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Modification of Switchgrass Substrate pH Using Compost, Peatmoss, and Elemental Sulfur

James E. Altland[1,3] and Charles Krause[2]

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SUMMARY. Switchgrass (*Panicum virgatum*) biomass is being evaluated as a potential alternative to pine bark as the primary potting component in containerized nursery crops. Substrates composed entirely of switchgrass have higher pH than what is considered desirable in container substrates. The objective of this research was to evaluate the influence of elemental S, sphagnum moss, and municipal solid waste compost (MSC) as amendments for reducing substrate pH and buffering it against large changes over time. Three experiments were conducted; the first two experiments were conducted using annual vinca (*Catharanthus roseus* 'Pacifica Blush') to quickly assess how pH was affected by the three amendments, and the final experiment was conducted with blueberry (*Vaccinium corymbosum* 'Duke') to assess the long-term effects of substrate amendments. Summarizing across the three experiments, elemental S was effective in reducing substrate pH; however, rates 1 lb/yard^3 or greater reduced pH below the recommended level of 5.5 and lower S rates did not maintain lowered pH over time. Sphagnum moss and MSC together at 20% and 10% (v/v), respectively, were effective at reducing substrate pH and buffering against change. Sphagnum moss and MSC provided the additional benefit of improving physical properties of the switchgrass substrates.

Switchgrass is a perennial grass currently being developed for its biofuel potential. Our laboratory has been exploring the possibility of using switchgrass as a raw material for nursery container substrates. Baled switchgrass processed through a hammer mill can be modified such that it makes a suitable nursery substrate for short-production cycle crops (Altland and Krause, 2009). One of the problems with switchgrass and other grass-based substrates is that pH of these ground materials is 7 to 7.5, higher than what is typically recommended for nursery crop production (4.5 to 6.5) (Yeager et al., 2007). Substrate pH could be lowered in switchgrass substrates by amending with other physical components that have lower pH (e.g., sphagnum moss). It is also possible that the addition of organic substrates with high cation exchange capacity, in the form of compost, might reduce and buffer substrate pH over time.

Chemical amendments can also be used to lower pH of soils and substrates. Elemental S has been used to lower pH in field soils and container substrates. Bishko and Fisher (2003) demonstrated that flowable elemental S reduced a peat-based medium by 3.3 pH units over the course of 28 d. Rathier (1983) demonstrated that flowable elemental S applications up to 2400 lb/acre (2.2 lb/yard^3) reduced substrate pH by more than 3 units in a compost and peat substrate and caused no injury to container-grown 'Rosebud' azaleas (*Rhododendron* sp.). Giblin and Gillman (2006) showed that various formulations of elemental S incorporated into the substrate reduced pH by 1–2 units below non-amended controls over a duration of 84 d while having no adverse effect on blueberry (*Vaccinium* × 'Northcountry') growth in a peat and pine bark substrate.

The objective of this research was to determine the effect of sphagnum moss, municipal solid waste compost (MSC), and elemental S on pH of substrates composed primarily of switchgrass and subsequent plant growth. Our approach was to initially use a short-production cycle annual crop to determine the immediate impacts of the aforementioned amendments, followed

USDA-ARS, Application Technology Research Unit, Ohio Agricultural Research and Development Center, 1680 Madison Ave., Wooster, OH 44691

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[1]Research Horticulturist

[2]Research Leader and Plant Pathologist

[3]Corresponding author. E-mail: James.Altland@ars.usda.gov.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.7457	horsepower	kJ·s^{-1}	1.3410
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
1.1209	lb/acre	kg·ha^{-1}	0.8922
0.5933	lb/yard^3	kg·m^{-3}	1.6856
28.3495	oz	g	0.0353
1.7300	oz/inch^3	g·cm^{-3}	0.5780
1	ppm	mg·kg^{-1}	1
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

by a long-term woody crop to document long-term effects on pH, pH buffering, and plant growth.

Materials and methods

Switchgrass was cut and baled early Spring 2009 on a farm in Meadeville, PA, and stored in a barn until needed. One day before starting each experiment, materials were processed through a 15-horsepower hammer mill (C.S. Bell, Tiffin, OH) equipped with a 0.188-inch screen. MSC was obtained from the Lake County Department of Utilities, Painesville, OH, and was commonly used in the Ohio nursery industry.

