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Biochar Affects Macronutrient Leaching from a Soilless Substrate

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***Abstract*. Byproducts of pyrolysis, known collectively as biochar, are becoming more common and readily available as ventures into alternative energy generation are explored. Little is known about how these materials affect greenhouse container substrates. The objective of this research was to determine the effect of one form of biochar on the nutrient retention and release in a typical commercial greenhouse container substrate. Glass columns filled with 85:15 sphagnum peatmoss:perlite (v:v) and amended with 0%, 1%, 5%, or 10% biochar were drenched with nutrient solution and leached to determine the impact of biochar on nutrient retention and leaching. Nitrate release curves were exponential and peaked lower, at later leaching events, and had higher residual nitrate release over time with increasing biochar amendment rate. This suggests that biochar might be effective in moderating extreme fluctuations of nitrate levels in container substrates over time. Peak phosphate concentration decreased with increasing biochar amendment rate, whereas time of peak release, girth of the peak curve, and final residual phosphate release all increased with increasing biochar amendment. Additional phosphate levels in leachates from biochar-amended substrates, in addition to the higher phosphate concentrations present in later leaching events, suggest this form of biochar as a modest source of phosphate for ornamental plant production. Although there was not sufficient potassium (K) from biochar to adequately replace all fertilizer K in plant production, increasing levels of this form of biochar will add a substantial quantity of K to the substrate and should be accounted for in fertility programs.**

Modern pyrolysis systems are used to extract liquid and gas petroleum products from biomass for fuel or other chemical products. Biochar is the charred organic matter that remains after pyrolysis of biomass or manure. Biochar is essentially the same as charcoal with the primary distinction being that biochar is intended for some form of soil or agricultural application (Lehmann and Joseph, 2009). Return of biochar to soil systems, where it is believed to be stable for hundreds or thousands of years, is touted as a promising solution to reducing atmospheric carbon (Glaser et al., 2002).

The influence of biochar in mineral soil systems has been studied and reviewed extensively (Lehmann et al., 2011; Spokas et al., 2011). Some of the most commonly cited beneficial impacts of biochar have been improved crop growth in highly weathered or sandy soils (Lehmann et al., 2003; Novak et al., 2009), increased soil pH (Novak et al., 2009), shifts to beneficial microbial populations (Lehmann et al., 2011), increased mycorrhizal associations (Warnock et al., 2007), and improved nutrient retention (Clough and Condron, 2010). Benefits of biochar are not consistently realized in temperate soils. A meta-analysis on 100 biochar studies concluded that variability in biochar source and application parameters resulted in ≈20% negative results, 30% nonsignificant difference in results, and 50% short-term positive results (Spokas et al., 2011). However, the authors of the meta-analysis caution that there was a greater number of increased yield results reported for studies that occurred in weathered or degraded soils that had prior limited fertility and productivity.

The influence of biochars on soilless substrates used in greenhouse and nursery container substrates has been studied less, and only a few citations tangentially related to greenhouse and nursery production in soilless substrates are available. Kadota and Niimi (2004) reported 10% or 30% additions of biochar combined with either pyroligneous acid (wood vinegar) or barnyard manure to a 2:1:1:1:1 peatmoss:soil:vermiculite:perlite: sand (v/v) substrate had either no effect or minor changes (positive and negative) in growth parameters of several bedding plant species. Graber et al. (2010) reported that biochar improved growth and productivity of pepper (*Capsicum annuum* L.) and tomato (*Lycopersicum esculentum* Mill.) plants in a blend of coconut fiber and tuff and attributed improvements to either stimulated shifts in microbial populations toward beneficial plant growth-promoting rhizobacteria or fungi or low doses of phytotoxic biochar chemicals, which may have stimulated plant growth at low doses. Ruamrungsri et al. (2011) reported that gloriosa lily (*Gloriosa rothschildiana* L.) in a 1:1:1 sand:rice husk charcoal:coconut fiber substrate did not respond to varying levels of applied calcium (Ca) fertilizers as a result of high Ca levels in rice husk charcoal. Santiago and Santiago (1989) briefly summarized their work using wood-based charcoal chips for hydroponic culture in humid tropical regions of Asia but provided few details other than plants grew well when fertilized with resin-coated fertilizers. Dumroese et al. (2011) evaluated pelletized biochar (pellets were 43% biochar, 43% wood flour, 7% polyacetic acid, and 7% starch) in combination with sphagnum peatmoss for production of forest seedlings. They found that amendment with 25% biochar pellets improved hydraulic conductivity and water retention at high matric potentials and beneficially increased substrate pH, although concern was noted about lower cation exchange capacity and higher carbon: nitrogen ratio. Beck et al. (2011) showed that amendment of an unspecified greenroof media with 7% biochar increased water retention and decreased total nitrogen and phosphorus, nitrate, phosphate, and organic carbon in runoff.

