								
Ammonium sulfate	0.22		0.15	0.42	0.25		0.38	
Urea	0.24		0.15	0.42	0.24		0.37	
Significance	NS		NS	NS	NS		NS	
N rate (N)	Fertig.	Gran.			Fertig.	Gran.	Fertig.	Gran.
67 to 93 kg·ha^{-1} N	0.26	0.18	0.13	0.43	0.25	0.23	0.36	0.30
133 to 187 kg·ha^{-1} N	0.28	0.18	0.16	0.43	0.27	0.23	0.44	0.37
200 to 280 kg·ha^{-1} N	0.33	0.15	0.16	0.40	0.31	0.18	0.50	0.28
Significance	$M \times N_L$**		Q*	NS	$M \times N_L$***		$M \times N_L$***	

[z]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 kg·ha^{-1} N in 2008; 75, 150, and 225 kg·ha^{-1} N in 2009; 83, 167, and 250 kg·ha^{-1} N in 2010; and 93, 187, and 280 kg·ha^{-1} N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as "Fertig." and "Gran.," respectively. There were no significant two-way interactions with N source or any significant three-way interactions among the test factors.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; "L" and "Q" indicate significant linear and quadratic responses to N rate, respectively; and "$M \times N_L$" indicates that a significant interaction between method and N rate is primarily the result of the difference in the linear part of the pruning weight responses to N rate of the two methods.

Leaf N concentrations. Leaf N concentrations ranged from 1.16% to 1.88% (Table 3). In 4 of 5 years, leaf N was greater with fertigation than with granular fertilizer although, in one of those years (2008), was only greater with fertigation when ammonium sulfate was applied. Leaf N was also greater, in most cases, with ammonium sulfate than with urea and, each year, increased linearly with N rate. Two-way interactions indicated that leaf N responded more to N rate with fertigation than with granular fertilizer in 2009

Table 2. Effects of different methods, sources, and rates of nitrogen (N) fertilizer on yield and berry weight of 'Bluecrop' blueberry during the first 5 years of fruit production (2008–12) in Oregon.

	Yield (t·ha^{-1})								Berry wt (g)				
Treatment	2008		2009		2010	2011	2012	Total	2008	2009	2010	2011	2012
Non-fertilized plants													
Drip	2.2		5.6		9.9	5.7	9.5	32.5	1.59	1.75	1.38	1.98	1.97
Microsprinklers	2.5		6.5		10.5	6.7	10.5	36.6	1.63	1.84	1.51	2.11	1.99
Significance	NS		NS		NS	NS	NS	NS	NS	NS	***	NS	NS
Fertilized plants[z]													
Method (M)													
Fertigation	3.5		8.2		15.1	12.8	17.6	57.2	1.69	1.65	1.30	2.04	2.19
Granular fertilizer	2.5		7.2		12.5	11.5	15.3	49.0	1.56	1.66	1.47	2.06	2.21
Significance	***		**		***	*	**	***	***	NS	***	NS	NS
Source (S)	Fertig.	Gran.											
Ammonium sulfate	3.6 a[y]	2.2 c	7.4		14.0	13.1	17.1	54.5	1.63	1.64	1.36	2.04	2.22
Urea	3.5 a	2.9 b	8.0		13.6	11.2	15.7	51.7	1.62	1.67	1.41	2.06	2.17
Significance	M × S*		NS		NS	**	NS	NS	NS	NS	**	NS	NS
N rate (N)			Fertig.	Gran.									
67 to 93 kg·ha^{-1} N	3.2		8.2	7.7	14.8	12.4	17.0	55.4	1.69	1.71	1.41	2.10	2.16
133 to 187 kg·ha^{-1} N	3.0		7.7	7.7	13.6	12.0	16.0	52.4	1.60	1.66	1.39	2.04	2.21
200 to 280 kg·ha^{-1} N	2.9		8.5	6.3	12.9	12.0	16.3	51.6	1.58	1.58	1.35	2.01	2.22
Significance	NS		$M \times N_L$**		L*	NS	NS	NS	L***	L*	L*	NS	NS

[z]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 kg·ha^{-1} N in 2008; 75, 150, and 225 kg·ha^{-1} N in 2009; 83, 167, and 250 kg·ha^{-1} N in 2010; and 93, 187, and 280 kg·ha^{-1} N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N source, method, and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as "Fertig." and "Gran.," respectively. There were no significant interactions between N source and N rate or any significant three-way interactions among the test factors.

