Substrate pH and Butterfly Bush Response to Dolomitic Lime or Steel Slag Amendment[1]

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Abstract

Steel slag (SS) is a fertilizer amendment with a high concentration of calcium oxide, and thus capable of raising substrate pH similar to dolomitic lime (DL). Steel slag, however, contains higher concentrations of some nutrients, such as iron, manganese, and silicon, compared to DL. The objective of this research was to determine the effect of SS rate on pH in a substrate composed of 80 pine bark:20 sphagnum peatmoss (v:v), as well as growth and nutrient concentration of butterfly bush (*Buddleja davidii* 'Pink Delight' Franch.). The base substrate was amended with either DL or SS at rates of 0, 0.6, 2.4, 4.8, 9.5, or 14.3 kg·m^{-3}. Substrates were placed into 12-L nursery containers and potted with a single butterfly bush per container. Dolomitic lime amendment resulted in higher substrate pH at rates from 0.6 to 4.8 kg·m^{-3} while the SS amendment caused a greater increase in pH at rates higher than 4.8 kg·m^{-3}. Butterfly bush responded well to all but the highest SS rate applied. As the rate of SS increased to 14.3 kg·m^{-3}, decreased Mg availability may have reduced shoot growth. Based on the results of this experiment, SS could be used as an alternative to DL. However, incorporation rates would need to be adjusted slightly higher for SS compared to DL to achieve a desired pH in the range of 6 to 6.5.

Index words: calcium, container production, magnesium, nursery substrate.

Species used in this study: 'Pink Delight' butterfly bush (*Buddleja davidii* Franch.).

Significance to the Horticulture Industry

Steel slag (SS) is a byproduct of the steel industry. Similar to dolomitic lime (DL), it is white to gray in color, available in a range of particle sizes, and useful for raising soil pH. A SS material has recently been made available for horticultural uses. In addition to its use as a liming agent, SS typically has high concentrations of micronutrients and provides a source for plant-available silicon. The objective of this research was to determine how SS rates affects pH of pine bark substrates, as well as growth of butterfly bush, in comparison to DL. Dolomitic lime resulted in higher substrate pH at rates from 0.6 to 4.8 kg·m^{-3} while the SS caused a greater increase in pH at rates higher than 4.8 kg·m^{-3}. Butterfly bush grew well when amended with either DL or SS, except the highest SS rate of 14.3 kg·m^{-3}.

Introduction

Substrates used in production of container-grown trees and shrubs are composed primarily of softwood tree bark amended with peatmoss, sand, gravel, compost, or other minor components. The species of softwood tree is highly dependent on the dominant forest species in the region where the nursery operation is located. Pine bark is typically used in the eastern United States, comprising 75 to 100% of the substrate volume in most nursery operations (Lu et al. 2006).

Ground pine bark pH ranges from 4 to 4.5 prior to amendment with other components or fertilizers. Dolomitic limestone (DL) is used almost universally as the neutralizing agent for raising pH in nursery substrates to a desired range of 6 to 6.5. Plant growth and substrate pH response to DL rate varies by crop and substrate type, respectively. Harvey et al. (2004) demonstrated that DL rates from 0 to 9.5 kg·m^{-3} in a pine bark:sphagnum peatmoss:sand (3:2:1, by vol) substrate resulted in a pH range from 4.5 to 7.2, with optimal hakonachloa [*Hakonachloa macra* 'Aureola' (Munro) Makino] growth at pH 4.5. Walden and Epelman (1988) grew boxwood [*Buxus microphylla* var. *japonica* (Müll. Arg.) Rehd. & E. H. Wils.] in a 6 pine bark:1 sand substrate with lime rates from 0 to 8 kg·m^{-3} and found that root and shoot growth was maximized at the highest lime rate, which resulted in a pH of 6.1. Butterfly bush (*Buddleia davidii* 'Royal Red' Franch.) grown in 100% pine bark over a pH range of 4.4 to 6.4 had optimal growth and flowering at pH 5.6 (Gillman et al. 1998).

In addition to changing substrate pH, DL also provides a source of calcium (Ca) and magnesium (Mg) for container-grown plants. Gillman et al. (1998) showed that substrate solution and butterfly bush leaf concentrations of Ca and Mg increased with increasing DL rate. Argo and Biernbaum (1996) suggested that DL can buffer Ca and Mg concentrations and pH due to the amount of unreactive DL that remains after initial reaction at substrate mixing. Dolomitic lime can contain trace amounts of other elements depending on the location and geologic properties of the mined deposits. The DL used in Ohio nurseries are typically mined from northwest Ohio and originated from bedrock of Devonian and Silurian age deposits (Wolfe 2009). These would have been formed from marine water, with a low percentage (< 3%) of silica (SiO_2), aluminum (Al), and iron (Fe) compounds, with trace amounts of strontium (Sr), sulfur (S), and zinc (Zn) (Wolfe 2009).

