Improving water use efficiency of containerized crops using biochar and precision irrigation scheduling

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Improving water use efficiency of containerized crops using biochar and precision irrigation scheduling

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Nastaran Basiri Jahromi
May 2019
To my family

Whose love, support, and encouragement over the years have made the writing of this dissertation possible.
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Abstract

Developing management practices that make more efficient use of irrigation is important for improving the sustainability of agriculture. Biochar, a byproduct of pyrolysis, can potentially increase the amount of available water and improve irrigation efficiency and plant growth. The goal of this study was to evaluate the impact of irrigation schedules and biochar on water use and biomass gain of container crops. Containers were filled with pine bark and amended with 10% or 25% by volume of biochar. Boxwood and hydrangea plants were irrigated when the volumetric water content reached the water buffering capacity set point of 0.25 cm$^3$ cm$^{-3}$ in the first experiment. Biochar amendment increased water-holding capacity and reduced water consumption of a high water use crop, hydrangea. However, reduction of plant biomass in 25% biochar treatment suggests that sufficient water might not be available to plants in this substrate. Another study was initiated to address this problem by using physiological parameters to monitor hydrangea plant water status under different irrigation schedules that were designed to maximize plant available water. Plant physiology or substrate physical properties basis irrigation scheduling, in combination with biochar substrate amendment, reduced the water requirement for hydrangea without any negative effect on plant dry weight by maintaining sufficient plant water status and gas exchange rate. In order to validate the irrigation schedules in an outdoor environment, independently controlled irrigation zones were designed to test irrigation schedules. Total water use was unaffected or lower in the on-demand irrigation systems. However, plant dry weight and water use efficiency was greater in on-demand irrigation scheduling systems compared to the conventional irrigation. This research demonstrated that automated irrigation systems coupled with plant physiology or substrate-based irrigation scheduling and a water retentive substrate amendment have the potential to reduce nursery water use without negatively affecting plant growth.
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Chapter 1

Introduction

Water scarcity is a growing concern across the globe due to increasing world’s population, climate change and water demand in agriculture and industry (Jury and Vaux, 2005). Agricultural irrigation is a major water consumer, using about 70% of worldwide consumptive use (Food and Agricultural Organization of the United Nations, 2007) and about 30 percent of total withdrawals in the US (Kenny et al., 2005). Nursery production is an intensive part of agricultural that uses relatively large amounts of water, nutrients, and pesticides (Beeson, 2010; Bethke and Cloyd, 2009; Wilson and Albano, 2011). A container nursery consumes over 72 m³ water per acre per day during the growing season (Fulcher and Fernandez, 2013).

Inefficient use of irrigation can exacerbate the present shortages of water, and is likely to increase drought, which results in imposing restrictions on irrigation (Caron et al., 2005). Regulations currently limit nursery water use in California, Florida, North Carolina, Texas, and Oregon and are expected to become more stringent (Beeson et al., 2004). Integrating precise irrigation application systems with proper irrigation scheduling can increase water use efficiency (Regan, 1999). Proper irrigation scheduling applies the appropriate amount of water when needed to support plant growth and avoids over- or under-watering (Nemali and Van Iersel, 2006).

Irrigation timers or manually operated systems are the most common irrigation scheduling methods in container production systems. Fixed irrigation rate in these systems may lead to over- or under-watering (Warsaw et al., 2009), which might cause an increase in crop vulnerability to disease (Chappell et al., 2013), a decrease in nursery crop growth due to human error (Belayneh et al., 2013; Million et al., 2007; Warsaw et al., 2009; Welsh and Zajicek, 1993) and an increase in leachate volume.

Scheduling irrigation based on estimated crop water use results in higher irrigation efficiency rather than relying only on periodically adjusting irrigation volume based on perceived water needs (van Iersel et al., 2013). Estimating crop water requirements by measurements derived from the physiological status of the plant (e.g., Cifre et al., 2005; Jones, 2004) can be used as an irrigation-scheduling basis. For example, irrigation based on the relationship between photosynthetic rate and substrate moisture content has been successfully used to improve crop water use efficiency (Fulcher et al., 2012; Hagen et al., 2014; Nambuthiri et al., 2017). However, visual indicators of physiological response to water deficit such as wilting cannot generally be
used to schedule irrigation because plant growth is negatively affected at the water deficits associated with wilting (Jones, 2004; Slatyer, 1967).

