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Compost Feedstock and Compost Acidification Affect Growth and Mineral Nutrition in Northern Highbush Blueberry

Ryan C. Costello[1] **and Dan M. Sullivan**[3]
Department of Crop and Soil Science, Agricultural and Life Science Building 3017, Oregon State University, Corvallis, OR 97331

David R. Bryla
U.S. Department of Agriculture, Agricultural Research Service, 3420 NW Orchard Avenue, Corvallis, OR 97330

Bernadine C. Strik and James S. Owen[2]
Department of Horticulture, Agricultural and Life Science Building 4017, Oregon State University, Corvallis, OR 97331

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***Abstract*. New markets for organic northern highbush blueberry (*Vaccinium corymbosum* L.) have stimulated interest in using composts specifically tailored to the plant's edaphic requirements. Because composts are typically neutral to alkaline in pH (pH 7 to 8), and blueberry requires acidic soil (pH 4.2 to 5.5), we investigated elemental sulfur (S^0) addition as a methodology for reducing compost pH. The objectives were to 1) characterize initial compost chemistry, including the pH buffering capacity of compost (acidity required to reduce pH to 5.0), 2) measure changes in compost chemistry accompanying acidification, and 3) evaluate plant growth and mineral nutrition of blueberry in soil amended with an untreated or acidified compost. Ten composts prepared from diverse feedstocks were obtained from municipalities and farms. Addition of finely ground S^0 reduced compost pH from 7.2 to 5.3, on average, after 70 d at 22 °C, and increased the solubility of nutrients, including K (from 22 to 36 mmol$^{(+)}$/L), Ca (from 5 to 19 mmol$^{(+)}$/L), Mg (from 5 to 20 mmol$^{(+)}$/L), and Na (from 6 to 9 mmol$^{(+)}$/L). Sulfate-S, a product of S^0 oxidation, also increased from 5 to 45 mmol$^{(-)}$/L. The composts were incorporated into soil at a high rate (30% v/v) in a greenhouse trial to evaluate their suitability for use in blueberry production. Shoot and root growth were strongly affected by compost chemical characteristics, including pH and electrical conductivity (EC). Potassium in compost was highly variable (2–32 g·kg^{-1}). Concentration of K in the leaves increased positively in response to compost K, whereas shoot dry weight and root growth declined. Leaf Mg also declined in response to compost K, suggesting that elevated K concentrations in compost may cause Mg deficiency. Composts with the highest K were also high in total N, pH, and EC. Compost acidification to pH ≤ 6 improved growth and increased leaf Mg concentration. On the basis of these results, composts derived from animal manures or young plant tissues (e.g., green leaves) appear to be unsuitable for high-rate applications to blueberry because they usually require high amounts of S^0 for acidification and are often high in EC and K, whereas those derived from woody materials, such as local yard debris, appear promising based on their C:N ratio, compost acidification requirement, and EC.**

Highbush blueberry (*Vaccinium* sp.) is adapted to acidic soils with high organic matter content (Gough 1994; Haynes and Swift, 1986). Maintaining these conditions is essential for good production in both conventional and organic blueberry plantings (Clark, 1991; Clark and Moore, 1991; Lareau, 1989; Moore, 1979; Strik et al., 2016; White, 2006). Organic matter has been traditionally supplied to blueberry by mulching and amending the soil with woody materials such as coniferous bark and sawdust (Retamales and Hancock, 2012). The use of these materials as a mulch improves soil water retention and reduces the need for herbicides. However, the cost of bark and sawdust are increasing, and many blueberry growers are switching to using "weed mat" (porous geotextile landscape fabric) (B. Strik, personal observations). Weed mat reduces weed management costs relative to sawdust mulch but, without organic amendments, results in diminished levels of soil organic matter within a matter of years (Julian et al., 2012; Strik et al., 2017). Therefore, a suitable replacement for bark and sawdust is needed to maintain soil organic matter within production systems that use weed mat.

Compost has many characteristics that are similar to soil organic matter such as a low carbon (C):nitrogen (N) ratio, high cation exchange capacity, and high stability (i.e., resistance to further decomposition), and most are rich in nutrients that gradually mineralize in the soil for years after application (He et al., 2001; Sikora and Szmidt, 2001; Sullivan et al., 2003). However, composts are ordinarily neutral or alkaline in pH and frequently contain high amounts of soluble salts. Highbush blueberry grows best at a soil pH of 4.2 to 5.5 (Retamales and Hancock, 2012) and is readily susceptible to salt damage (Machado et al., 2014). Furthermore, composts are often high in K, and excessive K has been observed to induce Mg deficiency in highbush blueberry (Eck, 1988; Forge et al., 2013; Krewer and Ruter, 2012). Ideally, a suitable compost for blueberry will contain manageable levels of soluble salts and K and will not increase soil pH above 5.5.

Costello and Sullivan (2014) successfully acidified a wide range of composts by adding elemental sulfur (S^0). The process, which is often used to reduce soil pH before planting blueberry, is typically rapid in compost (2–6 weeks) and occurs when the S^0 is oxidized to sulfuric acid by autotrophic bacteria (e.g., *Thiobacillus* sp.) and heterotrophic bacteria and fungi (Carrión et al., 2008; García de la Fuente et al., 2007; Germida and Janzen, 1993). The amount of S^0 required to acidify a compost is a function of its pH buffering capacity and is usually greater in animal manure composts than in those derived from plant materials (Wong et al., 1998).

The objective of the present study was to identify composts that could be potentially used to amend or replace bark and sawdust in highbush blueberry production systems. Ten composts, produced from locally available organic materials, were evaluated for chemical characteristics, with or without S^0 acidification. Plant response to compost was evaluated under controlled greenhouse conditions using potted plants of 'Duke' northern highbush blueberry (*V. corymbosum* L.). 'Duke' is commonly grown commercially and tends to be sensitive to N limitations and high soil pH (Strik and Yarborough, 2005; Strik et al., 2014).

Materials and Methods

Compost feedstocks and sampling. Compost samples originated from on-farm or municipal composting facilities in western Oregon and Washington. Organic materials were composted for a minimum of 90 d before sample collection. Bulk compost samples (≈100 L) for our research were collected at the end of the summer dry season, when compost curing piles were moist but not saturated. A wide range of feedstocks was represented (Table 1). Bulk composite compost samples were collected from curing piles. Each composite sample comprised 15 subsamples (5 to 10 L per subsample). At some locations, compost was subsampled by opening up the pile with a front-end loader and collecting samples from inside the pile face. In all cases, care was taken not to collect compost that had dried on the outside of the curing piles. After collection, each bulk composite compost sample (≈100 L) was stored in a plastic container

Table 1. Organic feedstocks used to prepare different composts for northern highbush blueberry.

Compost	Feedstock sources and mixture
Bark:biosolids	60% douglas fir bark, 20% fine sawdust, and 20% digested, dewatered municipal wastewater treatment biosolids
Dairy solids	Dairy solids collected from flushed dairy manure by a mechanical separator
Dairy:hops	80% dairy solids and 20% spent hop cones from a brewery
Grass:mint	80% grass seed hulls from seed cleaning and 20% peppermint hay (residue from peppermint oil steam extraction)
Horse manure	Horse manure with pelletized wood bedding
Horse:hay:hops	45% scraped horse manure, 45% spoiled grass hay, and 10% spent hop cones
Leaf	Chipped deciduous tree leaves from municipal street sweeping
Mint hay	Peppermint hay
Mixed manure	Mixture of horse manure, dairy manure, chicken manure, cereal straw, and douglas fir sawdust
Yard debris	Ground urban yard debris (grass, leaves, woody debris)

with a loose fitting lid that allowed air entry. Compost subsamples for laboratory analysis (10 L) were collected by spreading out the 100-L bulk compost sample on a tarp and then systematically subsampling it. Before chemical and physical analyses (Table 2), compost subsamples were stored indoors at room temperature (22 °C) for up to 30 d.