[y]Means (n = 6) followed by the same letter are not significantly different, according to Tukey's honestly significant difference test ($P \leq 0.05$).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; "L" indicates a significant linear response to N rate; and "$M \times N_L$" indicates that a significant interaction between method and N rate is primarily the result of the difference in the linear part of the yield responses to N rate of the two methods.

Table 3. Effects of different methods, sources, and rates of nitrogen (N) fertilizer on leaf N concentration in 'Bluecrop' blueberry during the first 5 years of fruit production (2008–12) in Oregon.

	Leaf N (%)							
Treatment	2008		2009		2010	2011	2012	
Non-fertilized plants								
Drip	1.34		1.35		1.16	1.23	1.23	
Microsprinklers	1.43		1.31		1.27	1.30	1.29	
Significance	**		NS		*	NS	NS	
Fertilized plants[z]								
Method (M)								
Fertigation	1.71		1.72		1.58	1.72	1.69	
Granular fertilizer	1.64		1.73		1.46	1.64	1.57	
Significance	***		NS		***	***	***	
Source (S)	Fertig.	Gran.						
Ammonium sulfate	1.79 a[y]	1.64 b	1.76		1.57	1.74	1.67	
Urea	1.64 b	1.64 b	1.70		1.48	1.62	1.59	
Significance	M × S***		***		**	***	***	
N rate (N)			Fertig.	Gran.			A. sulf.	Urea
67 to 93 kg·ha^{-1} N	1.57		1.62	1.64	1.45	1.61	1.56	1.44
133 to 187 kg·ha^{-1} N	1.69		1.71	1.77	1.54	1.70	1.74	1.61
200 to 280 kg·ha^{-1} N	1.76		1.82	1.79	1.59	1.73	1.72	1.70
Significance	L***		$M \times N_L$***		L***	M × S × N**	$S \times N_L$*	

[z]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 kg·ha^{-1} N in 2008; 75, 150, and 225 kg·ha^{-1} N in 2009; 83, 167, and 250 kg·ha^{-1} N in 2010; and 93, 187, and 280 kg·ha^{-1} N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N source, method and N rate, or N source and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as "Fertig." and "Gran.," respectively, and the column heading for ammonium sulfate is abbreviated as "A. sulf." Results of a significant three-way interaction on leaf N in 2011 are presented in Figure 2. In no instance did N rate interact significantly with both method and N source.

[y]Means (n = 6) followed by the same letter are not significantly different, according to Tukey's honestly significant difference test ($P \leq 0.05$).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; "L" indicates a significant linear response to N rate; and "$M \times N_L$" and "$S \times N_L$" indicate that a significant interaction between method and N rate and source and N rate is primarily the result of the difference in the linear part of the leaf N responses to N rate of the two methods and N sources, respectively.

and with ammonium sulfate than with urea in 2012 (Table 3), while a three-way interaction in 2011 revealed that leaf N was greater with fertigation and ammonium sulfate than the other treatments at the lower N rates but was similar among each treatment except granular urea at the highest N rate (Fig. 2).

Leaf N concentration was negatively correlated to soil pH each year (r^2 = –0.59 to –0.87; $P < 0.001$) and positively correlated to yield every year except 2009 (r^2 = 0.30 to 0.75 in 2008 and 2010–12; $P < 0.05$).

