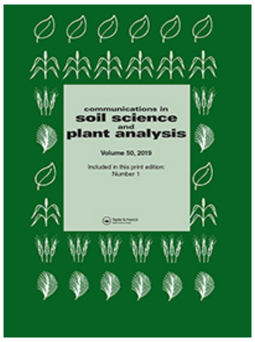

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Lime Rate Affects Substrate pH and Container-grown Birch Trees

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ABSTRACT

Nursery production of birch (*Betula nigra* L.) trees commonly occurs in containers using a soilless substrate such as pine bark or peat moss. Birch trees have been reported to suffer from pH-induced micronutrient deficiencies in landscapes; thus, they are recommended to be planted in low-pH soils (<6.5). Little research has addressed the influence of substrate pH on birch trees during container production. Therefore, the objective of this research was to determine if substrate pH influences birch tree growth and development. Birch (*Betula nigra* 'NBMTF') liners were transplanted into 11.4 L plastic nursery containers filled with an 80 pine bark: 20 sphagnum peat moss (v:v) amended with either 0.6 kg.m^{-3} of elemental sulfur (S) or 0, 1.8, 3.5, or 7.1 kg.m^{-3} dolomitic lime. Substrate pH ranged from 4.8 to 7.3. There were only a few and minor differences in leaf chlorophyll content and no differences in plant growth. Differences in leachate and plant tissue nutrient concentration occurred for some elements, although these differences were not enough to affect plant growth. Container-grown birch trees can be grown over a wide range of substrate pH (4.8 to 7.3) with little or no effect on their growth.

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Introduction

Pine (*Pinus taeda*) bark is the predominant substrate used for container production in the eastern US. The pH of pine bark substrates, prior to amendment, ranges from 4.1 to 5.1 (Brown and Pokorny 1975; Gillman, Dirr, and Braman 1998; Wright et al. 1999a, 1999b). Dolomitic lime (DL) is traditionally used to raise the pH of pine bark substrates to a range of 5.5 to 6.5.

DL affects the chemical properties of pine bark substrates. Nitrification, the biological conversion of ammonium (NH_4^+) to nitrate (NO_3^-), occurs more rapidly at elevated pH (Niemiera and Wright 1986). Higher nitrification rates in limed containers are beneficial to crops with a preference for NO_3^-N, such as Japanese boxwood (*Buxus microphylla* var. *japonica*) (Walden and Epelman 1988) and nandina (*Nandina domestica*) (Walden and Wright 1995). However, elevated pH can reduce micronutrient availability in soilless substrates (Altland and Buamscha 2008; Peterson 1980). And finally, DL is composed almost entirely of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) (Barber 1984), providing a source of calcium (Ca) and magnesium (Mg) in the substrate which may antagonize potassium (K) uptake (Altland and Jeong 2016).

Some plant species respond favorably to higher or lower substrate pH, while others have no apparent response (Altland and Jeong 2016). Differences in plant response could be related to a specific characteristic of the plant's native habitat. For example, Harvey, Elliott, and Brand (2004) reported that Hakonechloa (*Hakonechloa macra* 'Aureola') grew best in a 3 pine bark: 2 sphagnum peat; 1 sand (by volume) substrate with no DL amendment (pH 4.5). They speculated the reason for this favorable response to low pH was due to the plant's adaptation to low soil pH found in the mesic, forested mountains of its native range in Hakone, Japan. River birch is native to alluvial floodplains (Wolfe and Pittillo 1977) throughout the southeastern US, although natural populations

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can be found as far north as Wisconsin and New York (Dirr 1998). In native populations, river birch tolerates a wide range of soil pH but tends to colonize moist sites with extremely low pH (McClelland and Ungar 1970). The establishment in low pH soils may be due to lack of competition from other species rather than having a preference for low pH (Wolfe and Pittillo 1977). In reference to urban landscapes, Dirr (1998) recommends birch be planted in soils with pH below 6.5 due to prevalent chlorosis that occurs when planted in higher pH soils. Adkins et al. (2012) suggest that this pH-induced chlorosis in landscape soils is the result of iron (Fe), manganese (Mn), or zinc (Zn) deficiency but does not provide data to support this hypothesis.