Steel slag (SS) has been identified as a possible alternative for adjusting substrate pH in nursery containers. Steel slag is a byproduct of the steel industry, with potential as a liming agent for container substrates. As steel scraps and iron ore are melted in a basic oxygen furnace (BOF), calcium oxide (CaO) and DL are introduced as fluxing agents to remove impurities from the molten steel (Yildirim and Prezzi 2011). Mineral impurities removed by the fluxing agents, along with the CaO and DL, form a molten slag. The slag is poured off from the steel, cooled, and processed into particle size frac-

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tions ranging from dust to gravel. Properties of SS vary by the type of furnace in which steel is produced (Yildirim and Prezzi 2011). Despite these differences, most SS are similar in chemical composition, being composed primarily of CaO, SiO_2, and iron oxide (FeO), with CaO making up more than 35% of SS mass (Yildirim and Prezzi 2011).

To serve as an acceptable alternative to DL, SS should not only elevate pH, but also provide a source of Ca and Mg, while buffering these two nutrients and pH over time. Rodriguez et al. (1994) demonstrated increased soil pH and yield of perennial ryegrass (*Lolium perenne* L.), orchardgrass (*Dactylis glomerata* L.), and white clover (*Trifolium repens* L.) following applications of SS on pastures. Likewise, Ali and Shahram (2007) showed SS elevated pH of acidic soils and increased corn (*Zea mays* L.) shoot dry mass. While no research could be found that addressed the use of SS as a container substrate amendment, Mayfield et al. (2002) demonstrated that CaO, the primary neutralizing compound in SS, was a suitable alternative to DL for the production of container-grown heavenly bamboo (*Nandina domestica* 'nana purpurea' Thunb.). The objective of this research was to measure substrate pH over time, as well as butterfly bush growth, in substrates amended with either SS or DL.

Materials and Methods

The base substrate was comprised of pine bark (Buckeye Resources, Dayton, OH) and sphagnum peatmoss (Sun Gro Horticulture, Seba Beach, Alberta, Canada) (80:20, by vol), amended with 4.8 $kg \cdot m^{-3}$ of a controlled release fertilizer with micronutrients (Osmocote 15N-3.9P-10K-1.3Mg-6S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn, The Scotts Co., Marysville, OH). The base substrate was amended with either dolomitic lime (DL) or steel slag (SS) at rates of 0, 0.6, 2.4, 4.8, 9.5, or 14.3 $kg \cdot m^{-3}$. The DL (ECOPHRST, National Lime and Stone Co., Findlay, OH) contained 52.4% calcium carbonate ($CaCO_3$) and 41.6% magnesium carbonate ($MgCO_3$), had 103% calcium carbonate equivalency (CCE) and 100% of the material passing through a 100-mesh sieve. The SS (Plant Tuff, Edward C. Levy Co., Dearborn, MI) contained 38.4% CaO, 29.5% FeO, 13.3% SiO_2, 8.5% magnesium oxide (MgO), 3.8% aluminum oxide (Al_2O_3), and 3.4% manganese oxide (MnO), had 73% CCE with 27% passing through a 100-mesh sieve.

Butterfly bush (*Buddleja davidii* 'Pink Delight' Franch.) were transplanted from a 72-cell flat on May 13, 2014, into 11.4 L (3 gal) black nursery containers filled with the amended substrates, with one plant per container. There were five single-container replications per substrate amendment, arranged in a completely randomized design on a gravel-covered outdoor nursery production site in Wooster, OH. Containers were initially irrigated with 0.64 cm (0.25 in) water per day in two cycles from an overhead irrigation system, and at 6 weeks after potting the irrigation was increased to 1.2 cm (0.5 in) per day.

At 1, 4, and 16 weeks after potting (WAP), 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, electrical conductivity (EC), and nutrient analyses. Substrate solutions were immediately measured for pH and EC then frozen until nutrient analyses were performed. At the time of nutrient analysis, samples were thawed and filtered through GF/F binder-free borosilicate glass fiber filter paper (Whatman Ltd., Kent, UK) to remove particles greater than 0.7 µm. Concentration of macro and micronutrients (excluding N) were determined by adding 1 mL of filtered solution sample with 9 mL of 3.89% nitric acid (HNO_3) in 18 MΩ water, and then analyzed with optical emission spectroscopy (iCAP 6300 Duo, Thermo Scientific, Waltham, MA). Relative chlorophyll content of butterfly bush foliage was determined at 4, 8, 12, and 16 WAP 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 for each experimental unit. At the conclusion of the experiment, 16 WAP, recently matured butterfly bush foliage was harvested for foliar nutrient analyses (Mills and Jones 1996), rinsed with deionized water, then oven dried at 55 C for 3 d. Samples were ground in a mill (Tecator Cyclotec AB, Hogenas, Sweden) through a 0.5 mm screen. Foliar nitrogen (N) was determined measuring approximately 2.5 mg of dry tissue into tin capsules (Costech Analytical, Valencia, CA) and analyzing with a CHNS/O PerkinElmer 2400 Series II Analyzer (PerkinElmer, Waltham, MA). Other macronutrients and micronutrients were determined by first processing samples with microwave digestion (MARS 6, CEM Corp., Matthews, NC) then injection in an optical emission spectrometer (iCAP 6300 Duo). Immediately after leaf tissue harvests at 16 WAP, shoot dry weight (SDW) was determined by removing the above ground portion of the plant, oven drying at 55 C for 3 d, 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.

