

Growth Response, Mineral Nutrition, and Water Utilization of Container-grown Woody Ornamentals Grown in Biochar-amended Pine Bark

Nastaran Basiri Jahromi and Forbes Walker

Biosystems Engineering and Soil Science Department, University of Tennessee, Knoxville, TN 37996

Amy Fulcher¹

Department of Plant Sciences, University of Tennessee, Knoxville, TN 37996

James Altland

USDA Technology Application Unit, Wooster, OH 44691

Wesley C. Wright

Biosystems Engineering and Soil Science Department, University of Tennessee, Knoxville, TN 37996

Additional index words. boxwood, dielectric sensors, hydrangea, irrigation, leachate volume, water buffering capacity

Abstract. Container-grown nursery crops generally require daily irrigation applications and potentially more frequent applications during the hottest part of the growing season. Developing management practices that make more efficient use of irrigation water is important for improving the sustainability of nursery crop production. Biochar, a byproduct of pyrolysis, can potentially increase the water-holding capacity and reduce water and nutrient leaching. In addition, the development of sensor-based irrigation technologies has made monitoring substrate moisture a practical tool for irrigation management in the nursery industry. The objective of this research was to determine the effect of switchgrass biochar on water and nutrient-holding capacity and release in container substrates of *Buxus sempervirens* L. × *Buxus microphylla* ('Green Velvet' boxwood) and *Hydrangea paniculata* (Pinky Winky® hardy hydrangea). Containers were filled with pine bark and amended with 0%, 10%, or 25% volume of biochar. Plants were irrigated when the volumetric water content (VWC) reached the water-buffering capacity set point of 0.25 cm³·cm⁻³. The sensor-based irrigation in combination with the low cost biochar substrate amendment increased substrate water-holding capacity and reduced irrigation requirements for the production of hydrangea, a high water use plant. Biochar application rate influenced irrigation frequency, which likely affected plant biomass for hydrangea, but boxwood dry weight was unaffected by biochar rate. Total irrigation applied was decreased by 32% in 10% biochar treatment without reducing hydrangea dry weight. However, in the 25% biochar treatment, total irrigation applied was reduced by 72%, whereas dry weight decreased by 50%. Biochar application reduced leaching volume and leaching fraction in both plants. Leachate analysis over the course of the 8-week experiment showed that the average mass of phosphate (PO₄), potassium (K), and total carbon was greater in the leachate from containers that received 25% biochar compared with those receiving 0% or 10% biochar for both plant species. For hydrangea, mass of total nitrogen (TN) and nitrate (NO₃) in leachate was not significantly affected by increasing the biochar rate. However, for boxwood, the mass of NO₃ and TN was greater in the 25% biochar treatment leachate, whereas the mass of ammonium (NH₄) was unaffected. In hydrangea, total nutrients lost from the containers was lower in biochar-amended containers (both 10% and 25% biochar) because of receiving a lower total volume of water. Amendment with biochar also affected concentration of phosphorus (P) and K, with the highest concentration in both leaf tissue and substrate from the 25% biochar application rate.

Greenhouse and nursery producers are facing increasing fertilizer costs and greater scrutiny toward nutrient use efficiency and retention (Altland and Locke, 2013). Lea-Cox and Ristvey (2003) reported that in containerized crop production, nutrient management practices are built on the "Sprengel-Liebig law of the minimum"

(Epstein and Bloom, 2005). Excessive nutrients are supplied to prevent plant growth restriction. This, in combination with the low water and nutrient-holding capacity of traditional container substrates, results in nutrients leaching from the container that are lost in runoff. Future management strategies should be based on economic and

environmental concerns and modified to increase nutrient uptake efficiency and reduce nutrient losses (Owen et al., 2008). Nutrient use efficiency is closely related to irrigation management (Warren and Bilderback, 2005). Developing management practices that make more efficient use of irrigation water is important for improving the sustainability of nursery crop production. Use of accurate, site-specific plant water use systems in support of precise application of water could improve water and nutrient use efficiency and proactively address nutrient and agrichemicals in container effluent by reducing runoff (Warsaw et al., 2009). Real-time substrate moisture data provide an opportunity for automated irrigation according to species-specific demand (Daniels et al., 2012).

Substrate and soil water retention characteristics are affected by the components' inherent physical properties and the number and size of pores (Handreck and Black, 2002). Manipulating the size and shape of the substrate components to decrease the proportion of large pores can potentially increase the amount of available water, which can improve irrigation efficiency and plant growth rates and reduce the production period (Caron et al., 2005). Also pore uniformity is as important as overall size. Smallest pore dictates much of hydrology and largest pore can dictate tendency for preferential flow. Pore size can be manipulated using different substrate amendments which includes biochar.

Biochar is a byproduct of pyrolysis or gasification, from the thermochemical decomposition of organic materials at high temperatures in the absence of oxygen. Biochar can be used as a soil conditioner in agriculture (Lehmann and Joseph, 2009). Over time, the addition of biochar can increase soil fertility by increasing the cation exchange capacity and surface area and also increase water retention, which can reduce nutrient leaching from soils (Glaser et al., 2002; Lehmann et al., 2006). Solute movement through soilless substrates depends on the distribution of ions through macropores and micropores, their diffusion across concentration gradients, and the interaction with bark particle exchange sites (Hoskins et al., 2014a). Therefore, biochar may influence nutrients leaching from a soilless substrate. Biochar can have a substantial impact on the release and retention of NO₃, PO₄, and K in a peat-based substrate (Altland and Locke, 2013). Biochar has been shown to increase soil pH in acid soils (Jeffery et al., 2011) and increase plant nutrient availability (Major et al., 2010). These factors, either individually or in combination, may increase yields of agricultural crops (Major et al., 2010; Vaccari et al., 2011; Zhang et al., 2011), horticultural crops (Altland and Locke, 2013), and microbial biomass (Jin, 2010; Liang et al., 2010; O'Neill et al., 2009).