Little research has addressed the nutritional requirements of birch trees in container production. Ruter (1998) compared two production systems (above-ground containers and pot-in-pot containers) and three rates of a controlled-release fertilizer (CRF) on growth and development of Heritage river birch 'Cully.' Increasing fertilizer rate resulted in greater canopy density, but not root weight or total biomass. Substrate pH was not affected by fertilizer rate, and there were only minor differences in foliar Fe, Mg, and Zn concentrations. Juntunen, Hammar, and Rikala (2003) evaluated different formulations (liquid feed or slow release) of nitrogen (N) and phosphorus (P) fertilizers on growth and nutrient leaching of container-grown silver birch (*Betula pendula* Roth), and all treatments had low pH (4.0–4.5) with little or no differences in seedling growth.

The incidence of chlorosis on birch trees in high-pH soils is observational, and the few studies that exist on nutrition in container production do not address issues of pH tolerance or its effect on plant growth and development. Therefore, the objective of this research was to evaluate growth and foliar nutrient response of river birch over a range of pH in a nursery container production setting using a predominantly pine bark substrate.

Materials and methods

The base substrate was 80 parts by volume pine bark (Buckeye Resources, Dayton, OH) and 20 parts of sphagnum peat moss (Sun Gro Horticulture, Seba Beach, Alberta, Canada), amended with 4.8 kg. m^{-3} of a CRF with micronutrients (Osmocote 15N-3.9P-10K-1.3Mg-6S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn, 8.4% NH_4-N, and 6.6% NO_3-N; The Scotts Co., Marysville, OH). The base substrate was amended with either elemental sulfur (S, Tiger 90CR Sulfur, Tiger-Sul Products, LLC, Atmore, AL) at 0.6 kg.m^{-3} or DL (ECOPHRST, National Lime and Stone Co., Findlay, OH) at 0, 1.8, 3.5, or 7.1 kg.m^{-3}. Elemental sulfur was 90% S and 10% bentonite, with a median particle diameter of 1.9 mm. The DL contained 52.4% $CaCO_3$ and 41.6% $MgCO_3$, had 103% $CaCO_3$ equivalency and 100% of the material passing through a 100-mesh sieve. Immediately after mixing the substrates, three samples of each were collected and analyzed for water- or diethylene triamine pentaacetic acid (DTPA)-extractable nutrients using a method described by Warncke (1990). Briefly, approximately 400 mL of the substrate was placed in a glass jar and saturated with either deionized water or 5 mM DTPA. The media remained saturated for 24 h, after which it was filtered (Q5 filter paper, Fisherbrand, Waltham, MA) under vacuum. Filtrate pH was determined with a pH/ion analyzer (MA 235, Metler Toledo, Columbus, OH) and electrical conductivity (EC) with a conductivity meter (Fisher 06–662-61, Thermo Fisher Scientific). Samples were subsequently filtered through GF/F binder-free borosilicate glass fiber filter paper (Whatman Ltd., Kent, UK) to remove particles greater than 0.7 µm. Each filtrate was poured into 5 mL autosampler vials, capped, and analyzed using ion chromatography (ICS 1600 Ion Chromatography System, Dionex, Bannockburn, IL) for concentrations of NO_3^-, NH_4^+, phosphate (PO_4^{3-}), K, Ca, Mg, and sulfate (SO_4^{2-}). Concentrations of micronutrients in the filtrate were determined with inductively coupled plasma optical emission spectroscopy (ICP-OES, iCAP 6300 Duo, Thermo Scientific, Waltham, MA).

