Effects of Biochar on Nutrient Leaching and Begonia Plant Growth[1]

Elizabeth F. Crutchfield[2], Milton E. McGiffen, Jr.[2], and Donald J. Merhaut[2]

Abstract

Biochar is a highly adsorptive carbon substrate. A study was conducted to determine the ability of biochar to reduce fertilizer runoff from nurseries. Potting mix was augmented with biochar at different rates, ranging from 0% to 30% by volume, with some treatments planted with *Begonia* x *semperflorens-cultorum* hort. 'Viva.' The pots were fertilized with a modified Hoagland solution and watered four times a week. The leachate was collected from each pot after watering and aggregated into weekly samples. Leachate from each week was analyzed photometrically for nitrate, ammonium and ortho-phosphate concentrations. Leaching of all three ions was reduced in the biochar-amended treatments. Biochar did not affect plant growth, nitrogen or phosphorus content of the plant material.

Index words: Ammonium, nitrate, phosphate, biochar, begonia, *Begonia* x *semperflorens-cultorum* hort. 'Viva,' media, container production.

Species used: *Begonia* x *semperflorens-cultorum* hort. 'Viva'.

Significance to the Horticulture Industry

Biochar, made from wheat straw, mixed into peat-moss based potting medium at as much as 30% by volume did not affect the growth of Begonia cv. 'Viva' plants. However, the biochar did reduce the leaching of nitrate, ammonium and ortho-phosphate from the potting mixes. We believe biochar could be used in a nursery setting to reduce fertilizer leaching without negatively affecting plant growth.

Introduction

Fertilizer use is an imperative agricultural practice. But fertilizers are frequently used in excess of plant needs and/or soil holding capacity (Raun and Johnson 1999). As a result, nutrient leaching from soil is a common occurrence that may lead to inefficient use of fertilizers (Raun and Johnson 1999) and environmental health problems, especially eutrophication of waterways (Daniel et al. 1998). In 2011, the U.S. E.P.A. estimated that nitrogen (N) and phosphorus (P) over-enrichment was the main cause of impaired waters (Hollister et al. 2013). Dodds et al. (2009) found that the value of damages due to eutrophication in the United States freshwaters was $2.2 billion. The Clean Water Act calls for research into preventing, reducing and eliminating pollution from agriculture (Clean Water Act of 1972). This applies not just to food crops but also to ornamental production. Surveys of container nurseries show that NO_3-N in leachate exceeds concentrations of 10 $mg{\cdot}L^{-1}$ (1.34 $oz{\cdot}gal^{-1}$) in both the eastern United States (Yeager et al. 1993) and southern California (Mangiafico et al. 2008), although values were variable.

A possible solution is a soil amendment called biochar. Biochar is pyrolyzed biomass, much like charcoal. Pyrolysis is the thermochemical decomposition of biomass at temperature upwards of 250 C (482 F) in the presence of little to no oxygen (Lehmann and Joseph 2015). One of the key benefits of using biochar is that it is sequesters carbon (Lehmann 2007). Biochar half-life can range from tens to hundred-thousands of years depending on the O:C ratio (Spokas 2010). In addition to biochar's carbon sequestering ability, it can have other properties that promote plant growth, including nutrient holding capacity (Xu and Chan 2012).

Nutrient-holding capacity is attributed to biochar in many different ways. The highly porous nature of biochar means that it can physically hold dissolved compounds in its water-filled pore space (Major et al. 2012). These ions would not be tightly bound but flow out easily with the addition of water. Because of its high surface area, there's a large area where chemical interactions can take place relative to the volume of the biochar. Many studies have shown that biochar can adsorb NH_4^+ (Angst et al. 2013, Asada et al. 2002, Ding et al. 2010, Hale et al. 2013, Lehmann et al. 2003, Steiner et al. 2010). Ammonium, as a cation, can be sorbed to the surface of biochars by negative functional groups such as hydroxyls, amines, ethers, esters, and carboxyls (Amonette & Joseph 2009). While soils and potting media often have components with a high cation exchange capacity, their anion exchange capacity is generally low, making them less useful for NO_3^- and PO_4^- adsorption. Several studies have investigated biochar's ability to adsorb NO_3^-. Some of these studies have found no effect (Eykelbosh et al. 2015, Hale et al. 2013, Hollister et al. 2013), while others did find an effect (Chintala et al. 2013, Kameyama et al. 2011). Biochars with relatively high anion exchange capacity compared to soil could also reduce P leaching (Angst et al. 2013, Hale et al. 2013, Hollister et al. 2013).

This study seeks to understand how well biochar can adsorb N and P liquid fertilizer in a container nursery setting. This is determined by comparing the amount of NO_3^-, NH_4^+, and PO_4^{3-} leached out of a peat-based potting mix augmented with different rates of biochar. This study

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[2]Department of Botany & Plant Sciences, University of California, Riverside, CA 92521, USA. Corresponding author: milt.mcgiffen@ucr.edu.

Table 1. The concentration of nutrients in the modified Hoagland solution and Sunshine Mix #2 used in this experiment.