The body of biochar research in soilless substrates is far less complete than that for mineral soils; however, the collection of papers thus far seems to indicate similar potential benefits in soilless substrates including additions of some nutrients, reduction in leaching of nitrates and phosphates, beneficial shifts in microbial populations, and improved physical properties. Despite this, these articles have limited applicability to production methods typical of greenhouse production in sphagnum peatmoss substrates. The objective of this research was to determine the effect biochar additions have on nutrient dynamics in a sphagnum peatmoss-based soilless substrate typical of those used in greenhouse production of ornamental crops.

Materials and Methods

A standard commercial soilless substrate composed of 85:15 sphagnum peatmoss: perlite (v:v) (BM-6; Berger Peat Moss, Saint-Modeste, Quebec, Canada) was selected as the base substrate for the study. The base substrate contained no incorporated macronutrient fertilizers. Biochar used in this study was obtained from a local bioenergy pyrolysis unit [Synterra Energy (formerly Red Lion Bio-Energy), Toledo, OH] with particle size distribution and chemical properties in Tables 1 and 2. Particle size distribution was determined by passing ≈100 cm^3 oven-dried (72 °C) biochar through 19.0-, 12.5-, 6.30-,

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4.0-, 2.8-, 2.0-, 1.4-, 1.0-, 0.71-, 0.50-, 0.35-, 0.25-, 0.18-, and 0.11-mm soil sieves. Particles 0.11 mm or less were collected in a pan. Sieves and pan were shaken for 3 min with a RX-29/30 Ro-Tap® test sieve shaker (278 oscillations/min, 150 taps/min) (W.S. Tyler, Mentor, OH). Biochar percent carbon and nitrogen (N) were determined with a PerkinElmer Series II CHNS/O Analyzer (PerkinElmer Instruments, Shelton, CT). Other macronutrients and micronutrients were determined with a Thermo Iris Intrepid ICP-OES (Thermo Electron Corp., Waltham, MA).

Table 1. Chemical properties of biochar before substrate amendment.[z]

	Units	Nutrient concn
Carbon	(%)	59.5
Nitrogen		0.2
Phosphorus		0.07
Potassium		0.50
Calcium		1.15
Magnesium		0.27
Sulfur		0.02
Silicon		3.01
Boron	$mg\cdot kg^{-1}$	17.01
Copper		10.87
Iron		1609.9
Manganese		323.3
Molybdenum		4.13
Zinc		9.26

[z]All analyses are expressed on a percent or concentration of oven dried biochar.

Table 2. Particle size distribution of biochar used as a greenhouse substrate amendment (n = 3).

Sieve size (mm)	Percent of sample	SD
<0.106	28.8	0.75
0.106	17.0	0.48
0.18	11.5	0.17
0.25	12.8	0.16
0.35	11.1	0.36
0.5	9.0	0.38
0.71	3.8	0.23
1	2.2	0.24
1.4	2.0	0.13
2	1.2	0.07
2.8	0.4	0.23
4	0.0	0.03
6.3	0.1	0.13
12.5	0.0	0.00

The peatmoss substrate was amended volumetrically with 0%, 1%, 5%, or 10% biochar (v/v). Quantities of biochar and substrate were measured more precisely by first establishing the weight of 60 and 600 cm^3 of biochar and substrate, respectively, and then weighing the appropriate amount of biochar and substrate to approximate the desired volumetric ratios.