Another irrigation scheduling technique, particularly suited for low water availability such as during water restrictions, is one in which irrigation is actuated based on substrate moisture availability derived from a moisture characteristic curve (Fields et al., 2016). Using substrate moisture sensors to implement water potential-based irrigation scheduling that maintains plant-available water in the range of -1 to -10 kPa can conserve water while avoiding plant water stress (Arguedas Rodriguez, 2009). Recent research suggests further water savings are possible by exploiting the area beyond -10 kPa tension (Fields et al., 2016). Scheduling irrigation based on substrate water status or a calculated crop evapotranspiration model reduced water use without affecting plant growth and quality in comparison to timer-based irrigation (Incrocci et al., 2014).

Pine bark is a commonly used substrate component that has high porosity and relatively low water holding capacity. Plants grown in pine bark must be irrigated frequently compared to field grown crops in order to supply adequate water (Hoskins et al., 2014a). Excessive irrigation may result in increasing water and nutrients leaching and runoff (Conover and Poole, 1992; Hoskins et al, 2014a; Majsztrik et al., 2011), crop losses and plant susceptibility to root diseases (O’Meara et al., 2013).

Substrate amendments may be used to increase substrate water holding capacity and decrease leaching (Mathers et al., 2005). Soil and soilless substrate water retention characteristics are strongly related and can be affected by the number and size of the pores (Handreck and Black, 2002). Manipulating the size and shape of the substrate to decrease the proportion of large component improve the amount of available water, irrigation efficiency, growth rates and reduce the growth period (Caron et al., 2005). 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 soil conditioner in agriculture (Lehmann and Joseph, 2009). Using amendments such as biochar can modify the average substrate particle size and reduce the proportion of larger-sized components. Such substrate particle size manipulation increases the amount of available water, which can improve irrigation efficiency and plant growth (Caron et al., 2005). Biochar can improve nutrient use efficiency by increasing cation exchange capacity, surface area and water retention of the soil/substrate (Altland and Locke, 2013; Glaser et al., 2002; Lehmann et al., 2006). Biochar also increases nutrient concentration and availability due to the initial nutrient concentration and high cation exchange capacity (CEC) (Headlee et al., 2014).
Total mineral nutrients in biochar products are higher than the feedstock (Judd, 2016).

Solute movement through soilless substrates depends on the distribution of ions through macro-pores and micro-pores, their diffusion across concentration gradients, and the interaction with bark particle exchange sites (Hoskins et al., 2014b). Therefore, biochar may influence nutrients leaching from a soilless substrate. Biochar can have a substantial impact on the release and retention of nitrate (NO$^-\text{}$), phosphate (PO$^4^-\text{}$), and potassium (K$^+\text{}$) 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).

The objective of this research was to assess the effect of biochar amendment on water and nutrient leaching for a low and high water use woody species. This research also evaluated the impact of biochar and two on-demand, need-based irrigation schedules on plant water relations, and biomass gain of container-grown *Hydrangea paniculata* with the goal of reducing water use by exploiting the water buffering capacity while maintaining or shortening production cycles in the greenhouse and outdoors.
1.1 References


Chapter 2
Growth response, mineral nutrition, and water utilization of container grown woody ornamentals grown in biochar amended pine-bark
This chapter is a reformatted version of a paper, by the same name published in HortScience journal, 53(3): 347–353, by Nastaran Basiri Jahromi, Forbes Walker, Amy Fulcher, James Altland and Wesley Wright.

2.1 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. × B. 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 (PO₄³⁻), 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.

