Micronutrient Availability from Steel Slag Amendment in Pine Bark Substrates[1]

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Abstract

Steel slag is a byproduct of the steel industry that can be used as a liming agent, but also has a high mineral nutrient content. While micronutrients are present in steel slag, it is not known if the mineral form of the micronutrients would render them available for plant uptake. The objective of this research was to determine if steel slag could be used as the sole micronutrient source for container-grown nursery crops. Butterfly bush (*Buddleja davidii* 'Pink Delight') and rose (*Rosa* 'Radrazz') were grown in #3 (3 gal) containers in a base substrate composed of pine bark and peatmoss (80:20, by vol). The base substrate was amended with the following treatments: with a complete controlled release fertilizer (CRF) including micronutrients (C-control), a substrate amended with a different CRF containing only N, P, and K along with a granular micronutrient package (M-control), and three additional treatments amended with the CRF (N, P, and K only) and either 1.2, 2.4, or 4.8 kg·m^{-3} (2, 4, and 8 lb·yd^{-3}) of steel slag. Plants were harvested at 2 and 4 months after potting (MAP). None of the plants displayed any sign of nutrient deficiency or toxicity throughout the experiment. However, plants grown in the substrate amended with the highest slag rate [4.8 kg·m^{-3} (8 lb·yd^{-3})] had lower shoot dry weight (SDW) than both control groups. Substrate pH increased with increasing slag rate, which may have affected micronutrient availability in those substrates. Among the micronutrients analyzed, only Copper (Cu) was consistently deficient in both the substrate and foliar tissue of slag-amended treatments. Steel slag either does not provide a sufficient quantity of Cu or the concomitant increase in pH with increasing rates of steel slag renders Cu unavailable for plant uptake. Steel slag should not be used as the sole source of micronutrients for shrubs grown in pine bark-based substrates.

Index words: substrate, pH, plant nutrition, fertilizer, nutrient deficiency.

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

Significance to the Horticulture Industry

Steel slag 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 substrate pH. A steel slag material has recently been made available for horticultural uses. In addition to its use as a liming agent, steel slags typically have measurable concentrations of micronutrients. The objective of this research was to determine if steel slag could be used as the sole micronutrient source for container-grown nursery crops. Butterfly bush (*Buddleja davidii* 'Pink Delight') and rose (*Rosa* 'Radrazz') were grown in #3 (3 gal) containers. A base substrate composed of pine bark and peatmoss (80:20, by vol) was amended with either 1.2, 2.4, or 4.8 kg·m^{-3} (2, 4, and 8 lb·yd^{-3}) of steel slag. Slag-amended substrates were compared with two control groups representing common industry methods for supplying micronutrients to container substrates. In one group, the base substrate was amended with a complete controlled release fertilizer (CRF) including micronutrients (C-control), and in the other the base substrate was amended with a different CRF containing only N, P, and K along with a granular micronutrient package (M-control). All plants appeared vigorous and green in color throughout the experiment, with no signs of nutrient deficiency or toxicity. However, plants grown in the substrate amended with the highest slag rate [4.8 kg·m^{-3} (8 lb·yd^{-3})] had less shoot growth than both control groups. Among the micronutrients analyzed, only cooper was consistently deficient in both the substrate and foliar tissue of slag-amended treatments. Steel slag either does not provide a sufficient quantity of copper or the concomitant increase in pH with increasing rates of steel slag renders copper unavailable for plant uptake. While steel slag is effective in raising substrate pH similar to dolomitic lime, it should not be used as the sole source of micronutrients for shrubs grown in pine bark based substrates.

Introduction

Container-grown trees and shrubs acquire micronutrients from three primary sources: irrigation water, the substrate, and applied fertilizers. Some micronutrients are available in irrigation water, although this will vary greatly with the mineralogical and geological properties of the aquifer. As an example, Ohio groundwater contains from trace to fertilizer levels of Cu, Fe, Mn, and Zn (Anonymous 2013) depending on the well location. Micronutrients can also be obtained from softwood barks, the primary components in most substrates used for container-grown trees and shrubs. Along the western coast of the United States, Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB) is the primary component in nursery container substrates. Buamscha et al. (2007) concluded DFB contains sufficiently high micronutrient levels to sustain growth of annual vinca [*Catharanthus roseus* (L.) G. Don 'Peppermint Cooler'] over a two month production period. Likewise, Altland and Buamscha (2008) showed that Fe and Mn concentrations in

[1]Received for publication December 18, 2015; in revised form April 13, 2016.