Expt. 1. Treatment design was a two by two by three factorial, with 0% or 10% MSC, 0% or 20% sphagnum moss (Conrad Fafard, Agawam, MA), and either 0, 1, or 4 lb/yard^3 elemental S (Yellow Jacket Wettable Dusting Sulfur; Georgia Sulfur, Valdosta, GA). All substrates were amended with 1.5 lb/yard^3 Micromax (Scotts, Marysville, OH) micronutrients and 2 lb/yard^3 gypsum. All aforementioned amendments were incorporated into the substrate by hand-mixing in a plastic container. Substrates were filled in containers 6 inches tall and wide and potted with a single 'Pacifica Blush' vinca on 13 Mar. 2009. Vinca were germinated and grown in 50-cell flats. Vinca were 5 to 6 cm tall, 10 to 12 cm wide, and not flowering at the time of potting. All containers were topdressed with 16 g 18N–2.6P–10K controlled-release fertilizer (Osmocote 18–6–12 Classic, 8 to 9-month release; Scotts).

Table 1. Physical properties of substrates composed of switchgrass after being processed through a hammer mill with 0.188-inch (4.7752-mm) screen and amended with 0% or 10% municipal solid waste compost (MSC), and 0% or 20% sphagnum moss (n = 3).

MSC (%)	Peatmoss (%)	Air space (%)	Container capacity (%)	Total porosity (%)	Bulk density ($g\cdot cm^{-3}$)[z]
0	0	55	37	92	0.07
	20	48	42	90	0.06
10	0	46	46	92	0.08
	20	42	47	89	0.08
$LSD_{0.05}$[y]		2	3	2	0.003
Main effects					
MSC		0.0001	0.0001	0.2066	0.0001
Peatmoss		0.0001	0.0080	0.0030	0.0005
Interaction		0.0393	0.0330	0.3585	0.5837

[z]1 $g\cdot cm^{-3}$ = 0.5780 oz/inch^3.
[y]Fisher's least significant difference (LSD) test within a column (α = 0.05).

Table 2. Substrate pH, chlorophyll content, and shoot dry weight (SDW) of annual vinca grown in substrates composed of switchgrass hammer milled with a 0.188-inch (4.7752 mm) screen and amended with 0% or 10% municipal solid waste compost (MSC), 0% or 20% sphagnum moss, and 0, 1, or 4 lb/yard^3 (0, 0.6, or 2.4 $kg\cdot m^{-3}$, respectively) elemental S.

MSC (%)	Peatmoss (%)	S (lb/yard^3)	Substrate pH 1 WAP[z]	Substrate pH 4 WAP	Substrate pH 6 WAP	Chlorophyll content[y] at 6 WAP	SDW at 6 WAP (g)[x]
0	0	0	7.7	7.7	7.5	46.7	2.4
		1	6.6	4.3	4.3	38.9	2.8
		4	5.6	2.9	2.6	32.1	1.7
	20	0	5.3	6.0	6.0	59.8	4.0
		1	3.6	3.0	2.6	22.9	2.2
		4	5.1	3.5	3.5	20.4	2.2
10	0	0	6.1	6.5	6.9	54.5	3.7
		1	4.8	4.8	5.0	47.6	3.0
		4	3.3	3.1	2.9	29.7	1.2
	20	0	5.5	5.6	5.7	58.3	5.1
		1	4.1	4.2	4.2	46.7	2.9
		4	3.3	3.1	3.0	22.7	1.9
$LSD_{0.05}$[w]			0.2	0.2	0.3	10.1	0.7
Main effects							
MSC (C)			0.0001	0.7814	0.0055	0.0030	0.0027
Peat (P)			0.0001	0.0001	0.0001	0.1354	0.0001
C × P			0.0001	0.0113	0.3364	0.3970	0.5482
S			0.0001	0.0001	0.0001	0.0001	0.0001
S × C			0.0001	0.0001	0.0001	0.0045	0.0001
S × P			0.0001	0.0001	0.0001	0.0006	0.0001
S × P × C			0.0001	0.0001	0.0001	0.0379	0.6004

[z]Weeks after potting.
[y]Chlorophyll content measured with a chlorophyll meter (SPAD-502; Minolta, Ramsey, NJ).
[x]1 g = 0.0353 oz.
[w]Fisher's least significant difference (LSD) test within a column (α = 0.05).