	NH4-N (ppm)	NO3-N (ppm)	P (ppm)	K (ppm)	S (ppm)	Ca (ppm)	Mg (ppm)
Hoagland solution	49.86	50	21.84	83.08	45.85	50.10	25.03
Sunshine Mix #2	7.5	5	2.5	18	85	60	60

aims to evaluate biochar's utility in reducing fertilizer runoff for container nursery growers.

Materials and Methods

Cultural practices. A greenhouse study was conducted over nine weeks in spring and summer of 2010 at the University of California, Riverside campus (lat. 33°53′30′N, long. 117°15′00′W). There were nine treatments in total and five replicates arranged in a complete random design. Two treatments contained no plants – potting mix (N0) without biochar and potting mix plus 10% by volume biochar in a layer at the bottom of the pot (N10). The other seven treatments had Begonia cv. 'Viva' planted in one of these media: unamended potting mix (Y0), potting medium mixed with 5% by volume biochar (Y5), potting medium with 10% biochar (Y10), 15% biochar (Y15), 20% biochar (Y20), 25% biochar (Y25), 30% biochar (Y30). Each 4 L (1 gal.) polyethylene pot sat inside of a bucket on top of a PVC ring, which allowed for leachate to drain freely into a bucket. All treatments were initiated on April 28, 2010.

Substrate, biochar and fertilizer. The potting medium used was Sunshine Mix 2 (SunGro Horticulture, Agawam, MA), a mix of 70% sphagnum peat moss and 30% coarse grade perlite, amended with dolomitic lime. The nutrient breakdown of the medium is found in Table 1. The biochar used was produced by pyrolyzing wheat straw at 650 C (1202 F) for 2 hours. The plants were fertilized with a modified Hoagland solution (Table 1) at 400 mL (13.52 fl oz) twice a week and watered with deionized water twice a week until the medium was saturated.

Data collection and analysis. Leachate were collected after each irrigation event and combined into a weekly sample that was stored in a freezer until analysis. All leachate water samples were filtered through a polycarbonate membrane with a 0.4-μm pore size (Millipore, Billerica, MA). Concentrations for NO_2^--N and NO_3^--N [U.S. Environmental Protection Agency (USEPA) method 353.2 (USEPA 1993)], NH_4^+-N [USEPA method 350.1 (USEPA 1979)], and PO_4^--P [USEPA method 365.2 (USEPA,19930] were determined with a segmented flow analyzer (Astoria model; Astoria-Pacific, Clackamas, OR). At the end of the experiment, above ground plant material was collected, dried and weighed. Plant and potting mix samples were analyzed for N and P content. Plants were analyzed for total Kjeldahl nitrogen (Jones 1991) for N content, and for P content a "wet ash" method (Kirkpatrick and Bishop 1971) was used. Nitrate was extracted using calcium sulfate; NH_4^+ extraction used potassium chloride.

Statistical analysis. NO_3^-, NH_4^+, and PO_4^{3-} data were all transformed by $y=x^{0.15}$ to improve normality while %N and %P from plant samples and extracted NO_3^- and NH_4^+ and %P from medium were not transformed. Means were compared using the Dunnett t-test. A P-value of 0.05 or less was considered significant.

Results and Discussion

Ammonium. Much less NH_4^+ leached from the unplanted pots with a layer of biochar (N10) than the unplanted pots without biochar (N0). The amount of NH_4^+ leached from the N0 treatment was significantly higher than N10 in the first five weeks (Fig. 1a). The total NH_4^+ leached from N0 pots was 34.0 mg per pot, significantly more than N10's 9.2 mg (Fig. 1a); the 10% biochar layer reduced leaching by 72% compared to the control. This is a greater reduction than seen by Yao et al. (2012) who used 2% (w/w) Brazilian pepperwood biochar in sandy soil and saw a 34% reduction; or Sika and Hardie (2014) who used 2.5% (w/w) pine wood biochar in sandy soils and saw a 50% reduction in leaching of ammonium ions. At the end of the experiment, the potting medium in treatments N0 and N10 contained equivalent amounts of NH_4^+ (Fig. 1b). However, significantly less NH_4^+ was extracted from the biochar in the N10 treatment than from the potting medium (Fig. 1b). This was perplexing based on the leaching data. If the potting mix was binding an equivalent amount of NH_4^+ in both N0 and N10, and more NH_4^+ was held by the biochar, we would expect the biochar in N10 to adsorb more than the potting mix, not less. Two possible explanations are that the potassium chloride extraction method was unable to remove all the ammonium ions from the biochar substrate, or the biochar could have influenced the rate of ammonia volatilization. Biochar has been shown to increase volatilization of N gasses by increasing soil pH (Chen et al. 2013), as well as decrease volatilization of N gasses by adsorption of NH_4^+ when pH is high (Chen et al. 2013, Mandal et al. 2016, Malińska, et al. 2014).