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DFB were higher than recommended for soilless substrates as long as pH was less than 7. Loblolly pine (*Pinus taeda* L.) bark, the predominant bark source in the central and eastern U.S., is also reported to provide sufficient micronutrients for crop growth. Niemiera (1992) concluded, based on laboratory leaching simulations, that pine bark can provide sufficient Cu, Fe, Zn, and Mn to support crop growth. Likewise, Rose and Wang (1999) reported a pine bark:hardwood bark: peat:sand (3:1:1:2, by vol) substrate contained sufficient DTPA-extractable Mn, Fe, Cu and Zn after one year in simulated nursery production. Finally, micronutrients are provided in numerous fertilizer packages, usually via one of three methods. Many water-soluble fertilizers provide both macronutrients (N, P, and K) as well as all secondary nutrients (Ca, Mg, and S) and micronutrients. This fertilization method provides low concentrations of water-soluble micronutrient salts or chelates with each irrigation event. Depending on the irrigation system, micronutrients in water-soluble fertilizers could be applied to the substrate (via drip irrigation) or to the foliage and substrate (via overhead irrigation). Micronutrients can also be pre-incorporated into the substrate using a granular fertilizer formulation. These products usually provide micronutrients in a water-soluble salt or chelate, but sometimes as finely ground minerals with limited solubility that presumably render the micronutrients available slowly over time. Micronutrients can also be incorporated with controlled release fertilizers (CRFs), usually coated with a resin or polymer, and thus released slowly for several weeks or months (depending on the product).

Steel slag is a byproduct of the steel industry with high mineral nutrient content. As steel scraps and iron ore are melted in a basic oxygen furnace (BOF), calcium oxide (CaO) and dolomitic lime 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 calcium oxide and dolomitic lime, form a molten slag. The slag is poured off from the steel, cooled, and processed into particle size fractions ranging from dust to gravel. Steel slag has been shown to be an effective liming agent for soilless substrates in container culture (Altland et al. 2015b) as well as field soils (Ali and Shahram 2007, Rodriguez et al. 1994).

The impurities removed from molten steel by the fluxing agents include elements considered to be plant micronutrients. Properties of steel slag and the elemental content of the impurities vary not only by the type of furnace in which steel is produced, but also within a particular furnace type (Yildirim and Prezzi 2011). Despite differences, most steel slags are similar in that they are composed primarily of calcium oxide (CaO), silicon dioxide (SiO_2), and iron oxide (FeO), with CaO making up more than 35% of steel slag mass (Yildirim and Prezzi 2011). While micronutrients are present in steel slag, it is not known if the mineral form of the micronutrients would render them available for plant uptake. Furthermore, the high CaO content of the steel slag causes a rapid increase in substrate pH (Altland et al. 2015b) which could render many of the micronutrients less available for plant uptake (Altland and Buamscha 2008, Wright and Hinesly 1991, Wright et al. 1999a). The objective of this research was to determine if steel slag could be used as the sole micronutrient source for container-grown nursery crops.

Materials and Methods

The base substrate for this experiment was composed of pine bark (Buckeye Resources, Dayton, OH) and peatmoss (80:20 v:v) (Sun Gro Horticulture, Seba Beach, Alberta, Canada). A group of #3 (3 gal) containers, referred to as the C-controls, were filled with the base substrate amended with 6 kg·m^{-3} (10 lb·yd^{-3}) of a complete CRF with micronutrients (Osmocote Plus 15N-3.9P-9.9K-1.3Mg-6.0S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn, The Scotts Co. LLC, Marysville, OH). A second group of containers, referred to as the M-controls, were filled with the base substrate amended with 4.7 kg·m^{-3} (8 lb·yd^{-3}) of a different CRF (Polyon 19N-2.6P-9.9K, J.R. Simplot Co., Boise, ID) as well as 0.9 kg·m^{-3} (1.5 lb·yd^{-3}) of a commercial granular micronutrient package (Micromax, 6Ca-3Mg-12S-0.1B-17Fe-2.5Mn-1Cu-0.05Mo-1Zn, The Scotts Co., Marysville, OH). Rates of the two CRF products were assigned to provide the same quantity of N. Three additional groups of containers were filled with the base substrate amended with 4.7 kg·m^{-3} (8 lb·yd^{-3}) CRF (Polyon 19N-2.6P-9.9K) and 1.2, 2.4, or 4.8 kg·m^{-3} (2, 4, or 8 lb·yd^{-3}) of steel slag (Plant Tuff, 0.004B-20.3Fe-2.22Mn-0.004Cu-0.00017Mo-0.017Zn, Plant Tuff Inc., Dearborn, MI). The mass of micronutrients applied to a #3 (3 gal) container, by treatment, are provided in Table 1. Immediately after mixing the substrates, four samples of each were analyzed for diethylene triamine pentaacetic acid

Table 1 Mass of micronutrients added to a #3 (3 gal) nursery container with various forms of micronutrient fertilizer amendments.