Containers were checked daily by weighing and overhead irrigated with 0.25 inch of water when substrates were dry. Vinca were grown in a heated polyethylene-covered hoop house with heat and cool set points at 74 and 80 °F, respectively. Light was supplemented with sodium vapor lights from 0600 to 2000 HR.

A sample of each substrate was set aside at the time of potting to determine physical properties. Substrates were packed in Al cores (3 inches tall by 3 inches i.d.) according to methods described by Fonteno and Bilderback (1993). There were three replications for each substrate. Aluminum cores were attached to substrate porometers for determination of air space (AS). Cores were weighed, oven dried for 4 d at 72 °C, and weighed again to determine container capacity (CC). Total porosity was calculated as the sum of AS and CC. Bulk density was determined using oven-dried substrate in Al cores.

Substrate pH was measured using the pour-through procedure at 1, 4, and 6 weeks after potting (WAP). Ten leaves of recently matured foliage were harvested (Mills and Jones, 1996) 6 WAP, rinsed with deionized water, and then oven dried at 72 °C for 3 d. Samples were ground in a Cyclotec mill (Tecator AB, Hogenas, Sweden) through a 0.5-mm screen. Foliar N was measured with a carbon and nitrogen analyzer (Vario Max; Elementar Americas, Mt Laurel, NJ). Other macronutrients and micronutrients were measured with an inductively coupled plasma optical emission spectrometer (Iris Intrepid; Thermo Fisher Scientific, Waltham, MA). Foliar chlorophyll content was measured with a chlorophyll meter (SPAD-502; Minolta, Ramsey, NJ) 6 WAP, by averaging five readings per single plant replication. Shoot dry weight (SDW) was measured 6 WAP by harvesting all shoot tissue and drying in an oven at 72 °C for 3 d. There were five single-plant replications per treatment combination arranged in a completely randomized design.

EXPT. 2. This experiment was conducted similar to Expt. 1, with the following exceptions. All substrates were amended with 10% MSC. Elemental S was applied at 0, 0.25, or 0.5 lb/yard³. Vinca were potted on 27 Apr. 2009 and averaged 6 cm tall and 12 cm wide at the time of potting. Data collected included substrate pH and SPAD chlorophyll readings taken 2, 4, and 7 WAP; foliar nutrient content of plant foliage measured 7 WAP; and SDW at 7 WAP.

EXPT. 3. 'Duke' blueberries from 50-cell packs were potted into one of four substrates composed of pine bark, or switchgrass amended with 0, 0.25, or 0.5 lb/yard³ S. Blueberries were ≈8 cm tall and 15 cm wide at the time of potting. All substrates were amended with 20% sphagnum moss (v/v), 10% MSC (v/v), 1.5 lb/yard³ Micromax micronutrients, and 2 lb/yard³ gypsum by incorporation. Containers were top-dressed with 20 g of Osmocote 18–6–12 Classic controlled-release fertilizer. Containers were grown outside on a gravel pad and irrigated overhead with 0.5 inches of water daily if needed. There were 12 single-pot replications per treatment at the start of the trial, arranged in a completely randomized design. Substrate pH was measured 1, 4, 12, and 20 WAP with the pour-through method, and SPAD chlorophyll content was measured 12 and 20 WAP. At 12 WAP, half of the replications in each treatment were randomly selected and destructively harvested to measure foliar nutrient content and SDW and record root ratings. Root ratings were assigned on a scale from 0 to 10 as an estimate of the percent of the substrate–container interface covered by roots, where 0 = no roots visible and 10 = complete coverage by root mass.

Data from all experiments were subjected to analysis of variance (ANOVA) with means separation by Fisher's protected least significant difference test (α = 0.05). Repeated-measures ANOVA was used when the same data were collected more than once over time. Regression analysis was used to relate vinca SPAD and SDW to substrate pH in Expt. 1.