The substrates were packed into glass columns 4.5 cm i.d. and 38 cm long with a volume of ≈600 cm^3. Columns have a flat, false bottom above a stopcock to prevent compression and to control drainage of added solutions. Each biochar treatment rate was packed into three columns by adding ≈150 cm^3 increments of substrate, gently packing with a wand, and repeating until the column was full and contained ≈600 cm^3 substrate. On 14 June 2011, each column was saturated with 215 mL deionized (DI) water, enough to saturate the entire column of substrate, and let stand for 1 h. The solution was drained through filters (Whatman #2 150 mm Qualitative Circular filter papers; Whatman Ltd., Kent, U.K.) into 50-mL vials placed in an ice bath. After 30 min, most of the solution was collected, stored in plastic vials, and frozen until analyzed. After removing the collected leachates, stopcocks were left open overnight to fully drain. On the second day the columns were saturated with 200 mL (enough to completely saturate the column) of a 100 $mg\cdot L^{-1}$ N fertilizer solution (20N–4.4P–16.6K; JR Peters, Inc., Allentown, PA). The substrates remained saturated for 30 min and then drained and filtered into vials on ice. Samples were frozen and stopcocks were left open overnight to drain fully.

The next day, 60 mL of DI water was added to each column leaving the stopcocks open the entire time and retrieving ≈55 mL from each column. The solution was filtered and chilled on ice and then frozen. Stopcocks were left open overnight to assure complete drainage. This process was repeated everyday for a total of 12 leaching events. Columns were not leached on weekends. The experiment was conducted on a laboratory bench with three single-column replications per biochar amendment rate.

At the time of analysis, samples were thawed and filtered through GF/F binder-free borosilicate glass fiber filter paper (Whatman) to remove particles greater than 0.7 μm. The filtrate was then poured into 5-mL autosampler vials, capped, and analyzed on an ICS 1600 (Ion Chromatography System; Dionex, Bannockburn, IL) for concentrations of nitrate (NO_3^-), ammonium (NH_4^+), phosphate (PO_4^{2-}), and K. Solution samples were also measured for pH (UB-10 pH/mv Meter; Denver Instruments, Bohemia, NY).

The leaching study was repeated 19 July 2011 with the following exceptions. The 1% biochar amendment rate was dropped from the study so that only the 0%, 5%, and 10% (v/v) rates were included. Each biochar amendment rate was packed into four columns (replications). Leachate volumes were recorded to determine the total mass of recovered nitrate, phosphate, and K.

Data were analyzed with non-linear regression techniques using SAS 9.1 (SAS Systems, Inc., Cary, NC). Nitrate and phosphate release patterns were fit to a modified exponential equation:

$$y = a + be^{-(x-c)2/d}$$

where y is nitrate or phosphate concentration measured in the leachate on leaching event x. The parameter a indicates the value of y, which the curve approaches asymptotically as x increases to infinity. The sum $a + b$ represents the maximum value of y at $x = c$. The parameter c = the leaching event of peak release and d is a scaling factor that reflects the girth of the curve's peak. Mass of nutrients recovered in the initial saturation and fertilization events as well as the sum of all leaching events were subjected to analysis of variance and means separation with Fisher's protected least significant difference test.