Treatment	NPK source	Micronutrient source	Micronutrient application rate	B	Fe	Mn	Cu	Mo	Zn
				mg					
C-control	15N-3.9P-9.9K	Impregnated in CRF[z]	6.0 kg·m^{-3}	13.6	313.8	40.9	34.1	13.6	34.1
M-control	19N-2.6P-9.9K[y]	Micronutrient package[x]	0.9 kg·m^{-3}	10.2	1739.6	255.8	102.3	5.1	102.3
Steel slag[w]	19N-2.6P-9.9K	Steel slag	1.2 kg·m^{-3}	0.55	2769.73	302.90	0.55	0.02	2.32
	19N-2.6P-9.9K	Steel slag	2.4 kg·m^{-3}	1.09	5539.46	605.79	1.09	0.05	4.64
	19N-2.6P-9.9K	Steel slag	4.8 kg·m^{-3}	2.18	11078.93	1211.59	2.18	0.09	9.28

[z]Controlled release fertilizer, Osmocote 15N-3.9P-9.9K-1.3Mg-6.0S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn.

[y]Controlled release fertilizer providing N, P, and K only.

[x]Micromax, 6Ca-3Mg-12S-0.1B-17Fe-2.5Mn-1Cu-0.05Mo-1Zn, at 0.9 kg·m^{-3}.

[w]Plant Tuff, 0.004B-20.3Fe-2.22Mn-0.004Cu-0.00017Mo-0.017Zn, applied at rates of 1.2, 2.4, or 4.8 kg·m^{-3}.

(DTPA) extractable micronutrients using a method described by Warncke (1990). Briefly, approximately 400 mL (13.5 oz) of substrate was placed in a glass jar and saturated with either deionized water or 5 mM DTPA. The media remained saturated for 24 hours, after which it was filtered (Q5 filter paper, Fisherbrand, Waltham, MA) under vacuum. Filtrate concentrations of macro and micronutrients (excluding N) were determined by adding 1 mL (0.03 oz) of solution sample with 9 mL (0.3 oz) of 3.89% HNO_3 in 18 MΩ water, and then analyzing with optical emission spectroscopy (iCAP 6300 Duo, Thermo Scientific, Waltham, MA).

On May 28, 2014, a single 'Pink Delight' butterfly bush or 'Radrazz' rose) were transplanted per pot from 72-count cell flats into amended containers. There were 10 single-plant replications per treatment among each species, arranged in a completely randomized design on an outdoor gravel bed in Wooster, OH. The two species were randomized separately. Plants were overhead irrigated daily, initially with 0.4 cm (0.15 in) per day, and increased to 0.8 cm (0.3 in) per day at 2 months after potting (MAP). Four irrigation water samples were collected monthly throughout the experiment and measured for pH and electrical conductivity (EC) (MA 235 pH/Ion Analyzer, Mettler Toledo, Columbus, OH) and alkalinity (G20 Compact Titrator, Mettler Toledo). Irrigation samples were also measured for micronutrient concentration using optical emission spectroscopy (Table 2).

At 2 and 4 MAP, five replicates from each species and treatment combination were randomly selected and destructively harvested. Relative chlorophyll content was determined with a chlorophyll meter (Minolta-502 SPAD meter, Spectrum Technologies, Inc., Plainfield, IL) by taking a measurement on five recently matured and fully expanded leaves per plant and recording the mean. Containers were subjected to the pour-through technique (Yeager et al. 2007) and a 50 mL (1.7 oz) sample of the substrate solution was collected for measurement of pH, electrical conductivity (EC), and nutrient analysis. Substrate solutions were immediately measured for pH and EC, then frozen until nutrient analysis was performed. At the time of nutrient analysis, solution 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. The filtrate was analyzed for concentration of macro and micronutrients (excluding N) with optical emission spectroscopy (iCAP 6300 Duo, Thermo Scientific, Waltham, MA). Fully expanded foliage was harvested for foliar nutrient analysis (Mills and Jones 1996), rinsed with deionized water, then oven dried at 55 C (131 F) for 3 d. Samples were ground in a mill (Tecator Cyclotec AB, Hogenas, Sweden) through a 0.5 mm (0.02 in) 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 PerkinElmer 2400 Series II Analyzer (PerkinElmer, Waltham, MA). Other macronutrients and micronutrients were determined by ICP-OES after nitric acid (15.8 N) digestion in a programmable microwave (MARS 6, CEM Corp., Matthews, NC).

Immediately after leaf tissue harvests for nutrient analysis, shoot dry weight (SDW) was determined by removing the above-ground portion of the plant, oven drying at 55 C (131 F) for 3 d, and weighing. Roots visibly growing along the substrate-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. Following each harvest (2 and 4 MAP), substrate from containers potted with roses were shaken from the roots, then extracted with DTPA as previously described.

Data were subjected to analysis of variance (ANOVA) and the least significant difference (LSD) was determined with Fisher's protected LSD where $\alpha = 0.05$. Orthogonal contrast analysis was used to determine if there was a significant rate response to steel slag incorporation rate for each measured parameter. Data from each species were analyzed separately. All statistical analyses were performed with SAS (v9.3, SAS Institute Inc., Cary, NC).