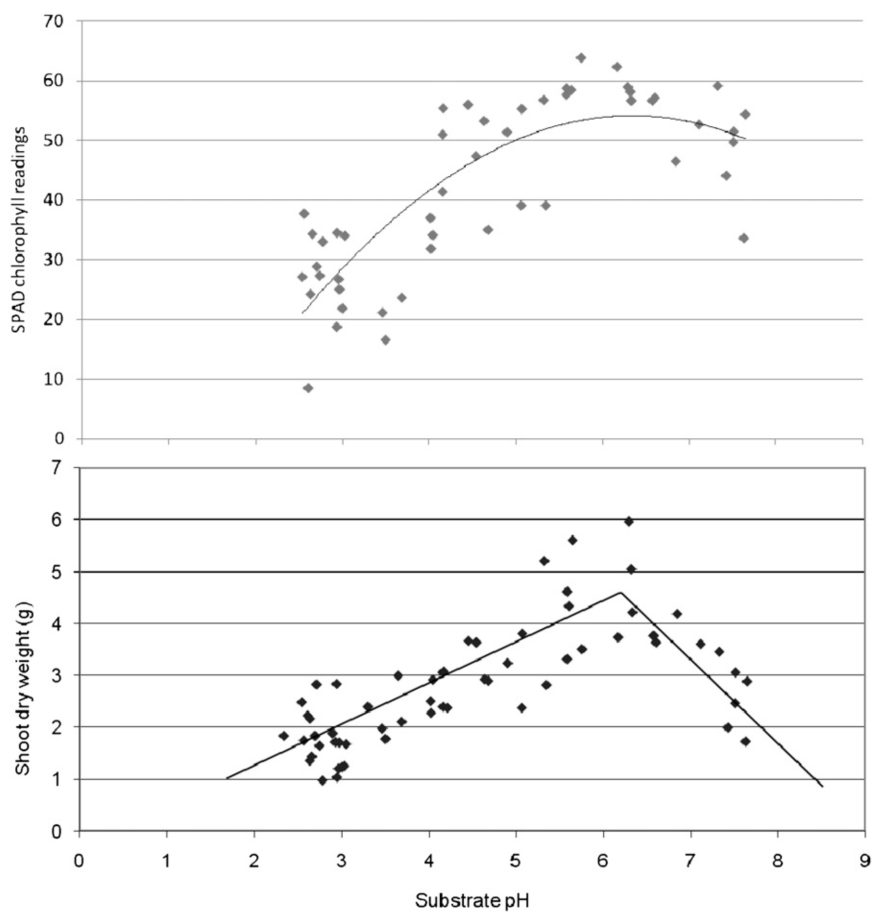

Fig. 1. Relationship between substrate pH and chlorophyll meter readings (SPAD-502; Minolta, Ramsey, NJ) or shoot dry weight (SDW) of 'Pacifica Blush' annual vinca grown in switchgrass substrates; SPAD = −2.29 × pH² + 29.10 × pH − 38.09, R^2 = 0.6578; SDW = 0.82 × pH – 0.55 over the pH range 2.3 to 6.3; SDW = −1.65 × pH + 15.60 over the pH range 6.3 to 7.6, R^2 = 0.7031; 1 g = 0.0353 oz.

Results and discussion

Expt. 1. Adding MSC and peatmoss affected substrate physical properties (Table 1). Ideal ranges for physical properties are 10% to 30% AS and 45% to 65% CC (Yeager et al., 2007). Substrates not amended with either MSC or peatmoss had high AS and low CC relative to ideal ranges. Adding 10% compost reduced AS and increased CC by 9%. Adding 20% peatmoss decreased AS by 7% and increased CC by 5%. Substrates amended with MSC, with or without peatmoss, had CC within the ideal range, but still had high AS. High AS has been associated with reduced root diseases in container substrates (Ownley et al., 1990). Differences in bulk density were minor. Across all substrates, bulk density averaged 0.07 $g \cdot cm^{-3}$, which is slightly less than bulk density of sphagnum moss (≈0.09 $g \cdot cm^{-3}$) and less than half the bulk density of pine bark (≈1.8 $g \cdot cm^{-3}$).

Repeated-measures analysis showed pH changed over time with significant time by treatment interactions ($P = 0.0221$). Substrate pH was 7.7 and declined slightly over time to 7.5 for substrates not amended with MSC, peatmoss, or S (Table 2). Substrates not amended with MSC or peatmoss but amended with 1 or 4 $lb/yard^3$ S decreased by more than 2 pH units from 1 to 4 WAP. Rathier (1983) reported that flowable elemental S applied as a drench application at rates of 1600 and 2400 lb/acre (≈1.5 and 2.25 $lb/yard^3$ S, respectively) reduced pH of a 2 hardwood bark : 1 sand : 1 peatmoss substrate by 2.1 and 2.4 pH units, respectively, after 77 d. Amendment with both peatmoss and MSC resulted in greater pH buffering than either component alone, with changes of 0.1 to 0.3 pH units over the course of the experiment. The combination of peatmoss and MSC reduced pH more than either component alone at 4 and 6 WAP. It is possible that the combination of peatmoss and MSC was most effective in buffering pH because of an additive effect from their chemical properties, or because addition of both components reduced the percent volume of switchgrass lower than either component alone. Amendment with S at either 1 or 4 $lb/yard^3$ reduced pH to below 5.5, the minimum of the range