On demand irrigation using soil moisture measurements in combination with a low-cost substrate amendment that increases

water-holding capacity may reduce the water requirement for high-value crops and mitigate water and nutrient leaching. The objective of this research was to provide a preliminary assessment of the effect of biochar amendment to a pine bark-based container substrate on water and nutrient leaching for a low and high water use woody species.

Materials and Methods

The experiment was conducted at the University of Tennessee North Greenhouse Complex, in Knoxville, TN, for 8 weeks and initiated on 15 June 2015. *Buxus sempervirens* L. × *B. microphylla* ('Green Velvet' boxwood) and *H. paniculata* (Pinky Winky® hardy hydrangea) liners from 32 cell trays were potted into 3.8 L containers with the substrate intact (without bare rooting the liner) (Spring Meadow Nursery Inc., Grand Rapids, MI) on 10 May 2015. Pots were filled with pine bark amended with biochar at 0%, 10%, or 25% by volume. Biochar was obtained from a local biochar producer (Proton Power Inc., Lenoir City, TN) comprising 100% switchgrass (*Panicum virgatum* L.) subjected to pyrolysis at ≈1000 °C. The chemical and physical properties of the biochar are summarized in Table 1.

Containers were irrigated by hand for 4 weeks before initiating the automatic sensor-based irrigation program. One week after transplanting, plants were top-dressed with 18N–2.6P–9.9K controlled release fertilizer with micronutrients (Osmocote Classic; Everris, Marysville, OH) at 24 g per container, which included 10% NH₄-N and 8% NO₃-N. Substrates were also drenched twice with a surfactant (Aquatrol L; Aquatrols, Paulsboro, NJ) at a rate of 600 ppm to prevent the substrate from becoming hydrophobic. The treatment design was a 2 × 3 factorial with two plant species (boxwood and hydrangea) and three substrates (100% pine bark with biochar at 0%, 10%, or 25% by volume). The experiment was arranged in a randomized complete block design with 10 replications, blocking on the placement of pots in the greenhouse. Data were subjected to analysis of variance using mixed models (SAS v9.4, Cary, NC). Because our research interest was focused on biochar differences

within a species, means were separated by species using the slice option. This is preferable to presenting the main effect means as they are the mathematical means of the two species and do not reflect the observed means because of the differences in the two plant species.

Substrate physical properties were determined using a 15-cm tall porometer (694 cm³ volume), according to the methods described by Fonteno and Harden (2010) with three replications. Briefly, aluminum cores were attached to North Carolina State University Porometers (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, NC) for the determination of air space. Cores were weighed, oven-dried for 4 d at 105 °C, and weighed again to determine container capacity. Total porosity was calculated as the sum of air space and container capacity. All physical properties were calculated as the algebraic mean of the cores. Bulk density was determined using oven-dried (105 °C) substrate in the same cores. In addition, particle size distribution of three replications of pine bark substrate were determined by passing the substrate through seven sieves (6.30, 2.00, 0.71, 0.50, 0.25, and 0.11 mm openings) and a lower catch pan, which was shaken for 5 min with a Ro-Tap shaker (Rx-29; W.S. Tyler, Mentor, OH).

Substrate moisture levels were controlled using dielectric sensors (ECHO-5; Decagon Devices Inc., Pullman, WA) connected to a data logger (CR1000; Campbell Scientific Inc., Logan, UT) with two multiplexers (AM16/32; Campbell Scientific Inc.) and a 16-channel relay controller (SDM-CD16AC; Campbell Scientific Inc.) to control solenoid valves. Six independent irrigation zones were constructed with one irrigation line per treatment combination. Ten plants of a species were irrigated by each irrigation line with 4-inch dribble ring (Dramm Corp., Manitowoc, WI) to achieve uniform irrigation on surface of the substrate by 4 gallon/h emitters. When the substrate dried such that the average VWC measured by the probes on a substrate-specific calibration for each sensor reached the set point (0.25 cm³·cm⁻³), the data logger supplied power to the valve, controlling irrigation to the containers in that treatment. Plants were irrigated when the VWC reached the estimated water buffering capacity, 0.25 cm³·cm⁻³. The set point is slightly greater than 0.20 cm³·cm⁻³, an accepted value for plant available water in soilless substrates (Drzal et al., 1999; Milks et al., 1989), to prevent the bark from becoming hydrophobic as bark has been shown to be less resilient than plants in conservative irrigation regimes (Hagen et al., 2014). The run time was individually calculated to apply 772 mL of water per plant per irrigation event based on the upper irrigation set point of 0.41 cm³·cm⁻³, lower set point, and the flow rate of each line. There was a 15 min pause time in the program after application of 150 mL of water to allow the water to move laterally and to prevent substrate hydrophobicity and channeling of water through the substrate.