Table 2. Irrigation water pH, electrical conductivity (EC), alkalinity, and micronutrient concentration used in the experiments (mean ± standard deviation). Water samples were collected monthly (n = 16) and the results were averaged across the monthly samples.

		mg·L^{-1}
pH	8.2 ± 0.4	
EC	0.59 ± 0.02 mS·cm^{-1}	
Alkalinity (HCO_3^-)		225.00 ± 8.40
Boron		0.13 ± 0.06
Iron		0.02 ± 0.05
Manganese		0.13 ± 0.17
Copper		0.00 ± 0.00
Zinc		0.17 ± 0.19

Results and Discussion

There were no treatment effects on relative foliar chlorophyll content (SPAD readings) for either crop ($P > 0.05$; data not presented). Foliar SPAD values for butterfly bush averaged 48.7 and 53.4 at 2 and 4 MAP, respectively; and for rose averaged 36.6 and 49.4 at 2 and 4 MAP, respectively. All plants appeared healthy with normal green foliage throughout the experiment, with no symptoms of nutrient deficiency or toxicity.

Substrate pH was similar between C-control and M-control substrates throughout the experiment, while substrate pH increased linearly with increasing slag rate (Table 3). In most cases, substrates amended with either 2.4 or 4.8 kg·m^{-3} (4 or 8 lb·yd^{-3}) steel slag had higher pH than either control substrate (with the exception of butterfly bush at 4 MAP with 2.4 kg·m^{-3} (4 lb·yd^{-3}) steel slag). The steel slag in this experiment was 38.4% CaO, which can be a powerful acid-neutralizing agent. Mayfield et al. (2002) demonstrated that CaO served as a suitable alternative to dolomitic lime for the production of container-grown heavenly bamboo (*Nandina domestica* Thunb. 'Nana purpurea') in a pine bark substrate. Previous research has shown a similar pH response to steel slag amendments in both pine bark and peatmoss substrates (Altland et al. 2015a, Altland et al. 2015b).

Substrate EC ranged from 0.71 to 2.92 mS·cm^{-1} throughout the experiment (Table 3). At 2 MAP, substrate EC was not affected by treatment in either species. At 4 MAP, EC decreased with increasing slag rate among butterfly bush but did not respond to steel slag rate among rose. Among rose, EC in C-control substrates was higher than all other treatments. The recommended EC for container substrates fertilized with CRF is 0.5 to 2.0 mS·cm^{-1} using the pour-through technique (LeBude and Bilderback 2009). While rose substrates exceeded the recommended range at 2 MAP

Table 3. Substrate pH and electrical conductivity (EC) in #3 (3 gal) containers potted with either a butterfly bush (*Buddleja davidii* 'Pink Delight') or rose (*Rosa* 'Radrazz') in an 80:20 pine bark:peatmoss substrate amended with a complete controlled release fertilizer including micronutrients (C-control), a substrate amended with a CRF granular micronutrient package (M-control), or three rates of a steel slag.

Months after potting	Amendment	Rate ($kg \cdot m^{-3}$)	Substrate pH		Substrate EC ($mS \cdot cm^{-1}$)	
			Butterfly bush	Rose	Butterfly bush	Rose
2	C-control[z]		5.73	5.36	1.09	2.92
	M-control[y]		5.82	5.31	1.28	2.46
	Steel slag	1.2	6.08	5.57	1.11	2.77
	Steel slag	2.4	6.56	5.85	1.06	2.56
	Steel slag	4.8	6.93	6.49	1.04	2.83
	Significance[x]		L***	L***	NS	NS
	$LSD_{0.05}$[w]		0.41	0.33	NS	NS
4	C-control		5.93	4.97	1.48	1.75
	M-control		6.01	5.33	1.02	0.80
	Steel slag	1.2	5.67	5.66	1.33	0.93
	Steel slag	2.4	6.25	6.11	0.90	0.76
	Steel slag	4.8	6.92	6.60	0.71	0.84
	Significance		L***	L***	L*	NS
	$LSD_{0.05}$		0.37	0.42	0.54	0.57

[z]Amended with 6.0 $kg \cdot m^{-3}$ of a complete controlled release fertilizer (CRF) with micronutrients (Osmocote 15N-3.9P-9.9K-1.3Mg-6.0S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn).

[y]Amended with 4.7 $kg \cdot m^{-3}$ of a different CRF (Polyon 19N-2.6P-9.9K) as well as 0.9 $kg \cdot m^{-3}$ of a commercial granular micronutrient package (Micromax, 6Ca-3Mg-12S-0.1B-17Fe-2.5Mn-1Cu-0.05Mo-1Zn).

[x]Linear or non-significant response to steel slag rate, where *, **, or *** correspond to p-values of 0.05, 0.01, and 0.001.

[w]Least significant difference value according to Fisher's test where $\alpha = 0.05$.

regardless of treatment, all substrates were within the recommend range by 4 MAP.