Compost nutrient analyses (n = 1) were performed by the Oregon State University Central Analytical Laboratory in Corvallis, OR (Table 2; Gavlak et al., 2005). Except as noted, compost samples were dry-ashed at 500 °C and analyzed for total P, K, Ca, Mg, B, Cu, Mn, and Zn using an inductively coupled plasma (ICP) spectrophotometer. Total C and N were determined by combustion analysis. Ammonium and NO_3-N were extracted with 2 M KCl and determined via automated colorimetric methods. The sum of cations (Ca, Mg, K) was calculated by dividing total cation analyses ($g\cdot kg^{-1}$) by the equivalent weights of a mole of positive charge (20 $g\cdot mol^{-1}$ for Ca, 12.1 $g\cdot mol^{-1}$ for Mg, and 39 $g\cdot mol^{-1}$ for K). Compost pH and EC were determined by the 1:10 (compost:water; w/w) method in our laboratory. Compost bulk density was determined by filling a 3-L plastic beaker with moist compost and measuring sample volume and weight after dropping the beaker six times from a height of 0.6 m above a hard surface (Thompson et al., 2001). The compost bulk density measurement was performed on a moist compost sample and then expressed on a dry weight basis. For the greenhouse experiment, the total N and mineral N applied per pot were estimated from compost N analyses ($g\cdot kg^{-1}$; Table 2) based on the bulk density of each compost ($g\cdot L^{-1}$ dry compost) and by the volume of compost added to the pots (0.7 L/pot).

Additional measurements were performed to determine the stability of compost organic matter (CO_2-C respired) and the quantity of N mineralized from compost (Table 2). Moist compost was incubated with moist Willamette silt loam [a fine-silty, mixed, superactive mesic Pachic Ultic Argixeroll; U.S. Department of Agriculture (USDA) National Resources Conservation Service, 2006] soil (200 $mL\cdot kg^{-1}$ dry soil) for determination of cumulative net respiration (21 d at 22 °C) and cumulative N mineralization (30 d at 22 °C) using a no-compost control soil as the baseline measurement. Willamette silt loam soil was also used for the greenhouse trial. Respiration was quantified using an alkaline trap method (Anderson, 1982), and cumulative N mineralized (NH_4 + NO_3) was determined via colorimetry (Gavlak et al., 2005).

Compost acidification. Compost buffering capacity (CBC), defined as the quantity of acidity needed to reduce pH by one unit (Table 3), was determined using a titration method (Costello and Sullivan, 2014). Titrations were performed with dilute H_2SO_4 at six rates (0.3 to 2 mol H^+ per kg of compost-C). Each rate of dilute H_2SO_4 addition was replicated twice. Five grams of compost was equilibrated in a 1:10 ratio of compost: liquid (w/w), and pH and EC were measured after 72 h. The CBC for each compost was calculated as the negative reciprocal of the slope of the linear regression between compost pH and acid addition rate. The quantity of S^0 required (S_{req}) to acidify the compost to a target pH of 5.0 was calculated as:

$$S_{req} = [\text{initial compost pH} - \text{target pH}(5)] \times \text{CBC} \times S_{eq}, \qquad [1]$$

where CBC equals the mol of H^+ per kg compost-C (from linear regression) and S_{eq} is the equivalent weight of S^0 (16 g S^0 per mol H^+).

To prepare acidified compost for the greenhouse experiment, S^0 was added to moist compost and then stored for 70 d at 22 °C (indoor room temperature). Composts were amended with S^0 at a single addition rate [32 g S^0 (or 2 mol H^+) per kg of compost-C], which was based on the average S_{req} (30 g S^0 per kg compost-C) of the composts. On a volumetric basis, ≈2 $g\cdot L^{-1}$ S^0 was added. The S^0 (0N–0P–0K–90S; Tiger 90 CR, Alberta, Canada) was ground into a powder with a mortar and pestle before mixing with compost. At mixing, water was added until the compost was moist by feel (an average of 550 $mL\cdot kg^{-1}$ in moist compost). Composts were then stored in 15-L buckets with lids. Each bucket lid had three 0.5-cm holes to allow air entry.

Acidified and non-acidified composts were subsampled for chemical analyses immediately after 70 d of storage (Table 3). Each compost sample collected for these analyses represented more than 5% of the compost volume used in the greenhouse experiment. Compost pH and EC were determined by the 1:10 (compost:water; w/w) method in our laboratory. Soluble nutrients were extracted from compost at a commercial laboratory (Brookside Laboratories, New Bremen, OH) using an adaptation of the saturated media extract method (Warncke, 1986). To do so, a 200-g "as-is" compost sample (not dried or ground) was moistened to saturation (when the compost began to flow when tilted and had minimal free water on the surface) and then extracted by filtration under vacuum. Soluble nutrients in the extract were determined by an ICP spectrophotometer in mg/L and converted to $mmol\cdot L^{-1}$ (+ or –), based on equivalent weight of a millimole of positive or negative charge.

Greenhouse experiment. The greenhouse experiment was conducted in a glasshouse located at the USDA Agricultural Research Service Horticultural Crops Research Laboratory in Corvallis, OR. One-year-old 'Duke' blueberry plants were obtained in 50-cell flats (5-cm^2 cells) from a commercial nursery (Fall Creek Farm & Nursery, Lowell, OR) and transplanted into 2.4-L black polyethylene pots (15.2 cm diameter × 12.4 cm deep) on 17 Feb. 2010. Plants were not removed from their nursery media [which contained peat and decomposed douglas fir (*Pseudotsuga menziesii*) bark] during transplanting to avoid damaging the root system. The pots were filled with one of 12 compost treatments, with or without S^0 added to each for acidification (a total of 24 treatments). The compost treatments included 10 soil-compost mixes, one soil-sawdust mix (industry standard), and one soil only control. Each mix contained six parts soil (air-dry), three parts compost or sawdust (air dry), and one part pumice, by volume. Pumice (10%) was incorporated for drainage and was also added to the soil only treatment. Initial pH of the soil was

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[1] Former graduate student. Current address: 2109 Rimrock Court, Olympia, WA 98512.

[2] Current address: Virginia Polytechnic Institute and State University, School of Plant and Environmental Sciences, Hampton Roads Agricultural Research and Extension Center, 1444 Diamond Springs Road, Virginia Beach, VA 23455.

[3] Corresponding author. E-mail: dan.sullivan@oregonstate.edu.

Table 2. Chemical analysis of 10 composts and uncomposted douglas fir sawdust (dry weight basis).

Compost	Total C $(g{\cdot}kg^{-1})$	C respired (% total)	Total N $(g{\cdot}kg^{-1})$	NO_3-N (% total)	NH_4-N (% total)	N_{min} pot. (%)	C:N	Total P $(g{\cdot}kg^{-1})$	Cations $(g{\cdot}kg^{-1})$ K	Ca	Mg	Total cations $[mol^{(+)}/kg]^z$	Micronutrients $(mg{\cdot}kg^{-1})$ Mn	Cu	Zn	B	Bulk density $(g{\cdot}L^{-1})^y$	Total C added $(g/pot)^x$	Total N added $(g/pot)^x$	Min. N added $(g/pot)^x$
Bark:biosolids	251	0.8	12	6.0	3	–2	21	7.3	2	12	3	0.91	255	81	160	9	290	55	2.6	0.2
Dairy solids	263	1.4	19	21.1	<1	–2	14	4.3	20	38	5	2.86	405	3	100	14	240	49	3.5	0.7
Dairy:hops	160	0.8	10	3.4	<1	–1	15	2.2	4	6	4	0.72	455	13	169	12	280	33	2.2	0.1
Grass:mint	187	1.4	22	6.4	1.5	–2	9	6.2	8	12	5	1.20	462	15	145	14	300	44	4.9	0.3
Horse manure	111	BD	10	12.6	<1	–3	12	2.2	5	6	3	0.66	769	17	75	8	500	43	3.6	0.5
Horse:hay:hops	162	0.9	12	4.4	<1	2	13	3.0	12	7	3	0.91	627	24	57	11	350	42	3.2	0.2
Leaf	163	2.0	8	5.4	<1	–2	20	2.1	3	17	3	1.11	494	24	218	82	310	38	1.9	<0.1
Mint hay	379	0.5	47	5.3	<1	0	8	5.8	32	23	7	2.56	127	29	54	30	190	54	6.7	0.4
Mixed manure	215	3.2	17	4.4	<1	–3	12	4.8	14	15	6	1.59	357	36	71	20	300	47	3.9	0.2
Yard debris	217	2.7	13	0.6	<1	1	17	2.3	5	16	4	1.23	348	33	131	18	350	56	3.3	<0.1
Uncomposted sawdust[w]	480	1.4	1	0.2	11	–17	400	<0.0	0.1	0.2	<0.0	0.02	86	5	11	11	140	46	0.1	<0.1

[z] Calculated by dividing each cation concentration by the equivalent weight of a mole of positive charge (20 $g{\cdot}mol^{-1}$ for Ca, 12.1 $g{\cdot}mol^{-1}$ for Mg, and 39 $g{\cdot}mol^{-1}$ for K) and adding the total.

[y] Expressed on a dry weight basis.

[x] Calculated by multiplying compost C and N concentration by compost bulk density (0.7 L of compost was added per pot).