Table 3. Estimated parameters (with standard errors in parentheses) for macronutrient release curves (Fig. 1) in a 85:15 sphagnum peat:perlite substrate amended with 0%, 1%, 5%, or 10% biochar.[z]

Nutrient	Biochar (%)	a^y		b		c		d		r^2
Nitrate	0	0.56	(3.74)	214.76	(7.01)	2.42	(0.08)	6.15	(0.66)	0.970
	1	4.83	(3.71)	242.62	(7.89)	2.89	(0.05)	4.88	(0.41)	0.973
	5	8.03	(4.04)	185.22	(6.93)	3.30	(0.07)	7.19	(0.72)	0.961
	10	11.95	(2.60)	172.78	(4.23)	3.76	(0.04)	6.35	(0.40)	0.982
Phosphate	0	1.88	(0.66)	32.21	(1.25)	2.86	(0.07)	5.48	(0.59)	0.958
	1	2.83	(0.62)	40.51	(1.30)	3.17	(0.05)	4.63	(0.37)	0.973
	5	3.47	(1.38)	32.02	(2.01)	3.38	(0.14)	9.17	(1.67)	0.890
	10	5.78	(0.67)	31.69	(1.03)	3.87	(0.07)	7.88	(0.67)	0.970
Potassium	0[x]	—		—		—		—		—
	1	—		—		—		—		—
	5	11.16	(0.21)	9.90	(0.35)	3.31	(0.08)	9.80	(0.95)	0.969
	10	17.35	(0.60)	23.40	(0.70)	3.25	(0.11)	16.58	(1.74)	0.977

[z]Columns were fertilized with a 20N–4.3P–16.6K solution and then leached 12 times over 16 d.
[y]Nitrate, phosphate and potassium leached from columns were fit to a modified exponential curve in the form of $y = a + be^{-(x-c)2/d)}$, where y is the nutrient concentration measured in the leachate on the xth leaching event, a indicates the value of y which the curve approaches asymptotically as x increases to infinity, $a + b$ represents the maximum value of y when $x = c$, and d is a scaling factor.
[x]Potassium release in substrates with 0% and 1% biochar was better fit with linear functions, where y = –0.03 + 0.37x (r^2 = 0.7428) and y = 1.57 + 0.38x (r^2 = 0.4157), respectively.

Results and Discussion

Nitrate release patterns varied by biochar amendment rate (Table 3; Fig. 1). Nitrate levels peaked highest (sum of parameters $a + b$) for 1% biochar and least for 5% and 10% biochar amendments (Table 3). Peak nitrate levels occurred (parameter c) later with increasing biochar rate. Girth of the release curve peaks (parameter d) was similar among each of the biochar treatments, although slightly smaller for the 1% rate. The nitrate concentration to which the curve approaches at the conclusion of the 12 leaching events (parameter a) increased with increasing biochar rate. All together Figure 1 and fitted parameters for the exponential curve show that as biochar amendment increases, the peak for the nitrate release curves