Table 1. Chemical and physical properties of a biochar derived from switchgrass (*Panicum virgatum* L.) and used as a substrate amendment for container nursery production.

| Parameter | Units | Value |
|----------------------------|---------------------------------|-------|
| Chemical properties | | |
| pH | | 10.8 |
| Electrical conductivity | dS·m ⁻¹ | 3.5 |
| Carbon | % | 79 |
| Nitrogen | % | 1.3 |
| Nitrate | mg·kg ⁻¹ | 3.4 |
| Ammonia | mg·kg ⁻¹ | 8.4 |
| Phosphorus | % | 1.2 |
| Potassium | % | 6.6 |
| Physical properties | | |
| Bulk density | g·cm ⁻³ | 0.1 |
| Surface area | m ² ·g ⁻¹ | 366 |
| Particle size distribution | % | |
| X-large (>6.3 mm) | % | 0.0 |
| Large (2–6.3 mm) | % | 6.7 |
| Medium (0.71–2 mm) | % | 20.7 |
| Fine (<0.71 mm) | % | 72.6 |

The results shown in this table were obtained from Control Laboratories, Watsonville, CA.

Leachate volume was measured daily one to 2 h after each irrigation event. Leaching fraction was calculated as [volume of leachate (mL)/total irrigation volume (mL) × 100] and reported as a percent. Water application efficiency (WAE) was calculated as {[total volume applied–total volume leached (mL)]/volume applied (mL) × 100} for the 8 weeks and reported as a percent. Water use efficiency (WUE) per plant was estimated as [increase in dry weight (g)/total irrigation volume applied (L) over the 8 weeks].

Leachate samples were collected from 30 containers (five replications per treatment) each week for 8 weeks. The samples were stored in plastic vials and kept refrigerated for 2 or 3 d until analyzed. Electrical conductivity (EC) was measured with a portable EC meter (HI 9811-5; Hanna Instruments, Smithfield, RI) and pH was measured with a pH meter (Denver Instrument, Bohemia, NY). At the time of analysis, leachate samples were filtered with a 0.45 μm syringe filter (Thermo Fisher Scientific, Pittsburgh, PA). The filtrate was then transferred to 5-mL vials, capped, and analyzed with a dual ICS 1100 (Ion Chromatography System; Dionex, Bannockburn, IL) for concentrations of NO₃, NH₄, PO₄, and K. TN and total carbon (TOC) were measured by total organic carbon analyzer (TOC-V_{CPH}; Shimadzu, Columbia, MD). Samples were filtered and then analyzed with optical emission spectroscopy (ICP-OES; Thermo Electron Corp., Waltham, MA) for calcium (Ca) and magnesium (Mg) concentration.

Shoots of all plants were harvested on 20 Aug. 2015, 8 weeks after initiation of the experiment. After harvesting the shoots and leaves, the top 2.5 cm of the substrate and root mass were removed, and representative substrate samples were collected from the substrate remaining in the containers. Water soluble elements were measured with the saturated media extract method (Warncke, 1986). The NO₃ and NH₄ were extracted

Received for publication 24 Oct. 2017. Accepted for publication 7 Jan. 2018.

This project was supported by Agriculture and Food Research Initiative Competitive Award No. #2015-68007-23212 from the USDA National Institute of Food and Agriculture.

We wish to acknowledge the USDA National Institute of Food and Agriculture for financial support, and Proton Power, Lenoir City, Tennessee, for the biochar source. We gratefully acknowledge Jim Owen and Grace Pietsch for their careful review, which greatly enhanced this manuscript; Galina Melnichenko, Grace Pietsch, Lori Osborne, and Melanie Stewart for their contributions; and Arnold Saxton for statistical analysis.

¹Corresponding author. E-mail: afulcher@utk.edu.

from the substrate using 2 M potassium chloride following the Mulvaney (1996) method. The filtrate was then analyzed on a flow injector analyzer (Lachat Quickchem 8500; HACH, Loveland, CO). Nutrient analysis was conducted by ICP-OES for P, K, Ca, and Mg.

For dry weight measurements, the above-ground portions of plants were harvested and handwashed of substrate at the initiation and termination of the experiment. Plant shoots and leaves were dried at 55 °C until there was no change in mass and then weighed to obtain dry weight. After drying, plant leaves and shoots were ground to pass a 1.0-mm screen (20 mesh) using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Samples from each treatment were thoroughly mixed and tissue samples withdrawn for analysis. Plant tissue nitrogen (N) was determined using a combustion CHNS/O analyzer (CE Elantech, Lakewood, NJ). Tissue used for analyses was prepared by acid digestion using concentrated nitric acid and analyzed by ICP-OES for P, K, Ca, and Mg concentration. All calculations at initiation and termination were based on data collected on 15 June and 20 Aug. 2015, whereas the automated irrigation was deployed.

Results and Discussion

Substrate physical properties, water use, irrigation efficiency and leachate volume. Container capacity increased and air space decreased with increasing biochar, while there was no change in total porosity (Table 2). Pore size distribution is an important substrate characteristic that controls water retention and drainage (Kevin and Black, 2010). Pine bark had 18.5% fines (<0.71 mm), 29.4% medium (0.71–2 mm), 43% large (2–6.3 mm), 9% very large (>6.3 mm) particle size distribution. The fine particles in the biochar (Table 1) likely nested within the larger pores of the pine bark substrate, causing the observed changes in container capacity and air space. Altland and Locke (2013) observed a similar response in container capacity and air space changes from biochar application in a peatmoss substrate.

Increasing biochar rate also caused a decrease in bulk density. The biochar used in this study had a bulk density of 0.10 g·cm⁻³, roughly half that of the pine bark with a bulk density of 0.18 g·cm⁻³. Bulk density of composite material can often be calculated as the weighted average of different substrate components (Altland and Locke, 2017; Pokorny et al., 1986), in that increasing

percentages of lower-density materials will decrease the bulk density of the composite material. Reduction in bulk density was reported in other studies following biochar application to soilless substrates (Altland and Locke, 2012; Beck et al., 2011; Dumroese et al., 2011; Tian et al., 2012).