Dura Heat river birch (*B. nigra* 'NBMTF') were transplanted from a 50-cell flat on 31 March 2016 into 11.4-L black plastic nursery containers filled with the amended substrates, with one plant per container. At transplant, birch trees were approximately 30 cm tall with 0.2 cm stem diameter. There were 12 single-container replications per substrate amendment so that six containers of each treatment could be destructively harvested on two different dates during the experiment. Containers were initially placed in a hoop house covered with a double layer of polyethylene with heat and vent setpoints at 1°C and 4°C, respectively. Containers were moved outdoors to a gravel-covered nursery bed on 16 May 2016 and arranged in a completely randomized design. Containers were initially irrigated with 1 cm of water per day in two cycles from an overhead irrigation system, and at 6 weeks after potting, the irrigation was increased to 1.5 cm per day. Four irrigation water samples were collected monthly throughout the experiment and measured for pH, EC, alkalinity (G20 Compact Titrator, Metler Toledo), and macronutrients with ion chromatography.

At 3 and 5 months after potting (MAP), the following data were collected on six destructively harvested containers per treatment. Containers were subjected to the pour-through technique (Wright 1986) in order to collect a 50-mL sample of the substrate solution for measurement of pH, EC, and nutrient analyses with ion chromatography and ICP as described previously. Relative chlorophyll content of birch foliage was determined with a chlorophyll meter (Minolta-502 SPAD meter, Spectrum Technologies, Inc., Plainfield, IL) by taking a measurement on five recently matured leaves per container and recording the mean. Recently matured foliage was harvested for foliar nutrient analyses (Mills and Jones 1996), rinsed with deionized water, and then oven dried at 55°C for 3 days. Samples were ground in a mill (Tecator Cyclotec AB, Hogenas, Sweden) through a 0.5 mm screen. Foliar N was determined by measuring approximately 2.5 mg of dry tissue into tin capsules (Costech Analytical, Valencia, CA) and analyzing with a CHNS/O Perkin Elmer Elementar Analyzer (PerkinElmer, Waltham, MA). Other macronutrients and micronutrients were determined using ICP after nitric acid (15.8 N) digestion in a programmable microwave (MARS 6; CEM Corp., Matthews, NC). Shoot dry weight (SDW) was determined by removing the above-ground portion of the plant, oven drying at 55°C for 3 days, and weighing. Roots visibly growing along the rootball–container interface were subjectively rated on a scale from 0 to 10, where 0 = no roots visible and 10 = 100% of the interface covered by white, healthy roots.

Data were analyzed using the general linear model procedure in SAS v9.3 (SAS Institute Inc., Cary, NC). Fisher's protected least significant difference was used to compare treatment means. Orthogonal contrast analyses were used to determine significant linear or quadratic rate responses across the DL rates, including the non-limed control.

Results and discussion

Amendment had no effect on SPAD foliar relative chlorophyll content 3 MAP ($P = 0.2420$, data not shown) and values averaged 43.4 across all treatments. By 5 MAP, the substrate amended with S resulted in the highest SPAD readings (29.2), and the non-amended control and all DL treatments had lower, but similar, SPAD readings (25.2). There was no difference in SDW at 3 MAP ($P = 0.8231$) or 5 MAP ($P = 0.1945$) with respect to lime or sulfur amendment (data not shown). Nor was there any difference in root ratings at 3 MAP ($P = 0.0681$) or 5 MAP ($P = 0.1626$). All plants grew vigorously and were of similar size and quality throughout the experiment.