**Keywords**: Boxwood, dielectric sensors, hydrangea, irrigation, leachate volume, water buffering capacity

### 2.2 Introduction

Greenhouse and nursery producers are facing increasing fertilizer costs and greater scrutiny towards nutrient use efficiency and retention (Altland and Lock, 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 in order 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 provides 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, 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 utilizing different substrate amendments that 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 soil conditioner in agriculture (Lehmann and Joseph, 2009). Over time, 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 macro-pores and micro-pores, their diffusion across concentration gradients, and the interaction with bark particle exchange sites (Hoskins et al., 2014b). Therefore, biochar may influence nutrients leaching from a soilless substrate. Biochar can have a substantial impact on the release and retention of $\text{NO}_3^-$, $\text{PO}_4^{3-}$, and $\text{K}^+$ 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.

### 2.3 Material and Methods

The experiment was conducted at the University of Tennessee North Greenhouse Complex, in Knoxville, Tennessee for eight weeks and initiated on 15 June 2015. *Buxus sempervirens* L. ×*B. microphylla* (‘Green Velvet’ boxwood) and *Hydrangea 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) comprised of 100% switchgrass (*Panicum virgatum* L.) subjected to pyrolysis at $\approx 1000^\circ\text{C}$. The chemical and physical properties of the biochar are summarized in Table 2.1.

Containers were irrigated by hand for four 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% $\text{NH}_4^-$N and 8% $\text{NO}_3^-$N. Substrates were also drenched twice with a surfactant (Aquagro L, Aquatrols, Paulsboro, NJ) at a rate of 600 ppm in
Table 2.1. Chemical and physical properties of a biochar derived from switchgrass (*Panicum virgatum* L.) and used as a substrate amendment for container nursery production.

<table>
<thead>
<tr>
<th>Parameter</th>
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<td><strong>Chemical properties</strong></td>
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<td>EC</td>
<td>dS/m</td>
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<td>Nitrogen</td>
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<td>Ammonia</td>
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<tr>
<td>Potassium</td>
<td>%</td>
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<tr>
<td><strong>Physical properties</strong></td>
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<tr>
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<tr>
<td>Surface area</td>
<td>m³/g</td>
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</tr>
<tr>
<td>Particle size distribution</td>
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</tr>
<tr>
<td>Large (2-6.3mm)</td>
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</tr>
<tr>
<td>Medium (0.71-2mm)</td>
<td>%</td>
<td>20.7</td>
</tr>
<tr>
<td>Fine (&lt;0.71mm)</td>
<td>%</td>
<td>72.6</td>
</tr>
</tbody>
</table>

The results that are shown in Table 2.1 were obtained from Control Laboratories, Watsonville, CA.

In order 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 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 determination of air space. Cores were weighed, oven dried for four days 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, 0.11 mm openings) and a lower catch pan, which was shaken for 5 minutes 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 per hour 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 volumetric water content (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), in order 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 minutes 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.

Leachate volume was measured daily one to two hours 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 eight 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 eight weeks).

Leachate samples were collected from 30 containers (5 replications per treatment) each week for eight weeks. The samples were stored in plastic vials and kept refrigerated for 2 or 3 days until analyzed. Electrical conductivity (EC) was measured with a portable EC meter (HI 9811-5, Hanna Instruments, Smithfield, RI, USA) 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 um
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 NO$_3^-$, NH$_4^+$, PO$_4^{3-}$, and K$^+$. TN and total carbon (TOC) were measured by total organic carbon analyzer (TOC-VCPH; Shimadzu, Columbia, MD). Samples were filtered and then analyzed with optical emission spectroscopy (ICP-OES, Thermo Electron Corp., Waltham, MA) for calcium (Ca$^{2+}$) and magnesium (Mg$^{2+}$) concentration.

Shoots of all plants were harvested on 20 August 2015, 8 weeks after initiation of the experiment. After harvesting the shoots and leaves, the top 2.5 cm of substrate and the 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 NO$_3^-$ and NH$_4^+$ were extracted from the substrate using 2M 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$^{2+}$, and Mg$^{2+}$.