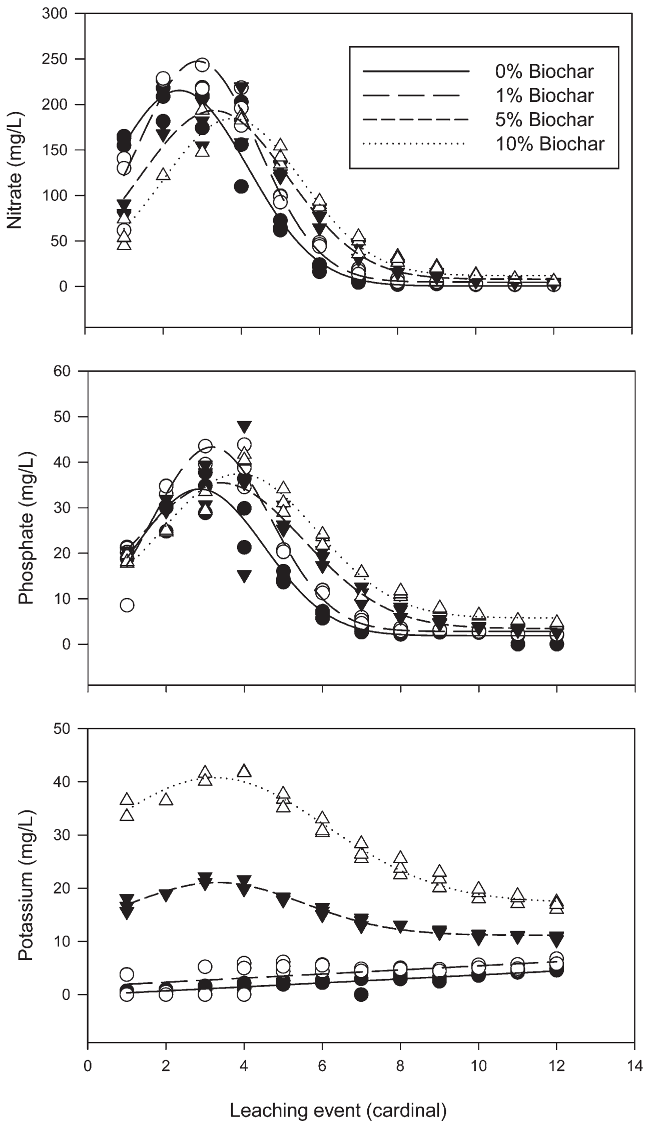

Fig. 1. Nitrate, phosphate, and potassium leaching from 85:15 sphagnum peat:perlite substrates amended with 0%, 1%, 5%, or 10% biochar. Columns were initially fertilized with 200 mL a 100 $mg \cdot L^{-1}$ nitrogen fertilizer (20N–4.3P–16.6K) solution. Columns were then leached 12 times over the course of 16 d by adding 60 mL of water to the top of the column and collecting leachate from the bottom. Parameter estimates of fitted curves are detailed in Table 3.

Table 4. Estimated parameters (with standard errors within parentheses) for macronutrient release curves (Fig. 2) in a 85:15 sphagnum peat:perlite substrate amended with 0%, 5%, or 10% biochar.[z]

Nutrient	Biochar (%)	a[y]		b		c		d		r^2
Nitrate	0	8.86	(3.23)	218.39	(6.98)	2.30	(0.06)	4.26	(0.41)	0.963
	5	16.47	(3.01)	148.61	(5.26)	3.45	(0.06)	5.76	(0.53)	0.950
	10	19.12	(5.99)	101.81	(9.21)	4.20	(0.16)	6.43	(1.51)	0.737
Phosphate	0	3.95	(0.54)	29.4	(0.94)	2.50	(0.08)	7.21	(0.77)	0.960
	5	5.20	(0.74)	26.0	(0.94)	3.85	(0.08)	11.18	(1.15)	0.947
	10	9.50	(1.43)	14.0	(1.53)	4.71	(0.21)	13.00	(3.82)	0.694
Potassium	0[x]	—		—		—		—		—
	5	13.31	(0.34)	7.16	(0.47)	2.70	(0.22)	11.27	(2.69)	0.841
	10	20.45	(1.62)	22.55	(1.86)	1.39	(0.61)	41.44	(12.7)	0.938

[z]Columns were fertilized with a 20N–4.3P–16.6K solution and then leached 12 times over 16 d.

[y]Nitrate, phosphate, and potassium leached from columns were fit to a modified exponential curve in the form of $y = a + be^{-[(x-c)2/d]}$, where y is the nutrient concentration measured in the leachate on the xth leaching event, a indicates the value of y which the curve approaches asymptotically as x increases to infinity, $a + b$ represents the maximum value of y when $x = c$, and d is a scaling factor.

[x]Potassium release in substrates with 0% biochar was better fit with a linear function where y = 1.68 + 0.43x (r^2 = 0.7105).

occur later and the level of nitrate at which the curve settles is greater.