Electrical conductivity, substrate pH, and SPAD were subjected to repeated measures analysis of variance (ANOVA) using the 'repeated' option in the general linear model (GLM) procedure of SAS v.9.3 (SAS Institute Inc., Cary, NC). Substrate extractable nutrients, shoot dry weight, and foliar nutrient data were subjected to ANOVA using the GLM procedure. Fisher's protected least significant difference was used to compare treatment means. Substrate pH response to amendment rate were fit to exponential curves ($pH = a + b \cdot (1 - e^{-cx})$ where x = amendment rate, a is the predicted pH when $x = 0$, the sum $a + b$ is the maximum extrapolated pH as x approaches infinity, and c is a scaling parameter. Exponential models were fit using the 'NLIN' procedure in SAS. Fitted parameters were compared using the sums of squares reduction (SSR) test (Schabenberger and Pierce 2002), in which *P*-values were generated to test the hypothesis that the fitted equations were similar. All statistical analyses were conducted with SAS v.9.3, while exponential functions were plotted with SigmaPlot v.12 (Systat Software, Inc., San Jose, CA).

Results and Discussion

Substrate pH responded to DL and SS differently (P = 0.0001). At 1 WAP, substrate pH in DL-amended substrates increased up to a maximum of 6.5, the sum of parameters $a + b$ in the fitted equation (Fig. 1). Substrate pH in these containers leveled off above the 4.8 $kg \cdot m^{-3}$ rate. In contrast, substrate pH did not level off within the range of applied SS rates. The exponential equation suggests that the extrapolated maximum pH would be 8.7. The same disparity in pH response curves between DL and SS amendments were observed in an 85 sphagnum peatmoss:15 perlite substrate (Altland et al. 2015). By 4 WAP, the maximum pH for DL-

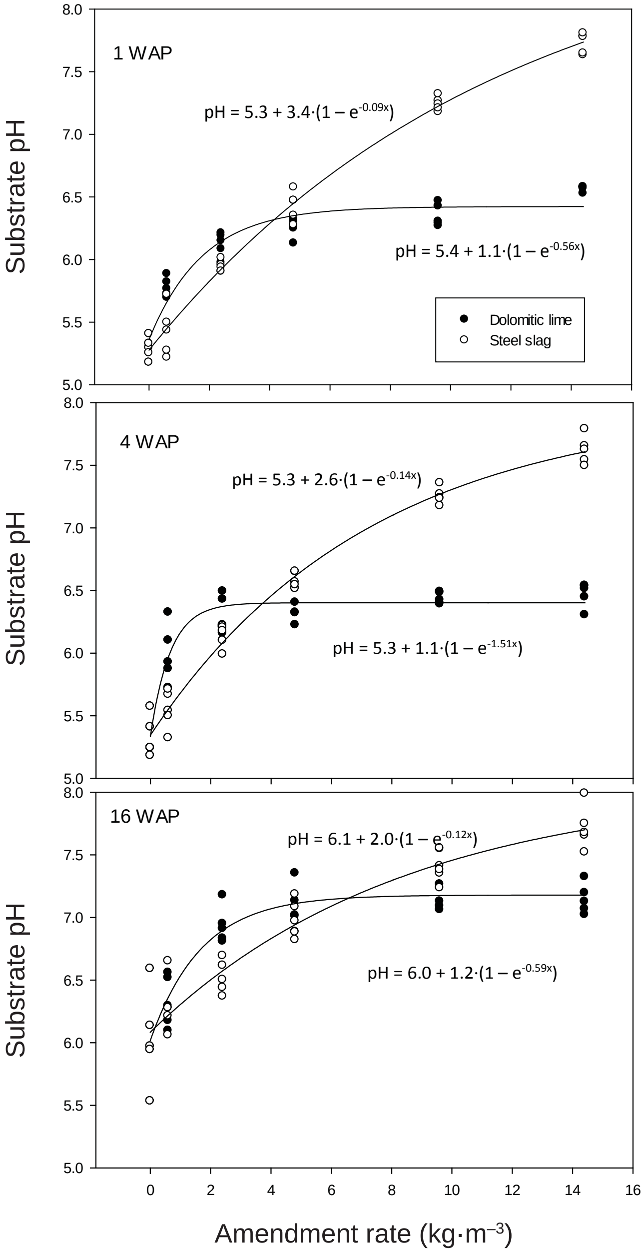

Fig. 1. Response of a 80 pine bark:20 sphagnum peatmoss substrate amended with 0, 0.6, 2.4, 4.8, 9.5, or 14.3 kg·m^{-3} dolomitic lime or steel slag and planted with a single butterfly bush (*Buddleja davidii* 'Pink Delight'). Substrate pH was measured 1 week after potting (WAP, top), 4 WAP (middle), and 16 WAP (bottom).