Butterfly bush SDW were similar between M-controls and C-control at 2 and 4 MAP (Table 4). Shoot dry weight for butterfly bush decreased linearly with increasing slag rate, and plants grown in the substrate amended with the highest slag rate [4.8 $kg \cdot m^{-3}$ (8 $lb \cdot yd^{-3}$)] had lower SDW than both control groups. This could be at least partially the result of the increased pH observed with higher incorporation rates of steel slag. For example, Gillman et al. (1998) reported reduced butterfly bush growth in pine bark substrates amended with greater than 2.4 $kg \cdot m^{-3}$ (4 $lb \cdot yd^{-3}$) dolomitic lime. Butterfly bush root ratings responded similarly to SDW with respect to the two control groups and slag rate. Other research has shown a decline in SDW and root ratings of butterfly bush with 4.8 $kg \cdot m^{-3}$ (8 $lb \cdot yd^{-3}$) or greater steel slag amendment (Altland et al. 2015c). Neither rose SDW nor root ratings were affected by treatment at 2 MAP. By 4 MAP, SDW of rose growing in the C-control group was greater than those in the M-control. Similar to butterfly bush, rose SDW decreased linearly with increasing slag rate and plants amended with the highest rate were smaller than both control groups. Rose root ratings also decreased linearly with increasing slag rate, and the 2.4 and 4.8 $kg \cdot m^{-3}$ (4 and 8 $lb \cdot yd^{-3}$) rates were lower than the M-control and similar to the C-controls.

Prior to potting, DTPA-extractable boron (B) was highest in M-control substrates, and decreased linearly with increasing slag rate (Table 5). Increasing slag rates should have provided an increasing mass of B. The decrease in extractable B, therefore, is likely a function of increased pH (Altland and Buamscha 2008). At 2 and 4 MAP, DTPA-extractable B was greater in C-controls than all other substrates. This could be a delayed response from the gradual release of B from the CRF. Throughout the experiment, DTPA-extractable B levels were lower than recommended (Warncke 1990). Despite lower than recommended substrate levels, foliar B in butterfly bush and roses were within or slightly above the recommended range (Table 6). Irrigation water used for this experiment contained 0.13 $mg \cdot L^{-1}$ (ppm) B, which is as high as the concentration of B found in commercial micronutrient fertilizer packages formulated for continuous feed applications [0.1 to 0.3 $mg \cdot L^{-1}$ (ppm)]. Foliar B increased with increasing slag rate. Other research has shown a trend for increased foliar B in sunflower (*Helianthus annuus* L. 'Pacino Gold') with increasing steel slag rate (Altland et al. 2015b).

DTPA-extractable iron (Fe) decreased, although slightly, with increasing steel slag rate throughout the experiment (Table 5). This was somewhat surprising considering that the slag used in this experiment was composed of 25.9% FeO. Ferrous oxide in the steel slag consists of the divalent form of Fe, which is water soluble and readily available to plants (Mills and Jones 1996). However, exposure of ferrous oxide in well-aerated soilless substrates can cause oxidation to the trivalent form which is insoluble in water and thus not available for plant uptake. Foliar Fe concentration in neither butterfly bush nor rose responded to slag rate (Table 6). At 2 MAP, foliar Fe was highest in both species growing in the C-control substrate, although there were no differences in foliar Fe among treatments by 4 MAP. A lack of response with increasing slag rate suggests that Fe from the slag was not in a form available for plant uptake. Despite differences in foliar Fe, plants in all treatments were within or above their

Table 4. Butterfly bush (*Buddleja davidii* 'Pink Delight') and rose (*Rosa* 'Radrazz') shoot dry weights and root ratings growing in #3 (3 gal) containers in an 80:20 pine bark:peatmoss substrate amended with a complete controlled release fertilizer including micronutrients (C-control), a substrate amended with a granular micronutrient package (M-control), or three rates of a steel slag.

Months after potting	Amendment	Rate ($kg \cdot m^{-3}$)	Shoot dry weight (g)		Root rating[z]	
			Butterfly bush	Rose	Butterfly bush	Rose
2	C-control[y]		87.1	24.9	6.6	2.6
	M-control[x]		90.6	24.6	6.2	2.6
	Steel slag	1.2	76.0	20.4	6.4	3.0
	Steel slag	2.4	83.3	19.3	6.0	2.2
	Steel slag	4.8	57.8	19.5	4.2	2.4
	Significance[w]		L*	NS	L***	NS
	$LSD_{0.05}$[v]		17.9	NS	0.9	NS
4	C-control		135.1	60.2	7.0	3.2
	M-control		126.0	44.0	7.6	4.2
	Steel slag	1.2	140.2	49.9	7.8	4.0
	Steel slag	2.4	115.2	30.6	7.0	2.8
	Steel slag	4.8	92.3	23.0	5.6	2.4
	Significance		L**	L**	L**	L**
	$LSD_{0.05}$		33.5	14.1	1.3	0.8

[z]Roots 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]Amended with 6.0 $kg \cdot m^{-3}$ of a complete controlled release fertilizer (CRF) with micronutrients (Osmocote 15N-3.9P-9.9K-1.3Mg-6.0S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn).