The treatments with plants showed a similar trend – high rates of biochar decreased the amount of NH_4^+ leached (Fig. 1c). In the early weeks, the high rates of biochar dramatically reduced the amount of NH_4^+ leached compared to the control. For instance, in week 1, pots with 25% and 30% by weight biochar mixed with the Sunshine mix and planted with begonias (Y25 and Y30, respectively) leached only 1.5 mg compared to the control's 8.6 mg (Fig. 1c).

After week 5, the amount of NH_4^+ leached began to plateau. Increased uptake by growing plants is an, obvious reason for decreased leaching. Other possibilities include increased conversion of NH_4^+ to NO_3^-, or increased volatilization of N gasses. The cumulative amount of NH_4^+ leached over all nine weeks was significantly lower from the pots in treatments Y5, Y15, Y20, Y25, and Y30

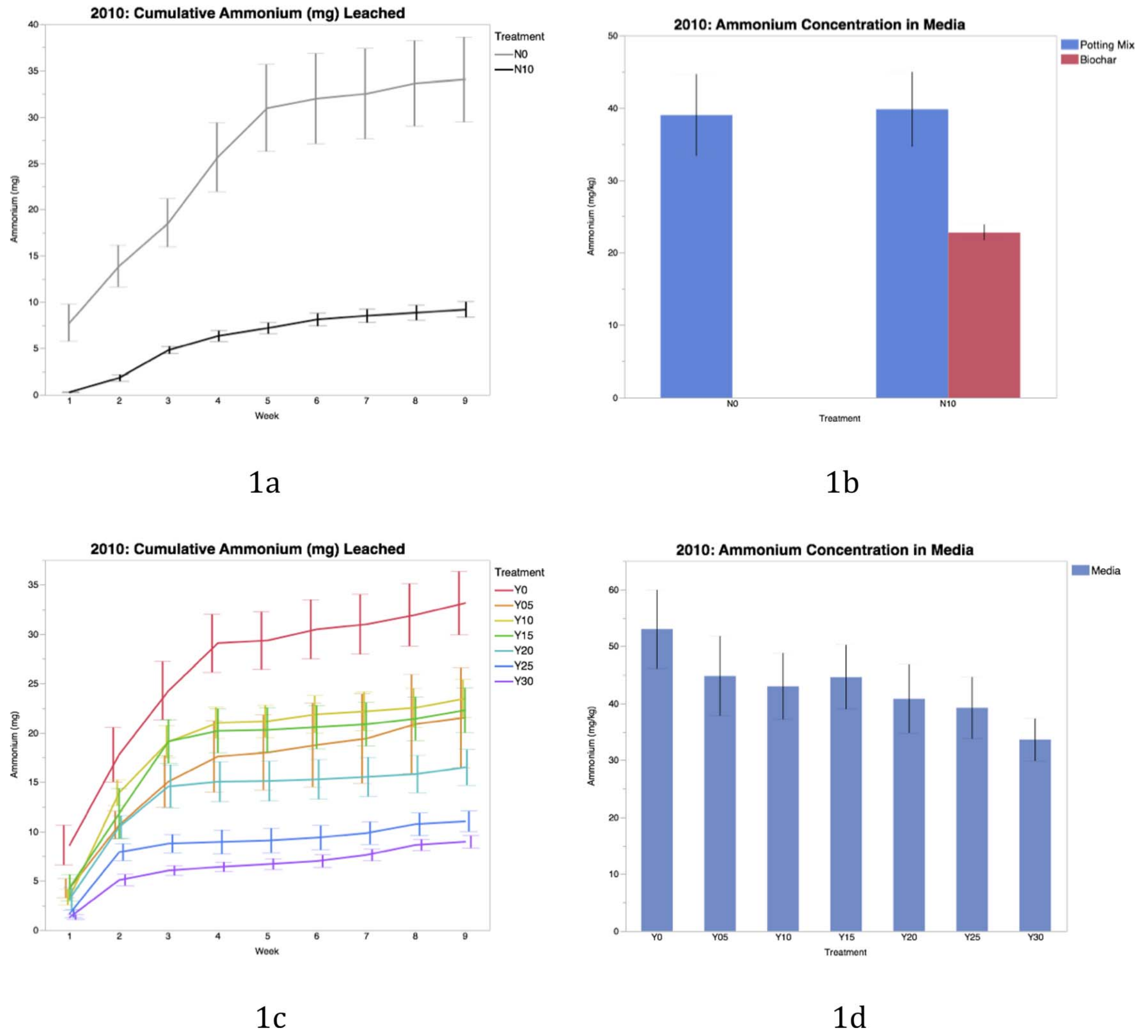


Fig. 1. The cumulative mg of ammonium leached from the pots for each week of the experiment for the treatments without plants (a) and with a begonia (c). The mg/kg of ammonium extracted from the potting medium of those without plants (b; potting mix and biochar blends in blue bars) and those with a begonia (d; pure potting mix in blue bars), in the biochar layer (b; biochar in the red bar). N0 –pure potting mix, without a plant. N10 – 10% by volume layer of biochar at the bottom of the pot, topped by 90% by volume potting mix, without a plant. Y0 – pure potting mix, with a begonia. Y05 – 5% by volume biochar incorporated into the potting mix, with a begonia. Y10 – 10% by volume biochar incorporated, with a begonia. Y15 – 15% by volume biochar incorporated, with a begonia. Y20 – 20% by volume biochar incorporated, with a begonia. Y25 – 25% by volume biochar incorporated, with a begonia. Y30 - 30% by volume biochar incorporated, with a begonia.

compared to treatments Y0 (Fig. 1c). Pots containing Y30 leached only about 9.0 mg compared to Y0's 33.1 mg, about one third the amount. At the end of the experiment the amount of NH_4^+ that remained in the potting media was statistically equivalent across treatments (Fig. 1d), despite the decreasing trend in NH_4^+ concentration of the leachate as biochar levels increased (Fig. 1c).