For dry weight measurements, the above ground portions of plants were harvested and hand-washed of substrate at 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$^{2+}$ concentration. All calculations at initiation and termination were based on data collected on June 15 and August 20 2015, while the automated irrigation was deployed.

2.4 Results and Discussion

2.4.1 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 2.2). Pore size distribution is an important substrate characteristic that controls water retention and drainage (Kevin and Black, 2010). Pine bark had 18.5% fines (<0.71mm), 29.4% medium (0.71–2 mm), 43% large (2–6.3 mm), 9% very large
Table 2.2. Physical properties of pine bark substrate amended with 0%, 10%, or 25% of switchgrass (*Panicum virgatum* L.) biochar by volume (n = 3).

<table>
<thead>
<tr>
<th>Biochar rate (%)</th>
<th>Container capacity</th>
<th>Air space</th>
<th>Total porosity</th>
<th>Bulk density</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>---------------</td>
<td>-----------</td>
<td>----------------</td>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>0</td>
<td>31.20c</td>
<td>44.13a</td>
<td>75.37a</td>
<td>0.17a</td>
<td>0.017</td>
</tr>
<tr>
<td>10</td>
<td>34.87b</td>
<td>41.40ab</td>
<td>76.45a</td>
<td>0.16b</td>
<td>0.061</td>
</tr>
<tr>
<td>25</td>
<td>38.89a</td>
<td>38.87b</td>
<td>77.76a</td>
<td>0.15c</td>
<td>0.056</td>
</tr>
<tr>
<td>P-value</td>
<td>0.017</td>
<td>0.061</td>
<td>0.056</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

*Values in same column with same letter are not significantly different at P < 0.05.*

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

(>6.3 mm) particle size distribution. The fine particles in the biochar (Table 2.1) 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 peat moss 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; Pokorný 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 2.3). 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.
Table 2.3. Total number of irrigation events, leachate data, water application efficiency and water use efficiency 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.

<table>
<thead>
<tr>
<th>Species</th>
<th>Biochar rate (%)</th>
<th>Total number of irrigation events</th>
<th>Total irrigation applied per container (L)</th>
<th>Leachate volume per irrigation event (ml)</th>
<th>Leaching fraction (%)</th>
<th>Water application efficiency (cm·L⁻¹)</th>
<th>Water use efficiency (g·L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>40</td>
<td>30.9</td>
<td>219.8a²</td>
<td>28.5a</td>
<td>71.5b</td>
<td>1.5b</td>
</tr>
<tr>
<td>Hydrangea</td>
<td>10</td>
<td>26</td>
<td>20.9</td>
<td>179.6ab</td>
<td>23.3ab</td>
<td>76.7ab</td>
<td>1.8b</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>11</td>
<td>8.5</td>
<td>123.0b</td>
<td>16.2b</td>
<td>83.8a</td>
<td>2.5a</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>5</td>
<td>3.9</td>
<td>315.0a</td>
<td>40.8a</td>
<td>59.2b</td>
<td>0.5a</td>
</tr>
<tr>
<td>Boxwood</td>
<td>10</td>
<td>4</td>
<td>3.1</td>
<td>270.4ab</td>
<td>35.0ab</td>
<td>65.0ab</td>
<td>0.6a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>5</td>
<td>3.9</td>
<td>227.8b</td>
<td>29.7b</td>
<td>78.5a</td>
<td>1.0a</td>
</tr>
</tbody>
</table>

Significance (P-value)

<table>
<thead>
<tr>
<th>Species</th>
<th>Biochar</th>
<th>Species* biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td>0.940</td>
<td>0.940</td>
</tr>
</tbody>
</table>

² ANOVA not conducted because there was only one solenoid valve for species* biochar combination.

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

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

In each case calculation used values from the day the automated irrigation system was deployed on June 15 2015.
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), approximately once every other week. Total irrigation volume ranged from 3.1 to 3.9 L per 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 not affected 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 2.2) 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 to 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., 2014a) and thus would have higher leaching fractions.
2.4.2 Leachate analysis

Among hydrangea, EC was greater at the 25% biochar rate, but there was no difference between 0% and 10% rates (Table 2.4). Among boxwood, EC was substantially greater for the 25% biochar rate, approximately 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 to 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 peat moss and a coarse perlite-based substrate (Sunshine Mix #2, Sun Gro Horticulture, Agawam, MA.) was not affected by addition of 10% gasified rice hull biochar (Altland and Locke, 2013). However, 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 2.7). 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).
Table 2.4. 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).

