

Substrate pH Affects Nutrient Availability in Fertilized Douglas Fir Bark Substrates

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Abstract. An experiment was conducted to determine how pH and nutrient availability in douglas fir bark (DFB) substrates respond to lime and sulfur (S) rates. The treatment design was a two-by-nine factorial arrangement with two substrate types and nine pH-altering amendments. The two substrates were 100% DFB or 75 DFB:15 sphagnum peatmoss:10 pumice (by volume). Substrate pH-altering amendments included elemental S amended at either 0.6 or 2.4 kg·m⁻³; calcium carbonate amended at 0.6, 1.5, and 5.9 kg·m⁻³; calcium hydroxide amended at 4.4, 8.9, or 23.7 kg·m⁻³; and a nonamended control. All substrates were amended by incorporating 0.9 kg·m⁻³ Micromax micronutrients before potting and topdressing 8 g/pot of 14N–4.2P–11.6K Osmocote controlled-release fertilizer after potting. A group of controls was also maintained for each substrate that received no fertilizer amendment (no S, lime, Micromax, or Osmocote). Four containers of each treatment were randomly selected and harvested 4 and 8 weeks after potting. Amendment with S decreased pH with increasing rate, whereas both lime types increased pH with increasing rate. The two substrates in general responded similarly to S and lime amendments, although there were some significant effects and interactions caused by substrate type. Ammonium-N and NO₃-N both decreased exponentially with increasing substrate pH, whereas water-extractable phosphorus decreased linearly with increasing pH. Water-extractable potassium, calcium, magnesium, and sodium responded quadratically to increasing pH by initially decreasing and then increasing. The micronutrients boron and iron decreased with increasing pH, whereas DTPA extractions of manganese, zinc, and copper initially increased and then decreased over the range of observed pH.

Ornamental container crops in the Pacific Northwest are grown primarily in douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB). Similar to pine (*Pinus taeda* L.) bark in the southeast United States, DFB comprises the highest portion of most nursery substrates (60% to 80% of the substrate mix; personal observation). Buamscha et al. (2007) documented that DFB alone provides sufficient micronutrients for annual vinca

[*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] grown at low pH (4.5 to 5.5). Macronutrient and micronutrient availability may not be sufficient to support plant growth when substrate pH is higher. Altland (2006b) reported reduced growth of japanese maple (*Acer palmatum* var. *atropurpureum* Thunb.), hydrangea [*Hydrangea macrophylla* Thunb. (Ex J.A. Murr.) Ser. 'Endless Summer'], and leucothoe [*Leucothoe axillaris* (Lam.) D. Don] caused by a pH-induced reduction of available nitrogen, phosphorus (P), and micronutrients in DFB. Similar observations of reduced plant growth with high substrate pH have been reported for crops grown in pine bark (Wright and Hinsley, 1991).

Unfertilized DFB response to substrate pH has recently been documented (Altland and Buamscha, 2008). Water-extractable P and DTPA-extractable boron, iron, copper, and aluminum were responsive to pH, whereas other nutrients were either nonresponsive to substrate pH or the observed response was deemed more likely caused by

calcium competition on cation exchange sites. Lucas and Davis (1961) determined the relationship between pH and nutrient availability in organic soils. They concluded that the ideal pH range (in terms of total nutrient availability) to be pH 5.5 to 5.8 for wood-sedge soils and pH 5.0 for sphagnum peat soils. They further commented that this range is 1 to 1.5 pH units lower than what was considered ideal for mineral soils. This report formed the basis for future studies as the greenhouse industry switched from mineral soils to those composed primarily of peat or bark.

Peterson (1980) documented the effect of substrate pH on macronutrient and micronutrient availability in a well-fertilized commercial greenhouse substrate (peatmoss, perlite, vermiculite, granite sand, and composted pine bark; ratios not given). His study agreed with Lucas and Davis (1961) in that the optimum pH range was 5.2 to 5.5, which he characterized as being a whole pH unit

Table 1. Chemical characteristics of groundwater used for irrigation at the Oregon State University North Willamette Research and Extension Center.

pH	7.0
Alkalinity	87.3 mg·L ⁻¹
Hardness	86.8 mg·L ⁻¹
Total dissolved solids	129.5 mg·L ⁻¹
Electrical conductivity	0.2 dSm ⁻¹
Sodium	6.9 mg·L ⁻¹
Chloride	1.5 mg·L ⁻¹
Potassium	2.1 mg·L ⁻¹
Calcium	19.8 mg·L ⁻¹
Magnesium	8.9 mg·L ⁻¹
Sulfate	12.9 mg·L ⁻¹
Iron	0.3 mg·L ⁻¹
Manganese	0.1 mg·L ⁻¹
Boron	0.0 mg·L ⁻¹
Copper	0.0 mg·L ⁻¹
Zinc	0.1 mg·L ⁻¹
Aluminum	0.2 mg·L ⁻¹

Table 2. Initial substrate pH and nutrient values of douglas fir bark (DFB) and 75 DFB:15 peat:10 pumice mix (BPP).

Substrate parameter ^z	DFB	BPP
pH	3.7	4.2
	----- (mg·L ⁻¹) -----	
Salt	438.5	246.5
NO ₃ -N	0.3	0.2
NH ₄ -N	0.8	0.3
P	24.2	10.7
K	139.1	65.9
Ca	44.3	38.3
Mg	28.3	14.0
SO ₄	10.0	11.8
Na	13.6	15.9
B	0.6	0.4
Fe	84.3	69.3
Mn	12.9	10.9
Cu	0.5	0.5
Zn	3.8	3.2
Al	49.7	28.6

^zAll units are in mg·L⁻¹ with the exception of pH. P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Na = sodium; B = boron; Fe = iron; Mn = manganese; Cu = copper; Zn = zinc; Al = aluminum.

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Table 3. Substrate pH, nitrate (NO₃-N), ammonium (NH₄-N), and phosphorus (P) response to amendment with sulfur (S), calcium carbonate (CaCO₃), or calcium hydroxide [Ca(OH)₂].^z