[w] Commonly used as a soil amendment and mulch for northern highbush blueberry in northwestern United States and British Columbia, Canada.

BD = below detection limits; Min. = mineral; N_{min} = N mineralization; pot = potential.

5.4, and the organic matter content was 4.1%. The S^0 was added at potting to acidify sawdust and soil only treatments at a rate of 1.4 g/pot, which approximated the average amount of S^0 added to the pots with acidified compost as already described.

The pots were arranged on a bench in the glasshouse in a randomized complete block design, with five replicates per treatment. The replicates were blocked to minimize variation in lighting and air movement. Air temperature in the glasshouse averaged 20 °C during the experiment and reached a maximum of 33 °C and a minimum of 13 °C. The readings were recorded every 15 min with a data logger (model LI-1400; LI-COR Biosciences, Lincoln, NE) and measured using a temperature sensor (model 1400-101; LI-COR Biosciences) located near the top of the plant canopy. Supplemental lighting was provided by 1000-W high-pressure sodium lamps set to turn on at 0600 HR and turn off at 1800 HR. Plants were watered by hand three times per week with 200 mL of water and were fertigated every 14 d, starting at 7 d after transplanting (DAT), with 200 mL of fertilizer solution (Miracle-Gro Water Soluble Azalea, Camellia, Rhododendron Plant Food, Marysville, OH). The fertilizer contained 3% NH_4-N and 27% urea-N, and was composed primarily of $(NH_4)H_2PO_4$, $(NH_2)_2CO$, KH_2PO_4, and KCl. A total of 70 mg of N was applied to each plant during the study.

Plants were dormant when transplanted. Bud break took place starting at 7 DAT. Pour-through leachate was collected and analyzed for EC at 10 and 50 DAT. Leachate was produced by applying 150 mL of water per pot at 1 h after the plants were irrigated. Leachate temperature was 20 °C when EC was determined.

Plants were destructively harvested at 78 DAT. Each plant was partitioned into stems and leaves, oven-dried at 70 °C, and weighed. Nitrogen in harvested leaves was determined by combustion analysis, and other nutrients via ICP spectroscopy, following acid digestion (Gavlak et al., 2005). At harvest, a soil sample was collected from the pots by discarding a 5-cm depth of soil from the top and bottom of each pot, compositing the remaining soil, and collecting a 60-cm^3 subsample for pH and EC determination (1 soil : 2 water method; Gavlak et al., 2005).

At harvest, root development was assessed by measuring the distance roots spread into the pots from the original transplant plug. Rooting distance was measured laterally in four directions from the plug, and downward from the plug, and then averaged. The rooting distance rating was equal to 1 when 0 to 1 cm of new root growth was present, 2 to 6 (in 1-cm increments) when 2 to 6 cm was of new growth were present, and was equal to 7 when more than 6 cm of new growth were present.

Statistical analysis. The main effects of compost and acidification and the interaction (compost × acidification) were evaluated by analysis of variance using Proc GLM (general linear model) with Statistical Analysis

Software (SAS Institute, Cary, NC). Means were separated at $P \leq 0.05$ using Tukey's honestly significant difference test, and groups of treatments were compared by contrast analysis using the CONTRAST statement. Linear regression analysis was done using SigmaPlot v. 13.0 (SPSS, Chicago, IL). The relationship between soil pH and shoot dry weight was segmented and hence analyzed using two-segment piecewise regression (Bates and Watts, 1988). The breakpoint was defined by the pH where the fitted functions intersected and was interpreted as the critical value beyond which the plants were severely stunted by high pH composts. Spearman's rank correlations were calculated to assess all relationships between key compost traits (total N concentration, pH, EC, and total and soluble K concentrations) and plant growth.

Results and Discussion

Initial compost chemistry

Compost C and organic matter added to soil. Across composts, compost C averaged 210 g·kg^{-1} and ranged from 111 to 379 g·kg^{-1} (Table 2). Compost organic matter, which is equivalent to about twice the C analysis value (Sullivan and Miller, 2001) averaged 422 g·kg^{-1}. The addition of compost increased soil organic matter in pots by an average of 6.0% by weight [calculated from compost C multiplied by 2, and the volume and dry bulk density measurements of the soil (1.4 L/pot and 1.0 kg·L^{-1}, respectively) and composts (0.7 L/pot and 0.2–0.5 kg·L^{-1}, Table 2) respectively].

Field trials in western Oregon and Washington using composts similar to some of those used in the present study have demonstrated their ability to increase soil organic matter, without increasing pH significantly or providing excessive soluble salts and mineral N. For example, in Oregon, yard debris composts were applied as mulch (not incorporated) in two separate trials on a silt loam soil (Sullivan and Bell, 2015; Sullivan et al., 2015). In both field trials, surface application of yard debris

Table 3. Compost acidification and chemical characteristics of 10 untreated (–S^0) and sulfur-acidified (+S^0) composts.[z]

	Compost acidification[y]						Soluble nutrients [mmol$^{(+\text{ or }-)}$/L][w]														Total charge	
	pH buffering capacity (mol H^+ per kg compost-C)	S^0 required to reduce pH to 5.0 (g per kg compost-C)	pH[x]		EC[x] (dS·m^{-1})>		K		Ca		Mg		Na		SO_4-S		NO_3-N		NH_4-N		(mmol·L^{-1})[v]	
Compost			–S^0	+S^0	–S^0	+S^0	S^0	+S^0	–S^0	+S^0	–S^0	+S^0	–S^0	+S^0	–S^0	+S^0	–S^0	+S^0	–S^0	+S^0	–S^0	+S^0
Bark:biosolids	0.85	5	5.4	4.3	0.9	1.7	3	3	12	22	6	12	2	2.5	10	28	2	1	0.6	0.2	36	69
Dairy solids	1.20	58	8.0	7.0	5.1	6.9	62	57	5	13	4	9	20	16	3	36	3	4	<0.1	0.5	97	136
Dairy:hops	0.78	35	7.8	5.2	0.6	1.8	9	13	5	19	5	17	10	12	1	41	8	2	<0.1	0.1	38	104
Grass:mint	0.89	10	5.7	4.3	2.2	3.8	29	35	10	25	18	40	4	3.8	12	45	9	6	0.1	0.7	82	156
Horse manure	1.13	25	6.4	4.9	1.1	2.0	24	30	9	22	10	31	7	9	7	42	7	2	0.3	0.1	64	136
Horse:hay:hops	0.87	38	7.7	5.2	1.7	3.5	23	43	3	16	2	17	7	12	3	52	1	2	<0.1	0.3	39	142
Leaf	0.80	28	7.2	5.1	0.4	1.3	3	7	2	18	1	8	2	2.1	1	22	1	1	0.1	0.4	10	59
Mint hay	0.56	28	8.1	5.1	4.2	8.1	39	110	3	23	3	34	4	10	2	85	3	8	<0.1	0.6	54	271
Mixed manure	0.81	38	7.9	6.0	1.7	4.0	20	50	2	18	2	21	6	15	5	58	0	2	<0.1	0.4	35	164
Yard debris	0.65	28	7.7	6.1	0.8	1.6	12	17	4	20	2	12	3	3.7	1	40	1	0	<0.1	0.5	23	93
Average	0.85	30	7.2	5.3	1.9	3.5	22	36	5	19	5	20	6	9	5	45	3	3	0.1	0.4	48	133
P value for *t* test	—	—	<0.001		0.002		0.020		<0.001		<0.001		NS		<0.001		NS		0.035		<0.001	

[z]Elemental sulfur (S°) was added to each compost at a rate of 32 g (or 2 mol H^+) per kg of compost-C. The composts were then incubated for 70 d at 22 °C before determination of pH, EC, and soluble nutrients.

[y]Compost acidification requirement (S_{req}) was determined by titration of compost with dilute sulfuric acid (Costello and Sullivan, 2014; Eq. [1]).

[x]pH and EC were determined by the 1:10 (compost to water; w/w) method.

[w]Soluble nutrients were extracted from compost at a commercial laboratory (Brookside Laboratories, New Bremen, OH) using an adaptation of the saturated media extract method (Warncke, 1986).

[v]Total charge equals the sum of cations (mmol$^{(+)}$) and anions (mmol$^{(-)}$) per L of saturated extract.

NS = nonsignificant.

Table 4. Soil pH and the electrical conductivity of leachate and soil in pots of 'Duke' blueberry plants. The plants were grown in soil amended with untreated (–S^0) or sulfur-acidified (+S^0) compost or douglas fir sawdust (industry standard), or in soil only.