[x]Amended with 4.7 $kg \cdot m^{-3}$ of a different CRF (Polyon 19N-2.6P-9.9K) as well as 0.9 $kg \cdot m^{-3}$ of a commercial granular micronutrient package (Micromax, 6Ca-3Mg-12S-0.1B-17Fe-2.5Mn-1Cu-0.05Mo-1Zn).

[w]Linear or non-significant response to steel slag rate, where *, **, or *** correspond to p-values of 0.05, 0.01, and 0.001.

[v]Least significant difference value according to Fisher's test where $\alpha = 0.05$.

recommended range (Mills and Jones 1996). Iron concentration in irrigation water was low at 0.02 $mg \cdot L^{-1}$ (Table 2), and not likely to be a substantive source of Fe.

DTPA-extractable manganese (Mn) increased with increasing slag rate throughout the experiment (Table 5). Steel slag provided a higher mass of Mn than either control group (Table 1). Despite this, foliar Mn concentrations decreased with increasing slag rate throughout the experiment (except for rose at 2 MAP). The decrease in foliar Mn could be a function of substrate pH, since Mn availability decreases with increasing pH (Peterson 1980). Despite treatment differences and response to slag rate, all treatments were within or above the recommended range for foliar Mn concentration (Mills and Jones 1996). Irrigation water Mn concentrations were relatively low at 0.13 $mg \cdot L^{-1}$ (ppm) (Table 2) compared to concentrations typically found in continuous feed fertilizer solutions [0.6 to 1.8 $mg \cdot L^{-1}$ (ppm)].

DTPA-extractable Cu levels were consistently higher than recommended for soilless substrates in both control groups, while Cu levels were consistently lower than recommended for all slag-amended substrates (Table 5). Consequently, foliar Cu concentrations of plants grown in substrates amended with 2.4 and 4.8 $kg \cdot m^{-3}$ (4 and 8 $lb \cdot yd^{-3}$) steel slag were lower than recommended for both species at and 4 MAP (Table 6). Foliar Cu concentration decreased with increasing slag rate in butterfly bush, while it was not affected by slag rate in rose. Averaged across slag rates, there was approximately 0.3 $mg \cdot L^{-1}$ (ppm) DTPA-extractable Cu at each date of analysis, while both control groups had concentrations seven to 15 times higher (Table 5). Niemiera (1992) reported a similar disparity in substrate Cu concentrations in pine bark substrates amended with the same micronutrient package and rate used in our experiment; DTPA-extractable Cu was 5.0 $mg \cdot L^{-1}$ (ppm), compared to just 0.1 $mg \cdot L^{-1}$ (ppm) in non-amended bark. In our study, low substrate Cu concentration resulted in lower than recommended foliar Cu concentrations for both species (Table 6), as well as lower foliar concentrations than the two control groups. Handreck (1990) reported that DTPA-extractable Cu in substrates should be greater than 0.25 $mg \cdot L^{-1}$ (ppm) to avoid deficiency symptoms in flowering mums (*Chrysanthemum ×morifolium* Ramat. 'Yellow Mandalay'), but levels should be at least 5.1 $mg \cdot L^{-1}$ (ppm) to maximize plant growth. Our results concur with those of Handreck (1990), in that butterfly bush and rose appeared to grow normally (no obvious deficiency symptoms) with DTPA-extractable Cu concentrations of approximately 0.3 $mg \cdot L^{-1}$ (ppm); however, growth was limited in these two species at these lower substrate Cu concentrations. There was no detectable Cu in the irrigation water.

DTPA-extractable zinc (Zn) was not affected by steel slag rate throughout the experiment (Table 5). At 2 and 4 MAP, Zn concentrations were higher in C-control substrates than all other substrates. Throughout the study, most treatments were near or within the recommended range for substrate Zn levels. Likewise, foliar Zn concentrations in both species did not respond to slag rate (Table 6). Foliar Zn in plants amended with the M-control were similar or higher than those amended with the C-control. Despite these differences, all treatments resulted in foliar Zn concentrations within the recommended range. Zinc concentrations in irrigation water averaged 0.17 $mg \cdot L^{-1}$ (ppm), which is below but near concentrations that are typical of continuous feed fertilizer

Table 5. Diethylene triamine pentaacetic acid (DTPA) extracted micronutrients from an 80:20 pine bark:peatmoss substrate amended with a complete controlled release fertilizer including micronutrients (C-control), a substrate amended with a granular micronutrient package (M-control), or three rates of a steel slag. Substrate was collected after 0 (prior to transplant), 2, or 4 months of production with a single rose (*Rosa* 'Radrazz') growing in each container.