Soil conditions. Depending on the year and treatment, soil pH ranged from 4.2 to 6.9 (Table 4). On average, the values were 0.2 to 0.4 units lower with granular fertilizer than with fertigation in 2008 through 2010, 0.3 to 1.0 units lower with ammonium sulfate than with urea in every year except 2010, and 0.7 to 0.8 units lower with microsprinklers than with drip in the non-fertilized plants in 2011 and 2012. Soil pH also decreased with N rate each year, particularly with fertigation in 2008, and with ammonium sulfate in 2011. By 2012, soil pH was lowest at each N rate when the plants were fertigated with ammonium sulfate (pH 4.2 to 4.9) and highest when the plants were fertigated with urea (pH 5.3 to 6.7) (Fig. 3).

Soil EC was greater with granular fertilizer and ammonium sulfate in most years (but not in 2010) and increased with N rate each year (Table 4). In some years, soil EC was also slightly greater with microsprinklers than with drip in the non-fertilized plants, which may have contributed to differences in the fertilizer treatments. Interactions indicated that the response of EC to N rate was greater when granular fertilizer or ammonium sulfate was applied in 2011 and that EC was only greater with ammonium sulfate when the plants were fertigated in 2012 (Table 4).

Discussion

Fertigation with ammonium sulfate or urea consistently increased yield by 12% to 40% over the use of granular fertilizer applications during the first 5 years of fruit production. Ehret et al. (2014) found similar results in ‘Duke’ blueberry in British Columbia and likewise concluded that fertigation with ammonium sulfate was more effective than broadcast applications of the fertilizer. In both cases, higher yields with fertigation were associated with greater plant growth, especially during the first 3 to 4 years after planting. The benefits of fertigation in blueberry are consistent with other high-value fruit and vegetables crops, including apple [*Malus* ×*sylvestris* (L.) Mill. var. *domesticus* (Borkh.) Mansf.], orange (*Citrus sinensis* Osb.), and bell pepper (*Capsicum annum* L.), which all had greater production when N fertilizer was injected through a drip system than when it was broadcast at the same rate on the soil surface (Dasberg et al., 1988; Haynes, 1986; Nielsen et al., 1999).

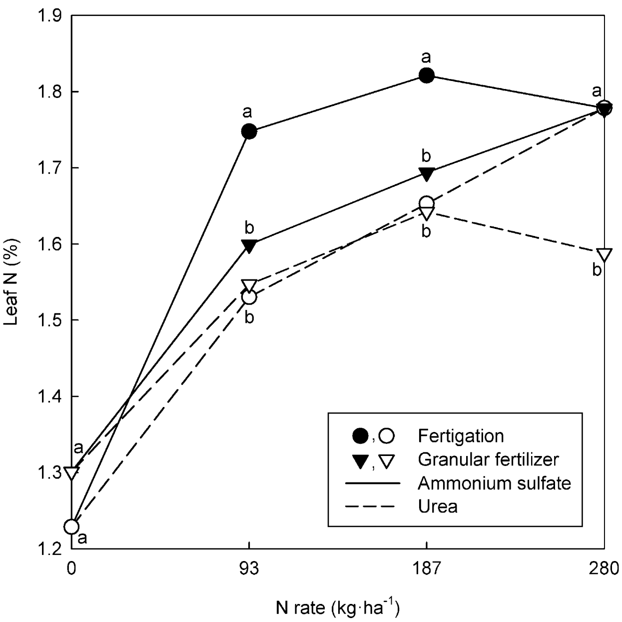

Fig. 2. Leaf nitrogen (N) concentration in ‘Bluecrop’ blueberry during the fourth year of fruit production (2011) in Oregon. Plants were non-fertilized or fertilized with three rates of ammonium sulfate or urea applied by fertigation or as granular fertilizer each year. Each symbol represents the mean of six replicates. Means with the same letter within each N rate are not significantly different, according to Tukey’s honestly significant difference test ($P \leq 0.05$).