Harvest date (WAP) ^y	Amendment	Rate (kg·m ⁻³)	pH		NO ₃ -N		NH ₄ -N		P	
			DFB ^x	BPP	DFB	BPP	DFB	BPP	DFB	BPP
(mg·L ⁻¹)										
4	S	2.4	3.7	2.9	13.1	3.6	9.8	4.4	9.7	8.9
		0.6	3.9	3.7	2.0	1.6	0.5	1.6	4.1	4.7
		0	4.6	4.8	0.3	0.3	0.0	0.0	5.6	5.2
	CaCO ₃	0.6	5.2	5.3	0.5	0.3	0.0	0.0	4.6	5.0
		1.5	5.8	6.1	0.4	0.3	0.0	0.0	2.8	2.5
		5.9	6.6	6.7	0.1	0.3	0.0	0.0	4.1	1.8
	Ca(OH) ₂	4.4	7.2	7.1	0.1	0.0	0.0	0.0	3.5	3.7
		8.9	7.3	7.3	0.0	0.1	0.0	0.0	1.7	0.6
		23.7	7.8	7.6	0.0	0.0	0.0	0.0	1.1	0.6
	Nonfertilized control ^w	0	4.8	5.0	0.5	0.5	0.0	0.1	9.5	4.4
8	S	2.4	2.3	2.1	27.1	34.8	32.4	51.0	26.1	30.4
		0.6	3.5	3.5	25.5	11.5	29.3	17.2	12.9	15.6
		0	4.9	4.9	5.9	3.9	3.6	2.6	13.3	14.7
	CaCO ₃	0.6	5.4	5.4	4.8	2.0	2.0	1.1	13.1	11.1
		1.5	5.7	6.1	7.0	4.0	2.8	0.8	11.9	11.1
		5.9	6.9	6.9	0.4	2.6	0.0	0.3	8.7	10.0
	Ca(OH) ₂	4.4	7.3	7.2	0.8	2.4	0.2	0.1	8.8	8.0
		8.9	7.7	7.5	1.4	0.9	1.3	0.3	3.7	2.8
		23.7	8.0	7.8	0.3	0.3	0.1	0.2	0.5	0.5
	Nonfertilized control	0	5.8	5.5	0.4	0.5	0.0	0.2	4.1	6.5
			<i>P</i> > <i>F</i>							
Harvest date (D)			0.1444	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Substrate (S)			0.1678	0.0669	0.8953	0.8953	0.8953	0.7098	0.7098	
D*S			0.4158	0.9028	0.6406	0.6406	0.1793	0.1793	0.1793	
pH amendment (A)			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
D*A			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
S*A			<0.0001	0.1552	0.9761	0.9761	0.2466	0.2466		
D*S*A			0.0169	0.8343	0.5389	0.5389	0.4859	0.4859		
Rate (amendment) [R(A)]			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		
D*R (A)			<0.0001	0.3338	0.0426	0.0426	<0.0001	<0.0001		
S*R (A)			0.0002	0.3305	0.0549	0.0549	0.9989	0.9989		
D*S*R (A)			0.802	0.0001	0.0002	0.0002	0.6686	0.6686		

^zAll substrates except for controls were fertilized with Micromax micronutrient fertilizer as well as Osmocote 14N-4.2P-11.6K controlled-release fertilizer.

^yWAP = weeks after potting, indicating when substrates were harvested for analysis.

^xSubstrates were either DFB = 100% douglas fir bark or BPP = 75 DFB:15 peat:10 pumice (by volume).

^wNonfertilized controls consisted of substrates alone, not amended with any supplemental fertilizers.

or more below what is considered optimum for mineral soils. Peterson (1980) reported decreasing availability of P, iron (Fe), manganese (Mn), boron (B), zinc (Zn), and copper (Cu) with increasing pH. Argo (1998) reviewed the effects of pH on nutrient availability in soilless substrates citing numerous sources and generally agreed with conclusions from Peterson (1980).

In view of the widespread use of DFB in the Pacific Northwest and the lack of information on its chemical properties, an experiment was initiated to document the influence of pH on nutrient availability in a well-fertilized substrate. The objectives were to determine the influence of elemental sulfur (S) and two lime sources on DFB pH, nutrient availability with respect to changes in substrate pH, and if relationships between pH and nutrient availability in DFB alone are similar to DFB amended with peatmoss and pumice.

Materials and Methods

On 6 Feb. 2007, 20 different substrates were mixed and filled into 2.7-L containers. The treatment design was a two-by-nine factorial arrangement with two substrate types and nine pH-altering amendments.

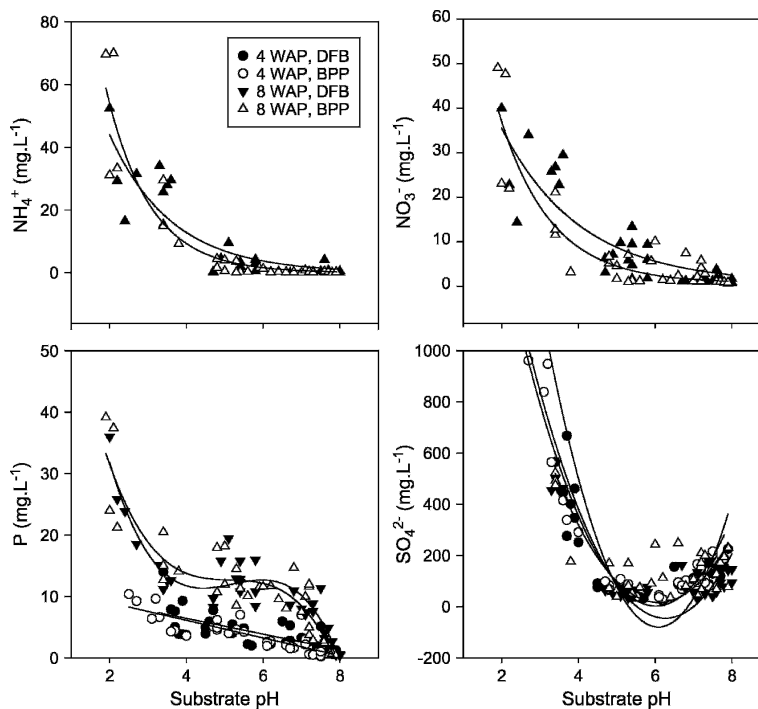


Fig. 1. Water-extractable nitrate (NO₃⁻), ammonium (NH₄⁺), phosphorus (P), and sulfate (SO₄²⁻) response to substrate pH in a douglas fir bark (DFB) or 75 DFB:15 peat:10 pumice (by volume) substrate. All substrates were amended with Osmocote and Micromax fertilizers and harvested either 4 or 8 weeks after potting (WAP).