There were no species by biochar interactions for water use and irrigation metrics (Table 3). Total number of irrigation events decreased with increasing addition of biochar for hydrangea. Irrigation was triggered most frequently for hydrangea plants growing in the 0% biochar treatment, 40 events, compared with 26 and 11 events for 10% and 25% biochar, respectively. Average number of days between irrigation events was 1.4, 2.2 and 5.2 for hydrangea plants in 0%, 10% and 25% biochar, respectively. Over the 8-week experiment, the 10% and 25% biochar treatments were irrigated with 32% and 72% less water, respectively, than the 0% biochar treatment. Leachate volume per irrigation event and leaching fraction were lower for 25% biochar than for 0% biochar. Conversely, WAE and WUE were greater for the 25% biochar treatment than the 0% biochar amendment treatments.

Boxwood plants reached the set point, triggering irrigation four to five times during the 8-week experiment regardless of substrate composition. The average number of days between irrigation events ranged from 11.2 (0% and 25% biochar) to 14.0 (10% biochar), about once every other week. Total irrigation volume ranged from 3.1 to 3.9 L/plants. Boxwood leachate volume and leaching fraction decreased with increasing biochar amendment. Addition of 25% biochar amendment reduced the per irrigation event leachate volume by 28% for boxwood and improved WAE by 33% compared with 0% biochar; however, WUE was unaffected by biochar amendment.

Hydrangea paniculata is considered a high water use plant and a fast growing species (Owen et al., 2016; Warsaw et al., 2009), while *Buxus* spp. is considered a low water use and slow growing genus (Nambuthiri et al., 2017; Niemiera, 2013). Our results support substrate physical properties analysis (Table 2) that substrates with increasing amounts of biochar have greater water holding capacity, which can translate to a greater water storage and subsequent delivery between irrigation events resulting in a reduction in overall water use among high water use species. Additional water holding capacity might be of little or no benefit to slow growing or low water use species such as *Buxus* spp. The 25% biochar

amendment also helped reduce leachate volume per irrigation event and achieve a leaching fraction within the recommended range, 10% to 20% for hydrangea (Yeager et al., 2007). Additionally, less frequent irrigation associated with the high biochar amendment also resulted in fewer leaching events among hydrangea. The total leachate volume (leachate volume × total number of irrigation events) per treatment was lower in 25% biochar treatment.

While addition of 25% biochar decreased the leaching volume of boxwood plants on an individual irrigation event basis, and decreased the leaching fraction by 27% compared with 0% biochar, the leaching fraction was above recommended guidelines for all treatments (Yeager et al., 2007). This is likely related to the infrequent irrigation of all boxwood treatments. Infrequent irrigation can cause pine bark based substrates to become hydrophobic (Hagen et al., 2014) and this would be exacerbated in controlled environment conditions where there is no rain. Hydrophobic substrates can be more prone to channeling of water through the substrate (Hoskins et al., 2014b) and thus would have higher leaching fractions.

Leachate analysis. Among hydrangea, EC was greater at the 25% biochar rate, but there was no difference between 0% and 10% rates (Table 4). Among boxwood, EC was substantially greater for the 25% biochar rate, about double that of the 0% and 10% rate. The recommended range for EC in container substrate via pour through extraction method is 0.5 to 1.0 dS·m⁻¹ for plants fertilized with controlled-release fertilizer (Yeager et al., 2007). It is important to note that our values were therefore diluted, potentially at different rates, when compared with extracts collected by a pore-water exchange. For hydrangea, EC leachate was less than 0.5 dS·m⁻¹ at 0% and 10% biochar rate and for boxwood EC is less than 0.5 dS·m⁻¹ at 0% biochar rate. Addition of 25% biochar in hydrangea and 10% and 25% in boxwood increased leachate EC, bringing it in the recommended range. Similar to our results higher pH and EC have also been reported in biochar treatments in soilless substrates (Conversa et al., 2015; Kaudal et al., 2016).

Substrate pH increased with increasing rates of biochar in hydrangea. Among boxwood, substrate pH was unaffected by biochar incorporation, but turbidity of leachate samples was greater for the 25% biochar rate than for the 0% and 10% rates (data not shown). Addition of biochar has been shown to increase soil pH in acidic soils because of its generally neutral to alkaline pH, although this is contingent upon feedstock type, soil type, and application rate (Jeffery et al., 2011). In this study, leachate pH increased with increasing biochar treatments in hydrangea but did not for boxwood. Leachate pH for a sphagnum peatmoss and a coarse perlite-based substrate (Sunshine Mix #2; Sun Gro Horticulture, Agawam, MA) was unaffected by addition of 10% gasified rice hull biochar (Altland and Locke, 2013). However,

Table 2. Physical properties of pine bark substrate amended with 0%, 10%, or 25% of switchgrass (*Panicum virgatum* L.) biochar by volume (n = 3).

| Biochar rate (%) | Container capacity (%) | Air space (%) | Total porosity (%) | Bulk density (g·cm ⁻³) |
|------------------|------------------------|---------------|--------------------|------------------------------------|
| 0 | 31.20 c ^z | 44.13 a | 75.37 a | 0.17 a |
| 10 | 34.87 b | 41.40 ab | 76.45 a | 0.16 b |
| 25 | 38.89 a | 38.87 b | 77.76 a | 0.15 c |
| P value | 0.017 | 0.061 | 0.056 | 0.005 |

Substrate physical properties were determined using a 15-cm tall Porometers procedure.

^zValues in same column with same letter are not significantly different at P < 0.05.