In most cases, N fertilizer increased yield compared with no N in the present study, indicating that N was limited at the site. However, yield did not increase with increasing N rates and, in fact, declined in 2010 at the highest N rate (i.e., 250 kg·ha^{-1} N) when granular fertilizer was applied. Several studies have suggested that high N rates may be detrimental to fruit production in highbush blueberry, including ‘Wolcott’ blueberry in North Carolina (Ballinger et al., 1963), ‘Collins’ blueberry in Arkansas (Clark et al., 1988), and ‘Bluecrop’ blueberry in Michigan (Hanson and Retamales, 1992) and Oregon (Bañados et al., 2012). In each case, N fertilizer was applied in the granular form in one or more applications per season. Using the blueberry plants from the present study, Bryla and Machado (2011) found that plant growth also declined with higher rates of granular ammonium sulfate during the first 2 years after planting and suggested that less growth was the result of high salinity from the fertilizer (up to 8 dS·m^{-1}). They concluded that fertigation was safer in terms of soil salinity (always 1 dS·m^{-1} or less) but was less efficient at lower N rates than granular fertilizer because at least half of the fertilizer delivered through drip emitters was located outside of the root zone. However, once the plants grew and developed a larger root system, we found in the present study that only 63 to 93 kg·ha^{-1} N was needed

Table 4. Effects of different methods, sources, and rates of nitrogen (N) fertilizer on soil pH and electrical conductivity (EC) at a depth of 0 to 20 cm in a field of ‘Bluecrop’ blueberry during the first 5 years of fruit production (2008–12) in Oregon.[z]

	Soil pH							Soil EC (dS·m^{-1})								
Treatment	2008		2009	2010	2011		2012	2008	2009	2010	2011				2012	
Non-fertilized plants																
Drip	6.2		6.1	5.9	6.8		6.9	0.09	0.09	0.16	0.07				0.06	
Microsprinklers	6.1		6.1	6.0	6.1		6.1	0.17	0.10	0.12	0.10				0.19	
Significance	NS		NS	NS	***		***	*	NS	NS	**				***	
Fertilized plants[y]																
Method (M)																
Fertigation	5.9		5.5	5.5	5.7		5.3	0.13	0.19	0.37	0.14				0.15	
Granular fertilizer	5.6		5.1	5.3	5.7		5.3	0.39	0.44	0.48	0.34				0.33	
Significance	**		**	*	NS		NS	***	***	NS	***				***	
Source (S)															Fertig.	Gran.
Ammonium sulfate	5.6		5.1	5.3	5.4		4.8	0.30	0.39	0.46	0.32				0.21 b[x]	0.33 a
Urea	5.9		5.5	5.5	6.0		5.7	0.22	0.23	0.38	0.16				0.09 c	0.32 a
Significance	**		**	NS	***		***	*	**	NS	***				M × S**	
N rate (N)	Fertig.	Gran.			A. sulf.	Urea					Fertig.	Gran.	A. sulf.	Urea		
67 to 93 kg·ha^{-1} N	6.3	5.8	5.7	5.6	6.0	6.1	5.8	0.20	0.18	0.25	0.11	0.14	0.14	0.11	0.16	
133 to 187 kg·ha^{-1} N	6.0	5.6	5.3	5.4	5.3	5.9	5.1	0.24	0.34	0.43	0.16	0.46	0.44	0.18	0.28	
200 to 280 kg·ha^{-1} N	5.5	5.5	4.9	5.2	5.0	5.8	4.9	0.35	0.42	0.59	0.16	0.42	0.39	0.19	0.27	
Significance	$M \times N_L$**		L***	L***	$S \times N_L$***		M × S × N*	L*	L***	L***	$M \times N_Q$***		$S \times N_Q$***		Q**	

[z]Precipitation during the month before sampling was minimal, totaling only 1 to 4 mm in 2008, 2010, and 2012 and 19 and 27 mm, respectively, in 2009 and 2011.
[y]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 kg·ha^{-1} N in 2008; 75, 150, and 225 kg·ha^{-1} N in 2009; 83, 167, and 250 kg·ha^{-1} N in 2010; and 93, 187, and 280 kg·ha^{-1} N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N source, method and N rate, or N source and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as “Fertig.” and “Gran.,” respectively, and the column heading for ammonium sulfate is abbreviated as “A. sulf.” Results of a significant three-way interaction on soil pH in 2012 are presented in Figure 3. In no instance did N rate interact significantly with both method and N source.
[x]Means (n = 6) followed by the same letter are not significantly different, according to Tukey’s honestly significant test ($P \leq 0.05$).
NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; “L” and “Q” indicate a significant linear or quadratic response to N rate, respectively; and “$M \times N_L$,” “$S \times N_L$,” “$M \times N_Q$,” and “$S \times N_Q$” indicate that a significant interaction between method and N rate and source and N rate are primarily the result of the difference in the linear or quadratic part of the soil pH and EC responses to N rate of the two methods and N sources, respectively.