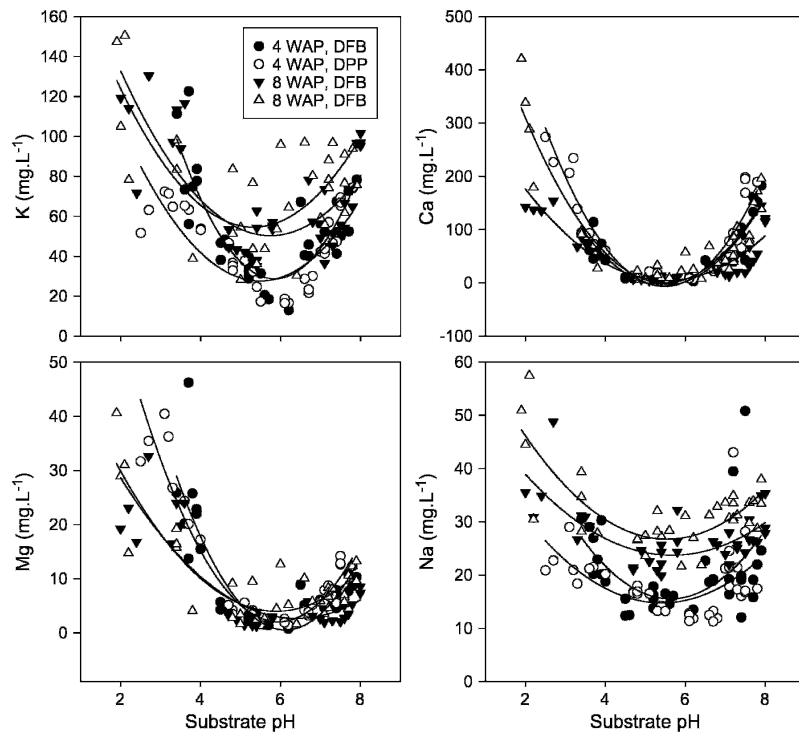


Fig. 2. Water-extractable potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) response to substrate pH in a douglas fir bark (DFB) or 75 DFB:15 peat:10 pumice (by volume) substrate. All substrates were amended with Osmocote and Micromax fertilizers and harvested either 4 or 8 weeks after potting (WAP).

The two substrate types were 100% DFB or 75 DFB:15 sphagnum peatmoss:10 pumice (by volume; hereafter referred to as BPP). Substrate pH-altering amendments included elemental S (Yellowstone Sulfur; MT Sulfur Co., Billings, MT) amended at either 0.6 or 2.4 kg·m⁻³; calcium carbonate (CaCO₃; Imperial Limestone; J.A. Jack and Sons Inc., Seattle, WA) amended at 0.6, 1.5, and 5.9 kg·m⁻³; hydrated lime [calcium hydroxide, Ca(OH)₂]; Kemilime; Ash Grove Cement Co., Portland, OR) amended at 4.4, 8.9, or 23.7 kg·m⁻³; and a nonamended control. All substrates were further amended by incorporating 0.9 kg·m⁻³ Micromax micronutrients (The Scotts Co., Marysville, OH) before potting and topdressing 8 g/pot of 14N-4.2P-11.6K (Osmocote 14-14-14; The Scotts Co.) after potting. A group of controls were also maintained for each substrate that received no fertilizer amendment (no S, lime, Micromax, or Osmocote). Rates of lime and S were selected to provide substrates with a spectrum of low to high pH and were based on previous research by the authors (unpublished data). Calcium carbonate [97% CaCO₃, 2% MgCO₃, 97 calcium carbonate equivalency (CCE)] was processed such that 100% and 80% passed through 40 and 100 mesh, respectively. Hydrated lime [94% Ca(OH)₂, 126 CCE] was processed such that

Table 4. Potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) response to amendment with sulfur (S), calcium carbonate (CaCO₃), or calcium hydroxide [Ca(OH)₂]^z

Harvest date (WAP) ^y	Amendment	Rate (kg·m ⁻³)	K		Ca		Mg		Na	
			DFB ^x	BPP	DFB	BPP	DFB	BPP	DFB	BPP
(mg·L ⁻¹)										
4	S	2.4	81.2	64.7	68.6	235.3	20.7	36.0	27.5	23.4
		0.6	82.3	61.7	69.5	91.5	27.4	22.1	22.2	20.3
		0	44.6	37.8	9.8	11.8	4.7	4.0	14.3	17.0
	CaCO ₃	0.6	33.4	28.0	8.0	13.1	2.7	3.2	15.9	14.3
		1.5	20.8	17.3	4.9	8.9	1.3	2.0	15.1	12.1
		5.9	48.4	26.0	29.1	28.2	5.7	4.1	19.9	12.2
	Ca(OH) ₂	4.4	54.0	42.3	41.9	57.5	5.3	6.2	32.0	21.2
		8.9	51.3	50.3	76.0	78.6	6.1	7.2	17.6	24.4
		23.7	69.4	69.0	157.4	187.9	9.4	13.0	20.4	19.8
	Nonfertilized control ^w	0	39.2	14.7	12.0	3.2	3.0	0.9	16.3	14.7
8	S	2.4	108.9	120.3	142.6	306.6	22.9	28.8	37.5	45.8
		0.6	105.3	75.9	76.8	77.6	21.1	13.8	29.5	32.5
		0	45.9	54.4	6.5	11.4	2.8	4.2	22.4	26.0
	CaCO ₃	0.6	41.1	50.0	5.8	16.0	1.9	4.6	22.2	28.9
		1.5	57.1	61.0	11.7	27.9	3.1	6.0	26.8	25.4
		5.9	55.4	73.0	21.8	43.3	3.4	6.3	24.5	32.1
	Ca(OH) ₂	4.4	56.5	78.7	25.7	60.8	2.8	6.8	25.7	32.3
		8.9	64.8	81.5	49.0	87.6	4.2	6.9	27.4	32.0
		23.7	97.7	98.1	125.9	164.7	8.3	11.4	31.8	33.5
	Nonfertilized control	0	15.3	27.6	3.6	5.0	0.6	1.4	16.1	22.2
<i>P</i> > <i>F</i>										
Harvest date (D)			<0.0001		0.1431		0.0390		<0.0001	
Substrate (S)			0.4193		<0.0001		0.0115		0.1169	
D*S			0.0026		0.3667		0.8843		0.0004	
pH amendment (A)			<0.0001		<0.0001		<0.0001		<0.0001	
D*A			0.1224		0.0002		0.0141		0.0895	
S*A			0.0646		<0.0001		0.7519		0.7439	
D*S*A			0.8759		0.4552		0.0910		0.5471	
Rate (amendment) [R(A)]			<0.0001		<0.0001		<0.0001		0.0011	
D*R (A)			0.0554		0.0005		0.4848		0.0372	
S*R (A)			0.3947		<0.0001		<0.0001		0.2097	
D*S*R (A)			0.1605		0.9322		0.7786		0.0240	

^zAll substrates except for controls were fertilized with Micromax micronutrient fertilizer, as well as Osmocote 14N-4.2P-11.6K controlled-release fertilizer.

^yWAP = weeks after potting, indicating when substrates were harvested for analysis.

^xSubstrates were either DFB = 100% douglas fir bark or BPP = 75 DFB:15 peat:10 pumice (by volume).

^wNonfertilized controls consisted of substrates alone, not amended with any supplemental fertilizers.