amended substrates was 6.4 and thus changed very little from 1 WAP. However, the estimated parameter *c* was more negative at 4 WAP compared to 1 WAP (–0.90 vs –0.34), and thus the steepness of the sloped portion of the curve was greater at 4 WAP, resulting in a curve with a more distinct elbow shape. Substrate response to SS was slightly less at 4 WAP compared to 1 WAP, with a maximum extrapolated pH of 7.9 (compared to 8.7 at 1 WAP). However, the pH-response curve was similar in that maximum pH was not achieved with the SS rates used, and maximum pH could only be calculated with the fitted exponential function. By 16 WAP, substrate pH in DL-amended substrates increased, with a maximum pH of 7.2. The alkalinity of the irrigation water used in this experiment contains approximately 220 mg·L^{-1} total carbonates, which is considered moderate to high by most irrigation standards (Lopez and Mickelbart 2010) and has the potential to raise pH of soilless substrates over time. The maximum extrapolated pH of SS-amended substrates was 8.1.

While maximum attainable pH was greater for SS amendments at each sampling date, the shape of the response curves show that DL is more effective than SS at elevating pH at lower rates. At rates up to and including 4.8 kg·m^{-3}, pH response was higher for DL-amended substrates. This is reflected in the more negative c parameter in each of the fitted equations for DL-amended substrates compared to SS-amended substrates (Fig. 1). It is also visually apparent in the pH-response curves by the steeper slope of DL-amended substrates at lower amendment rates, and the more pronounced curve of DL-amended substrates compared to the relatively arching curve of SS-amended substrates.

The greater impact of SS on substrate pH at higher rates was surprising considering the DL used in this trial had greater CCE than the SS (103 v. 73%, respectively). Another factor that affects the neutralizing power of a liming agent is particle size. Some states incorporate particle size of the lime material into the CCE calculation, to determine what is often referred to as 'effective calcium carbonate equivalency' (ECCE). In this trial, the DL had finer particle size distribution than the SS and thus should have been more reactive, but was not at higher rates. The primary liming agent is CaO in SS, and $CaCO_3$ in DL. The SS used in this experiment contained 34.8% CaO. Calcium oxide, the primary liming agent in SS, is over 100 times more water-soluble than $CaCO_3$, the primary liming agent in DL [0.19 vs 0.0013 g·100 mL in water at 25 C (Wulfsberg 2000)]. The greater solubility of CaO allowed for quicker reaction in soilless substrates and greater attainable substrate pH at higher rates. Similar and stable pH response curves were reported for a 85 peatmoss:15 perlite substrate over a period of 8 weeks (Altland et al. 2015); however, it was suggested that over a longer period of time, the higher CCE of DL might ultimately result in a greater increase in pH (Altland et al. 2015). This was not the case as the higher pH levels from the CaO in the SS-amended substrates was maintained through a 16-week production cycle in this experiment, a period of time that would be typical for many container-grown shrubs in pine bark-based substrates.

Repeated measures showed that EC was affected by an interaction between time, amendment, and rate ($P = 0.0006$). There were differences among treatments with respect to EC at each date, however, differences were inconsistent and lacked any generalizations with respect to treatment (data not shown). Furthermore, all substrate EC of all treatments were within normal and acceptable ranges for container production (Yeager et al. 2007). Across all treatments, substrate EC peaked at 4 WAP when values ranged from 2.0 to 2.9 mS·cm^{-1}, then declined to levels ranging from 0.9 to 1.5 throughout the remainder of the study.

Foliar SPAD chlorophyll readings were not affected by treatment throughout the experiment (data not shown). Repeated measures showed that SPAD values changed over time ($P < 0.0001$), but there was no interaction between time and amendment or rate. Average foliar SPAD was 48.1 across all treatments at 4 WAP, and increased slightly to 50.2 by 16 WAP. All plants appeared to have healthy green foliage throughout the experiment, with no visual signs of nutrient deficiency or toxicity.

At the conclusion of the experiment, 16 WAP, butterfly bush SDW and root rating were affected by an interaction between amendment type and rate (Table 1). Shoot dry weight was unaffected by DL rate, and all plants amended with DL were similar to the non-amended controls. In contrast, SDW decreased linearly with increasing SS rate. Butterfly bush SDW was greatest with 2.4 kg·m^{-3} SS; at this rate, SS-amended plants were larger than those amended with the same rate of DL. However, SDW decreased with higher SS rates, and plants amended with 14.3 kg·m^{-3} SS had less SDW than those amended with the same DL rate. Root ratings did not respond to amendment rate in DL or SS amended substrates but did respond to amendment type. Similar to SDW, root ratings from plants amended with 2.4 kg·m^{-3} SS were greater than those amended with the same rate of DL and plants amended with 14.3 kg·m^{-3} SS had lower root ratings than those amended with the same rate of DL.