<table>
<thead>
<tr>
<th>Species</th>
<th>Biochar rate (%)</th>
<th>EC dS m⁻¹</th>
<th>pH</th>
<th>NO₃⁻</th>
<th>NH₄⁺</th>
<th>TN mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrangea</td>
<td>0</td>
<td>0.3b</td>
<td>4.0c</td>
<td>1.9ns</td>
<td>0.6ns</td>
<td>2.5a</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.4b</td>
<td>5.2b</td>
<td>2.1</td>
<td>1.5</td>
<td>3.1a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.6a</td>
<td>6.0a</td>
<td>2.5</td>
<td>1.0</td>
<td>3.7a</td>
</tr>
<tr>
<td>Boxwood</td>
<td>0</td>
<td>0.5b</td>
<td>5.5a</td>
<td>5.2</td>
<td>2.7</td>
<td>9.9b</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.5b</td>
<td>5.4a</td>
<td>9.0</td>
<td>2.2</td>
<td>13.2ab</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.1a</td>
<td>5.8a</td>
<td>13.6</td>
<td>3.3</td>
<td>18.4a</td>
</tr>
</tbody>
</table>

Significance (P-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

*Values within each column followed by the same letter by species were not significantly different (P < 0.05).
*ns Values in each column followed by the ns letters are not significantly different (P < 0.05).
Nitrate, ammonium, and TN are expressed as mass calculated by concentration*leachate volume.

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 Mg²⁺ and Ca²⁺, and Ca uptake was highest for hydrangea in 0% biochar but not significantly different than 10% biochar rate (Table 2.7) resulting in a greater release of H⁺ and its concomitant pH reduction.

2.4.3 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 both hydrangea and boxwood, mass of leachate NO₃⁻ and NH₄⁺ was not affected by increasing biochar rate (Table 2.4). There was a significant interaction for species and biochar rate for leachate TN with the addition of biochar (Table 2.4). 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 $\text{PO}_4^{3-}$ with the addition of biochar (Table 2.5). Among hydrangea, the 25% rate biochar had a greater TOC and $\text{PO}_4^{3-}$ mass loss than the 0% biochar. In leachate, TOC and $\text{PO}_4^{3-}$ 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$^{2+}$ 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$^{2+}$ 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 $\text{PO}_4^{3-}$ and K$^+$ in soilless substrate. Application of 10% gasified rice hull biochar increased P and K concentrations in leachate compared to 0% or 1% biochar rate. However, similar NO$_3^-$ 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 days (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., 2014b; Majsztik 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 total nitrogen and total P, NO$_3^-$, $\text{PO}_4^{3-}$ and TOC released in leachate (Beck et al., 2011).
Table 2.5. Leachate total organic carbon (TOC), phosphate (PO$_4^-$), potassium (K$^+$), calcium (Ca) and magnesium (Mg$^{2+}$) 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 per container).

<table>
<thead>
<tr>
<th>Species</th>
<th>Biochar rate (%)</th>
<th>TOC</th>
<th>PO$_4^-$</th>
<th>K$^+$</th>
<th>Ca</th>
<th>Mg$^{2+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrangea</td>
<td>0</td>
<td>3.3b$^*$</td>
<td>0.2b</td>
<td>2.1b</td>
<td>3.2a</td>
<td>1.4a</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4.3b</td>
<td>0.4ab</td>
<td>5.6a</td>
<td>1.9b</td>
<td>1.3a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>6.1a</td>
<td>0.7a</td>
<td>7.6a</td>
<td>1.8b</td>
<td>1.5a</td>
</tr>
<tr>
<td>Boxwood</td>
<td>0</td>
<td>6.6c</td>
<td>0.8c</td>
<td>8.1b</td>
<td>4.0a</td>
<td>1.9b</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10.0b</td>
<td>1.6b</td>
<td>18.3a</td>
<td>4.5a</td>
<td>3.3a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>20.1a</td>
<td>4.3a</td>
<td>32.3a</td>
<td>4.1a</td>
<td>4.1a</td>
</tr>
</tbody>
</table>