In response to DL, substrate pH increased quadratically at 3 MAP and linearly and quadratically at 5 MAP (Table 1). At both dates, all limed substrates had higher pH than the non-amended control or S-amended substrate. At 3 MAP, 7.1 $kg.m^{-3}$ resulted in the highest substrate pH; however, all limed rates were similar by 5 MAP. Increasing substrate pH with the DL rates used in this study was expected and is well documented in the literature (Altland and Jeong 2016). Sulfur amendment at 0.6 $kg.m^{-3}$ did not reduce pH below that of the non-amended controls at either date. Lack of effect from the S amendment was surprising. The same rate reduced Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark pH by 1.4 units after just 2 months (Altland, Buamscha, and Horneck 2008). Likewise, Giblin and Gillman (2006) showed that various formulations of elemental S incorporated into a peat and pine bark substrate reduced pH 1 to 2 units below non-amended controls over a duration of 84 days while having no adverse effect on blueberry (*Vaccinium* ×'Northcountry')

Table 1. Nutrient levels of an 80 bark: 20 peat moss substrates amended with varying rates of elemental sulfur or dolomitic lime, prior to potting (n = 3).

	Rate	pH	Nitrate	Phosphate	Potassium	Calcium	Magnesium	Boron	Iron	Manganese	Copper	Zinc
	(kg m^{-3})		mg·L^{-1}									
Sulfur	0.6	4.8	322.4	73.4	46.2	40.9	21.8	0.2	24.6	8.6	3.8	4.6
Control		4.9	388.8	75.7	46.7	42.4	21.8	0.2	13.7	5.9	2.0	2.9
Lime	1.8	5.7	481.8	101.0	62.0	47.4	35.7	0.0	2.6	2.3	0.7	1.2
	3.5	6.0	634.3	139.9	76.4	65.2	52.6	0.1	9.1	10.0	2.4	2.9
	7.1	6.3	550.4	101.9	56.0	63.3	49.4	0.0	9.8	12.1	2.8	5.3

growth. Averaging across all treatments, substrate pH increased by 1.0 unit from the beginning of the experiment to 3 MAP and an additional 0.3 pH units by 5 MAP (Tables 1 and 2). The increase in pH over time was likely the result of irrigation water alkalinity (208.3 mg.L^{-1}) (Table 3), which was typical of irrigation water used by greenhouse and nursery producers in the US (Argo, Biernbaum, and Warncke 1997) but still three times higher than recommended (Yeager et al. 2007).

At 3 MAP, substrate EC was not affected by treatment (Table 1). By 5 MAP, substrates receiving 7.1 kg.m^{-3} DL had higher EC than those amended with 0 or 1.8 kg.m^{-3}. Despite these minor differences, all substrates had EC near or within the recommended range of 1.0–3.5 mS.cm^{-1} (Cavins et al. 2000).

Leachate NO_3^- concentrations were similar across treatments 3 MAP (Table 1), although this was likely due to high variability in the data. By 5 MAP, S-amended substrates had higher NO_3^- concentrations than all other treatments except the non-limed control. Leachate NH_4^+ concentrations were greatest in S-amended substrates at 3 and 5 MAP. At 3 MAP, NH_4^+ concentrations decreased with increasing DL rate. By 5 MAP, there was a similar trend across DL rates, although there was no significant rate response. Nitrification of NH_4^+ increases with pH in soilless substrates (Niemiera and Wright 1986), and thus, slightly higher NH_4^+ concentrations would be expected in lower pH substrates.

Foliar N decreased linearly with increasing DL rate at 3 and 5 MAP (Table 4). Others have also shown decreasing foliar N in container-grown plants with increasing pH. Harvey, Elliott, and Brand (2004) reported a decrease in foliar N in *Hakonechloa* with increasing DL rate from 0 to 9.5 kg.m^{-3} and suggested that more N was available for plant uptake at lower DL incorporation rates and pH. Likewise, Chrustic and Wright (1983) reported higher shoot N in holly (*Ilex crenata* 'Helleri'), juniper (*Juniperus chinensis* 'San Jose'), and azalea (*Rhododendron obtusum* 'Rosebud') at lower DL rates and attributed greater growth of these crops at low lime rates to greater N, P, and K availability. Gillman, Dirr, and Braman (1998) reported that butterfly bush (*Buddleia davidii* 'Royal Red') foliar N was highest in non-limed controls; however, trends in shoot N with increasing DL rates did not follow a clear pattern. Reduced foliar N could be due to a combination of increased nitrification (biological conversion of NH_4^+ to NO_3^-) in higher pH substrates, followed by greater leaching of NO_3^-N compared to NH_4^+ -N. For example, Niemiera and Wright (1986) reported that in a 100% pine bark substrate fertilized with ammonium sulfate [$(NH_4)_2SO_4$], NH_4^+ concentration decreased rapidly and NO_3^- concentration increased when it was amended with 3 or 6 kg.m^{-3} DL. Ammonium