Table 3. Total number of irrigation events, leachate data, water application efficiency (WAE) and water use efficiency (WUE) for 'Green Velvet' boxwood and Pinky Winky® hardy hydrangea in substrates amended with 0%, 10%, or 25% of switchgrass (*Panicum virgatum* L.) biochar by volume ($n = 10$) over 8 weeks experiment.

| Species | Biochar rate (%) | Total number of irrigation events | Total irrigation applied per container (L) | Leachate volume per irrigation event (mL) | Leaching fraction (%) | WAE (cm·L ⁻¹) | WUE (g·L ⁻¹) |
|--------------------------------|------------------|-----------------------------------|--|---|-----------------------|---------------------------|--------------------------|
| Hydrangea | 0 | 40 | 30.9 | 219.8 a ^z | 28.5 a | 71.5 b | 1.5 b |
| | 10 | 26 | 20.9 | 179.6 ab | 23.3 ab | 76.7 ab | 1.8 b |
| | 25 | 11 | 8.5 | 123.0 b | 16.2 b | 83.8 a | 2.5 a |
| Boxwood | 0 | 5 | 3.9 | 315.0 a | 40.8 a | 59.2 b | 0.5 a |
| | 10 | 4 | 3.1 | 270.4 ab | 35.0 ab | 65.0 ab | 0.6 a |
| | 25 | 5 | 3.9 | 227.8 b | 29.7 b | 78.5 a | 1.0 a |
| Significance (<i>P</i> value) | | | | | | | |
| Species | — | — ^y | — | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Biochar | — | — | — | 0.0003 | 0.0003 | 0.0003 | 0.004 |
| Species × biochar | — | — | — | 0.940 | 0.940 | 0.940 | 0.501 |

^zValues within each column followed by the same letter by species were not significantly different ($P < 0.05$).

^yAnalysis of variance not conducted because there was only one solenoid valve for species × biochar combination.

Water application efficiency was calculated as $\{[\text{volume applied} - \text{volume leached (mL)}] / \text{volume applied (mL)} \times 100\}$ and reported as a percent. Water use efficiency per plant was estimated as $[\text{increase in dry weight over the course of the experiment (g)} / \text{total irrigation volume applied (L)}]$.

In each case calculation used values from the day the automated irrigation system was deployed on 15 June 2015.

Table 4. Leachate electrical conductivity (EC), pH, nitrate (NO₃), ammonium (NH₄) and total nitrogen (TN) averaged over four time periods for 'Green Velvet' boxwood and Pinky Winky® hardy hydrangea in substrates amended with 0%, 10%, or 25% of switchgrass (*Panicum virgatum* L.) biochar by volume ($n = 5$).

| Species | Biochar rate (%) | EC (dS·m ⁻¹) | pH | NO ₃ (mg) | NH ₄ (mg) | TN (mg) |
|--------------------------------|------------------|--------------------------|--------|----------------------|----------------------|---------|
| Hydrangea | 0 | 0.3 b ^z | 4.0 c | 1.9 ^{NS} | 0.6 ^{NS} | 2.5 a |
| | 10 | 0.4 b | 5.2 b | 2.1 | 1.5 | 3.1 a |
| | 25 | 0.6 a | 6.0 a | 2.5 | 1.0 | 3.7 a |
| Boxwood | 0 | 0.5 b | 5.5 a | 5.2 | 2.7 | 9.9 b |
| | 10 | 0.5 b | 5.4 a | 9.0 | 2.2 | 13.2 ab |
| | 25 | 1.1 a | 5.8 a | 13.6 | 3.3 | 18.4 a |
| Significance (<i>P</i> value) | | | | | | |
| Species | — | 0.016 | 0.052 | 0.419 | 0.623 | 0.033 |
| Biochar | — | 0.0002 | 0.0001 | 0.322 | 0.962 | 0.034 |
| Species × biochar | — | 0.439 | 0.059 | 0.184 | 0.608 | 0.012 |

^zValues within each column followed by the same letter by species were not significantly different ($P < 0.05$).

^{NS}Values in each column followed by NS are not significantly different ($P < 0.05$).

Nitrate, ammonium, and TN are expressed as mass calculated by concentration × leachate volume.

application of 15% to 20% gasified rice hull biochar rate increased substrate pH in tomato and geranium plants (Altland and Locke, 2017). The ecosystem or cropping systems to which biochar is applied influences the effect of biochar, as well as the type of feedstock and the pyrolysis conditions (Sohi et al., 2009).

Plant species might also explain some of the pH differences. Plant roots can affect pH and most notably reducing substrate pH by releasing exudates (Rukshana et al., 2012). Inorganic ions and organic acids such as amino acids and fatty acids are some of the important components of root exudates that affect nutrient availability and act as soil acidifiers (Dakora and Phillips, 2002). Hydrangea had a greater final dry weight (stems, leaves) than boxwood, and final dry weight was greatest for hydrangea in 0% biochar (Table 7). Therefore, root mass were also substantially greater for hydrangea and may explain the lower pH among hydrangea grown in 0% biochar (based on limited root dry weight samples data that are not shown here).

Furthermore, substrate pH changes as a result of nutrient uptake. Nutrient uptake,

especially cation uptake, reduces soil pH as plants release protons (H⁺) to compensate for cation uptake (Brady and Weil, 2002). Hydrangea had substantially greater uptake (dry weight × nutrient concentration) of Mg and Ca, and Ca uptake was highest for hydrangea in 0% biochar but not significantly different from 10% biochar rate (Table 7) resulting in a greater release of H⁺ and its concomitant pH reduction.

Nutrient analysis. Because the volume of leachate differed among treatments, the mass of nutrients (concentration × leachate volume) was calculated as a way to normalize the effect of biochar on nutrient release.