Nitrate. Like ammonium, nitrate leaching was also reduced by the presence of biochar in the pots. The amount of NO_3^- leached was significantly greater from pots of the N0 treatment compared to N10 in weeks 1, 5 and 6 (Fig. 2a). N0 pots accumulated 139.1 mg of NO_3^- over the over the study period, which was significantly more than the N10 pot's total of 92.3 mg (Fig. 2a). The 10% biochar layer found at the bottom of the N10 treatment reduced NO_3^- leaching by 34%. This is a similar finding to Yao et al. (2012) who saw a 34% reduction when applying 2% by weight of either Brazilian pepperwood biochar or peanut hull biochar to a sandy soil, or the 42% reduction Sika and Hardie (2014) found when applying 2.5% (w/w) of pine wood biochar to a sandy soil. Unlike the NH_4^+, NO_3^- leaching was low initially and increased in weeks 4 through 6 before tapering off. NO_3^- concentrations probably increased in the middle of the experiment due to nitrification of NH_4^+ in the medium. Like NH_4^+, there was no statistical difference between the amount of NO_3^- held in the potting mix for the N0 and N10 treatments (Fig. 2b). Although there was more NO_3^- extracted from the biochar in the N10 treatment, it was not significantly greater than that found in the potting mix (Fig. 2b). The reduction in leaching indicates biochar adsorbs both NO_3^- and NH_4^+.

Just as with the unplanted treatments, biochar significantly reduced nitrate leaching from pots planted with begonias (Fig. 2c). Although biochar didn't significantly

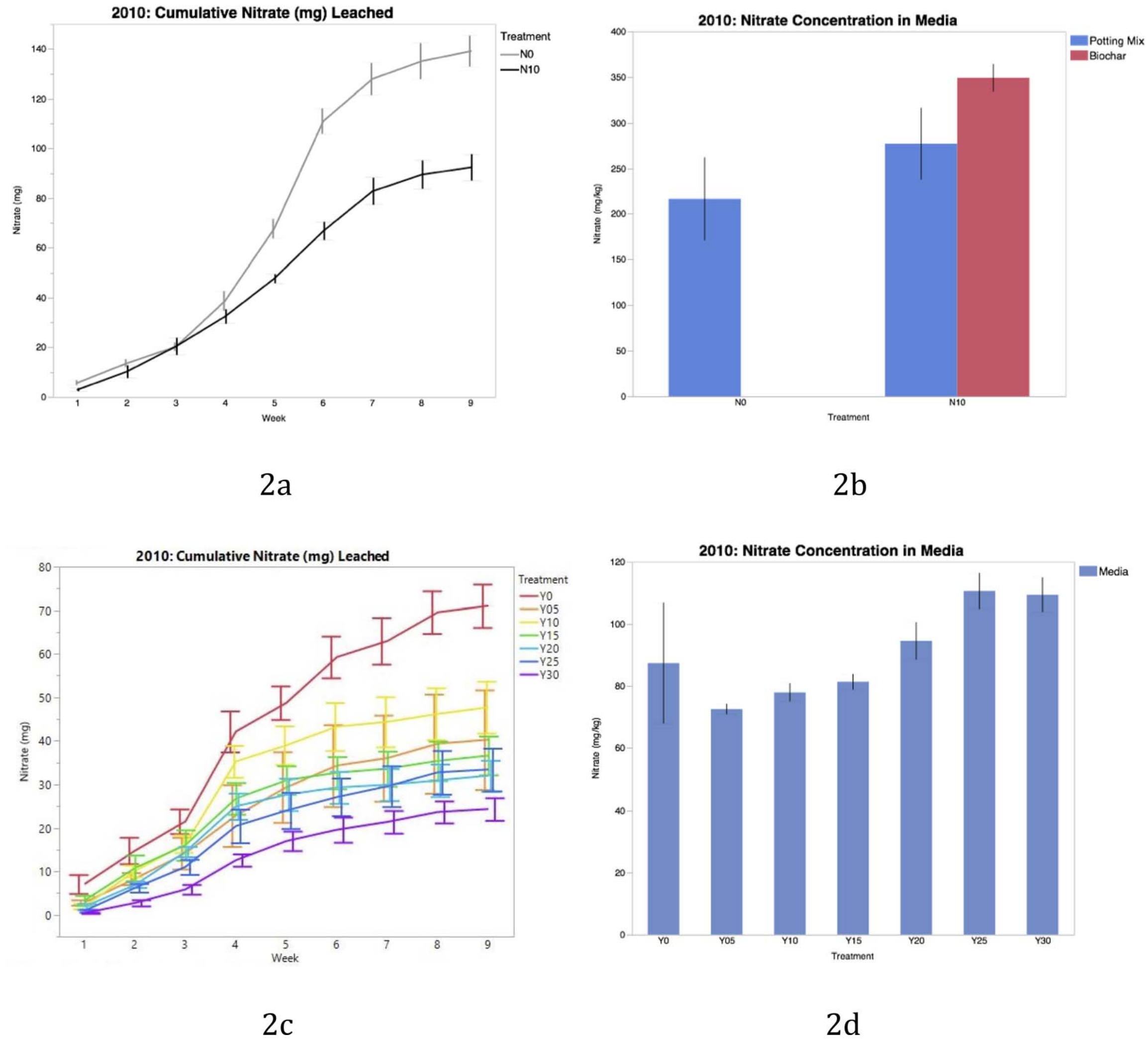
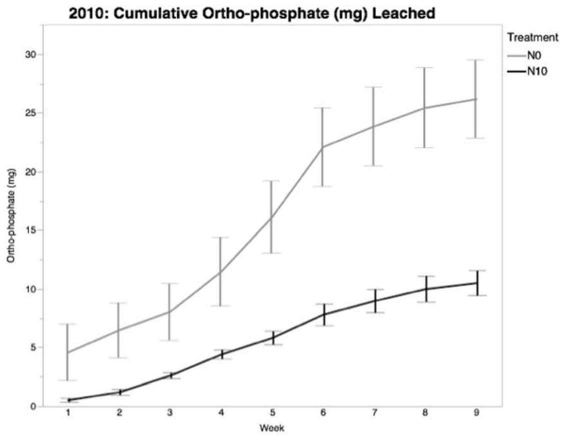