Similar to nitrate release curves in Expt. 1, curve peaks decreased with increasing biochar amendment rate in Expt. 2 (Table 4) from 227.24 $mg \cdot L^{-1}$ down to 120.93 $mg \cdot L^{-1}$. The parameters a, c, and d increased with increasing biochar rate. Similar to the first experiment, nitrate release curves peaked lower, at later leaching events, and had higher residual nitrate release over time with increasing biochar amendment rate. There was 88.5 mg of nitrate added to each column through the fertilization event. No nitrate was recovered after the initial saturation event was drained, which was expected because the commercial potting mix was selected to have no incorporated macronutrient fertilizers. Immediately after the fertilization event, columns with no biochar leached 6.5 mg of nitrate, accounting for 7.3% of the total nitrate applied (Table 5). Columns with 5% or 10% biochar leached less than 1% of the applied nitrate. Over the 12 leaching events, the sum of nitrate released from the columns did not differ for the three biochar amendment rates and ranged from 37.1 to 44.7 mg, which averaged ≈47% of the applied nitrate from liquid feed fertilization. Although the nitrate release was lower and occurred later with increasing biochar amendment rate, the total amount of nitrate did not differ among treatments. This suggest that nitrate was not irreversibly bound to the biochar but retained and more slowly released.

Ammonium recovered in leachates was low relative to nitrate throughout both experiments, averaging just 1.4 $mg \cdot L^{-1}$ with a maximum 3.3 $mg \cdot L^{-1}$ across all treatments and collection dates (data not shown). The fertilizer used in this experiment was comprised of 8% ammonium-N and 12% nitrate-N. It is likely that the ammonium was quickly converted to nitrate, which has been shown to occur rapidly in soilless substrates (Lang and Elliott, 1991; Niemiera and Wright, 1986). Solution pH of the leachates was greater than 6.2 throughout the experiment and thus sufficiently high for nitrification to proceed (Lang and Elliott, 1991).

Phosphate levels in Expt. 1 peaked highest for substrates containing 1% biochar (Table 3; Fig. 1) and were similar for all other substrates. Peak phosphate levels occurred slightly later with increasing biochar level and peaks were wider with 5% and 10% biochar compared with 0% or 1%. Final phosphate concentrations increased with increasing biochar levels. Similar to nitrate release curves, biochar amendments tended to decrease peak phosphate release and caused it to be released more slowly over time. Results were similar in Expt. 2 in that peak phosphate concentration decreased with increasing biochar amendment rate, whereas time of peak release, girth of the peak curve, and final residual phosphate release all increased with increasing biochar amendment rate. There was 10 mg of phosphate added to each column through the fertilizer application. However, there was 1.3 and 1.8 mg

Table 5. Mass of fertilizer nutrients collected in leachates from columns with an 85:15 sphagnum peatmoss:perlite substrate amended with 0%, 5%, or 10% biochar and fertilized with a 20N–4.3P–16.6K solution.[z]

Nutrient	Event	0% Biochar	5% Biochar	10% Biochar	LSD[y]
		---------- (mg) ----------			
Nitrate	Water saturation	0.0	0.0	0.0	NS
	Fertilizer saturation	6.5	0.8	0.7	1.9
	Summed leach events	44.7	44.0	37.1	NS
Phosphate	Water saturation	0.0	1.3	1.8	0.3
	Fertilizer saturation	2.1	1.9	2.8	0.6
	Summed leach events	9.1	11.2	10.9	1.0
Potassium	Water saturation	0.7	7.9	13.3	1.7
	Fertilizer saturation	0.3	4.2	9.9	0.9
	Summed leach events	2.9	10.7	21.5	1.2

[z]Leachates were collected after an initial water saturation, a fertilizer saturation, and then leached 12 times over 16 d.

[y]Fisher's protected least significant difference (LSD) value ($\alpha = 0.05$) for comparing means within a row. NS = nonsignificant difference between means within a row.

phosphate recovered from the 5% and 10% columns, respectively, after the water saturation event and before fertilizer application. This, along with the observation of 0 mg phosphate from the non-amended columns, suggests the phosphate recovered after the first water saturation event was derived from the biochar additions. Leachates recovered from the fertilizer event contained similar quantities of phosphate in the 0% and 5% biochar columns and slightly higher amounts in the 10% columns. Even among the columns not amended with biochar, 21% of the applied phosphate was leached in that drainage event. Others have shown that in contrast to mineral soils, phosphates are readily leached in peatmoss-based soilless substrates (Owen et al., 2008; Warren et al., 1995). By the conclusion of the study, the cumulative recovered phosphate in leachates was 91%, 112%, and 109% for 0%, 5%, and 10% biochar-amended columns. Add to this the phosphate recovered immediately after the fertilizer drench and all three treatments yielded more phosphate than was added by the fertilizer.