Amendment type or rate affected all of the measured foliar nutrient concentrations (Table 2, micronutrient data not shown). Despite differences, all nutrients were at or above recommended levels for butterfly bush (Mills and Jones 1996). Foliar phosphorus (P), calcium (Ca), and S concentrations were affected by amendment type. Foliar P was slightly higher in plants growing with DL-amended substrates compared to those with SS-amended substrates (0.29 vs 0.27%). Leachate P concentration, however, was affected by an interaction between amendment type and rate (Table 3). Leachate P concentration decreased linearly with increasing DL rate at 1 WAP, but did not respond to DL rate thereafter (Table 3). This agrees with other studies that have shown a decrease in leachate P with increasing DL rate and a concomitant increase in pH (Altland et al. 2008; Chrustic and Wright 1983; Midcap 1999). In contrast, leachate P concentration decreased with increasing SS rate throughout the experiment. This may be due to higher Ca concentrations in SS-amended substrates that could lead to the formation of calcium phosphate precipitates. Despite wide-ranging concentrations of leachable P throughout the experiment, there was very little difference in foliar P concentrations, demonstrating the relatively low levels of substrate P needed to support crop growth. In contrast, Chrustic and Wright (1983) reported a significant linear decrease in foliar P of 'Rosebud' azalea (*Rhododendron obtusum* (Lindl.) Planch.) and Helleri' holly (*Ilex crenata* Thunb.) with increasing DL rate, from 0 to 8 kg·m^{-3}; however, the decreases in foliar P were relatively minor.

Foliar Ca was higher in SS-amended substrates than DL-amended substrates (1.82 vs 1.73%) (Table 2). Leachate Ca increased with increasing DL and SS amendment rate at 1 WAP, although the magnitude of the increase was greater in SS-amended substrates (Table 3). The greater solubility of CaO in SS is likely responsible for higher foliar and leachate Ca in SS-amended substrates. By 4 WAP, leachate Ca increased across all treatments relative to concentrations at 1 WAP. At 4 WAP, only amendment rate affected leachate Ca concentration, with concentration increasing with increasing rate. By 16 WAP, concentrations were again affected by an interaction between amendment type and rate, with leachate Ca increasing more in SS-amended substrates than DL-amended substrates.

Foliar S was also slightly higher in plants growing in DL-amended substrates compared to those in SS-amended substrates (0.53 vs 0.47%) (Table 2). Leachate S concentration was affected by amendment type and rate, although trends were difficult to characterize with consistency (Table 3). Like foliar S concentrations, leachate S concentrations were slightly higher in DL-amended substrates than SS-amended substrates.

Foliar potassium (K) was affected only by amendment rate (Table 2) and decreased linearly with increasing amendment rate. A similar response was observed in 'Sky Rocket' juniper (*Juniperus virginiana* L.) (Cobb and Zarko 1983), 'Rosebud' azalea, and 'Helleri' holly (Chrustic and Wright, 1983). Foliar K levels by treatment were not reflective of leachate K concentrations throughout the experiment. At 1 and 4 WAP, leachate K in substrates amended with 0.6 kg·m^{-3} DL were lower than non-amended controls, but then increased with increasing DL, up to the 9.5 kg·m^{-3} rate. Leachate K concentrations at 1 and 4 WAP in SS-amended substrates were more erratic, despite the significant quadratic response indicated. Leachate K concentrations did not respond to treatment at 16 WAP. Considering the different response to treatment observed in leachate versus foliar K concentrations, it is likely that foliar K levels responded to some factor other than K concentration in the substrate solution. Potassium, Ca, and Mg uptake are each affected by the concentration ratios of these three cations in solution, with a notable antagonism between K and Ca (Mills and Jones

Table 1. Butterfly bush (*Buddleja davidii* 'Pink Delight') shoot dry weight and root ratings 16 weeks after planting into containers filled with an 80 pine bark:20 sphagnum peatmoss substrate amended with five rates of dolomitic limestone or steel slag.

Amendment	Rate (kg·m^{-3})	Shoot dry weight (g)	Root rating[z]
None	0	163.4	5.4
Dolomitic lime	0.6	143.2	5.8
	2.4	153.6	5.2
	4.8	153.0	6.4
	9.5	150.6	6.2
	14.3	156.8	6.2
Significance[y]		NS	NS
Steel slag	0.6	151.1	5.8
	2.4	178.2	6.4
	4.8	143.8	5.6
	9.5	142.2	6.2
	14.3	106.9	5.0
Significance		L***	NS
$LSD_{0.05}$[x]		22.5	1.1
Main effects			
Amendment		0.1688	0.5327
Rate		0.0031	0.6349
Interaction		0.0005	0.0476

[z]Rated on a scale from 0 to 10 where 0 = no roots visible and 10 = 100% of the interface covered by white, healthy roots.