For hydrangea, mass of leachate NO₃ and NH₄ was unaffected by increasing biochar rate (Table 4). However, for boxwood, leachate NO₃ in the 25% biochar treatment increased, while NH₄ was unaffected by biochar amendment. There was a significant interaction for species and biochar rate for leachate TN with the addition of biochar (Table 4). Increasing rate of biochar did not influence leachate TN for hydrangea. For boxwood, there was greater leachate TN from 25% biochar amendment than for 0% biochar amendment.

There was a significant interaction for species and biochar rate for leachate TOC and PO₄ with the addition of biochar (Table 5). Among hydrangea, the 25% rate biochar had a greater TOC and PO₄ mass loss than the 0% biochar. In leachate, TOC and PO₄ increased with increasing biochar amendment among boxwood. The mass of K released in leachate increased in 10% and 25% biochar treatment for both plant species.

There was a significant interaction for species and biochar rate for leachate Ca and Mg mass with the addition of biochar. Biochar amendment of 10% and 25% caused a decrease in leachate Ca mass for hydrangea, but not for boxwood. Mg in leachate was not different in hydrangea but increased with 25% biochar application in boxwood.

Our nutrient leaching results are consistent with other published studies. Altland and Locke (2013) reported that gasified rice hull biochar acts as a source of PO₄ and K in soilless substrate. Application of 10% gasified rice hull biochar increased P and K concentrations in leachate compared with 0% or 1% biochar rate. However, similar NO₃ concentration was observed across all treatments (Altland and Locke, 2013). An increase in P losses has been reported in biochar treatments in pine bark and peat-based substrate incubated at constant temperature for 90 d (Kaudal et al., 2016).

Total nutrients lost was estimated as number of irrigation events multiplied by the average nutrient lost from the four sampling periods combined, since there was no significant effect of sampling time (data not shown). The total amount of water leached and nutrients lost from hydrangea containers were lower in biochar-amended substrates due to improvements in the water holding capacity of the substrate and fewer irrigation events in the biochar treatments (data not shown). Over-irrigation of soilless substrates often results in greater leaching and runoff of water and nutrients (Conover and Poole, 1992; Hoskins et al., 2014a; Majsztzik et al.,

2011). However, adjusting the irrigation amount and frequency can offset nutrient leaching (Lea-Cox et al., 2011; Owen et al., 2008; Tyler et al., 1996; Warsaw et al., 2009). Using biochar as a component of a soilless substrate reduced nutrient and water losses in several studies (Altland and Locke, 2012; Beck et al., 2011; Dumroese et al., 2011; Tian et al., 2012). Biochar also has potential to improve water retention and reduce nutrient leaching in unconventional container cropping systems; addition of 7% biochar to greenroof soil growing sedum or ryegrass reduced TN and total P, NO₃, PO₄ and TOC released in leachate (Beck et al., 2011).

Substrate analysis. In hydrangea, amendment with either 10% or 25% biochar increased extractable substrate NO₃ concentration, but NH₄ concentration was unaffected. In boxwood, substrate NO₃ concentration was greater in the 10% and 25% biochar amendment while NH₄ was lower at the 25% rate than the 0% rate (Table 6).

There was a significant species and biochar rate interaction for substrate P and K concentration. P concentration was higher in 25% biochar treatment for hydrangea but there was no difference between 0% and 10%, while for boxwood there was increasing P with increasing biochar amendment. For hydrangea, there were no differences in substrate K levels due to biochar amendment but for boxwood, the 25% biochar had greater K levels than both 0% and 10%, by 170% and 83%, respectively. In hydrangea, Ca concentration decreased as biochar amendment increased, but Mg concentration was unaffected. In boxwood Ca and Mg substrate levels were unaffected by biochar amendment.

Both the leachate and substrate nutrient analysis showed that application of 25% biochar rate increased P concentration in both plant species and K concentration in boxwood. Hydrangea leachate K concentration increased after biochar application, while substrate K concentration was unaffected by biochar application.

Similar to our results, Dumroese et al. (2011) reported that increasing pelleted biochar (agricultural or forestry residues) rates up to 100% increased amounts of soluble K and P. Altland and Locke (2013) suggested a possible fertilizer contribution from biochar. Application of up to 25% switchgrass biochar amendment to sand-based substrate with creeping bentgrass showed potential to increase nutrient release as the P and K released to pore water was increased (Brockhoff et al., 2010). Higher nutrient P load was reported in incorporation of up to 60% of biochar (biosolids and municipal softwood garden waste) and pine bark substrate (Kaudal et al., 2016). Therefore, biochar application can increase substrate nutrient concentration in soilless systems.

Plant biomass. There was a significant interaction for final dry weight (Table 7). Hydrangea final dry weight was reduced by the 25% biochar amendment, but boxwood

Table 5. Leachate total organic carbon (TOC), phosphate (PO₄), potassium (K), calcium (Ca) and magnesium (Mg) were averaged over four time periods for 'Green Velvet' boxwood and Pinky Winky® hardy hydrangea in a pine bark substrate amended with either 0%, 10%, or 25% of switchgrass (*Panicum virgatum* L.) biochar by volume and a controlled release fertilizer (Osmocote 18N-2.6P-9.9K at 24 g/container).