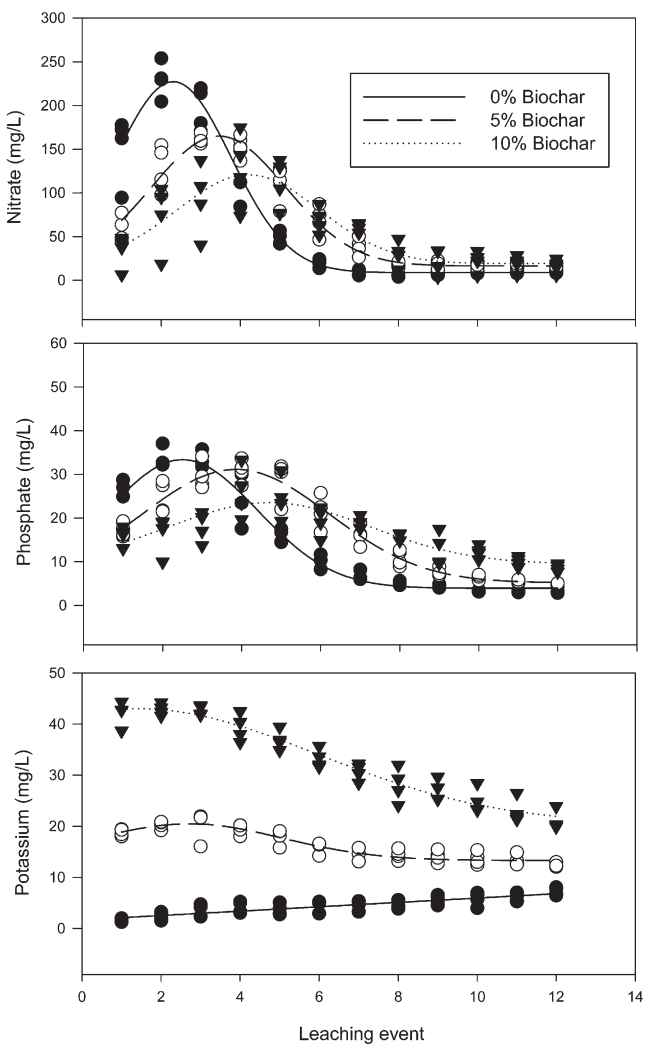

Fig. 2. Nitrate, phosphate, and potassium leaching from 85:15 sphagnum peat:perlite substrates amended with 0%, 5%, or 10% biochar. Columns were initially fertilized with 200 mL of a 100 mg·L^{-1} nitrogen fertilizer (20N–4.3P–16.6K) solution. Columns were then leached 12 times over the course of 16 d by adding 60 mL of water to the top of the column and collecting leachate from the bottom. Parameter estimates of fitted curves are detailed in Table 4.

Potassium levels in substrates with 0% or 1% biochar increased linearly across leaching events from 0 to a maximum of ≈5 mg·L^{-1}. Substrate with 5% or 10% biochar exhibited an exponential release over leaching events similar to nitrate and phosphate. Release curves for potassium were similar in Expts. 1 and 2 when comparing 0%, 5%, and 10% biochar amendment rates. Biochar used in this study provided an abundant source of potassium. After the water drench at the beginning of Expt. 2, leachates from the 10% biochar-amended substrate had a 20-fold increase in K recovered compared with the non-amended substrate. A total of 16.6 mg K+ was added to the columns through the fertilizer application, of which only 20% (3.2 mg) was recovered in non-amended substrates, whereas 89% (14.9 mg) and 188% (31.4 mg) were recovered in 5% and 10% biochar-amended substrates, respectively. This demonstrates both that the sphagnum peat substrate used in this study retained a high percentage of the applied K+ and that biochar is a significant source of K+ and should be accounted for in fertility programs.