100% and 99% passed through 40 and 100 mesh, respectively. Sulfur (80%) was processed as a fine dust (particle size not provided). Bark was ground with a hammer-mill, passed through a 2.2-cm screen, and aged for ≈ 6 months (Marr Bros. Co., Monmouth, OR). Eight No. 1 containers (2.8 L) were filled with each treatment and maintained in a hoop house in Aurora, OR. Temperatures within the hoop house were maintained above 15 °C. Containers received overhead irrigation with groundwater at a rate of 1.2 cm·d⁻¹. Chemical properties of irrigation water used for the experiment were determined (Table 1). Before amendment with fertilizers, two samples from each substrate were collected to determine initial nutrient levels (Table 2). Four containers of each treatment were randomly selected and harvested 4 and 8 weeks after potting (WAP). Substrates were harvested by first scraping the top 1.5 cm of substrate away and thereby removing all controlled-released fertilizer (CRF) prills. The remaining substrate was placed into a plastic bag, rechecked to ensure no CRF prills remained, and then delivered to the laboratory. Bark samples were analyzed for pH, ammonium (NH₄-N), nitrate (NO₃-N), P, potassium (K), calcium (Ca), magnesium (Mg), and sulfate (SO₄²⁻) using the saturated media extract (SME) method with deionized water as the extractant (Gavlak et al., 2003; Warncke, 1998). Boron, Fe, Mn, Cu, Zn, and aluminum (Al) were analyzed using a SME with diethylenetriaminopentaacetic acid (DTPA) as the extractant (Warncke, 1998). Following Gavlak et al. (2003), separate subsamples of each replicate were soaked in either water or 0.005 M DTPA for 24 h. Ammonium and NO₃-N in extracted solutions were analyzed colorimetrically using a Lachat Quick Chem 8000 (Lachat Instruments, Milwaukee, WI). All other elements were analyzed with inductively coupled plasma-emission spectrometry (Thermo Jarrel Ash, Offenbach, Germany).

Data were analyzed with analysis of variance to determine significant main effects. Nonlinear regression was used to determine the most appropriate model for pH response to lime rate as well as nutrient availability response to substrate pH. Procedures described by Schabenberger and Pierce (2002) were used for nonlinear model selection and comparison. Linear, curvilinear, and piecewise regression models were compared using the lack of fit test to determine the most appropriate model for regressing substrate pH on each extractable nutrient. All statistical analyses were conducted with SAS 9.1 (SAS Institute, Cary, NC), although figures were constructed with SigmaPlot 10.0 (Systat Software, Inc., San Jose, CA).

Results and Discussion

Sulfur amendment reduced pH with increasing S rate, whereas lime additions [both CaCO₃ and Ca(OH)₂] increased pH (Table 3). Substrate pH declined from 4 to 8 WAP with S additions and increased

Table 5. Salt, sulfate (SO₄²⁻), and aluminum (Al) response to amendment with sulfur (S), calcium carbonate (CaCO₃), or calcium hydroxide [Ca(OH)₂].^z

Harvest date (WAP) ^y	Amendment	Rate (kg·m ⁻³)	SO ₄ ²⁻		Al	
			DFB ^x	BPP	DFB	BPP
4	S	2.4	436.8	952.8	13.4	41.8
		0.6	417.0	402.4	10.0	6.3
		0	82.4	78.8	8.9	4.6
	CaCO ₃	0.6	62.2	68.0	4.9	3.5
		1.5	34.0	37.4	2.8	1.9
		5.9	100.8	87.5	0.7	1.4
	Ca(OH) ₂	4.4	122.2	117.8	0.6	1.1
		8.9	139.9	107.3	1.4	0.5
		23.7	164.5	202.2	1.7	1.6
	Nonfertilized control ^w	0	10.3	8.1	21.8	5.9
8	S	2.4	1343.7	2273.8	82.8	151.0
		0.6	468.7	416.5	7.1	7.3
		0	57.1	86.2	3.2	5.0
	CaCO ₃	0.6	37.9	94.5	1.8	5.3
		1.5	69.2	120.3	2.2	1.5
		5.9	81.1	121.0	0.7	0.8
	Ca(OH) ₂	4.4	69.5	141.0	0.5	0.7
		8.9	95.5	143.2	1.3	0.7
		23.7	132.9	168.4	1.0	0.6
	Nonfertilized control	0	8.3	12.9	5.1	6.1
			<i>P</i> > <i>F</i>			
Harvest date (D)			0.0024		0.0183	
Substrate (S)			<0.0001		0.0136	
D*S			0.0006		0.3000	
pH amendment (A)			<0.0001		<0.0001	
D*A			<0.0001		0.0019	
S*A			<0.0001		<0.0001	
D*S*A			<0.0001		0.0683	
Rate (amendment) [R(A)]			<0.0001		<0.0001	
D*R (A)			<0.0001		0.0096	
S*R (A)			<0.0001		0.0004	
D*S*R (A)			0.8204		0.4413	

^zAll substrates except for controls were fertilized with Micromax micronutrient fertilizer as well as Osmocote 14N-4.2P-11.6K controlled-release fertilizer.

^yWAP = weeks after potting, indicating when substrates were harvested for analysis.

^xSubstrates were either DFB = 100% douglas fir bark or BPP = 75 DFB:15 peat:10 pumice (by volume).

^wNonfertilized controls consisted of substrates alone, not amended with any supplemental fertilizers.

slightly with lime additions. Substrate response to S is biological, because bacteria from the genus *Thiobacillus* converts S to SO₄²⁻ and concomitantly release H⁺ ions. This biological reaction generally takes place over several weeks or months pending adequate moisture and temperature (greater than 10 °C). Substrate reaction to lime is chemical in nature and dependent on lime acid neutralizing capacity, lime type, and lime particle size (Fisher et al., 2006); thus, reaction to pulverized lime (like used in this study) can be immediate. Substrate type had no effect on substrate pH (*P* = 0.1678), although there were several significant interactions with other main effects. Within a treatment, there were generally minor differences in pH response between the two substrate types, suggesting that both substrates responded similarly to S and lime.

Nitrate-N and NH₄-N both responded to the three-way interaction of date, substrate type, and rate of pH amendment (Table 3). Ammonium and NO₃-N levels were relatively low across all treatments at 4 WAP but higher by 8 WAP. Nutrient release from the CRF is likely responsible for changes in N levels over time. Ammonium-N and NO₃-N both decreased exponentially with increasing substrate pH (Fig. 1). The response to pH for

both nitrogen (N) forms was more evident 8 WAP when overall N levels were higher. Ammonium-N response to pH was likely the result of pH-dependent nitrification. Ogden et al. (1987) attributed the increased nitrification response to greater activity of nitrifying bacteria in higher pH substrates. Niemiera and Wright (1986) demonstrated that nitrifying bacteria were largely responsible for loss of ammonium in container substrates with lime-induced high pH. Nitrate-N response may be linked to anion exchange capacity (AEC). Anion exchange capacity increases with decreasing pH as a result of protonation of carboxyl and hydroxyl groups. This has been demonstrated in two organic arboreal soils comprised primarily of redwood [*Sequoia sempervirens* (D. Don) Endl.] leaves and bark, in which AEC at pH 4 was 1.2 to two times more than at pH 7 (Enloe et al., 2006). Increased AEC at lower pH in our study may have allowed more readily extractable NO₃ to be retained by the substrate. This may also allow for greater N availability to plants and less NO₃-N leaching in production situations.