Table 3. Foliar nutrient concentration in annual vinca grown in a switchgrass substrate amended with 0% or 10% municipal solid waste compost (MSC); 0% or 20% sphagnum moss; and 0, 1, or 4 $lb/yard^3$ (0, 0.6, or 2.4 $kg \cdot m^{-3}$, respectively) elemental S.

MSC (%)	Peatmoss (%)	S ($lb/yard^3$)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	B (ppm)[z]	Fe (ppm)[z]	Mn (ppm)[z]	Cu (ppm)[z]	Zn (ppm)[z]
0	0	0	2.9	0.3	1.8	0.7	0.3	0.3	126.1	30.8	115.0	4.6	46.8
		1	4.0	0.5	2.6	0.7	0.4	0.5	120.2	13.0	212.6	3.4	48.0
		4	3.9	0.3	1.6	0.5	0.3	0.5	84.0	22.5	157.0	4.2	56.6
	20	0	3.9	0.4	2.1	0.7	0.3	0.3	152.4	53.1	159.7	3.5	67.6
		1	4.5	0.4	1.9	0.6	0.3	0.5	160.0	26.9	177.0	2.9	42.1
		4	4.3	0.4	1.9	0.6	0.4	0.5	138.4	36.5	144.8	2.7	40.4
10	0	0	4.1	0.5	2.1	0.8	0.3	0.3	103.7	44.1	132.7	6.8	66.3
		1	3.5	0.5	2.5	0.7	0.3	0.4	101.6	79.4	278.7	5.2	70.4
		4	4.7	0.3	1.5	0.3	0.3	0.5	96.6	21.5	231.6	4.7	55.5
	20	0	3.4	0.4	2.0	0.8	0.3	0.3	137.3	62.2	198.4	6.8	68.6
		1	4.6	0.5	2.5	0.7	0.4	0.5	111.4	47.2	282.5	5.5	80.0
		4	4.9	0.3	1.6	0.3	0.3	0.5	114.5	19.5	277.4	4.9	63.2
$LSD_{0.05}$[y]			1.0	0.1	0.4	0.2	NS	0.1	NS	24.0	64.1	1.6	18.1
Adequate range[x]			2.7–6.3	0.28–0.64	1.88–3.48	0.93–1.13	0.32–0.78	0.22–0.5	21–49	72–277	135–302	6–16	30–51
Main effects													
MSC (C)			0.2040	0.9479	0.8171	0.1653	0.6916	0.2410	0.0721	0.0047	0.0001	0.0001	0.0001
Peat (P)			0.0468	0.8652	0.2341	0.9359	0.7607	0.9627	0.0354	0.3062	0.4328	0.0809	0.7500
C × P			0.2293	0.4630	0.5277	0.6143	0.1790	0.5357	0.2863	0.0197	0.3889	0.1902	0.6569
S			0.0070	0.0001	0.0001	0.0001	0.0407	0.0001	0.1916	0.0006	0.0001	0.0007	0.0374
S × C			0.2464	0.0012	0.0251	0.0005	0.3093	0.2111	0.8277	0.0003	0.1542	0.0670	0.0215
S × P			0.4200	0.4086	0.0600	0.5818	0.8312	0.7179	0.9837	0.0557	0.0577	0.4327	0.0674
S × P × C			0.0855	0.0177	0.0146	0.3764	0.1276	0.2808	0.5612	0.2213	0.8817	0.9638	0.1190

[z] 1 ppm = 1 $mg \cdot kg^{-1}$.
[y] Fisher's least significant difference (LSD) test within a column ($\alpha = 0.05$).
[x] Range for each nutrient determined to be adequate for high-quality plants (Mills and Jones, 1996).

considered optimum for annual vinca (Kessler, 1998).