Table 2. Water pH, electrical conductivity (EC), alkalinity, and macronutrients in irrigation water.

pH		8.1
EC	mS·cm^{-1}	0.6
Alkalinity	mg L^{-1}	208.3
Nitrate	mg L^{-1}	1.2
Phosphate	mg L^{-1}	2.4
Potassium	mg L^{-1}	0.4
Calcium	mg L^{-1}	58.6
Magnesium	mg L^{-1}	23.5
Sulfate	mg L^{-1}	20.6

Table 3. Leachate pH, electrical conductivity (EC), and nutrient concentration from container-grown birch (*Betula nigra* ‘NBMTF’) trees in an 80 pine bark: 20 peat moss substrates amended with either elemental sulfur or dolomitic lime at three rates. Leachates were collected by using the pour-through procedure and 3 and 5 months after potting (MAP).

MAP	Amendment	Rate	pH	EC	NO_3^-	NH_4^+	PO_4^{3-}	K	Ca	Mg	SO_4^{2-}	B	Fe	Cu	Mn	Zn
		(kg m^{-3})			(mg L^{-1})											
3	Sulfur	0.6	6.1	3.1	726.3	7.7	35.1	125.9	153.8	36.0	825.1	0.56	1.40	0.09	4.10	0.59
	Control	0	6.2	2.1	477.7	4.5	209.9	78.1	88.8	33.8	207.9	0.47	0.86	0.06	1.71	0.66
	Dol. lime	1.8	6.6	2.7	894.6	0.6	28.3	103.8	143.2	42.6	402.1	0.41	0.61	0.11	0.97	0.55
		3.6	6.8	3.1	1070.8	0.3	16.7	104.5	176.4	48.0	513.2	0.23	0.04	0.06	0.22	0.22
		7.1	7.2	2.1	412.5	0.0	17.1	79.9	105.0	37.8	369.8	0.11	0.05	0.03	0.05	0.15
			Q*[a]	NS	NS	L***Q***	NS	NS	L**	NS	L**	L***	L***	L*Q*	L***	L***
		LSD$_{0.05}$[b]	0.4	NS	NS	1.2	NS	33.6	62.7	NS	212.3	0.11	0.42	0.04	0.78	0.20
5	Sulfur	0.6	6.2	1.1	34.4	7.6	43.1	31.2	42.5	21.6	184.2	0.17	0.23	0.03	0.29	0.13
	Control	0	6.4	0.9	21.7	1.1	36.9	19.3	32.0	21.5	74.9	0.21	0.15	0.03	0.15	0.30
	Dol. lime	1.8	7.1	0.9	15.9	0.4	49.1	19.3	32.7	27.4	61.9	0.16	0.06	0.01	0.04	0.07
		3.6	7.3	1.2	5.8	0.1	8.9	25.6	39.8	36.1	125.8	0.12	0.03	0.02	0.02	0.11
		7.1	7.2	1.5	10.6	0.0	7.6	40.9	58.6	44.5	191.9	0.08	0.06	0.03	0.03	0.08
			L**Q*	NS	NS	NS	NS	NS	NS	NS	NS	L***	L*Q*	NS	L*	L***Q***
		LSD$_{0.05}$	0.5	0.34	15.5	3.12	NS	13.52	19.12	8.2	98.0	0.07	0.07	NS	0.10	0.05

[a] L and Q represent linear and quadratic response to lime rate, respectively. *, **, and *** represent significance at the 0.05, 0.01, and 0.001 levels, respectively. NS indicates no significant rate response.