**Significance (P-value)**

<table>
<thead>
<tr>
<th>Species</th>
<th>Biochar</th>
<th>Species*biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>0.488</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>-</td>
<td>0.733</td>
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</tr>
<tr>
<td>-</td>
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<td>0.031</td>
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<tr>
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<td>0.703</td>
<td>0.0005</td>
</tr>
<tr>
<td>-</td>
<td>0.494</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

$^*$Values 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 $\times$ leachate volume.

2.4.4 Substrate analysis

In hydrangea, amendment with either 10% or 25% biochar increased extractable substrate NO$_3^-$ concentration, but NH$_4^+$ concentration was not affected. In boxwood, substrate NO$_3^-$ concentration was greater in the 10% and 25% biochar amendment while NH$_4^+$ was lower at the 25% rate than the 0% rate (Table 2.6).

There was a significant species and biochar rate interaction for substrate PO$_4^-$ 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 PO$_4^-$ with increasing biochar amendment. For hydrangea, there were no differences in substrate PO$_4^-$ 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$^{2+}$ concentration decreased as biochar amendment increased, but Mg$^{2+}$ concentration was not affected. In boxwood Ca$^{2+}$ and Mg$^{2+}$ substrate levels were not affected by biochar amendment.

Both the leachate and substrate nutrient analysis showed that application of 25% biochar rate increased PO$_4^-$ concentration in both plant species and PO$_4^-$ concentration in boxwood. Hydrangea leachate K concentration increased after biochar application, while substrate K
Table 2.6. ‘Green Velvet’ boxwood and Pinky Winky® hardy hydrangea substrate nitrate (NO$_3^-$), ammonium (NH$_4^+$), phosphorous (PO$_4^{3-}$), potassium (K$^+$), calcium (Ca$^{2+}$) and magnesium (Mg$^{2+}$) concentration in a pine bark substrate amended with either 0%, 10%, or 25% switchgrass biochar by volume of and a controlled release fertilizer (Osmocote, Everris, Marysville, OH. 18N-2.6P-9.9K at 24 g per container).

<table>
<thead>
<tr>
<th>Species</th>
<th>Biochar rate (%)</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
<th>PO$_4^{3-}$</th>
<th>K$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrangea</td>
<td>0</td>
<td>41.0b$^z$</td>
<td>10.5a</td>
<td>6.0b</td>
<td>79.9a</td>
<td>80.6a</td>
<td>38.9a</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>119.0a</td>
<td>9.9a</td>
<td>8.6b</td>
<td>109.7a</td>
<td>36.6ab</td>
<td>28.2a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>130.4a</td>
<td>9.0a</td>
<td>14.8a</td>
<td>102.7a</td>
<td>23.0b</td>
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</tr>
<tr>
<td>Boxwood</td>
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<td>9.9a</td>
<td>4.8c</td>
<td>60.7b</td>
<td>17.3a</td>
<td>11.9a</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>154.3a</td>
<td>5.8ab</td>
<td>9.7b</td>
<td>89.6b</td>
<td>14.6a</td>
<td>10.8a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>161.3a</td>
<td>2.0b</td>
<td>25.0a</td>
<td>164.0a</td>
<td>8.2a</td>
<td>8.6a</td>
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Significance (P-value)

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<tr>
<th>Species</th>
<th>0.155</th>
<th>0.027</th>
<th>0.013</th>
<th>0.613</th>
<th>&lt;0.0001</th>
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<tbody>
<tr>
<td>Biochar</td>
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<td>0.006</td>
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</tr>
<tr>
<td>Species*biochar</td>
<td>0.776</td>
<td>0.287</td>
<td>0.003</td>
<td>0.052</td>
<td>0.642</td>
<td>0.894</td>
</tr>
</tbody>
</table>

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

concentration was not affected by biochar application.