SPAD chlorophyll content was affected by an interaction between MSC, peatmoss, and S rate (Table 2). Chlorophyll content decreased with increasing S rate within each of the four MSC and peatmoss substrate combinations, although the amount of decrease varied with each substrate type. There was a quadratic relationship between substrate pH and chlorophyll readings at 6 WAP (Fig. 1). Maximum chlorophyll content occurred at pH 6.3, a level provided most closely by amendment with MSC, peatmoss, or both, and exclusion of S. Chlorophyll content is often correlated to N content, in particular with annual vinca (Altland et al., 2002). Foliar N increased with addition of S in this study (Table 3) and is thus not likely the cause of the observed chlorosis. Furthermore, all vinca had adequate foliar N levels (Mills and Jones, 1996). Foliar K, Ca, Fe, and Cu were affected by amendments and were below the adequate range, whereas all other measured nutrients were within or above the adequate range. Foliar K and Ca dropped below the adequate range only in substrates amended with 4 lb/yard^3 S. High S rates would result in elevated H^+ concentrations in the substrate, displacing K and Ca cations from exchange sites in the substrate. Foliar Fe and Cu levels were affected by MSC and S amendments. MSC increased foliar Fe and Cu, whereas S had variable effect on both nutrients depending on substrate type. No single nutrient deficiency or toxicity explains the observed chlorosis. Instead, it was likely a combination of nutritional factors related to low or high pH.

Shoot dry weight was greatest for plants growing in substrate amended with MSC and peatmoss but without S (Table 2). Addition of 1 or 4 lb/yard^3 S decreased SDW of annual vinca in all substrates except 100% switchgrass. Similar to chlorophyll content, SDW was correlated to substrate pH but instead fit with a two-segment linear regression model. Maximum SDW, as indicated by the break point in the piecewise regression analysis, occurred when substrate pH was 6.3. This value is the same pH that maximized foliar

Table 4. Substrate pH, foliar chlorophyll content, and shoot dry weight (SDW) of annual vinca growing in switchgrass substrates amended with 0% or 20% sphagnum moss and 0, 0.25, or 0.5 lb/yard^3 (0, 0.148, or 0.297 kg·m^{-3}, respectively) elemental S.

Peatmoss (%)	S (lb/yard^3)	Substrate pH: 2 WAP^z	Substrate pH: 4 WAP	Substrate pH: 7 WAP	Chlorophyll content^y: 2 WAP	Chlorophyll content^y: 4 WAP	Chlorophyll content^y: 7 WAP	SDW at 7 WAP (g)^x
0	0	6.2	6.3	6.5	60.4	50.3	52.3	6.9
	0.25	5.7	6.1	6.1	60.0	46.7	52.5	6.9
	0.5	4.5	5.4	5.8	57.2	48.8	52.7	7.9
20	0	4.7	5.4	5.7	57.5	48.3	54.8	8.4
	0.25	4.2	4.8	4.9	57.1	47.3	50.2	8.5
	0.5	3.8	4.2	4.6	56.4	53.5	54.6	9.6
LSD$_{0.05}$^{w}		0.1	0.2	0.6	2.8	4.1	NS	1.3
Main effects								
Peat		0.0001	0.0001	0.0001	0.0087	0.3436	0.5624	0.0002
S		0.0001	0.0001	0.0006	0.0664	0.0227	0.2202	0.0258
Interaction		0.0001	0.0019	0.5533	0.4630	0.0792	0.2266	0.9682

^{z}Weeks after potting.
^{y}Chlorophyll content measured with a chlorophyll meter (SPAD-502; Minolta, Ramsey, NJ).
^{x}1 g = 0.0353 oz.
^{w}Fisher's least significant difference (LSD) test within a column (α = 0.05).

Table 5. Substrate pH, chlorophyll content, shoot dry weight (SDW), and root ratings of blueberry growing in pine bark and switchgrass substrates amended with 0, 0.25, or 0.5 lb/yard^3 (0, 0.148, or 0.297 kg·m^{-3}, respectively) elemental S.