[b] Fisher’s least significant difference value where α = 0.05.

Table 4. Foliar nutrient concentration in leaves of birch (*Betula nigra* ‘NBMTF’) trees grown in an 80 pine bark: 20 peat moss substrates amended with elemental sulfur or several rates of dolomitic lime. Foliar tissue samples were collected 3 and 5 months after potting (MAP).

WAP	Amendment	Rate	N	P	K	Ca	Mg	S	B	Fe	Cu	Mn	Mo	Zn
		(kg m^{-3})				-(%)-						-(mg kg^{-1})-		
3	Sulfur	0.6	2.89	0.38	0.99	0.57	0.28	0.27	28.5	179.9	7.5	1676.4	0.000	133.2
	Control	0	2.99	0.38	1.04	0.60	0.30	0.27	30.9	215.3	7.3	1467.5	0.005	124.5
	Dol. lime	1.8	3.40	0.37	1.11	0.66	0.34	0.31	23.6	159.9	4.8	996.9	0.000	91.8
		3.6	2.72	0.34	1.04	0.61	0.33	0.27	20.6	74.6	3.5	268.3	0.061	79.2
		7.1	2.39	0.32	1.07	0.61	0.38	0.23	21.5	51.1	3.1	140.9	0.137	90.2
			L*[a]	L***	NS	NS	L***	L**	L***Q***	L***Q*	L***Q***	L***Q***	L***	L***Q***
		LSD$_{0.05}$[b]	0.71	0.03	NS	0.05	0.03	0.04	2.3	51.1	0.8	273.3	0.075	10.9
5	Sulfur	0.6	3.44	0.42	1.46	0.54	0.38	0.27	41.5	135.1	8.8	708.2	0.000	111.2
	Control	0	2.89	0.31	1.29	0.48	0.35	0.21	33.5	93.7	7.6	568.8	0.028	94.1
	Dol. lime	1.8	3.06	0.37	1.26	0.60	0.41	0.22	34.2	118.4	4.3	429.8	0.066	78.2
		3.6	2.66	0.30	1.03	0.64	0.44	0.18	32.6	73.3	3.5	128.4	0.144	62.7
		7.1	2.43	0.30	1.09	0.71	0.49	0.18	35.5	69.5	3.1	91.2	0.275	71.8
			L***	NS	L***Q*	L***Q**	L***Q*	L**	NS	L***	L***Q***	L***Q***	L***	L***Q***
		LSD$_{0.05}$	0.32	0.04	0.12	0.05	0.03	0.03	2.8	17.9	0.9	84.9	0.062	7.5

[a] L and Q represent linear and quadratic response to lime rate, respectively. *, **, and *** represent significance at the 0.05, 0.01, and 0.001 levels, respectively. NS indicates no significant rate response.

[b] Fisher’s least significant difference value where α = 0.05.

decreased more slowly, and NO_3^- was not detected in the substrate not amended with DL. They attributed this effect to the limed containers having more rapid nitrification. Pine bark substrates have a cation exchange capacity similar to other organic substrates and generally ranges from 40 to 75 meq/L (Altland, Locke, and Krause 2014). In contrast, pine bark has no measurable anion exchange capacity (personal observation, data not published). Therefore, NO_3^- anions leach readily, while NH_4^+ cations are bound. Higher pH substrates that promote the conversion of NH_4^+ into NO_3^- via nitrification would presumably leach N more quickly than lower pH substrates, assuming that some fraction of the applied N was in the form of urea or NH_4^+, as it was in this study.

There were no differences in leachate PO_4^{3-} concentrations due to lime or S treatment at either date (Table 1). Leachate K, Ca, Mg, SO_4^{2-}, and Cu were affected by treatment, but with no clear or consistent trend. Although leachate Ca and Mg were somewhat erratic as DL rate increased, foliar Ca (5 MAP) and Mg (3 and 5 MAP) increased with increasing lime rate (Table 4). DL, the lime source used in this study, would have provided an increasing concentration of Ca and Mg with an increasing rate of incorporation.