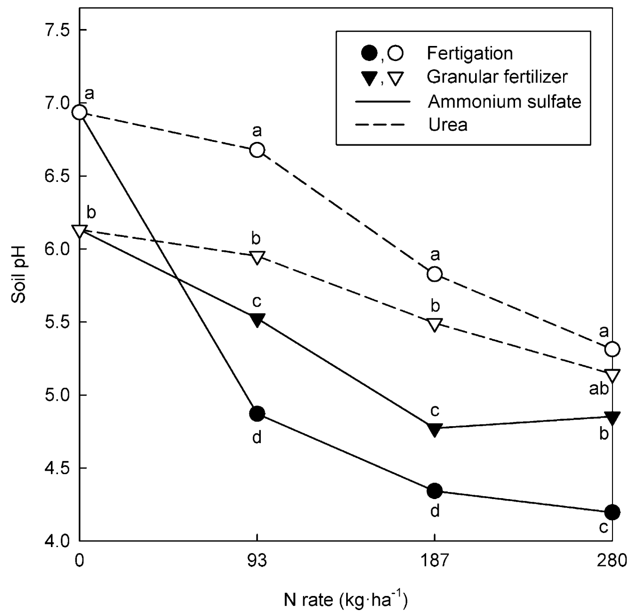

Fig. 3. Soil pH at a depth of 0 to 20 cm in a field of 'Bluecrop' blueberry during the fifth year of fruit production (2012) in Oregon. Plants were non-fertilized or fertilized with three rates of ammonium sulfate or urea applied by fertigation or as granular fertilizer each year. Each symbol represents the mean of six replicates. Means with the same letter within each nitrogen (N) rate are not significantly different, according to Tukey's honestly significant difference test ($P \leq 0.05$).

to maximize fruit production with either fertigation or granular fertilizer (Table 2). The larger plants also appeared to be more tolerant of higher granular N rates than during first 2 years after planting (Bryla and Machado, 2011), and they showed no evidence at this point of salinity stress such as wilting, leaf reddening, or leaf necrosis (Caruso and Ramsdell, 1995).

Fruit size, measured in terms of berry weight, was also affected by method of N application, although not consistently from year to year. For example, fertigation produced larger berries than granular fertilizer during the first year of fruit production but smaller berries in the third year. Ehret et al. (2014) also obtained smaller berries with fertigation than with granular ammonium sulfate in 'Duke' blueberry and suggested that reduced fruit size may have been a result of greater flower production with fertigation, which then resulted in heavier croploads. Heavy croploads reduce fruit size in blueberry (Strik et al., 2003) and probably explains why berry weight was lower in the third year than any other year, particularly with fertigation (1.2 to 1.4 g/berry). Interestingly, fruit size also decreased with N rate during the first 3 years of fruit production in the present study, despite similar or lower yields at the higher rates. Excess N results in greater vegetative growth in blueberry and can delay fruit development (Bañados et al., 2012).

Leaf N concentration increased with N rate and, in general, was greater with fertigation than with granular fertilizer or greater with ammonium sulfate than with urea. Leaf N increased by an average of 0.5% with N fertilizer, but it was always below the recommended range of 1.76% to 2.00% (Hart et al., 2006) at the lower N rates, and it never exceeded the range at the highest N rate. Leaf N concentration averaged 1.68% with fertigation and 1.61% with granular fertilizer and was often higher with ammonium sulfate than with urea. Fertigation enhances N uptake in many crops by improving the timing and placement of the N fertilizer and, therefore, often increases leaf N concentration relative to granular fertilizer (Bryla, 2011b; Bryla et al., 2010; Bryla and Vargas, 2014). Ammonium sulfate may also increase N uptake relative to urea as a result of lower soil pH and increased availability of NH_4-N (Haynes, 1990), both of which are beneficial in blueberry. Weekly measurements of the soil solution at the site indicated that NH_4-N concentrations were three times greater with ammonium sulfate than with urea when the plants were fertigated and nine times greater when the plants were grown with granular fertilizer (Machado et al., 2014).