Substrate	S (lb/yard^3)	Substrate pH: 1 WAP^z	Substrate pH: 4 WAP	Substrate pH: 12 WAP	Substrate pH: 20 WAP	Chlorophyll content^y: 12 WAP	Chlorophyll content^y: 20 WAP	SDW (g)^x: 12 WAP	SDW (g)^x: 20 WAP	Root rating^w: 12 WAP	Root rating^w: 20 WAP
Switchgrass	0	5.6	6.4	6.4	6.3	48.9	38.8	18.7	34.2	4.7	5.3
	0.25	5.3	6.0	6.0	5.9	48.2	40.7	23.0	32.2	6.0	6.3
	0.5	5.1	5.6	5.9	5.9	49.8	41.8	18.1	33.6	5.3	6.3
Pine bark	0	4.6	5.3	6.1	5.9	51.2	44.1	25.3	37.2	5.2	6.3
LSD$_{0.05}$^{v}		0.1	0.1	0.2	NS	NS	NS	4.5	NS	NS	NS

^{z}Weeks after potting.
^{y}Chlorophyll content measured with a chlorophyll meter (SPAD-502; Minolta, Ramsey, NJ).
^{x}1 g = 0.0353 oz.
^{w}Root ratings estimate the percentage of substrate–container interface covered by roots and are on a scale from 0 to 10, where 0 = no roots visible and 10 = complete coverage of the substrate–container interface.
^{v}Fisher's least significant difference (LSD) test within a column (α = 0.05).

SPAD readings. SDW increased with increasing pH from 2.3 to 6.3 and then decreased with increasing pH from 6.3 to 7.6.

Expt. 2. The experiment was repeated with lower S rates and with all substrates amended with MSC to reduce treatment numbers. Repeated-measures analysis indicated a significant time by peatmoss by S interaction (P = 0.0001). Substrates amended with peatmoss were more buffered against change in pH than those not amended. At 2 WAP, difference in pH of substrates amended with peatmoss and 0.5 lb/yard³ S was 0.9 pH units lower than those with peatmoss but without S (Table 4). In contrast, substrates lacking peatmoss were reduced by 1.7 pH units when comparing the 0 and 0.5 lb/yard³ S rates. Among containers amended with peatmoss, those amended with S were below the recommended pH range of 5.5 to 6.5 for annual vinca (Kessler, 1998).

Foliar SPAD readings were high among all treatments throughout the experiment (Table 4). There were differences in SPAD readings 2 and 4 WAP, although these differences were minor. By 7 WAP, there were no differences in foliar SPAD readings among substrate or S treatments and all readings were high (>50) relative to well-fertilized vinca in other research (Altland et al., 2002). Foliar nutrient concentrations were largely unaffected by peatmoss or S rate. Only foliar Ca, Mn, Cu, and Zn differed among treatments, and these differences were all minor (data not shown).

Vinca SDW was affected by peatmoss and S rate, but not by their interaction (Table 4). Across peatmoss rates, the largest vinca were those receiving the highest S rate (contrast analysis, P = 0.0075, data not shown). Across S rates, substrates amended with peatmoss were larger than those not amended (contrast analysis, P = 0.0002, data not shown).

Expt. 3. At 1 WAP, substrate pH in switchgrass substrates decreased with increasing S rate (Table 5). Substrate pH of pine bark substrates was lower than all switchgrass substrates. This trend continued until 12 WAP, when pine bark and switchgrass substrates amended with either 0.25 or 0.5 lb/yard³ S were similar and only slightly lower than non-amended switchgrass. By 20 WAP, all substrates had similar pH averaging 6.0. After 20 weeks in production, there was less than 1 unit change in pH for the three switchgrass substrates. Similar to Expts. 1 and 2, amendment with both peatmoss and MSC buffered pH against drastic change over the production period of the crop.

SPAD chlorophyll readings were similar across treatments at 12 and 20 WAP (Table 5). There were differences in foliar nutrient content, although most were unremarkable. Across 12 and 20 WAP, foliar K, S, B, and Mn were less in some switchgrass substrates compared with pine bark (Table 6), but all treatments were within sufficiency ranges (Mills and Jones, 1996). At 20 WAP, foliar N of plants growing in switchgrass amended with 0.25 lb/yard³ S was less than those growing in pine bark. Foliar Fe was the most deficient nutrient in switchgrass substrates. Despite amendment with 1.5 lb/yard³ micronutrient package containing 17% Fe by weight (from ferrous sulfate), Fe levels in plants growing in switchgrass 20 WAP were consistently lower than those growing in pine bark and at or below the sufficiency range for blueberries. Considering the similarity in pH levels between pine bark and switchgrass substrates in this experiment, it is unlikely that substrate pH is the cause of the observed Fe deficiency. Pine bark alone has been shown to be an excellent source of micronutrients in

Table 6. Foliar nutrient concentration in foliage of blueberry grown in pine bark and switchgrass substrates amended with 0, 0.25, or 0.5 lb/yard³ (0, 0.148, or 0.297 kg·m⁻³, respectively) elemental S.