Leachate B, Fe, Mn, and Zn decreased with increasing DL rate (Table 1). Leachate Fe and Mn were higher in S-amended substrates compared to all other treatments at both dates. Increased lime rate and substrate pH have been shown to reduce micronutrient availability in organic soils and soilless substrates. Peterson (1980) documented the effect of substrate pH on micronutrient availability in a well-fertilized commercial greenhouse substrate (peat moss, perlite, vermiculite, granite sand, and composted pine bark; ratios not given) and also reported decreasing availability of B, Fe, Mn, and Zn, along with Cu, with increasing pH. In non-fertilized douglas fir (*Pseudotsuga menziesii*) bark (DFB), Altland and Buamscha (2008) found that DTPA-extractable B and Fe, in addition to Cu and aluminum (Al), decreased with increasing pH. In fertilized DFB, however, B and Fe still decreased with increasing pH, but Cu, Mn, and Zn behaved unexpectedly; they increased and then decreased over the range of observed pH (Altland, Buamscha, and Horneck 2008).

Foliar Fe, Cu, Mn, and Zn decreased linearly with increasing lime DL rate at 3 and 5 MAP, while B decreased with increasing DL rate only at 3 MAP (Table 4). Adkins et al. (2012) hypothesized that pH-induced chlorosis in river birch grown in landscape soils results from Fe, Mn, or Zn deficiency. These three nutrients indeed decreased with increasing DL rate in our study in both leachates and foliar tissue, but only Cu and Mn fell slightly below the minimum recommended values for foliar nutrient concentrations of 4 and 151 $mg.kg^{-1}$ (Mills and Jones 1996), respectively, at DL rates of 3.6 $kg{\cdot}m^{-3}$ or higher. Leachate Mo concentrations were undetectable in leachates (data not shown). Foliar Mo increased with increasing DL rate (Table 4). Foliar Mo often increases with increasing pH in soilless substrates. Smilde (1975) reported decreased foliar tissue concentrations of B, Fe, Mn, and Zn in chrysanthemum (*Dendranthema ×grandiflorum* L. 'Neptune') with increasing lime application, while Mo was the only micronutrient that increased. Likewise, Cox (1988) showed that using lime to raise the pH of a peat moss substrate alleviated Mo deficiency symptoms in poinsettia (*Euphorbia pulcherrima* Willd. ex Klotz).

The objective of this research was to determine growth and foliar nutrient response of container-grown river birch to pH in a predominantly pine bark substrate. Substrate pH ranged from 4.8 to 7.3 throughout the experiment (Tables 1 and 3). Despite differences in substrate pH between treatments at 3 and 5 MAP, there were only a few and minor differences in plant appearance and no differences in plant growth. While there were measurable differences in nutrient concentrations in substrate leachates and foliar tissue, these differences were not substantial enough to affect the appearance or growth of birch trees. Although nutrient availability in bark-based substrates is dependent on substrate pH (Altland, Buamscha, and Horneck 2008; Peterson 1980), it may not be as critical to birch trees in container substrates as it is in mineral soils. Physical properties of mineral field soils vary depending on their texture class but have approximately 50% total porosity (TP), which is constituted by 20–30% each for airspace (AS) and water holding capacity (WHC) (Brady and Weil 1996). In contrast, substrates used in container-grown crops have up to 85% TP, comprised of 20–30% AS and 50–60% WHC

(Yeager et al. 2007). Greater porosity of container substrates requires near-daily irrigation of plants and provides a large reservoir of nutrient solution within the container. It is possible that the near-hydroponic nature of container growing media renders container-grown plants less sensitive to pH-dependent changes in nutrient availability. Based on data presented here, birch trees grown in a pine-bark substrate can be grown over a wide range of substrate pH with little or no effect on their growth or nutrient status.

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