Neither substrate type nor any of its interactions affected water-extractable P (Table 3). Previous research has shown that

Table 6. Boron (B), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) response to amendment with sulfur (S), calcium carbonate (CaCO₃), or calcium hydroxide [Ca(OH)₂].^z

Harvest date (WAP) ^y	Amendment	Rate (kg·m ⁻³)	B		Fe		Mn		Cu		Zn		
			DFB ^x	BPP	DFB	BPP	DFB	BPP	DFB	BPP	DFB	BPP	
4	S	2.4	0.4	0.6	103.1	109.9	9.4	28.5	4.1	3.7	6.6	10.5	
		0.6	0.8	0.5	121.4	90.0	20.5	21.5	6.5	4.3	8.5	9.3	
		0	0.5	0.5	80.6	94.0	11.0	9.0	5.4	6.9	7.9	10.4	
	CaCO ₃	0.6	0.4	0.3	74.4	84.4	16.8	12.8	4.8	7.2	9.5	11.2	
		1.5	0.2	0.3	60.0	59.7	16.3	23.3	3.7	6.0	6.7	9.6	
		5.9	0.1	0.1	25.5	26.0	26.5	32.4	3.1	4.7	7.9	10.1	
	Ca(OH) ₂	4.4	0.1	0.1	27.1	21.0	26.9	25.9	3.4	3.9	8.2	8.5	
		8.9	0.1	0.1	7.7	6.9	26.6	22.5	3.0	3.1	7.9	8.0	
		23.7	0.1	0.1	2.4	2.4	20.8	23.1	2.3	3.0	6.4	6.9	
	Nonfertilized control ^w	0	0.2	0.2	43.9	39.4	10.8	10.6	0.3	0.3	2.2	2.0	
	8	S	2.4	0.4	0.4	113.8	90.7	8.1	9.6	4.6	4.5	3.3	3.8
			0.6	0.5	0.3	115.5	91.0	16.9	6.0	6.0	4.8	6.8	4.9
0			0.2	0.3	85.3	81.1	12.8	15.2	5.6	6.0	8.0	9.5	
CaCO ₃		0.6	0.2	0.3	85.0	82.2	16.3	17.2	6.1	7.6	9.7	11.3	
		1.5	0.2	0.3	70.4	64.5	27.3	25.7	5.8	7.4	10.6	12.8	
		5.9	0.1	0.1	25.6	29.0	28.0	30.9	4.6	6.5	9.9	13.0	
Ca(OH) ₂		4.4	0.1	0.1	25.7	22.9	37.2	25.5	6.3	6.9	12.6	14.3	
		8.9	0.0	0.0	6.6	6.3	30.7	18.8	3.7	4.2	9.3	10.0	
		23.7	0.0	0.0	2.4	3.1	18.9	18.9	2.3	3.1	5.6	7.3	
Nonfertilized control		0	0.2	0.2	43.7	38.5	11.3	12.1	0.3	0.3	2.3	2.0	
<i>P</i> > <i>F</i>													
Harvest date (D)				<0.0001		0.7396		0.2389		<0.0001		0.6434	
Substrate (S)			0.4469		0.0016		0.9579		<0.0001		<0.0001		
D*S			0.7996		0.0032		<0.0001		0.7308		0.1782		
pH amendment (A)			<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		
D*A			<0.0001		0.0463		<0.0001		0.0005		<0.0001		
S*A			0.0039		<0.0001		<0.0001		<0.0001		0.029		
D*S*A			0.0011		0.0578		<0.0001		0.2761		0.0137		
Rate (amendment [R(A)])			<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		
D*R (A)			0.0112		0.8801		0.0021		0.0001		<0.0001		
S*R (A)			<0.0001		0.0026		<0.0001		0.2264		0.0878		
D*S*R (A)			0.0301		0.0072		0.0313		0.8796		0.9616		

^zAll substrates except for controls were fertilized with Micromax micronutrient fertilizer as well as Osmocote 14N-4.2P-11.6K controlled-release fertilizer.

^yWAP = weeks after potting, indicating when substrates were harvested for analysis.

^xSubstrates were either DFB = 100% douglas fir bark or BPP = 75 DFB:15 peat:10 pumice (by volume).

^wNonfertilized controls consisted of substrates alone, not amended with any supplemental fertilizers.

P is pH-dependent in nonamended DFB (Altland and Buamscha, 2008). Water-extractable P decreased with increasing pH at 4 and 8 WAP (Fig. 1) and thus is pH-dependent even with higher levels of P made available by CRF. Favaretto et al. (2006) showed that applications of Ca in the form of gypsum (CaSO₄) reduced P concentration in mineral soil by converting the readily desorbable P to less soluble Ca-P compounds. This phenomena was not observed in our study, because P increased with decreasing pH concomitantly with sharply increasing levels of soluble Ca (Fig. 2).

Potassium, calcium, magnesium, and sodium. Water-extractable K, Ca, Mg, and sodium (Na) each responded differently to main effects of substrate type, amendment, and amendment rate (Table 4). All responded quadratically to increasing pH (Fig. 2). The pH resulting in minimal nutrient availability was calculated for each nutrient by setting the first derivative of the quadratic function to zero and solving for pH. Substrate pH at which extracted levels were minimal for K, Ca, and Na was 5.5, whereas it was 6.2 for Mg. In previous research, water-extractable K, Ca, and Mg increased with increasing pH in nonamended DFB, whereas Na did not respond to pH (Altland and Buamscha, 2008). Increased Ca availability was attrib-

uted to increased rate and solubility of Ca(OH)₂, and a similar rationale is appropriate here. Increased K and Mg availability was attributed to dislodging of the cations from cation exchange sites with increasing levels of soluble Ca. The same explanation can be applied for K, Mg, and Na in this study. Increased water-extractable K, Ca, Mg, and Na from pH-lowering S applications may be caused by elevated H⁺ concentrations. Hydrogen ions have large atomic radii and thus would displace cations with smaller radii (i.e., K, Ca, Mg, and Na) on cation exchange sites, causing their availability to increase with decreasing pH. Berghage et al. (1987) similarly reported that Ca decreased from 700 to 800 mg·L⁻¹ when pH was just below 4 to under 300 mg·L⁻¹ at pH 5.5. They (Berghage et al., 1987) also reported a similar trend with Mg and to a lesser extent K (without data).