				Electrical conductivity (dS·m^{-1})							
				Pour-through leachate							
	Soil pH at 78 DAT			10 DAT			50 DAT			Soil at 78 DAT	
Soil amendment	–S^0	+S^0	Difference	–S^0	+S^0	Difference	–S^0	+S^0	Difference	–S^0	+S^0
Compost											
Bark:biosolids	5.4 e	4.6 e	–0.7***	1.1 cd	2.4 d	1.4***	0.2 efg	0.8 cd	0.6***	0.2 bcd	
Dairy solids	7.0 a	6.7 a	–0.4***	4.1 a	4.8 a	0.7***	1.2 a	1.4 a	0.2**	0.4 a	
Dairy:hops	5.8 cd	5.0 bcd	–0.7***	0.7 defg	1.9 de	1.3***	0.3 de	0.7 de	0.3***	0.2 abcd	
Grass:mint	5.5 de	5.0 cd	–0.5***	2.2 b	3.9 b	1.7***	0.7 b	1.0 bc	0.4***	0.3 abcd	
Horse manure	5.5 de	4.9 cde	–0.6***	1.6 bc	3.3 c	1.7***	0.5 cd	1.0 bc	0.6***	0.3 abc	
Horse:hay:hops	5.7 cd	5.1 bcd	–0.7***	1.7 b	3.5 bc	1.8***	0.6 bc	1.1 b	0.5***	0.4 ab	
Leaf	5.7 cd	5.2 bc	–0.6***	0.4 efg	1.7 e	1.3***	0.3 def	0.6 e	0.3***	0.2 bcd	
Mint hay	5.9 c	5.2 bc	–0.8***	2.1 b	5.3 a	3.2***	0.7 b	1.5 a	0.8***	0.5 a	
Mixed manure	6.4 b	5.4 b	–1.1***	1.0 de	3.5 bc	2.5***	0.3 def	1.0 bc	0.7***	0.3 abcd	
Yard debris	6.0 c	5.1 bc	–0.9***	0.7 def	2.4 d	1.7***	0.3 ef	1.0 bc	0.8***	0.3 abcd	
Sawdust	5.5 de	4.8 de	–0.7***	0.1 g	0.2 f	0.1^{NS}	0.1 g	0.3 f	0.3***	0.1 d	
Soil only	5.4 e	4.6 e	–0.8***	0.2 fg	0.5 f	0.3^{NS}	0.2 fg	0.8 d	0.6***	0.1 cd	
Average	5.8	5.1		1.3	2.8		0.4	0.9		0.2	0.4
Significance											
Soil amendment	<0.001			<0.001			<0.001			<0.001	
S° acidification	<0.001			<0.001			<0.001			<0.001	
Interaction	0.001			<0.001			<0.001			NS	
Contrasts											
All composts vs. soil only	<0.001			<0.001			<0.001			<0.001	
Sawdust vs. soil only	NS			NS			<0.001			NS	

[z]Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ (n = 5).

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

DAT = days after transplanting.

compost increased soil organic matter from 31 to 47 g·kg^{-1} (0–20 cm depth) within 2–4 years. The net increase in soil organic matter in these earlier trials accounted for 18% to 30% of compost organic matter applied. Likewise, in Washington, composted yard/food waste significantly increased soil C relative to no compost, following a high rate of application to a fine sandy loam soil (Sullivan et al., 2003). The net increase of soil C in this case was equal to 35% of applied compost-C at 3 years after application, 20% at 6 years, and 18% at 7 years.

Compost N. Total N added by compost ranged from 1.9 to 6.7 g/pot and averaged 3.6 g/pot, whereas total N added by sawdust was <0.1 g/pot. Mineral N ranged from 4% to 21% of the total N present in the composts (Table 2).

Nitrogen mineralization potential was negligible and near zero in each compost (Table 2). Plant-available NO_3-N mineralized from compost during a 21-d incubation period in soil ranged from –0.1 to 0.1 g/pot and averaged –0.04 g/pot (data not shown). In contrast, sawdust was deficient in N, as indicated by the high C:N ratio (480; Table 2) and a negative N mineralization potential (–17%).

Compost C:N ratio. Compost C:N was a rough indicator of the mineral N supplied by compost. Composts with C:N ratios <15 supplied an average of 0.4 g of mineral N per pot, whereas those with C:N ratios ≥15 supplied ≤0.2 g of mineral N (Table 2). To increase soil organic matter without supplying excessive soluble salts, Sullivan et al. (2014) recommended choosing a compost with a C:N ratio of 15 to 25, which usually corresponds to 10 to 20 g·kg^{-1} total N in compost dry matter. Such composts typically mineralize –5% to 5% of compost total N in the first summer following application, with annual mineralization equivalent to 5% of compost total N in the second through fourth year after application (Bary et al., 2016).

Compost stability. Organic matter was stable and resistant to further decomposition in the composts, by virtue of the fact that C respiration, C:N ratio, and ratio of NH_4-N to NO_3-N were all low in each compost (Table 2). Stability, as indicated by the amount of CO_2 respired during a 21-d incubation in soil, was ≤3% in each compost. Compost C:N ratios averaged 14 and were similar to those reported for stable soil C (C:N of 10–12; Stevenson 1994). The ratio of NH_4-N to NO_3-N in compost is an indirect indicator of compost stability, with ratios <1 indicating stability (Sullivan and Miller, 2001). Our composts had NH_4-N to NO_3-N ratios of <0.5.

Compost K and Mg. Compost total K varied among composts, ranging from 2 to 32 g·kg^{-1}, whereas the range of compost Mg concentrations was more limited (3–7 g·kg^{-1}). As a result, differences in compost K:Mg ratio were largely due to variability in K concentration. Compost K:Mg ratios (w/w) ranged from 0.7 to 4.6. Composts with K:Mg ratios greater than 2 included mixed manure (2.3), horse:hay:hops and dairy solids (4.0), and mint hay (4.6), whereas those with the lowest ratios were bark:biosolids (0.7), dairy:hops and leaf (1.0), and yard debris (1.3). Compost total K concentration was also positively correlated to total N concentration in the composts ($r^2 = 0.77$; $P < 0.001$; n = 10).

Compost micronutrients. The concentrations of micronutrients in the compost averaged 430 mg·kg^{-1} Mn, 28 mg·kg^{-1} Cu, 118 mg·kg^{-1} Zn, and 22 mg·kg^{-1} B (Table 2). Leaf compost was high in B (82 ppm) and Zn (218 ppm) relative to the average value for all composts. The bark:biosolids had high Cu (81 ppm), and the horse manure and horse:hay:hops composts had high Mn (769 and 627 ppm, respectively) relative to the average value for all composts. With the exception of Cu, micronutrient concentrations in bark:biosolids compost, which is not Organic Materials Review

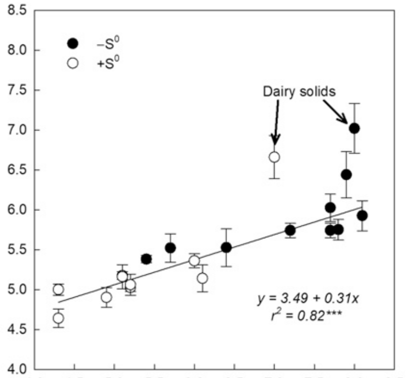

Fig. 1. Relationship between initial compost pH (1:10 method) and soil pH (1:2 method) determined at 78 d after transplanting (DAT). Composts were untreated ($-S^0$) or acidified ($+S^0$) by adding 32 g of elemental S per kg compost-C. Data points for dairy solids compost were outside of the confidence interval for the regression equation and therefore were considered outliers and excluded from the regression dataset. Once adjusted, the regression was significant at $P < 0.001$ (***). Error bars indicate standard deviation of the mean (n = 5).