Fig. 2. The cumulative mg of nitrate leached from the pots for each week of the experiment for the treatments without plants (a) or with a begonia (c). The mg/kg of nitrate extracted from the potting medium of those without plants (b; blue bars) and those with a begonia (d; blue bars), in the biochar layer (b; red bar). N0 –pure potting mix, without a plant. N10 – 10% by volume layer of biochar at the bottom of the pot, topped by 90% by volume potting mix, without a plant. Y0 –pure potting mix, with a begonia. Y05 – 5% by volume biochar incorporated into the potting mix, with a begonia. Y10 – 10% by volume biochar incorporated, with a begonia. Y15 – 15% by volume biochar incorporated, with a begonia. Y20 – 20% by volume biochar incorporated, with a begonia. Y25 – 25% by volume biochar incorporated, with a begonia. Y30 - 30% by volume biochar incorporated, with a begonia.

reduce the amount of NO_3^- leached in weeks 3, 5, and 7 compared to the control, medium consisting of 30% biochar by volume (Y30) reduced the amount of leaching during all other weeks (1, 2, 4, 6, 8, and 9), resulting in a total decrease of 24.4 mg from the control's 71.0 mg, a 34% decrease. Lower rates of biochar resulted in less leaching than higher rates of biochar, although leaching in all biochar rates were significantly less than the control over the course of the experiment. However, none of the biochar treatments had significantly altered extractable NO_3^- from the growing medium compared to the control due to outliers in the data (Fig. 2d). If the outliers are ignored, significantly more NO_3^- was held by the potting mixes with 20-30% biochar.

Phosphorus. When comparing the phosphate leached from the treatments without plants, the one with the layer of biochar leached much less than those without biochar. The N10 pots leached less PO_4^{3-} than the N0 ones in almost every week, 1, 2, 4, 5, 6, 7, and 8 (Fig. 3a). The total amount of PO_4^{3-} leached from the N0 pots was 26.2 mg, significantly more than the N10 pots, which leached only 10.5 mg (Fig. 3a). The 60% reduction that we saw was substantially more than the 20.6% reduction seen by Yao et al. (2012) who used 2% by weight Brazilian pepperwood in sandy soil, or by Hale et al. (2013) who found no sorption of phosphate to the biochars they used. Additionally, the biochar in N10 was found to contain more P than the potting mix of the same treatment (Fig. 3b). The N0 potting mix had significantly less P than the potting mix in N10 (Fig. 3b), presumably because the biochar had a greater holding capacity for P. The layer of biochar at the bottom of N10 must have adsorbed the P preventing it from leaching out, but the P was still able to exchange with the water solution and therefore move onto the exchange sites in the potting mix.