Analysis of variance shows that all main effects influenced substrate SO₄²⁻ levels (Table 5). Addition of lime and subsequent increase in pH caused an increase in water-extractable SO₄²⁻ (Fig. 1). This is similar to what was observed with the nonamended DFB response to lime (Altland and Buamscha, 2008). With increasing pH there is a logarithmic increase in OH⁻ concentration. Similar to cation competition described for K,

Mg, and Na, elevated levels of OH⁻ may have displaced sulfate ions on anion exchange sites causing an increase in water-extractable sulfate levels. Bennett and Peterson (1989) reported a slight increase in sulfate from pH 3.7 to 4.7 in sphagnum peat amended with increasing rates of Ca(OH)₂ but declining sulfate levels with pH increasing from 4.7 to 7.0. Differences in response between the two studies may be caused by the different substrates or extraction procedures used. Handreck (1986) states that 6 mg·L⁻¹ water-extractable SO₄²⁻ is sufficient for any crop. By this standard, even nonfertilized controls would contain sufficient extractable SO₄²⁻ for plant growth. Amendment with S resulted in SO₄²⁻ levels greater than 10 to 100 times more than needed for crop growth. Elevated SO₄²⁻ levels in S-amended containers are more likely the result of S and not related to low pH. Across all lime and S treatments, water-extractable SO₄²⁻ levels were higher in fertilized containers compared with nonfertilized controls (Table 5). The N-P-K fertilizer in this experiment used potassium sulfate as the sole K source, whereas the micronutrient fertilizer was comprised partly of copper sulfate, manganese sulfate, ferrous sulfate, and zinc sulfate. Thus, DFB alone likely has sufficient SO₄²⁻ to support plant growth, whereas addition of typical sulfated

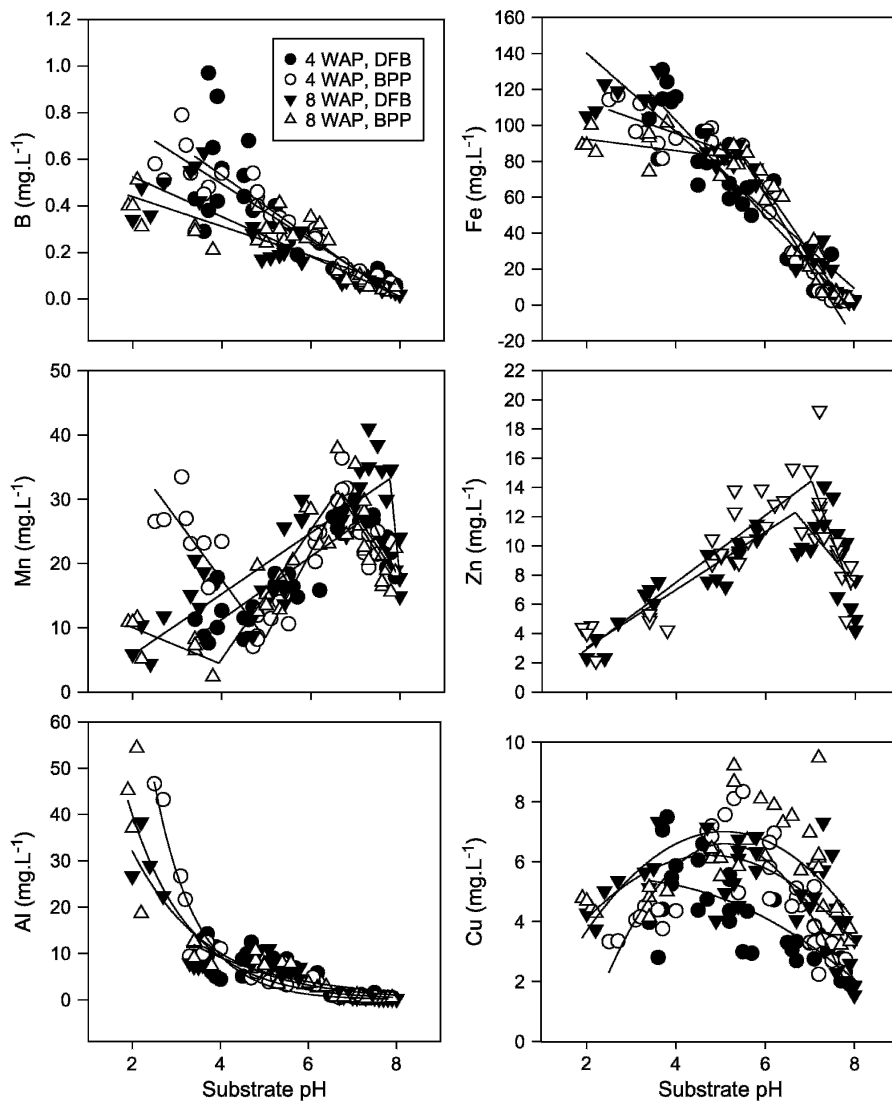


Fig. 3. DTPA-extractable boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and aluminum (Al) response to substrate pH in a douglas fir bark (DFB) or 75 DFB:15 peat:10 pumice (by volume) substrate. All substrates were amended with Osmocote and Micromax fertilizers and harvested either 4 or 8 weeks after potting (WAP).

N-P-K and micronutrient fertilizers certainly provide sufficient SO_4^{2-} .

Micronutrients. The main effect of substrate type did not affect DTPA-extractable B ($P = 0.4469$; Table 6); however, there were several significant interactions between substrate type and other main effects. DTPA-extractable B decreased linearly with increasing pH (Fig. 3). DTPA-extractable B in nonfertilized DFB (Altland and Buamscha, 2008) was similar to B levels in fertilized DFB across the range of observed pH. The micronutrient fertilizer package used in this study contains 0.1% B in the form of sodium borate. Within the substrate, sodium borate probably changes to boric acid $[\text{B}(\text{OH})_4^-]$, which is very water-soluble ($\approx 57,000 \text{ mg}\cdot\text{L}^{-1}$). Lack of discernible differences in DTPA-extractable B between DFB amended with micronutrient fertilizers and those not amended can be attributed to either rapid leaching of water-soluble boric acid or the B fraction of the fertilizer is minor compared

with the fraction provided by DFB and other substrate components. Available B in container plants can also originate from irrigation water (Ogden et al., 1987). Boron levels in irrigation water in this experiment were negligible (Table 1) and, across container nurseries in Oregon, were found to be very low (0 to $0.07 \text{ mg}\cdot\text{L}^{-1}$) (Altland, 2006a). Plant-available B is governed by the amount of B in solution (Goldberg, 1997), which these data show is governed primarily by substrate pH and influenced little by B amendment through micronutrient packages.

DTPA-extractable Fe was influenced by numerous main effects and interactions (Table 6). Substrate type was a significant effect ($P = 0.0016$), although DFB had only a marginally higher level of Fe than BPP (56 versus $52 \text{ mg}\cdot\text{L}^{-1}$) averaged across all treatments. DTPA-extractable Fe decreased with increasing pH (Fig. 3; Table 7). Available Fe was responsive to substrate pH, even with the addition of micronutrient fertilizer contain-

ing 17% Fe in the form of ferrous sulfate. Adding the micronutrient package increased available Fe \approx twofold over nonfertilized controls in this study. DTPA-extractable substrate Fe levels should range from 15 to $40 \text{ mg}\cdot\text{L}^{-1}$ (Warncke, 1998); thus, extra available Fe from micronutrient packages may be excessive considering levels provided by DFB alone.