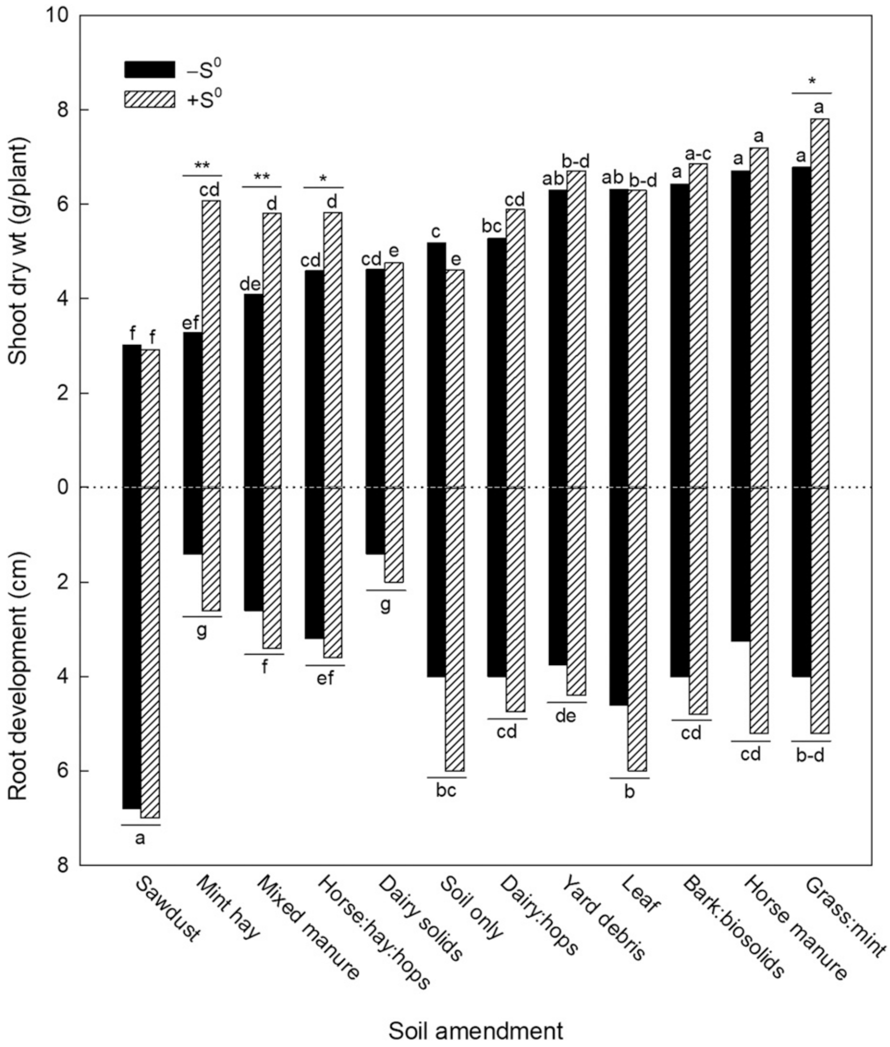

Fig. 2. Shoot dry weight and root development of 'Duke' blueberry plants grown in soil amended with untreated ($-S^0$) or sulfur-acidified ($+S^0$) compost or douglas fir sawdust (industry standard), or in soil only. Bars are arranged according to rank of shoot dry weight in treatments without S^0 (n = 5). Asterisks indicate shoot dry weight or root growth were affected by S^0 acidification at $P \leq 0.05$ (*) or 0.01 (**).

Institute–approved for organic production, were similar to that found in composts derived exclusively from agricultural feedstocks.

Changes in compost chemistry accompanying acidification with elemental sulfur

Compost acidification. Acidification with S^0 reduced compost pH by an average of 1.9 units and increased compost EC by an average of 1.6 $dS \cdot m^{-1}$ (Table 3). Once acidified, pH differed by as much as 2.7 units among the composts, which was expected given the differences in pH and pH buffering capacity before acidification. The total amount of S^0 estimated to reduce compost pH to 5.0 averaged 30 $g \cdot kg^{-1}$ (Table 3). On a whole compost basis, this is equivalent to 6 kg S^0 per tonne of compost dry matter or ≈1.8 kg S^0 per m^3 compost. This estimate assumes that bulk density of the compost (dry weight basis) is 300 $kg \cdot m^{-3}$, and all of the S^0 added to the compost is oxidized to H^+. Costello and Sullivan (2014) reported that finely ground S^0 was more than 85% effective at reducing pH (relative to H^+ from H_2SO_4) when it was incubated with moist composts for 28 d. In an acid-base reaction, it takes 100 g $CaCO_3$ to neutralize the acidity from 32 g S^0. Therefore, compost-supplied alkalinity (greater than pH 5) in the present study was equivalent to 5.6 kg $CaCO_3$ per m^3 compost.

The impact of compost pH buffering capacity on compost acidification is well illustrated by the comparison between dairy solids and mint hay compost (Table 3). Both of these composts had a pre-acidification pH value of 8.1. However, after acidification, pH dropped to 5.1 in mint hay compost and only 7.0 in dairy solids compost. Buffering capacity of dairy solids compost was about twice that of the mint hay compost. Across all composts, the calculated S^0 requirement (S_{req}) was linearly related to the measured compost pH after reaction with S^0: [acidified compost pH (with uniform S^0 rate) = $0.0049 * S_{req} + 3.88$ ($r^2 = 0.74$; $P < 0.001$)].

Compost saturation extract. Sulfur addition increased soluble cations (K^+, Ca^{2+}, and Mg^{2+}) and SO_4^{2-} present in saturation extracts (Table 3). Across composts, acidification increased cation concentration in saturation extracts from 22 to 36 $mmol^{(+)}/L$ of K, 5 to 19 $mmol^{(+)}/L$ of Ca, 5 to 20 $mmol^{(+)}/L$ of Mg, and 6 to 9 $mmol^{(+)}/L$ of Na, and increased total cation charge by an average of 44 $mmol^{(+)}/L$. Acidification also increased total anion charge by 40 $mmol^{(-)}/L$ and extractable SO_4-S by 18 to 83 $mmol^{(-)}/L$. This latter increase in SO_4-S was expected because SO_4^{2-} is the product of S^0 oxidation. Soluble N in saturation extracts was low relative to SO_4-S (< 10 $mmol^{(+ \text{ or } -)}/L$ of NH_4-N and NO_3-N).

Effects of untreated and acidified composts on soil pH and EC

Soil pH. Compost increased soil pH, on average, while S^0 acidification of the composts reduced it (Table 4). Differences in soil pH in

Table 5. Leaf nutrient concentrations in 'Duke' blueberry plants grown in soil amended with untreated ($-S^0$) or sulfur-acidified ($+S^0$) compost or douglas fir sawdust (industry standard), or in soil only.[z]

	Leaf macronutrients ($g \cdot kg^{-1}$)													Leaf micronutrients ($mg \cdot kg^{-1}$)							
	N			P				Mg		S			B				Mn			
Soil amendment	$-S^0$	$+S^0$	Diff.	$-S^0$	$+S^0$	K	Ca	$-S^0$	$+S^0$	$-S^0$	$+S^0$	Diff.	$-S^0$	$+S^0$	Diff.	Cu	$-S^0$	$+S^0$	Diff.	Zn
Compost																				
Bark:biosolids	11.6 e[y]	13.4 cd	1.8^{NS}	1.3 abc		5.7 f	3.9 a	2.0 a		1.4 a	2.5 a	1.1***	40 cde	44 bc	4^{NS}	6 a	50 a	128 cd	77***	17 a
Dairy solids	20.1 b	15.7 bc	–4.4***	1.2 abc		13.8 b	2.6 c	1.1 d		1.2 a	1.9 c	0.6**	18 e	27 c	10**	7 a	67 a	83 cde	16^{NS}	18 a
Dairy:hops	15.1 cde	15.8 bc	0.7^{NS}	1.2 abc		6.1 ef	3.2 abc	1.8 abc		1.3 a	2.0 bc	0.7**	49 bcd	53 bc	4^{NS}	8 a	58 a	99 cde	41*	21 a
Grass:mint	19.7 b	17.5 abc	–2.2^{NS}	1.4 a		10.4 cd	3.2 abc	1.6 bc		1.3 a	1.8 c	0.5*	57 bcd	40 bc	–17**	6 a	72 a	188 ab	116***	18 a
Horse manure	19.1 bc	17.7 ab	–1.4^{NS}	1.0 bc		11.7 bc	2.8 bc	1.4 cd		1.2 a	2.1 abc	0.8***	40 cde	42 bc	2^{NS}	7 a	63 a	201 a	138***	16 a
Horse:hay:hops	16.8 bcd	17.5 abc	0.6^{NS}	1.2 abc		10.7 bcd	2.6 c	1.4 cd		1.3 a	2.1 abc	0.9***	32 de	50 bc	18**	8 a	84 a	138 bc	54**	20 a
Leaf	13.1 de	11.2 de	–2.0^{NS}	1.0 bc		6.0 ef	3.6 a	1.9 ab		1.4 a	1.9 bc	0.5*	385 a	353 a	–32**	6 a	69 a	73 de	4^{NS}	18 a
Mint hay	27.4 a	20.2 a	–7.2***	1.3 ab		19.4 a	2.3 c	1.1 d		1.5 a	2.2 abc	0.6*	49 bcd	52 bc	3^{NS}	7 a	99 a	133 bcd	34^{NS}	15 a
Mixed manure	13.1 de	14.1 bcd	1.0^{NS}	1.2 abc		9.1 cde	3.2 abc	1.9 ab		1.3 a	2.7 a	1.4***	67 b	64 bc	–3^{NS}	8 a	65 a	94 cde	29^{NS}	18 a
Yard debris	13.5 de	13.3 cd	–0.2^{NS}	1.1 abc		8.0 def	3.4 ab	1.8 abc		1.3 a	2.0 bc	0.7***	65 bc	71 b	6^{NS}	7 a	54 a	88 cde	34^{NS}	17 a
Sawdust	6.6 f	7.3 e	0.7^{NS}	0.9 c		5.0 f	3.7 a	1.8 abc		0.9 a	1.5 c	0.5*	38 de	48 bc	10**	7 a	47 a	50 e	3^{NS}	14 a
Soil only	11.1 e	14.0 bcd	2.9*	1.1 abc		5.1 f	3.9 a	2.1 a		1.1 a	2.6 ab	1.5***	36 de	45 bc	9**	7 a	46 a	106 cde	60**	16 a
Average	15.6	14.8		1.1	1.2	9.2	3.2	1.5	1.8	1.3	2.1		73	74		7	65	115		17
Significance																				
Soil amendment		<0.001			<0.001	<0.001	<0.001		<0.001		<0.001			<0.001		0.043		<0.001		NS
S° acidification		0.035			<0.001	NS	NS		<0.001		<0.001			NS		NS		<0.001		NS
Interaction		<0.001			NS	NS	NS		NS		0.005			<0.001		NS		<0.001		NS
Contrasts																				
All composts vs. soil only		<0.001			NS	<0.001	<0.001		<0.001		NS			<0.001		NS		NS		NS
Sawdust vs. soil only		<0.001			NS	NS	NS		NS		<0.001			NS		NS		NS		NS