Although the relationship between P uptake and percent biochar seems very strong in the treatments without



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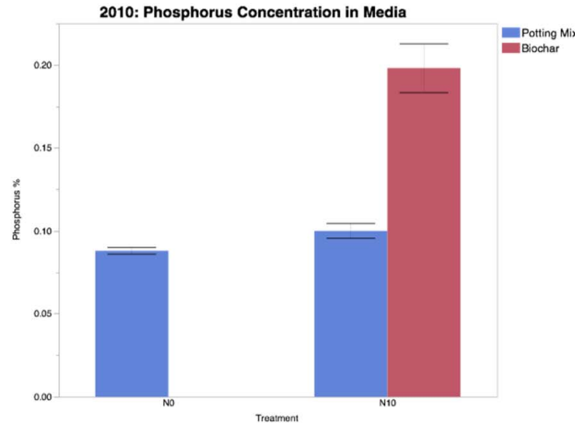

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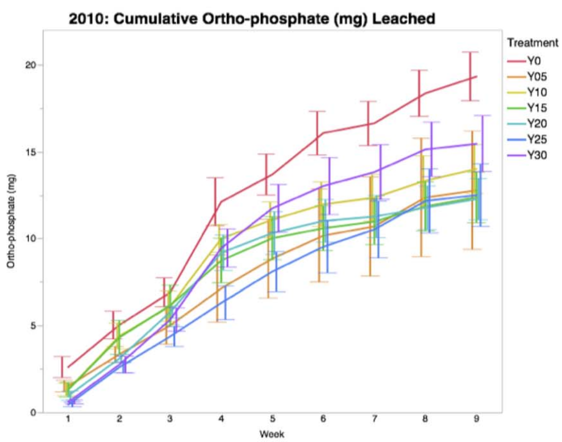

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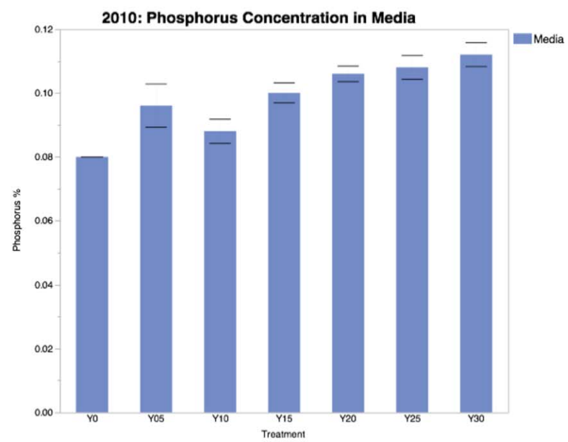

3d

Fig. 3. The cumulative mg of ortho-phosphate leached from the pots for each week of the experiment for the treatments without plants (a) and with a begonia (c). The percent phosphorous found in the potting medium of those without plants (b; blue bars) and those with a begonia (d; blue bars), and in the biochar layer (b; red bar). N0 –pure potting mix, without a plant. N10 – 10% by volume layer of biochar at the bottom of the pot, topped by 90% by volume potting mix, without a plant. Y0 –pure potting mix, with a begonia. Y05 – 5% by volume biochar incorporated into the potting mix, with a begonia. Y10 – 10% by volume biochar incorporated, with a begonia. Y15 – 15% by volume biochar incorporated, with a begonia. Y20 – 20% by volume biochar incorporated, with a begonia. Y25 – 25% by volume biochar incorporated, with a begonia. Y30 - 30% by volume biochar incorporated, with a begonia.

plants, it was less apparent in the treatments with begonias growing in them. In weeks 2, 3, 5, 6, and 7, there was no significant difference between the amounts of PO_4^{3-} leached from any of the treatments (Fig. 3c). In the first and last weeks, the pots from treatments Y25 and Y30 had significantly less PO_4^{3-} leaching compared to treatment Y0. In the end, treatment Y25 leached 12.3 mg compared to treatment Y0's 19.3 mg, and despite the decreasing trend as biochar levels increase, there was no significant difference between any of the treatments. We might infer that the begonias had a significant impact on phosphate movement within this system, obscuring the impact of biochar. This impact is also seen the P content of the media. There was significantly more P in the media of Y5, Y15, Y20, Y25 and Y30 than Y0 (Fig. 3d), just as there was between the media of N0 and N10. However, the differences found in the pots with plants is an order of magnitude smaller than those without plants, presumably due to plant uptake.

Plant growth. Although biochar is touted as a plant growth promoting amendment, in this experiment we found no evidence to support the claim. No treatments affected any of the data collected (dry shoot biomass, %N, and %P) (data not shown). Although in this experiment biochar did not improve plant growth, it also did not cause any detriment to the begonias. This is not an unusual finding; Spokas et al. (2012) found that approximately 30% of studies reviewed showed no effect of biochar on plant growth.

Overview. The presence of biochar was significantly correlated to reductions of NH_4^+ leaching. The 10% biochar disk layer reduced NH_4^+ leaching in a system without plants by 73%. When begonias were present, 5%

biochar reduced NH_4^+ leaching by 35%, 15% biochar resulted in a 33% reduction, 20% biochar lead to a 50% reduction, 25% biochar lead to a 67% reduction, and 30% biochar reduced leaching by 73%. NH_4^+ leaching reduction was observed mostly in the first several weeks of begonia growth, when roots were small and shoot demand was lower. The biochar in N10 had significantly less NH_4^+ extracted than the potting mix from the same pots. Since the amount of NH_4^+ leached was less in the N10 treatment, but the NH_4^+ extracted was less in the N10 treatment, this suggests that the extraction method used couldn't extract the NH_4^+ from the biochar and/or biochar increased N volatilization.