[y]Indicates a non-significant (NS), linear (L), or quadratic (Q) rate response in the measured parameter to amendment rate, where *, **, or *** represent P-values of 0.05, 0.01, or 0.001.

[x]Least significant difference within a column where α = 0.05.

Table 2. Foliar nutrient concentrations of butterfly bush (*Buddleja davidii* 'Pink Delight') grown for 16 weeks in a 80 pine bark:20 sphagnum peatmoss substrate amended with five rates of dolomitic lime or steel slag.

Amendment	Rate	P	K	Ca	Mg	S
	($kg \cdot m^{-3}$)	%				
None	0	0.28	0.99	1.63	0.40	0.45
Dolomitic lime	0.6	0.32	0.96	1.88	0.44	0.54
	2.4	0.28	0.95	1.59	0.40	0.52
	4.8	0.28	0.83	1.74	0.42	0.51
	9.5	0.28	0.79	1.71	0.45	0.55
	14.3	0.28	0.82	1.70	0.43	0.52
Significance[z]		NS	L***	NS	NS	NS
Steel slag	0.6	0.29	0.97	1.77	0.40	0.49
	2.4	0.26	0.94	1.68	0.30	0.46
	4.8	0.26	0.85	1.84	0.28	0.43
	9.5	0.28	0.75	1.87	0.27	0.50
	14.3	0.24	0.75	1.94	0.25	0.46
Significance		NS	L***	L**	L***Q***	NS
$LSD_{0.05}$[y]		0.04	0.14	0.20	0.04	0.07
Recommended values[x]		0.2–0.5	0.7–3.0	0.75–2.0	0.2–0.4	0.23–0.5
Main effects						
Amendment		0.0263	0.5930	0.0464	0.0001	0.0003
Rate		0.0769	0.0005	0.0593	0.0001	0.1851
Interaction		0.6595	0.8987	0.2054	0.0001	0.9594

[z]Indicates a non-significant (NS), linear (L), or quadratic (Q) rate response in the measured parameter to amendment rate, where *, **, or *** represent P-values of 0.05, 0.01, or 0.001.

[y]Least significant difference within a column where $\alpha = 0.05$.

[x]Mills and Jones 1996.

1996). Starr and Wright (1984) showed that Ca and Mg concentration interacted to affect foliar K concentration in 'Helleri' holly, although the effect was subtle. Leachate Ca and Mg increased with increasing amendment rate in both DL and SS amended substrates throughout the experiment (Table 3), and this is likely what suppressed K uptake with increasing amendment rate.

Foliar Mg concentration was affected by the interaction between amendment type and rate (Table 2). Foliar Mg did not respond to DL rate, and only the 9.5 $kg \cdot m^{-3}$ rate had higher foliar Mg than non-amended controls. In contrast, foliar Mg decreased with increasing SS rate, and all rates above 0.6 $kg \cdot m^{-3}$ had less foliar Mg than non-amended controls. The response of foliar Mg to amendment type and application rate is the only nutrient that reflects the same pattern as SDW. Thus, reduction in butterfly bush SDW at high rates of SS might have been caused by reduced Mg uptake. Leachate Mg concentration was affected by an interaction between amendment type and rate at 1 and 4 WAP (Table 3). At 1 WAP, leachate Mg increased and then decreased quadratically with increasing amendment rate with both DL and SS amendments; however, the increase was greater with the DL amendment. All DL rates except the lowest rate had higher leachate Mg concentrations than the non-amended controls. In contrast, none of the SS-amended substrates had higher leachate Mg concentrations than non-amended controls. By 4 WAP, leachate Mg concentration did not respond to SS rate, and no SS rate resulted in leachate Mg concentration higher than non-amended controls, whereas leachate Mg increased with increasing DL rate. By 16 WAP, leachate Mg concentration decreased in all treatments compared to levels at 4 WAP, although concentrations were still higher in DL-amended substrates than SS-amended substrates. The DL used in this experiment contained 12% elemental Mg, mostly in the form of $MgCO_3$ while the SS contained 4.6% elemental Mg in the form of MgO, which is less water soluble than the $MgCO_3$ in DL.