| Species | Biochar rate (%) | TOC (mg) | PO ₄ (mg) | K (mg) | Ca (mg) | Mg (mg) |
|--------------------------------|------------------|--------------------|----------------------|--------|---------|---------|
| | 0 | 3.3 b ^c | 0.2 b | 2.1 b | 3.2 a | 1.4 a |
| Hydrangea | 10 | 4.3 b | 0.4 ab | 5.6 a | 1.9 b | 1.3 a |
| | 25 | 6.1 a | 0.7 a | 7.6 a | 1.8 b | 1.5 a |
| Boxwood | 0 | 6.6 c | 0.8 c | 8.1 b | 4.0 a | 1.9 b |
| | 10 | 10.0 b | 1.6 b | 18.3 a | 4.5 a | 3.3 a |
| | 25 | 20.1 a | 4.3 a | 32.3 a | 4.1 a | 4.1 a |
| Significance (<i>P</i> value) | | | | | | |
| Species | — | 0.488 | 0.733 | 0.296 | 0.212 | 0.703 |
| Biochar | — | <0.0001 | <0.0001 | 0.031 | 0.223 | 0.494 |
| Species × biochar | — | 0.005 | 0.032 | 0.087 | 0.0005 | 0.0002 |

²Values within each column followed by the same letter by species were not significantly different (*P* < 0.05).

Nutrients are expressed as mass, calculated by concentration × leachate volume.

Table 6. 'Green Velvet' boxwood and Pinky Winky® hardy hydrangea substrate nitrate (NO₃), ammonium (NH₄), phosphorous (P), potassium (K), calcium (Ca) and magnesium (Mg) concentration in a pine bark substrate amended with either 0%, 10%, or 25% switchgrass biochar by volume of and a controlled release fertilizer (Osmocote 18N-2.6P-9.9K at 24 g/container).

| Species | Biochar rate (%) | NO ₃ (mg·L ⁻¹) | NH ₄ (mg·L ⁻¹) | P (mg·L ⁻¹) | K (mg·L ⁻¹) | Ca (mg·L ⁻¹) | Mg (mg·L ⁻¹) |
|--------------------------------|------------------|---------------------------------------|---------------------------------------|-------------------------|-------------------------|--------------------------|--------------------------|
| | 0 | 41.0 b ^c | 10.5 a | 6.0 b | 79.9 a | 80.6 a | 38.9 a |
| Hydrangea | 10 | 119.0 a | 9.9 a | 8.6 b | 109.7 a | 36.6 ab | 28.2 a |
| | 25 | 130.4 a | 9.0 a | 14.8 a | 102.7 a | 23.0 b | 21.3 a |
| Boxwood | 0 | 51.9 b | 9.9 a | 4.8 c | 60.7 b | 17.3 a | 11.9 a |
| | 10 | 154.3 a | 5.8 ab | 9.7 b | 89.6 b | 14.6 a | 10.8 a |
| | 25 | 161.3 a | 2.0 b | 25.0 a | 164.0 a | 8.2 a | 8.6 a |
| Significance (<i>P</i> value) | | | | | | | |
| Species | — | 0.155 | 0.027 | 0.013 | 0.613 | <0.0001 | <0.0001 |
| Biochar | — | 0.0003 | 0.086 | <0.0001 | 0.008 | 0.006 | 0.307 |
| Species × biochar | — | 0.776 | 0.287 | 0.003 | 0.052 | 0.642 | 0.894 |

²Values within each column followed by the same letter by species were not significantly different (*P* < 0.05).

Table 7. Final dry weight, foliar nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) concentration of 'Green Velvet' boxwood and Pinky Winky® hardy hydrangea in a pine bark substrate amended with either 0%, 10%, or 25% switchgrass biochar by volume and a controlled release fertilizer (Osmocote 18N-6P-12K at 24 g/container).

| Species | Biochar rate (%) | Final dry wt (g) | N (%) | P (mg·L ⁻¹) | K (mg·L ⁻¹) | Ca (mg·L ⁻¹) | Mg (mg·L ⁻¹) |
|--------------------------------|------------------|---------------------|---------|-------------------------|-------------------------|--------------------------|--------------------------|
| | 0 | 56.4 a ² | 2.3 b | 2,795 b | 7,382 b | 16,631 a | 4,553 b |
| Hydrangea | 10 | 46.0 a | 2.4 ab | 3,471 a | 8,882 b | 15,371 a | 5,450 a |
| | 25 | 27.8 b | 2.6 a | 3,805 a | 11,198 a | 12,518 b | 5,480 a |
| Boxwood | 0 | 6.0 a | 3.1 a | 2,347 b | 7,416 b | 9,784 a | 3,984 a |
| | 10 | 6.9 a | 2.8 b | 3,202 a | 8,506 b | 9,605 a | 3,926 a |
| | 25 | 7.4 a | 2.8 b | 3,770 a | 10,605 a | 8,311 a | 3,656 a |
| Significance (<i>P</i> value) | | | | | | | |
| Species | — | <0.0001 | <0.0001 | 0.157 | 0.536 | <0.0001 | <0.0001 |
| Biochar | — | 0.017 | 0.602 | <0.0001 | <0.0001 | <0.0001 | 0.1077 |
| Species × biochar | — | <0.0001 | <0.0001 | 0.606 | 0.863 | 0.072 | 0.006 |

²Values within each column followed by the same letter by species were not significantly different (*P* < 0.05).

final dry weight was unaffected by biochar rate.

Biochar application rate influenced irrigation frequency, which likely affected hydrangea plant biomass. Total irrigation applied was decreased by 32% in 10% biochar treatment without reducing the dry weight. However, in the 25% biochar treatment total irrigation applied was reduced by 72% while the dry weight decreased by 50%. Reduction in dry weight at the high biochar rate may be due to a reduction in plant available water. While the 25% rate of biochar increased the overall substrate water content, the reduction in irrigation frequency

may have decreased the portion of the irrigation cycle in which water was available, i.e., counter to our hypothesis, moisture in the substrate may not have been available to plants as the 0.25 cm³·cm⁻³ VWC set point was approached leading to an overall reduction in readily available water over the course of the experiment. This could be due to a shift in water potential at a given VWC occurring in 25% biochar treatment that exceeds the water buffering capacity resulting in periods where water was unavailable. So while there may have been sufficient water in terms of VWC in the 25% biochar substrate, the biochar held the water at

a higher tension, making the water unavailable to plants. This highlights the need to develop substrate water potential based irrigation scheduling as opposed to volumetric-based schedules.