The total amount of NO_3^- leached from the pots was significantly different for the biochar treatments compared to the control treatment for both the treatments with and the treatments without begonias. The N10 treatments had 34% less NO_3^- leaching than N0. In the Y treatments, 5%, 10%, 15%, 20%, 25% and 30% biochar lead to 43%, 33%, 48%, 70%, 53%, and 66% reduction, respectively, on average. Since the biochar tended to have a greater impact on NO_3^- leaching than NH_4^+ leaching, the biochar appears to be better at adsorbing anions that cations but is still better at adsorbing cations than the peat-moss based potting mix used in this study. It is possible that the impact of the biochar on NO_3^- leaching was more pronounced than the impact on NH_4^+ leaching because the concentrations of NO_3^- were higher. Because there was a significant difference between the leaching from N0 and N10, but not between the biochar and potting mix again suggests that the method of extraction used was not entirely successfully extracting NO_3^-. There was no difference in the amount of NO_3^- extracted from any of the potting mix of any of the treatments, due to outliers.

As with NO_3^- and NH_4^+, PO_4^{3-} leaching was reduced in the presence of biochar, both with and without plants, although the difference wasn't significant in the treatments with begonias. These results are comparable to those of Hale et al. (2013) and Angst et al. (2013). The 10% layer treatment (N10) reduced PO_4^{3-} leaching by 60% compared to the control. There was no effect of the biochar on the PO_4^{3-} leaching in the Y treatments. The % P found in the medium of the treatments with biochar was higher than the control, indicating greater adsorption.

Other studies support the idea of using biochar as a component of potting mixes. Dunroese et al. (2011) found that pelletized biochar mixed into peat moss at less than 50% by volume resulted in mixtures that enhanced hydraulic conductivity and increased water availability. Vaughn et al. (2013) believed that biochar would be a suitable replacement for other soilless substrates as they found no differences in biomass of tomato or marigold when grown with up to 15% by volume of pelletized wood and wheat straw biochars. Tian et al. (2012) saw an increase in biomass of *Calathea rotundifolia* cv. *Fasciata* when grown with 50% green waste biochar, as well as reduced medium degradation.

In summary, the treatments with biochar reduced leaching of all three tested ions, suggesting a capacity of biochar to adsorb anions, like PO_4^{3-} and NO_3^-, and cations like NH_4^+. Therefore, biochar could be a valuable tool in reducing fertilizer run off in a nursery setting. However, the amount of biochar used should be proportional to the amount of fertilizer used.

Literature Cited

Amonette, J. E., and S. Joseph. 2009. Characteristics of biochar: microchemical properties. p. 33–52 *In:* Biochar for environmental management: Science and technology. Routledge, New York, NY.

Angst, T. E., C. J. Patterson, D. S. Reay, P. Anderson, T. A. Peshkur, and S. P. Sohi. 2013. Biochar diminishes nitrous oxide and nitrate leaching from diverse nutrient sources. J. Environ. Qual. 42: 672–682.

Asada, T., S. Ishihara, T. Yamane, A. Toba, A. Yamada, and K. Oikawa. 2002. Science of Bamboo Charcoal: Study on Carbonizing Temperature of Bamboo Charcoal and Removal Capability of Harmful Gases. J. Health Sci., 48: 473–479.

Chen, C. R., I. R. Phillips, L. M. Condron, J. Goloran, Z. H. Xu, and K. Y. Chan. 2013. Impacts of greenwaste biochar on ammonia volatilisation from bauxite processing residue sand. Plant soil 367: 301–312.

Chintala, R., J. Mollinedo, T. E. Schumacher, S. K. Papiernik, D. D. Malo, D. E. Clay, and D. W. Gulbrandson. 2013. Nitrate sorption and desorption in biochars from fast pyrolysisR. Micropor. and Mesopor. Mat. 179: 250–257.

Clean Water Act of 1972. 23 U.S.C § 1251 ct seq. 2002, Section 105. https://www3.epa.gov/npdes/pubs/cwatxt.txt. Accessed Aug 30, 2018.

Daniel, T. C., A. N. Sharpley, and J. L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. J. Environ. Qual. 27: 251–257.

Ding, Y., Y. X. Liu, W. X. Wu, D. Z. Shi, M. Yang, and Z. K. Zhong. 2010. Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water Air Soil Poll. 213: 47–55.

Dodds, W. K., W. W. Bouska, J. L. Eitzmann, T. J. Pilger, K. L. Pitts, A. J. Riley, J. T. Scholoesser and D. J. Thornbrugh. 2009. Eutrophication of US freshwaters: analysis of potential economic damages. Environ. Sci. Technol 43: 12–19

Dumroese, R. K., J. Heiskanen, K. Englund, and A. Tervahauta. 2011. Pelleted biochar: Chemical and physical properties show potential use as a substrate in container nurseries. Biomass and Bioenerg. 35: 2018–2027.