DTPA-extractable Mn was affected by all interactions of main effects (Table 6). The relationship between Mn and substrate pH differed for DFB and BPP substrates. DFB was best fit with a two-segment piecewise linear regression model, whereas BPP was best fit with a three-segment model (Fig. 3; Table 7). Mn from DFB increased with increasing pH up to 7.3 and 7.7 at 4 and 8 WAP, respectively, and declined linearly with increasing pH thereafter (Table 7). Mn initially decreased with increasing pH in BPP substrates, then increased over the range of 5.0 to 6.7 and 3.9 to 6.6 at 4 and 8 WAP, respectively, and then declined thereafter. Among all nutrients analyzed in this and other research by the authors, measuring Mn availability has been most troublesome. Handreck (1995) reviewed research on Mn extraction from potting media and summarizes the body of work as conflicting, largely as a result of the complexity of Mn chemistry in soils and substrates. Further research focusing specifically on Mn is required to better understand how this nutrient reacts in DFB substrates.

DTPA-extractable Cu responded to numerous main effects and interactions (Table 6), including substrate type, although differences between the substrates were not remarkable. DTPA-extractable Cu responded quadratically with increasing substrate pH (Fig. 3). Across the range of pH, Cu levels ranged from 2.3 to $7.6 \text{ mg}\cdot\text{L}^{-1}$, whereas in nonamended DFB, Cu decreased exponentially with increasing pH with levels ranging from 0.13 to $0.40 \text{ mg}\cdot\text{L}^{-1}$ (Altland and Buamscha, 2008). Handreck (1994) reported no Cu response in pine bark substrates with pH adjusted from 4.5 to 6.5, although the lack of observed response in his study is likely the result of the narrow range of pH studied. In a separate study, Handreck (1990) concluded that chrysanthemum (*Chrysanthemum morifolium* Ramat.) requires $0.25 \text{ mg}\cdot\text{L}^{-1}$ of DTPA-extractable Cu for adequate vegetative growth but at least $5.1 \text{ mg}\cdot\text{L}^{-1}$ Cu for optimum flowering. By these standards, unamended DFB contains sufficient Cu for vegetative growth assuming pH is sufficiently low (less than 6.7) (Buamscha et al., 2007). Handreck (1990) goes on to suggest 2 or $20 \text{ mg}\cdot\text{L}^{-1}$ Cu (mass of Cu per volume of substrate) be amended to substrates to achieve levels necessary for optimum vegetative growth or flowering, respectively. Application of $0.9 \text{ kg}\cdot\text{m}^{-3}$ micronutrient package (1% Cu), like done in this study, is equivalent to an application of $8.9 \text{ mg}\cdot\text{L}^{-1}$ Cu (mass of Cu per volume of substrate). With this application rate, Cu was sufficiently high for vegetative growth regardless of pH but

Table 7. Regression equations for relationships between water-extractable NH_4^+ , NO_3^- , P, SO_4^{2-} , K, Ca, Mg, and Na and substrate pH; and DTPA-extractable B, Fe, Mn, Zn, Al, and Cu and substrate pH (Figs. 1, 2 and 3). Multiple equations within a date and substrate represent each of the segments from piecewise linear regression.

Nutrient	WAP ^a	Substrate ^b	Equation ^c	Range ^w	r ²
NH_4^+	8	DFB	$y = 313.47e^{-0.88x}$	2.0–8.0	0.87
		BPP	$y = 151.11e^{-0.62x}$	1.9–7.9	0.79
NO_3^-	8	DFB	$y = 92.46e^{-0.49x}$	2.0–8.0	0.77
		BPP	$y = 162.76e^{-0.75x}$	1.9–7.9	0.83
P	4	DFB	$y = 11.55 - 1.28x$	3.4–7.9	0.50
		BPP	$y = 11.87 - 1.44x$	2.5–7.8	0.71
	8	DFB	$y = 107.82 - 57.8x + 11.35x^2 - 0.73x^3$	2.0–8.0	0.88
		BPP	$y = 93.76 - 47.03x + 9.13x^2 - 0.59x^3$	1.9–7.9	0.85
SO_4^{2-}	4	DFB	$y = 2,602 - 849x + 69x^2$	3.4–7.9	0.79
		BPP	$y = 3,147 - 1,045x + 87x^2$	2.5–7.8	0.94
	8	DFB	$y = 3,222 - 1,043x + 83x^2$	2.0–8.0	0.94
		BPP	$y = 4,875 - 1,628x + 134x^2$	1.9–7.9	0.87
K	4	DFB	$y = 428 - 137x + 12x^2$	3.4–7.9	0.69
		BPP	$y = 221 - 71x + 6x^2$	2.5–7.8	0.60
	8	DFB	$y = 244 - 68x + 6x^2$	2.0–8.0	0.59
		BPP	$y = 232 - 67x + 6x^2$	1.9–7.9	0.53
Ca	4	DFB	$y = 751 - 276x + 25x^2$	3.4–7.9	0.82
		BPP	$y = 1,001 - 368x + 34x^2$	2.5–7.8	0.88
	8	DFB	$y = 426 - 153x + 14x^2$	2.0–8.0	0.80
		BPP	$y = 768 - 280x + 26x^2$	1.9–7.9	0.88
Mg	4	DFB	$y = 144 - 47x + 4x^2$	3.4–7.9	0.70
		BPP	$y = 124 - 41x + 3x^2$	2.5–7.8	0.90
	8	DFB	$y = 58 - 17x + x^2$	2.0–8.0	0.73
		BPP	$y = 63 - 20x + 2x^2$	1.9–7.9	0.78
Na	4	DFB	$y = 89 - 26x + 2x^2$	3.4–7.9	0.23
		BPP	$y = 55 - 14x + x^2$	2.5–7.8	0.23
	8	DFB	$y = 56 - 13x + x^2$	2.0–8.0	0.46
		BPP	$y = 74 - 17x + 2x^2$	1.9–7.9	0.62
B	4	DFB	$y = 1.07 - 0.13x$	3.4–7.9	0.71
		BPP	$y = 0.98 - 0.12x$	2.5–7.8	0.91
	8	DFB	$y = 0.7 - 0.09x$	2.0–8.0	0.81
		BPP	$y = 0.57 - 0.06x$	1.9–7.9	0.72
Fe	4	DFB	$y = 209.1 - 26.6x$	3.4–7.9	0.91
		BPP	$y = 130.3 - 21.7x$	2.5–7.8	0.97
	8	DFB	$y = 302.8 - 40.1x$	5.5–7.8	
		BPP	$y = 183.8 - 21.8x$	2.0–8.0	0.90
Mn	4	DFB	$y = 98.7 - 6.1x$	1.9–7.9	0.96
			$y = 282.7 - 36.2x$	5.6–7.9	
		BPP	$y = -8.2 + 16.6x$	3.4–7.9	0.81
			$y = 141.3 - 15.5x$	7.3–7.9	
	8	DFB	$y = 54.8 - 9.3x$	2.5–5.0	0.82
			$y = -56.7 + 13.1x$	5.0–6.7	
		BPP	$y = 101.2 - 10.5x$	6.7–7.8	
			$y = -3.7 + 9.5x$	2.0–7.7	0.71
Zn	8	DFB	$y = 568.7 - 68.8x$	7.7–8.0	
			$y = 15.8 - 2.9x$	1.9–3.9	0.81
	BPP	$y = -35.0 + 10.0x$	3.9–6.6		
		$y = 103.3 - 10.9x$	6.6–7.9		
Al	4	DFB	$y = -0.9 + 4.0x$	2.0–6.6	0.66
			$y = 36.4 - 3.6x$	6.6–8.0	
	BPP	$y = -1.7 + 4.4x$	1.9–7.0	0.76	
		$y = 74.4 - 8.5x$	7.0–7.9		
Cu	4	DFB	$y = 51.4e^{-0.43x}$	3.4–7.9	0.65
			$y = 660.0e^{-1.06x}$	2.5–7.8	0.94
	8	DFB	$y = 102.3e^{-0.58x}$	2.0–8.0	0.84
			$y = 172.1e^{-0.73x}$	1.9–7.9	0.87
Cu	4	DFB	$y = 4.5 + 0.7x - 0.1x^2$	3.4–7.9	0.75
			$y = -9.9 + 6.5x - 0.6x^2$	2.5–7.8	0.85
	8	DFB	$y = -0.1 + 2.6x - 0.3x^2$	2.0–8.0	0.68
			$y = -2.0 + 3.5x - 0.3x^2$	1.9–7.9	0.65