In summary, the SS used in this experiment provided a greater increase in pH than DL at rates greater than 4.8 $kg \cdot m^{-3}$ with pine bark. However, most nursery producers use DL rates between 0 and 4.8 $kg \cdot m^{-3}$ (personal observation). Over this range, DL is more effective than SS at increasing pH of pine bark substrates. The ideal pH varies with crop, although nursery crop producers generally perceive pH values in the range of 6.0 to 6.5 as being acceptable for most crops. This pH range can be achieved with DL at rates of 0.6 to 2.4 $kg \cdot m^{-3}$, or SS at rates of 2.4 to 4.8 $kg \cdot m^{-3}$. The high rates used in this experiment were included so that pH response to a wider range of rates could be established. Rates of 14.3 $kg \cdot m^{-3}$ would not normally be used for any form of lime or pH adjustment. Butterfly bush grew well in substrates amended with up to 2.4 $kg \cdot m^{-3}$ SS. Only the highest rate of SS decreased butterfly bush growth compared to non-amended controls, although there was a trend for decreased growth over the range of applied rates. As the rate of SS increased to the highest rate, foliar Mg decreased. This was likely due to excessively high levels of Ca in the substrate solution caused by the soluble nature of the CaO component of SS. Further

Table 3. Leachate macro- and secondary-nutrient concentration from containers with an 80 pine bark:20 sphagnum peatmoss substrate. Each container was potted with a butterfly bush (*Buddleja davidii* 'Pink Delight') and amended with five rates of dolomitic limestone or steel slag. Leachates were collected 1, 4, and 16 weeks after potting (WAP) using the pour-through procedure.

		Phosphorus			Potassium			Calcium			Magnesium			Sulfur		
Amendment	Rate	1 WAP[z]	4 WAP	16 WAP	1 WAP	4 WAP	16 WAP	1 WAP	4 WAP	16 WAP	1 WAP	4 WAP	16 WAP	1 WAP	4 WAP	16 WAP
		mg·L^{-1}														
None	0	27.3	36.4	1.3	156.4	207.2	6.9	60.8	97.7	64.1	34.5	54.0	26.0	63.7	98.2	56.5
Dolomitic lime	0.6	20.7	26.6	1.4	116.1	149.3	4.0	71.1	100.2	70.5	43.2	61.6	36.0	75.1	101.7	64.8
	2.4	21.4	23.4	1.9	144.1	187.3	10.3	60.9	97.3	58.1	42.8	70.8	46.2	65.9	89.9	55.3
	4.8	23.8	31.9	0.8	175.0	247.5	11.7	70.9	109.1	50.3	51.6	85.7	44.2	67.4	102.5	38.5
	9.5	23.9	30.4	1.2	185.3	267.7	14.9	83.1	143.1	49.0	63.4	114.3	43.3	84.0	134.4	36.9
	14.3	17.3	31.2	1.6	155.4	267.0	9.0	74.7	168.3	57.4	57.1	133.1	50.2	76.3	145.6	41.7
Significance[y]		L*	NS	NS	L*Q***	L***Q*	NS	L*	L***	NS	L***Q***	L***	L**	NS	L***	L*
Steel slag	0.6	20.5	34.3	0.7	159.0	258.3	5.2	62.1	114.6	46.9	31.6	60.4	20.6	48.48	100.17	38.58
	2.4	20.8	31.2	1.0	205.3	294.1	7.0	107.5	163.6	64.9	41.5	68.3	25.9	70.98	132.26	44.35
	4.8	16.1	19.7	3.1	179.6	233.1	16.8	117.0	166.4	59.3	39.8	60.5	22.3	76.01	112.92	37.73
	9.5	9.7	10.1	1.4	192.8	245.5	10.6	156.1	194.2	87.1	42.5	62.0	29.5	74.69	106.42	33.32
	14.3	4.8	4.5	0.9	162.0	214.0	9.6	158.9	188.5	87.4	35.3	54.3	28.6	49.61	91.07	27.73
Significance		L***	L***Q*	Q*	Q***	Q**	NS	L***Q***	L***Q**	L**	Q**	NS	NS	Q***	Q*	L*
$LSD_{0.05}$[x]		5.7	6.7	NS	22.6	37.5	NS	18.2	37.2	25.6	8.2	19.5	13.5	15.9	26.9	NS
Main effects																
Amendment		0.0001	0.0001	0.8890	0.0001	0.0041	0.9688	0.0001	0.4654	0.0397	0.0001	0.0001	0.0001	0.0081	0.3007	0.0322
Rate		0.0001	0.0001	0.5643	0.0001	0.0045	0.1624	0.0001	0.0001	0.3051	0.0001	0.0001	0.2001	0.0202	0.2457	0.0911
Interaction		0.0015	0.0001	0.0318	0.0013	0.0001	0.783	0.0001	0.1997	0.0132	0.0053	0.0001	0.8668	0.0038	0.0001	0.5362

[z]Weeks after potting, May 13, 2014.

[y]Indicates a non-significant (NS), linear (L), or quadratic (Q) rate response in the measured parameter to amendment rate, where *, **, or *** represent P-values of 0.05, 0.01, or 0.001.

[x]Least significant difference within a column where $\alpha = 0.05$.

testing should be done on other species to determine if high Ca levels with higher SS rates observed in this experiment cause reductions in growth of other plants.