Month	Amendment	Rate ($kg \cdot m^{-3}$)	B	Fe	Mn	Cu	Zn
					$mg \cdot L^{-1}$		
0	C-control[z]		0.17	27.9	2.9	3.2	5.4
	M-control[y]		0.49	32.3	4.7	2.1	3.1
	Slag	1.2	0.13	28.2	2.2	0.4	4.5
	Slag	2.4	0.09	28.6	4.4	0.3	4.3
	Slag	4.8	0.07	20.8	18.0	0.2	4.3
	Significance [x]		L*	L*	L***	NS	NS
	$LSD_{0.05}$ [w]		0.05	7.5	2.8	0.4	0.8
2	C-control[z]		0.28	40.5	17.0	4.4	8.3
	M-control[y]		0.19	52.1	3.6	4.0	5.9
	Slag	1.2	0.16	47.8	18.0	0.4	5.7
	Slag	2.4	0.14	45.6	13.9	0.2	4.5
	Slag	4.8	0.11	40.3	31.5	0.2	5.0
	Significance [x]		L**	L*	L***	NS	NS
	$LSD_{0.05}$ [w]		0.04	8.7	6.5	0.5	1.3
4	C-control[z]		0.19	30.5	10.1	3.7	6.4
	M-control[y]		0.06	47.5	2.8	2.9	4.6
	Slag	1.2	0.02	43.6	8.3	0.4	5.1
	Slag	2.4	0.01	40.3	8.2	0.2	4.9
	Slag	4.8	0.03	37.2	18.9	0.2	5.2
	Significance		NS	L**	L***	NS	NS
	$LSD_{0.05}$		0.06	4.5	5.8	0.4	0.8
Recommended value[v]:			0.7–2.5	15–40	5–30	0.5–1.5	5–30

[z]Amended with 6.0 $kg \cdot m^{-3}$ of a complete controlled release fertilizer (CRF) with micronutrients (Osmocote 15N-3.9P-9.9K-1.3Mg-6.0S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn).

[y]Amended with 4.7 $kg \cdot m^{-3}$ of a different CRF (Polyon 19N-2.6P-9.9K) as well as 0.9 $kg \cdot m^{-3}$ of a commercial granular micronutrient package (Micromax, 6Ca-3Mg-12S-0.1B-17Fe-2.5Mn-1Cu-0.05Mo-1Zn).

[x]Linear or non-significant response to steel slag rate, where *, **, or *** correspond to p-values of 0.05, 0.01, and 0.001.

[w]Least significant difference value according to Fisher's test where $\alpha = 0.05$.

[v]Warncke, 1990.

concentrations [0.25 to 1.0 $mg \cdot L^{-1}$ (ppm)]. While slag amendments provided relatively little Zn compared to the control groups, the Zn provided by the substrate or irrigation water may have masked this deficiency.

In summary, steel slag had a subtle but measurable effect on the growth of butterfly bush and rose when used as a micronutrient source. While there were no visual symptoms of nutrient deficiency or toxicity resulting from the steel slag, the highest rate resulted in reduced SDW and root ratings compared to the two control groups for both species by 4 MAP. Steel slag also caused an increase in substrate pH, likely the result of its high CaO content. While related research has shown reduced growth of butterfly bush with high rates of steel slag, similar rates of dolomitic limestone and its concomitant increase in pH also reduced shoot and root growth (Altland et al. 2015c). Root and shoot growth of the two control groups in this experiment were similar throughout, with the exception of greater shoot growth in the C-control compared to the M-control in rose 4 MAP. Furthermore, both control groups had SDW similar to or greater than plants growing in slag-amended substrates. Among the micronutrients analyzed, only Cu was consistently deficient in both the substrate and foliar tissue of slag-amended treatments. All other measured micronutrients were within or above the recommended range for each species.

The irrigation water used in this experiment was a source of micronutrients and could have impacted the results. Based solely on the amount of micronutrients provided by each treatment (Table 1), B, Cu, and Zn might have been limiting in our slag-amended substrates. However, the irrigation water used in this experiment was derived from a well and contained relatively high concentrations of B and Zn (Table 2), similar to what might be expected in commercial micronutrient fertilizer packages formulated for constant feed. A similar experiment conducted in a greenhouse with geranium (*Pelargonium ×hortorum* L.H. Bailey 'Maverick Red') and tomato (*Solanum lycopersicon* L. 'Megabite') in an 85 peatmoss:15 perlite substrate concluded that B, Cu, and Zn were limiting in steel-slag amended substrates (Altland et al. 2015a). However, this greenhouse experiment was conducted using seedlings transplanted into 10 cm diameter pots and grown for a shorter period of time (5 weeks), and

Table 6. Foliar micronutrient and silicon (Si) concentrations in butterfly bush (*Buddleja davidii* 'Pink Delight') and rose (*Rosa* 'Radrazz') growing in #3 (3 gal) containers in a 80:20 pine bark:peatmoss substrate amended with a complete controlled release fertilizer including micronutrients (C-control), a substrate amended with a granular micronutrient package (M-control), or three rates of a steel slag.