^aWAP = weeks after potting, or the time allowed between potting and substrate analysis.

^bSubstrates were either DFB = 100% douglas fir bark, or BPP = 75 DFB:15 peat:10 pumice (by volume).

^cEquations for each nutrient, WAP, and substrate combination represent each of the linear segments identified by piecewise regression analysis.

^wRange refers to the range of substrate pH to which each linear regression equation applies.

exceeded the 5.1 mg·L⁻¹ benchmark (for optimal flowering) with pH from ≈4 to 6 (Fig. 3).

DTPA-extractable Zn was affected by substrate type ($P < 0.0001$) and other main

effects (Table 6). Extractable Zn from DFB was less than that from BPP despite BPP having similar (or slightly less) extractable Zn just before potting. Zn response to substrate pH was best fit with two-segment

piecewise regression (Fig. 3). At 4 WAP, DTPA-extractable Zn did not respond to substrate pH in either substrate (data omitted for clarity). At 8 WAP, Zn increased as pH increased up to 6.6 and 7.0 for DFB and BPP, respectively, and then declined (Table 7). Handreck (1994) reported Zn did not respond to pH over the range of 4.5 to 6.5 in a fertilized pine (*P. radiata* D. Don) bark substrate. Ogden et al. (1987) also stated liming has no effect on Zn availability in pine (*P. taeda* L.) bark substrates. Our data show Zn responds to pH, but over a much wider range of pH than what was observed with others (Handreck, 1994; Ogden et al., 1987). Zn availability in this study might also be related to cation competition with K, Ca, and Mg (Fig. 2). As each of these nutrients decreased in availability, Zn availability increased and vice versa.

DTPA-extractable Al was affected by substrate type ($P = 0.0136$), although this difference manifested most prominently in the highest S amendment rate (Table 5). DTPA-extractable Al decreased exponentially with increasing pH (Fig. 3). A similar response to pH was observed in unamended DFB (Altland and Buamscha, 2008). Ogden (1982) showed that pine (*Pinus taeda* L.) bark ash contains high concentrations of Al, although no symptoms of Al toxicity were apparent in a series of experiments with tomato (*Lycopersicon esculentum* Mill.). Wright (1989) reviewed Al interactions with soils and crops and described Al speciation as complex, dependent on soil pH and other mineralogical factors, and difficult to predict. Wright (1989) also explains that Al forms complexing ligands with sulfate and soluble organic compounds, which alleviates Al toxicity. We speculate that Al is present in relatively high levels (pH-dependent) in DFB but in nontoxic forms as a result of a consistent supply of sulfate from bark (Table 1) and fertilizer amendments as well as the presence of soluble organic compounds in DFB.

These results have several practical implications. Both N forms and P were found in higher concentrations than at low pH. Although greater $\text{NH}_4\text{-N}$ retention was attributed to reduced nitrification rates at low pH, retention of the anions NO_3^- and P (as P_2O_4) is likely the result of higher AEC with decreasing pH. Nitrates and P are known to leach readily from substrates and often identified as the most serious threat for environmental contamination of surface waters and groundwater from container nurseries. It is possible that reduction in pH of substrates could lead to greater N and P retention, thus increasing N and P availability to crops and reducing their losses resulting from leaching.

The quadratic response of the cations K, Ca, Mg, and Na was most surprising. In a review of root medium chemical properties, Argo (1998) concludes that low pH does not reduce Ca availability but that low pH was an indication of a lack of Ca sources applied to the media. Our results provide a little more clarity in demonstrating that reducing pH with acidifying amendments (S, for example)

below the native pH of DFB results in elevated Ca availability. The rationale for applying lime to nursery containers is that it not only raises pH, but also provides a source of Ca (and Mg with dolomitic lime). However, our research shows that when lower pH is desired, there is sufficient Ca available from DFB so that additional Ca sources are not necessary.

The micronutrients B and Fe decreased with increasing pH, as expected. However, DTPA extractions of Mn, Zn, and Cu behaved unexpectedly in response to pH with each increasing and decreasing over the range of observed pH. Buamscha et al. (2007) showed that DTPA-extractable micronutrients are well correlated to foliar levels in annual vinca [*Catharanthus roseus* (L.) G. Don] but that plant Mn was better correlated to water extractions. However, the pH range in the referenced study (Buamscha et al., 2007) was much narrower than this study. Future research evaluating plant responses over a wide range of pH is necessary to more thoroughly understand how DTPA or water extractions correlate with plant availability.

The potential number of substrate combinations using DFB, peatmoss, pumice, and other substrate components is virtually limitless, thus defying a complete nutritional analysis of all substrate types. This research shows that DFB alone responds similarly to a typical combination of DFB, peatmoss, and pumice. Most nursery producers in the Pacific Northwest use substrates that are predominantly DFB (greater than 60%) amended to some extent with peatmoss, pumice, sand, compost, and other components (personal observation). Without testing each substrate combination, results from this experiment can be used as a model of how nutrient availability in DFB substrates respond to pH.

This research suggests that availability of most nutrients would be greater at lower pH. Despite this, no single pH range is universally ideal for all crops. In peatmoss substrates, Argo and Fisher (2002) explain that prefer-

ence for pH among bedding plants is tied primarily to species-dependent Fe uptake efficiency in that some plants overaccumulate Fe at low pH and thus are better suited to high pH substrates. Conversely, some plants are inefficient in absorbing Fe and other micronutrients and thus require lower pH. More research is needed to determine optimal pH ranges for woody plants grown in containers and how substrate pH affects nutrient availability to those crops.

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