There are several practical applications of these nutrient release curves. First is that biochar may absorb high concentrations of nitrate and release it more slowly over time. This retention and release mechanism might be exploited to increase N efficiency in container production. Nitrate could be applied less frequently while still maintaining adequate nitrate in solution. Yeager et al. (2007) suggest 50 to 100 mg·L^{-1} nitrate in crops fertilized through liquid feed as measured by the pour-through technique, analogous to the leachate collection procedures used in this study. Peak nitrate concentrations in substrates in this study for non-amended substrates were 215.3 and 227.3 mg·L^{-1}, whereas substrates amended with 10% biochar were 184.7 and 120.9 mg·L^{-1} nitrate. Compared with the standards described by Yeager et al. (2007), nitrate levels were high in substrates after a single moderate fertilizer application. These data portray nitrate levels in leachates as a single peak exponential curve after a single fertilizer application event. Presumably, multiple fertilizer applications would result in a multipeaked release curve. Ideally, nutrient levels in container substrates should be uniform over time. This expressed in terms of a release curve would be a curve with shallow but wide peaks and valleys. The single-peak nitrate release curves presented here are more shallow and wider with increasing biochar amendment rate, suggesting biochar might be effective in moderating extreme fluctuations of nitrate levels in container substrates over time.

Greater than 100% of the applied phosphate was recovered from all treatments in Expt. 2. This demonstrates the inability of sphagnum peat-based substrates to retain phosphate anions. Warren et al. (1995) also reported low phosphorus (P) retention in pine bark substrates with 57% to 88% of applied P recovered in leachates depending on fertilizer source. Phosphate release curves leveled off to 5.78 and 9.50 $mg \cdot L^{-1}$ phosphate from 10% biochar additions compared with 1.88 and 3.95 $mg \cdot L^{-1}$ for non-amended substrates in Expts. 1 and 2, respectively. Yeager et al. (2007) recommends 10 to 15 $mg \cdot L^{-1}$ for adequate plant growth in a soilless substrate, whereas Warncke (2011) suggests that 6 to 10 $mg \cdot L^{-1}$ P is sufficient for growth of most container crops. Although how long these elevated phosphate levels would occur is not certain, our data suggest that less frequent application of phosphate is necessary in biochar-amended substrates. This could have substantial environmental impacts because P is implicated in surface water pollution. Additional phosphate levels in biochar, in addition to the higher phosphate concentrations present in later leaching events, suggest this form of biochar as a modest source of phosphate for ornamental plant production.

Substrates amended with biochar at 5% and 10% biochar peaked with 21.1 and 40.8 $mg \cdot L^{-1}$ K, respectively, then leveled off to 11.2 and 17.4 $mg \cdot L^{-1}$ K, respectively. Yeager et al. (2007) state that substrate leachates should have 30 to 50 $mg \cdot L^{-1}$ K for adequate plant growth. Although there does not seem to be sufficient K from biochar to adequately supply plant development, increasing levels of this form of biochar will add a substantial quantity of K to the substrate and should be accounted for in fertility programs.

In conclusion, biochar used in this study affected nitrate, phosphate, and K dynamics in a sphagnum peat-based substrate after a single fertilizer event. Future research will need to address the impact of biochar on multiple fertilizer or constant-feed applications. Future research will also need to exploit the potential of biochar to develop new fertilizer strategies that enhance plant performance. Furthermore, biochar materials are diverse and can have diverse properties that are dependent on the nature and particle size of the original feedstock, pyrolysis conditions, and their storage or other post production processes applied (Spokas et al., 2011). Future research will need to explore the impact of the vast range of biochar properties on their potential use in greenhouse and nursery container production.

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