Leachate pH and EC associated with the biochar addition might also explain some of the growth differences (Table 4). Boxwood prefers high pH, which might explain why there were no significant differences in dry weight of boxwood as the leachate pH was similar in biochar and control treatments. But the leachate pH increased after addition of biochar in hydrangea, which might have caused a decrease in dry weight of hydrangea. While there is no literature on hydrangea response to substrate pH in pine bark substrates, other species have shown negative growth response to elevated pH (Altland and Jeong, 2016).

Similar to our results, some studies reported the beneficial effects of biochar on plant growth, and some reported no effect of biochar on plant growth. Addition of biochar to a peatmoss-based substrate had little or no effect on dry weights of tomato (*Solanum lycopersicum* L.) and marigold (*Tagetes erecta* L.) plants but significantly increased the plant heights (Vaughn et al., 2013). However, biochar increased pepper (*Capsicum annuum* L.) and tomato crop growth in coconut fiber: tuff substrate (Graber et al., 2010) and *Calathea rotundifolia* 'Fasciata' growth in peat substrate (Tian et al., 2012). Also, biochar as soil component increased tomato's ability to withstand drought (Mulcahy et al., 2013) and improved oat (*Avena sativa* L.) growth (Schulz and Glaser, 2012).

Plant tissue analysis. There was a significant species and biochar rate interaction in foliar nitrogen concentration (Table 7). The 25% biochar amendment increased hydrangea foliar nitrogen compared with 0%. Biochar application increased substrate NO₃ concentration. However, there was no change in NO₃ leaching for hydrangea indicating that biochar may have caused increase in NO₃ retention in the substrate resulting in higher N concentration in plants. For boxwood, 10% and 25% biochar amendment caused lower foliar N than 0% biochar. The 25% biochar amendment increased substrate and leachate NO₃ concentration. The higher leachate NO₃ mass in 25% biochar treatment might be due to the lower nutrient requirements of boxwood compared with hydrangea.

For both species, foliar P concentration was higher in the 10% and 25% biochar-amended treatments. K concentration was highest in 25% biochar treatment in both species, but there were no differences between 0% and 10% biochar application rate. P and K concentration also increased with 25% biochar application rate in leachate and substrate. The switchgrass biochar in this experiment was a source of P and K for the plants due to measurable differences in plant, substrate and leachate nutrient concentration caused by biochar amendment.

In hydrangea, Ca concentration decreased in foliar, substrate and leachate after 25% biochar amendment rate. However, in boxwood, increasing rate of biochar had no influence on foliar, substrate and leachate Ca concentration. There was a significant species and biochar rate interaction in foliar Mg concentration. Both 10% and 25% biochar amendment caused greater foliar Mg levels for hydrangea, but there was no change in substrate and leachate Mg concentration. In boxwood biochar application had no influence on foliar and substrate Mg concentration but increased Mg loss in leachate. A meta analysis of 114 published papers concluded that biochar addition to mineral soils caused an increase in plant tissue K concentration, but the concentration of plant tissue N and P did not show any significant effect from biochar (Biederman and Harpole, 2013). Therefore, biochar may be a more important source of P (and K) in soilless substrate (Altland and Locke, 2013).

Conclusion

A precision irrigation system in combination with biochar, a readily available, low cost substrate amendment, increased water holding capacity, reduced the water requirement for hydrangea and reduced leachate volume in both hydrangea and boxwood. Biochar application rate influenced irrigation frequency, which likely affected plant biomass for hydrangea, but the boxwood final dry weight was unaffected by biochar rate. The 10% biochar treatment reduced total irrigation applied by 32% without affecting the hydrangea dry weight. However, in the 25% biochar treatment total irrigation applied was reduced by 72% while the dry weight decreased by 50%. The total amount of water leached and nutrients lost from hydrangea containers were lower in biochar amendment pots due to improvements in the water holding capacity of the substrate and fewer irrigation events in the biochar treatments. The mass of P and K were higher in the leachate from containers that received 25% biochar compared with those amended with 0% biochar in each leachate event. Amendment with biochar was also shown to increase concentration of P and K in both plant tissues and substrate. Although there were measurable differences in substrate and plant P and K concentration caused by biochar amendment, it is unlikely such differences had any impact on the growth or performance of hydrangea plants in this experiment, this might be due to receiving less irrigation in biochar amended pots in hydrangea. In this study application of up to 25% biochar increased P and K concentration in plants and substrate, suggesting it might be able to replace fertilizer requirements if used commercially. However the effect of biochar depends on type of feedstock, pyrolysis/gasification conditions, and the ecosystem or cropping systems to which it is applied. Potential nutrient losses of biochar application will need to be addressed in case of

adopting biochar amendment in container nursery production. Fertilizer levels may need to be adjusted accounting for that and the nutrient levels supplied by biochar which can both reduce demand for P and decrease environmental concerns from mineral P applications from conventional fertilizers. Finally, development of substrate water potential-based irrigation logic or schedules based on cues from the crop's physiological status could help identify set points for on demand irrigation that exploit the water buffering capacity without exceeding it during irrigation cycles.

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