[z]Samples were collected at 78 d after transplanting for analysis of N (all leaves) and at 50 DAT for analysis of other nutrients (new, recently expanded leaves).

[y]Means followed by the same letter within a column are not significantly different at $P \le 0.05$ (n = 5).

NS, *, **, ***Nonsignificant or significant at $P \le 0.05$, 0.01, or 0.001, respectively.

response to compost or S^0 (Table 4) were associated with differences in compost pH and pH buffering capacity (Table 3). This was expected given that S_{req} was calculated from pH and from the pH buffering capacity measured in the composts (Table 3; Eq. [1]). As a result, soil pH at the termination of the growth trial at 78 DAT was linearly related to S_{req} [with S^0 addition, soil pH (78 DAT) = $4.32 + 0.24*S_{req}$ ($r^2 = 0.64$, $P < 0.05$, n = 10); and without S^0 addition, soil pH (78 DAT) = $5.07 + 0.21*S_{req}$ ($r^2 = 0.85$, $P < 0.01$, n = 10)]. With the exception of the dairy solids treatment, soil pH was also highly correlated to initial pH of the untreated and acidified composts (Fig. 1). Data points for dairy solids compost were excluded as outliers. Once these points were removed, soil pH increased by 0.3 units for every unit increase in compost pH.

Leachate and soil EC. Compost and S^0 acidification increased EC of the leachate collected during the greenhouse trial (Table 4). Leachate EC from the acidified treatments averaged twice that measured from those that were untreated. However, leachate EC did not respond uniformly to S^0 across the composts. For example, increases in leachate EC as a result of S^0 ranged from 0.7 to 3.2 $dS \cdot m^{-1}$ among composts at 10 DAT. At that point in time, leachate EC was positively correlated to the initial EC of the compost ($r^2 = 0.89$; $P < 0.001$).

Blueberry is sensitive to excessive soluble salts (EC > 2.0 $dS \cdot m^{-1}$) in soil solution (Machado and Bryla, 2014). However, plants in the present study grew better in acidified compost, even though EC of the compost was roughly doubled by acidification (Table 4). Two factors may have reduced damage from excessive soluble salts in this trial. First, when EC was high during the first days of the trial, evaporative demand was low because it was early spring and the plants at that point had limited leaf area. Second, the plants were well watered beyond container capacity (> 20% drainage), which likely leached a large amount of salts from the pots. Whether S^0 was added to the compost, EC declined over time to ≤ 1.5 $dS \cdot m^{-1}$ in the leachate at 50 DAT and to ≤ 0.5 $dS \cdot m^{-1}$ in the soil at 78 DAT (Table 4). Because issues with excessive mineral N, K, and other soluble salts will be greater when high rates of compost are applied immediately before planting, growers should consider applying compost a few months ahead of planting and, if necessary, leach the salts using sprinklers. In maritime climates such as western Oregon and Washington, precipitation typically exceeds 50 cm during the dormant season (October through March). Therefore, most of the soluble salt from a fall application of compost would be leached well below the root zone ($\approx$0.3 m deep; Bryla and Strik, 2007) by the following spring. Suitable composts for blueberry (i.e., those low in soluble salts, including NO_3-N) are unlikely to degrade groundwater quality via winter leaching (Sullivan et al., 2014).

Growth and nutrient status of blueberry plants grown in soil amended with acidified and nonacidified compost

Shoot dry weight and root development. Total shoot dry weight and root development were significantly affected by compost ($P < 0.001$) and S^0 acidification ($P < 0.001$). There was also an interaction between compost and S^0 acidification on shoot dry weight ($P < 0.001$), indicating that plant response to S^0 differed among the compost treatments.

Without S^0 acidification, the best composts, in terms of their effect on total shoot dry weight, were horse manure and most of the composts produced primarily from plant-based feedstocks, including grass:mint, bark:biosolids, leaf, and yard debris (6.3–6.8 g/plant) (Fig. 2). Nonacidified mint hay compost and those made from dairy manure (i.e., dairy solids, dairy:hops, and mixed manure), on the other hand, resulted in lower total shoot dry weights among the treatments (3.3–5.3 g/plant) and, with the exception of dairy: hops, the least amount of root development (1.4–3.4 cm). These latter composts had high pH initially and, in some cases, a high amount of soluble salts (Table 3).

Acidification with S^0 increased total shoot dry weight in mint (i.e., mint hay and grass: mint) or mixed horse manure (i.e., horse: hay:hops and mixed manure) composts but had no effect in soil only, sawdust, or other composts (Fig. 2). The use of S^0 also improved root development by an average of 27% (Fig. 2). However, none of the treatments had more root development than plants grown in soil amended with sawdust. Whether S^0 was added, roots of the plants in the sawdust treatment occupied nearly the entire volume of the pots by 78 DAT.