Although both of the fertilizers used in this study reduced the soil pH, pH was lower when the plants were fertilized with ammonium sulfate than with urea. Ammonium sulfate is known to be more acidifying than urea, because it produces twice as many H^+ ions from nitrification (Hart et al., 2013), and it is less prone to leaching (Clothier and Sauer, 1988; Haynes, 1990). Soil pH also declined with increasing N rates and averaged 5.1 to 5.7 with granular fertilizer and 5.2 to 5.9 with fertigation. Soil pH was often above the range of 4.0 to 5.5 recommended for northern highbush blueberry, particularly at the lower N rates. However, the measurements were based on bulk soil samples (0- to 20-cm depth) and, therefore, do not necessarily represent the pH in the rhizosphere. In most drip-irrigated crops, including blueberry, roots concentrate near the drip emitters (Bryla, 2011b). Intensive sampling in a nearby blueberry planting fertigated with urea indicated that, although the bulk soil pH was 6.4, soil pH at a depth of 5 cm directly under the drip emitter was 4.9 (Almutairi et al., 2013).

Soil EC increased as a function of N rate and was often greater with granular fertilizer than with fertigation or greater with ammonium sulfate than with urea. EC is a good indicator of soil salinity and tends to increase rapidly with high concentrations of N fertilizer (Bunt, 1988). In irrigation water or soil solution, EC increases linearly at a rate of 2 $dS \cdot m^{-1}$ for each $g \cdot L^{-1}$ of ammonium sulfate (Machado et al., 2014). Soil solution EC also increases with urea but generally less so than with ammonium sulfate (Machado et al., 2014). Although EC never exceeded 1 $dS \cdot m^{-1}$ in any treatment and was lower than reported previously with granular fertilizers, the differences among treatments were consistent (Bryla et al., 2010; Bryla and Machado, 2011; Machado et al., 2014). Soil EC in our previous reports was measured throughout the growing season, including after each fertilizer application, using soil solution samplers installed at a depth of 5 to 10 cm. In either case, the results indicate that both fertigation and the use of urea reduce soil salinity relative to granular ammonium sulfate and, therefore, may be safer alternatives, particularly in younger blueberry plants.

Conclusion

Fertigation resulted in more plant growth and yield than granular applications of N fertilizers during the first 5 years of fruit production. Plant growth was also greater at higher N rates each year. However, higher N rates did not improve yield in any year and resulted in smaller berries during the first 3 years of production and less yield during the third year when granular fertilizers were applied. Thus, 67 to 93 $kg \cdot ha^{-1}$ N was adequate to maximize fruit production, whether N was applied by fertigation or as granular fertilizer. These rates are lower than the 100 to 160 $kg \cdot ha^{-1}$ N recommended by Hart et al. (2006). Typical blueberry yields in western Oregon range from 2 to 16 $t \cdot ha^{-1}$ during the first 5 years and can reach more than 25 $t \cdot ha^{-1}$ by full production (typically 7 to 8 years after planting) (Julian et al., 2011). Yields in the present study were normal for the region and ranged from 2 to 4 $t \cdot ha^{-1}$ during the first year of fruit production and increased to 14 to 20 $t \cdot ha^{-1}$ (with N fertilizer) by the fifth year.

Ammonium sulfate resulted in higher leaf N concentrations as well as lower soil pH than urea and increased cumulative yield by 10% when the fertilizers were applied by fertigation. However, ammonium sulfate also increased soil EC more than urea and resulted in lower yields during the first 2 years than any other treatment when applied as a granular fertilizer. Thus, urea may be preferable initially when using granular fertilizers.

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