Substrate	S (lb/yard³)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	B (ppm)[z]	Fe (ppm)[z]	Mn (ppm)[z]	Cu (ppm)[z]	Zn (ppm)[z]
					12 WAP[y]							
Switchgrass	0	1.8	0.13	0.6	0.6	0.16	0.22	53.8	38.2	305.8	5.9	31.4
	0.25	1.8	0.15	0.7	0.6	0.17	0.24	45.0	67.4	357.7	6.5	37.3
	0.5	1.8	0.13	0.6	0.6	0.16	0.23	41.8	33.5	362.4	6.3	34.2
Pine bark	0	1.9	0.14	0.8	0.7	0.17	0.26	67.8	89.8	767.5	6.8	30.6
$LSD_{0.05}$[x]		NS	NS	0.1	0.1	NS	0.03	13.0	27.9	112.1	NS	NS
					20 WAP							
Switchgrass	0	1.6	0.18	0.8	0.4	0.16	0.20	23.7	52.7	152.5	7.1	16.1
	0.25	1.5	0.16	0.8	0.5	0.17	0.21	28.5	55.4	203.2	7.4	15.8
	0.5	2.0	0.20	0.9	0.5	0.14	0.24	26.3	61.3	291.1	7.6	17.1
Pine bark	0	1.8	0.20	0.7	0.6	0.17	0.27	39.1	119.0	555.4	8.0	17.6
$LSD_{0.05}$		0.3	NS	0.1	NS	NS	NS	NS	52.8	143.3	NS	NS
Adequate range[w]		1.8–2.1	0.12–0.40	0.35–0.65	0.4–0.8	0.12–0.25	0.12–0.20	25–70	60–200	50–350	5–20	8–30

[z]1 ppm = 1 mg·kg⁻¹.
[y]Weeks after potting.
[x]Fisher's least significant difference (LSD) test within a column (α = 0.05).
[w]Range for each nutrient determined to be adequate for high-quality plants (Krewer and Ruter, 2009).

the production of ornamental crops in containers (Niemiera, 1992; Rose and Wang, 1999). Switchgrass substrates will need to be further developed to avoid Fe deficiencies.

At 12 WAP, blueberries grown in pine bark substrate were ≈27% larger than those growing in switchgrass substrate amended with either 0 or 0.5 lb/yard³ S (Table 5). By 20 WAP, there were no differences in blueberry SDW. We have observed in other research (data not published) that plants growing in switchgrass substrates initially grow more slowly than those in pine bark substrates, but after 6 to 8 weeks, plants in switchgrass substrates will have grown similar to or larger than plants in pine bark substrates. Root ratings for blueberries were similar at 12 and 20 WAP. Giblin and Gillman (2006) showed that rates from 1.5 to 4.5 lb/yard³ S did not affect 'Northcountry' blueberry root or shoot growth compared with nonamended controls.

In summary, peatmoss and MSC improved the physical properties of switchgrass substrates by decreasing AS and increasing CC. Peatmoss and MSC also decreased substrate pH of switchgrass to a level more conducive to annual vinca production. Elemental S was effective at reducing pH, but rates should be limited to less than 1 lb/yard³ and varied depending on the species being grown and its pH requirement. Combinations of peatmoss and MSC were more effective in buffering pH against changes than either component alone. It is possible that the combination of peatmoss and MSC was most effective in buffering pH because of an additive effect from their chemical properties, or because addition of both components reduced the percent volume of switchgrass lower than either component alone. Plant growth and quality, in terms of SPAD readings and SDW, were improved with additions of peatmoss and MSC but negatively affected with higher rates of elemental S (>1 lb/yard³). When using switchgrass substrates, addition of up to 20% peatmoss and 10% MSC is recommended for improving physical properties, moderating and buffering pH, and improving crop growth. Nursery growers in Ohio already amend pine bark with ≈20% peatmoss and ≈10% MSC; thus, this aspect of substrate management would not be affected if growers changed to switchgrass-based substrates.

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