Months after potting	Amendment	Rate ($kg \cdot m^{-3}$)	Butterfly bush					Rose				
			B	Fe	Mn	Cu	Zn	B	Fe	Mn	Cu	Zn
			$mg \cdot kg^{-1}$									
2	C-control[z]		62.9	193.5	343.9	15.2	34.4	31.8	126.1	130.6	3.8	23.1
	M-control[y]		55.9	95.8	397.1	21.8	60.7	35.7	69.1	223.9	4.7	36.1
	Steel slag	1.2	41.3	81.8	224.9	3.8	26.6	42.6	63.3	191.3	0.8	32.6
	Steel slag	2.4	50.6	115.5	208.2	1.9	36.1	43.5	59.1	182.6	0.3	36.4
	Steel slag	4.8	53.2	86.8	99.5	1.1	22.1	38.1	60.5	206.7	0.3	35.2
	Significance [x]		L*	NS	L***	L*	NS	NS	NS	NS	NS	NS
	$LSD_{0.05}$ [w]		11.4	58.9	54.1	3.0	10.1	NS	33.5	NS	1.2	6.9
4	C-control		32.1	151.0	401.7	25.8	35.1	38.6	65.4	425.0	3.7	25.7
	M-control		35.7	106.1	449.4	27.9	41.3	37.5	55.7	601.3	4.4	41.4
	Steel slag	1.2	27.4	141.0	377.9	6.6	35.8	40.8	66.6	488.4	1.6	34.6
	Steel slag	2.4	42.3	157.2	252.0	3.6	31.2	42.3	64.8	470.0	1.5	38.1
	Steel slag	4.8	49.6	130.9	169.2	2.3	32.6	43.0	63.5	291.6	1.7	33.9
	Significance		L**	NS	L**	L*	NS	NS	NS	L***	NS	NS
	$LSD_{0.05}$		11.7	NS	118.7	4.5	NS	NS	NS	98.4	0.5	7.9
Recommended values[v]:			28–50	53–170	44–123	4–20	13–50	30–60	56–200	30–400	5–10	20–50

[z]Amended with 6.0 $kg \cdot m^{-3}$ of a complete controlled release fertilizer (CRF) with micronutrients (Osmocote 15N-3.9P-9.9K-1.3Mg-6.0S-0.02B-0.05Cu-0.46Fe-0.06Mn-0.02Mo-0.05Zn).

[y]Amended with 4.7 $kg \cdot m^{-3}$ of a different CRF (Polyon 19N-2.6P-9.9K) as well as 0.9 $kg \cdot m^{-3}$ of a commercial granular micronutrient package (Micromax, 6Ca-3Mg-12S-0.1B-17Fe-2.5Mn-1Cu-0.05Mo-1Zn).

[x]Linear or non-significant response to steel slag rate, where *, **, or *** correspond to p-values of 0.05, 0.01, and 0.001.

[w]Least significant difference value according to Fisher's test where $\alpha = 0.05$.

[v]Mills and Jones, 1996. Recommendations for rose are based on recommendations for hybrid tea roses.

thus it was practical to use purified water (18 $M\Omega \cdot cm^{-1}$) for making all fertilizer solutions. The lack of micronutrients in the greenhouse irrigation water exposed the deficient B and Zn levels in the substrate that were likely masked by the relatively high concentrations of those micronutrients in the irrigation water used for this nursery experiment.

Niemiera (1992) concluded that bark supplies sufficient micronutrients for plant growth in containers, but warned that decreased availability of some micronutrients could be caused by interactions with other fertilizers or substrate pH. This is supported by Rose and Wang (1999) who reported foliar micronutrient concentrations of rhododendron (*Rhododendron* L. × 'Girard's Scarlet') grown in non-amended pine bark to be similar to treatments receiving various micronutrient fertilizers. In addition, rhododendrons grown in non-amended control substrates were of similar or superior size and quality to the amended treatments after one year of production. Unlike Rose and Wang (1999), whose substrate pH in the non-amended pine bark ranged from 4.5 to 4.9 over the course of a year, substrate pH in our experiment ranged from 5.7 to 6.9 depending on slag rate. Similarly, Wright and Hinesly (1991) reported that Eastern redcedar (*Juniperus virginiana* L.) had similar foliar Cu concentration with or without micronutrient amendment, but substrate pH in their experiment ranged from 3.6 to 4.0. As suggested by Niemiera (1992), the decreased Cu in plant tissue in our experiment could have been a function of the increase in substrate pH caused by the addition of steel slag (Table 2).

The objective of this research was to determine if steel slag could be used as the sole micronutrient source for container-grown nursery crops in substrates composed primarily of pine bark. These data show that Cu is limiting in pine bark substrates amended solely with steel slag as a source of micronutrients. It either does not provide a sufficient quantity of Cu or the concomitant increase in pH with increasing rates of steel slag renders Cu unavailable for plant uptake. While steel slag is effective in raising substrate pH, it should not be used as the sole source for micronutrients in pine bark substrates. Pine bark itself might provide sufficient micronutrients without a supplemental micronutrient fertilizer, but it is unlikely to do so when amended with steel slag or other acid-neutralizing amendments.

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