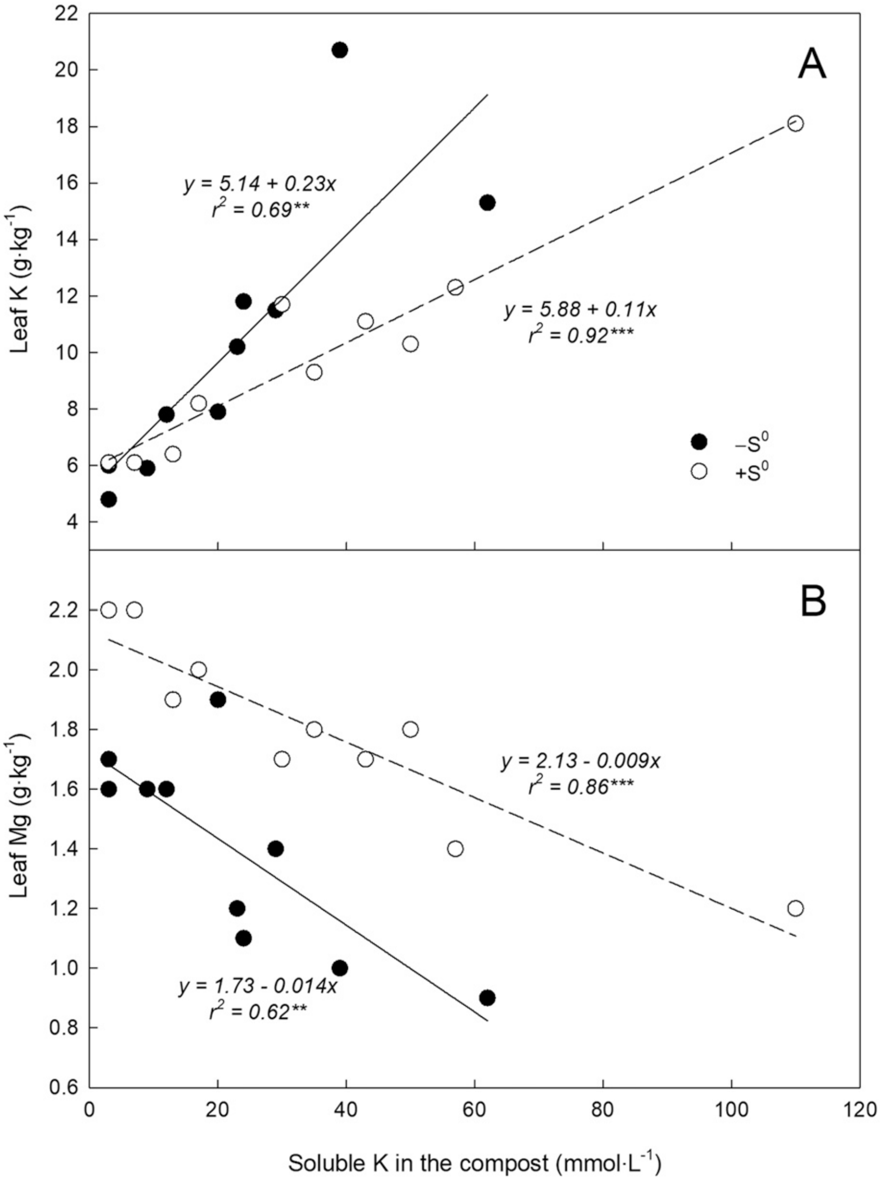

Fig. 3. Relationships between the concentration of K (**A**) and Mg (**B**) in the leaves of 'Duke' blueberry and soluble K in the compost. Composts were untreated ($-S^0$) or acidified ($+S^0$) by adding 32 g of elemental S per kg compost-C. Each regression was significant at $P < 0.01$ (**) or 0.001 (***).

Leaf nutrient analysis. The concentration of nutrients in the leaves responded to compost and S^0 acidification (Table 5). In many cases, compost increased the concentration of N, K, and/or B in the leaves, relative to soil only, and reduced the concentration of Ca and Mg. Acidification, on the other hand, reduced leaf N in two compost treatments (dairy solids and mint hay) and increased the concentration of P, Mg, and S in the leaves by an average of 0.1, 0.3, and 0.8 $g{\cdot}kg^{-1}$, respectively. Furthermore, it had mixed effects on B in the leaves and about doubled or tripled the concentration of Mn in the leaves when plants were grown with bark:biosolids, dairy:hops, grass:mint, horse manure, or horse:hay:hops compost, or in soil only.

Leaf N was linearly correlated to total N in the composts [leaf N ($g{\cdot}kg^{-1}$) = 11.05 + 0.347*compost total N ($g{\cdot}kg^{-1}$) (r^2 = 0.69; P < 0.01)] and was lowest when soil was amended with sawdust. Sawdust immobilizes soil N (Allison, 1965) and was the only treatment with obvious symptoms of N deficiency (chlorotic leaves with small, reddish, necrotic spots; Polashock et al., 2017). To avoid induced N deficiency, Bollen and Lu (1957) recommended applying 2.5 to 5.0 kg of N for each tonne of douglas fir sawdust incorporated into soil. Additional N fertilization is needed when sawdust is used as a mulch (Hart et al., 2006). Results of the present study suggest that compost incorporation into soil will reduce or eliminate the need for additional N fertilization when soil is mulched with sawdust.

Leaf K also increased linearly with increasing amounts of soluble K in the compost (Fig. 3A). In this case, the slope of the relationship was reduced by compost acidification. Increased leaf dry matter in plants grown with acidified compost likely diluted leaf K. Leaf Mg, in contrast, decreased as compost K and leaf K increased (Fig. 3B). Leaf Ca concentration also decreased with compost soluble K: Leaf Ca = –0.013 * Compost soluble K + 3.0 (r^2 = 0.36, P < 0.001). Magnesium deficiency may have played a role in declining root growth and shoot dry matter with increasing K inputs from compost. Competition between K^+ and Mg^{2+} has been reported to result in Mg deficiency in many plants (Dibb and Thompson 1985), including tree fruit and small fruit crops (Cummings 1985). However, this issue was not evident in a long-term field trial on organic northern highbush blueberry in Oregon (Sullivan et al., 2015). In this case, applying a 6-cm-deep layer of yard debris compost as mulch (4 cm at planting plus 2 cm at 4 years after planting) increased exchangeable soil K (0–20 cm depth) from 250 to 400 $g{\cdot}kg^{-1}$ K but had no effect on concentration of K (5.2 $g{\cdot}kg^{-1}$), Ca (4.5 $g{\cdot}kg^{-1}$), or Mg (1.5 $g{\cdot}kg^{-1}$) in recently expanded leaves of the plants. Forge et al. (2013), in contrast, conducted a similar study on northern highbush blueberry in British Columbia, Canada, and reported that the concentration of K in the leaves increased from 5 $g{\cdot}kg^{-1}$ with sawdust mulch to 8 $g{\cdot}kg^{-1}$ with a 7- to 10-cm-deep layer of yard debris compost mulch, while the concentration of Mg in the leaves declined from 1.4 $g{\cdot}kg^{-1}$ to 1.1 $g{\cdot}kg^{-1}$, respectively. Hart et al. (2006) recommend a concentration of 4 to 7 $g{\cdot}kg^{-1}$ K for the region, and 1.3 to 2.5 $g{\cdot}kg^{-1}$ Mg. Therefore, this latter study by Forge et al. (2013) raises concerns that high K in compost may result in Mg deficiency in northern highbush blueberry. In the present trial, acidification of compost or soil alone increased leaf Mg by an average of 0.3 $g{\cdot}kg^{-1}$ (Table 5). Therefore, compost acidification may be an effective means of reducing K-induced Mg deficiency when plants are grown with compost.

With respect to micronutrients, plants grown with leaf compost had high concentrations of B in the leaves (350–380 $mg{\cdot}kg^{-1}$). The current recommendation for northern highbush blueberry is only 31 to 80 $mg{\cdot}kg^{-1}$ B, and leaf B >150 $mg{\cdot}kg^{-1}$ is considered an indicator of possible toxicity (Hart et al., 2006). The deciduous tree leaves that were used as feedstock for the leaf compost were obtained from municipal street sweeping. Heckman and Kluchinski (1996) found that leaves collected from streets had higher levels of B than those collected directly from trees. Thus, a likely source of B in our leaf compost is grit and dust recovered from the surface of the street along with the leaves.

Solubility of metal micronutrients such as Cu, Mn, and Zn often increase with acidification in soil or organic media as well as with addition of organic matter (Handreck and Black, 2010; Havlin et al., 2014). However, neither leaf Cu nor Zn were strongly affected by compost or S^0 acidification in the present study. Leaf Mn, on the other hand, increased with S^0 in several compost treatments, as mentioned, and in two instances was higher with acidified compost (grass:mint and horse manure) than with acidified soil only. In each case, leaf Mn was well below those associated with Mn toxicity in blueberry (>400 $mg{\cdot}kg^{-1}$; Bañados et al., 2008). Leaf Mn is often high in blueberry due to the acidic growing conditions (Retamales and Hancock, 2012).

Relationships between key chemical compost traits and plant growth and mineral nutrition of northern highbush blueberry

One of the primary goals of this research was to identify composts that can be used to supply N to blueberry without causing damage from excessive nutrients or high pH. However, as compost N increased in the present study, so did compost EC, compost total K, and compost soluble K in both untreated and acidified composts (Table 6). We did not find any composts that supplied high concentrations of total N without accompanying

Table 6. Spearman rank order correlations of key chemical compost traits, total shoot dry weight, and root growth determined for 10 untreated or sulfur-acidified composts used as soil amendments in pots of 'Duke' blueberry.[z]

Trait	Compost total N	Compost pH	Compost EC	Compost total K	Compost soluble K	Total shoot dry wt
Untreated composts						
Compost pH	0.425					
Compost EC	0.841***	0.424				
Compost total K	0.774**	0.747*	0.866***			
Compost soluble K	0.719*	0.463	0.909***	0.860***		
Total shoot dry wt	–0.347	–0.905***	–0.364	–0.670*	–0.266	
Root growth	–0.619*	–0.741*	–0.784**	–0.895***	–0.753**	0.709*
Acidified composts						
Compost pH	0.126					
Compost EC	0.787**	0.171				
Compost total K	0.774**	0.429	0.912***			
Compost soluble K	0.750*	0.391	0.927***	0.997***		
Total shoot dry wt	–0.113	–0.782**	–0.407	–0.512	–0.498	
Root growth	–0.627*	–0.684*	–0.711*	–0.790**	–0.766**	0.762**
Pooled						
Compost pH	0.158					
Compost EC	0.736***	–0.124				
Compost total K	0.774***	0.372	0.802***			
Compost soluble K	0.675***	–0.072	0.891***	0.901***		
Total shoot dry wt	–0.217	–0.741***	–0.259	–0.575**	–0.312	
Root growth	–0.567**	–0.696***	–0.457*	–0.792***	–0.599**	0.756***

EC = electrical conductivity.