The objective of this research was to determine the utility of SS as an alternate to DL for increasing pH of container substrates composed primarily of pine bark. There were no phytotoxic effects observed from using SS at standard use rates (0 to 4.8 kg·m^{-3}). Butterfly bush grew well in substrates with either amendment. The SS used in this experiment had slightly less pH effect at low amendment rates (less than 4.8 kg·m^{-3}) but substantially greater pH adjustment at higher rates. The pH response from DL plateaued at 4.8 kg·m^{-3}, with no further increase in pH despite doubling or tripling the amendment rate. In contrast, pH response to SS continued to increase across all rates used in this study. This could be a useful tool for amending substrates when very high pH is desired, or if a substrate amendment with very acidic components needs to be counteracted. Based on the results of this experiment, SS could be used as an alternative to DL. However, incorporation rates would need to be adjusted slightly higher for SS compared to DL to achieve pH in the range of 6 to 6.5.

Literature Cited

Ali, M.T. and S.H. Shahram. 2007. Converter slag as a neutralizing agent in the amelioration of acidic soils. Int. J. Agri. Biol. 9:715–720.

Altland, J.E., M.G. Buamscha, and D.E. Horneck. 2008. Substrate pH affects nutrient availability in fertilized Douglas fir bark substrates. HortScience 43:2171–2178.

Altland, J.E., J.C. Locke, W.L. Zellner, and J.K. Boldt. 2015. Steel slag raises pH of greenhouse substrates. HortScience 50:603–608.

Argo, W.R. and J.A. Biernbaum. 1996. The effect of lime, irrigation-water source, and water-soluble fertilizer on root-zone pH, electrical conductivity, and macronutrient management of container root media with impatiens. J. Amer. Soc. Hort. Sci. 121:442–452.

Chrustic, G.A. and R.D. Wright. 1983. Influence of liming rate on holly, azalea, and juniper growth in pine bark. J. Amer. Soc. Hort Sci. 108:791–795.

Cobb, G.S. and M.S. Zarko. 1983. Medium pH and growth of two woody ornamentals as influenced by liming rate. Proc. South. Nurs. Assoc. Res. Conf. 28:46–48.

Gillman, J.H., M.A. Dirr, and S.K. Braman. 1998. Effects of dolomitic lime on growth and nutrient uptake of *Buddleia davidii* 'Royal Red' grown in pine bark. J. Environ. Hort. 16:111–113.

Harvey, M.P., G.C. Elliott, and M.H. Brand. 2004. Growth response of *Hakonechloa macra* (Makino) 'Aureola' to fertilizer formulation and concentration, and to dolomitic lime in the potting mix. HortScience 39:261–266.

Lopez, R.G. and M.V. Mickelbart. 2010. Alkalinity management in soilless substrates. Purdue Ext. Pub. HO-242-W.

Lu, W., J.L. Sibley, C.H. Gilliam., J.S. Bannon, and Y. Zhang. 2006. Estimation of U.S. bark generation and implications for horticultural industries. J. Environ. Hort. 24:29–34.

Mayfield, J.L., J.L. Sibley, E.H. Simonne, and D.J. Eakes. 2002. Effect of liming materials on media pH and overall growth and nutrition of dwarf nandina. J. Plant Nutr. 25:1377–1387.

Midcap, J.T. 1999. Dolomitic lime rates cause growth reduction and stem abnormality on 'Sizzling Pink' Loropetalum. Proc. South.. Nurs. Assoc. Res. Conf. 44:28–30.

Mills, H.A. and J.B. Jones. 1996. Plant Analysis Handbook II. MicroMacro Publishing. Athens, GA. 422 pp.

Rodriguez, M., F.A. Lopez, M. Pinto, N. Balcazar, and G. Besga. 1994. Basic Linz-Donawitz slag as a neutralizing agent for pastureland. Agron. J. 86:904–909.

Schabenberger, O. and F.J. Pierce. 2002. Contemporary Statistical Models for the Plant and Soil Sciences. CRC Press, Boca Raton, FL. p. 259–265.

Starr, K.D. and R.D. Wright. 1984. Calcium and magnesium requirements of Ilex crenata 'Helleri'. J. Amer. Soc. Hort. Sci. 109:857–860.

Walden, R.F. and G. Epelman. 1988. Influence of liming rate on growth of Japanese boxwood in pine bark media. Proc. South. Nurs. Assoc. Res. Conf. 33:52–57.

Wolfe, M.E. 2009. Aglime: Agricultural limestone and dolomite in Ohio. Ohio Dept. Natural Resources GeoFacts No. 26. p. 1–2.

Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227–229.

Wulfsberg, G. 2000. Inorganic Chemistry. University Science Books, Sausalito, CA. 156 pp.

Yeager, T.H., C.H. Gilliam, T.E. Bilderback, D.C. Fare, A.X. Niemiera, and K.M. Tilt. 2007. Best management practices: Guide for producing nursery crops. Southern Nursery Assoc., Atlanta, GA.

Yildirim, I.Z. and M. Prezzi. 2011. Chemical, mineralogical, and morphological properties of steel slag. Adv. Civil Eng. 2011:1–13.