Eykelbosh, A. J., M. S. Johnson, and E. G. Couto. 2015. Biochar decreases dissolved organic carbon but not nitrate leaching in relation to vinasse application in a Brazilian sugarcane soil. J. Environ. Manage. 149: 9–16.

Hale, S. E., V. Alling, V. Martinsen, J. Mulder, G. D. Breedveld, and G. Cornelissen. 2013. The sorption and desorption of phosphate-P, ammonium-N and nitrate-N in cacao shell and corn cob biochars. Chemosphere 91: 1612–1619.

Hollister, C. C., J. J. Bisogni, and J. Lehmann. 2013 Ammonium, nitrate, and phosphate sorption to and solute leaching from biochars prepared from corn stover (L.) and oak wood (spp.). J. Environ. Qual. 42: 137–144.

Jones Jr, J. B. 1991. Kjeldahl method for nitrogen determination. Micro-Macro Publishing, Inc, Athens, GA. p. 79

Kameyama, K., T. Miyamoto, T. Shiono, and Y. Shinogi. 2012. Influence of sugarcane bagasse-derived biochar application on nitrate leaching in calcaric dark red soil. J. Environ. Qual. 41: 1131–1137.

Kirkpatrick, D. S., and S. H. Bishop. 1971. Simplified wet ash procedure for total phosphorus analysis of organophosphonates in biological samples. Anal. Chem. 43: 1707–1709.

Lehmann, J., J. P. da Silva Jr, C. Steiner, T. Nehls, W. Zech, and B. Glaser. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant soil 249: 343–357.

Lehmann, J. 2007. A handful of carbon. Nature 447: 143–144.

Lehmann, J., and S. Joseph. (Eds.). 2015. Biochar for environmental management: science, technology and implementation. Routledge.

Major, J., C. Steiner, A. Downie, and J. Lehmann. 2012. Biochar effects on nutrient leaching. p. 271–287 *In:* Biochar for environmental management: Science and technology. Routledge, New York, NY.

Malińska, K., M. Zabochnicka-Świątek, and J. Dach. 2014. Effects of biochar amendment on ammonia emission during composting of sewage sludge. Ecol. Eng. 71: 474–478.

Mandal, S., R. Thangarajan, N. S. Bolan, B. Sarkar, N. Khan, Y. S. Ok, and R. Naidu. 2016. Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat. Chemosphere 142: 120–127.

Mangiafico, S. S., J. Gan, L. Wu, J. Lu, J. P. Newman, B. Faber, ... and R. Evans. 2008. Detention and recycling basins for managing nutrient and pesticide runoff from nurseries. HortScience 43: 393–398.

Raun, W. R., and G. V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91: 357–363.

Sika, M. P., and A. G. Hardie. 2014. Effect of pine wood biochar on ammonium nitrate leaching and availability in a South African sandy soil. Eur. J. Soil sci. 65: 113–119.

Spokas, K. 2010. Review of the stability of biochars in soils: predictability of O:C ratios. Carbon Manag 1: 289–303.

Spokas, K. A., K. B. Cantrell, J. M. Novak, D. W. Archer, J. A. Ippolito, H. P. Collins, and R. D. Lentz. 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. J. Environ. Qual. 41: 973–989.

Steiner, C., K. C. Das, N. Melear, and D. Lakly. 2010. Reducing nitrogen loss during poultry litter composting using biochar. J. environ. Qual. 39: 1236–1242.

Tian, Y., X. Sun, S. Li, H. Wang, L. Wang, J. Cao, and L. Zhang. 2012. Biochar made from green waste as peat substitute in growth media for Calathea rotundifola cv. Fasciata. Scientia hortic-amsterdam 143: 15–18.

U.S. Environmental Protection Agency. 1979. Methods for the chemical analysis of water and wastes EPA/600/4-79/020. https://www.wbdg.org/FFC/EPA/EPACRIT/epa600_4_79_020.pdf. Accessed Aug 30, 2018

U.S. Environmental Protection Agency. 1993. Methods for the determination of inorganic substances in environmental samples EPA/600/R-93/100. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=30002U3P.TXT. Accessed Aug 30, 2018

Xu, Z., and K. Y. Chan. 2012. Biochar: nutrient properties and their enhancement. p. 99–116 In Biochar for environmental management. Routledge.

Vaughn, S. F., J. A. Kenar, A. R. Thompson, and S. C. Peterson. 2013. Comparison of biochars derived from wood pellets and pelletized wheat straw as replacements for peat in potting substrates. Ind. Crops Prod. 51: 437–443.

Yao, Y., B. Gao, M. Zhang, M. Inyang, and A. R. Zimmerman. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere 89: 1467–1471.

Yeager, T., R. Wright, D. Fare, C. Gilliam, J. Johnson, T. Bilderback, and R. Zondag. 1993. Six state survey of container nursery nitrate nitrogen runoff. J. Environ. Hort. 11: 206–208.