[z] Untreated and acidified composts were analyzed separately (n = 10) and pooled (n = 20).

*, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

negative compost analysis characteristics. Total N in compost was not well correlated with compost pH.

Across composts (acidified and nonacidified), total shoot dry weight was negatively correlated to compost pH and total K but was not correlated to total N, EC, or soluble K (Table 6). Shoot dry weight increased linearly as compost pH declined from 7.6 to 4.3 and dropped sharply when compost pH exceeded 7.6 (Fig. 4A). At pH 8, total dry weight of the plants was ≈50% of that produced by a compost with a pH of 5. Each acidified compost had a pH ≤7 and, therefore, with the exception dairy solids, did not result in a severe yield reduction. The breakpoint shown for severe compost pH effects on shoot dry weight corresponded with a soil pH of 5.8 (Fig. 1). This finding is consistent with the many reports that northern highbush blueberry requires low pH conditions for optimum growth (Retamales and Hancock, 2012).

Root growth was negatively correlated with compost total N, pH, EC, total K, and soluble K (Table 6). Root growth declined linearly with increasing compost EC, and the slope of the regression was similar between acidified and nonacidified composts (Fig. 4B). However, root growth was superior overall in the acidified composts, even though acidification practically doubled compost EC, on average, and nearly tripled EC of the leachate collected from the pots at 10 DAT (Tables 3 and 4). The observed decline in root growth with compost EC was confounded by covariance of other nutrients present in the compost. For example, compost EC was highly correlated with total K and soluble K in the compost (Table 6). Furthermore, the effect of compost acidification on pH was more persistent than its effect on EC. High EC levels from compost were present in soil during the first 10 d of the growth trial but declined thereafter as salts were presumably leached from the pots by irrigation and drainage (Table 4). Because K is less attracted to cation-exchange sites in soil and compost than Ca or Mg, it is likely that K was the cation present in the highest concentration in leachate at 10 and 50 DAT in this trial.

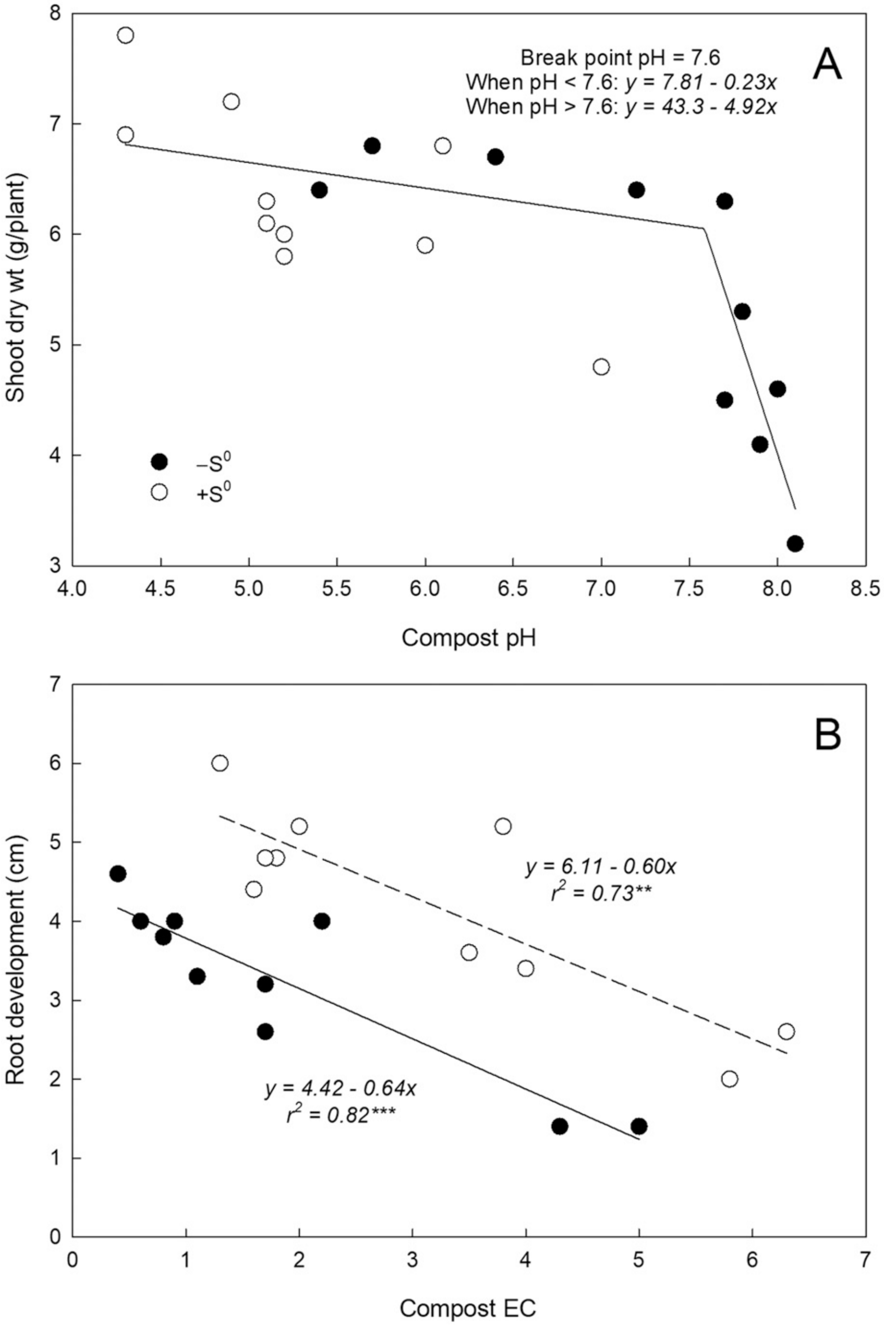

Fig. 4. Relationships between shoot dry weight and compost pH (**A**) and between root development and compost electrical conductivity (EC) (**B**) in 'Duke' blueberry. The plants were grown in soil amended with untreated ($-S^0$) or sulfur-acidified ($+S^0$) compost. Data in panel **A** were fit using piecewise, two segment linear regression ($r^2 = 0.76$, $P < 0.001$); a breakpoint was found at pH 7.6. Regressions in panel **B** were significant at $P < 0.01$ (**) or 0.001 (***).

Total K analysis of compost is likely a better indicator of the salt hazard of compost than extractable K or compost EC. Few laboratories provide saturated extract K analysis, and because a qualitative judgment has to be made about when the compost is "saturated" and ready for vacuum extraction, the saturation procedure is less reproducible than analysis of total K. Total K analysis is also a more universally reproducible method than is the measurement of compost EC. Compost EC will vary considerably depending on the amount of water added to the sample before analysis. Costello and Sullivan (2014) reported that compost EC determined in saturation extract was two to four times greater than EC measured in 1:10 compost to water ratio. Many commercial laboratories testing compost routinely use a 1:5 compost-to-water ratio (Thompson et al., 2001), but this method is not suitable for composts that have high water holding capacity or when pH is determined using larger diameter probes.

Conclusions

This research was designed as a screening study to evaluate the suitability of diverse composts for northern highbush blueberry and to determine chemical characteristics of composts that are associated with positive plant growth response. We found that aboveground growth of the plants was best when compost pH was <7.0, and both shoot and root growth were improved consistently when the composts were acidified with S^0. Among the most favorable composts for blueberry was grass:mint, horse manure, bark:biosolids, leaf, and yard debris compost. Availability of most of these composts may be limited in many regions. However, yard debris composts are widely available from commercial vendors, and their chemical characteristics are suitable for building soil organic matter without supplying excessive mineral N and excessive soluble salts. Sullivan et al. (2014) reported that, on average, yard debris compost obtained from commercial suppliers in Oregon had a pH of 7, an EC of 4 $dS \cdot m^{-1}$ (saturation extract), a C:N ratio of 21, and contained 560 $g \cdot kg^{-1}$ organic matter, 13 $g \cdot kg^{-1}$ total N, and 8, 17, 4, and 1 $g \cdot kg^{-1}$ of total K, Ca, Mg, and Na, respectively. The main concern with yard debris compost is that it supplies more K than needed by blueberry, which may become a problem if it is reapplied frequently to the same field. We recognize that this was a short-term study conducted in pots with small blueberry plants and therefore is only capable of providing a preliminary assessment of the composts. Further evaluation will be needed on a field basis to confirm our findings.

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