Similar to our results, Dumroese (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.

### 2.4.5 Plant biomass

There was a significant interaction for final dry weight (Table 2.7). Hydrangea final dry weight was reduced by the 25% biochar amendment, but boxwood final dry weight was not affected 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 cm$^3$·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 2.4). 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 peat moss-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).
2.4.6 **Plant tissue analysis**

There was a significant species and biochar rate interaction in foliar nitrogen concentration (Table 2.7). The 25% biochar amendment increased hydrangea foliar nitrogen compared with 0%. Biochar application increased substrate NO$_3^-$ concentration. However, there was no change in NO$_3^-$ leaching for hydrangea indicating that biochar may have caused increase in NO$_3^-$ 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 NO$_3^-$ concentration. The higher leachate NO$_3^-$ mass in 25% biochar treatment might be due to the lower nutrient requirements of boxwood compared to 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$^{2+}$ 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$^{2+}$ concentration. There was a significant species and biochar rate interaction in foliar Mg$^{2+}$ concentration. Both 10% and 25% biochar amendment caused greater foliar Mg$^{2+}$ levels for hydrangea, but there was no change in substrate and leachate Mg$^{2+}$ concentration. In boxwood biochar application had no influence on foliar and substrate Mg$^{2+}$ concentration but increased Mg$^{2+}$ 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; Basiri Jahromi et al., 2016).
Table 2.7. Final dry weight, foliar nitrogen (N), phosphorus (P), potassium (K\(^+\)), magnesium (Mg\(^{2+}\)), and calcium (Ca\(^{2+}\)) 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 per container).

<table>
<thead>
<tr>
<th>Species</th>
<th>Biochar rate (%)</th>
<th>Final dry weight (g)</th>
<th>N (%)</th>
<th>P</th>
<th>K(^+)</th>
<th>Ca(^{2+})</th>
<th>Mg(^{2+})</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td>----------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Hydrangea</td>
<td>0</td>
<td>56.4a(^z)</td>
<td>2.3b</td>
<td>2795b</td>
<td>7382b</td>
<td>16631a</td>
<td>4553b</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>46.0a</td>
<td>2.4ab</td>
<td>3471a</td>
<td>8882b</td>
<td>15371a</td>
<td>5450a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>27.8a</td>
<td>2.6a</td>
<td>3805a</td>
<td>11198a</td>
<td>12518b</td>
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</tr>
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<td>7416b</td>
<td>9784a</td>
<td>3984a</td>
</tr>
<tr>
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<td>10</td>
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<td>2.8b</td>
<td>3202a</td>
<td>8506b</td>
<td>9605a</td>
<td>3926a</td>
</tr>
<tr>
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<td>3770a</td>
<td>10605a</td>
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Significance (P-value)

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<th>Biochar</th>
<th>Species*biochar</th>
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<td>0.017</td>
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<td>0.602</td>
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<tr>
<td></td>
<td>&lt;0.0001</td>
<td>0.072</td>
<td>0.006</td>
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</table>

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

2.5 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 not affected 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 to 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.

**Acknowledgements**

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Chapter 3
Evaluating on-demand irrigation systems for container-grown woody plants grown in biochar-amended pine bark
3.1 Abstract

Developing management practices that make more efficient use of irrigation is important for improving the sustainability of nursery crop production. Biochar, a byproduct of pyrolysis or gasification, is becoming increasingly available for use in agriculture and can increase the water holding capacity of some growing substrates. Integrating refined irrigation scheduling with a substrate amendment like biochar can improve irrigation efficiency. The objective of this research was to evaluate the impact of biochar and need-based irrigation scheduling on gas exchange, plant water relations, and biomass gain of container-grown *Hydrangea paniculata* ‘Silver Dollar’ with the goal of reducing water use and maintaining or shortening production cycles. Containers were filled with one-year-old pine bark and amended with either 10% or 25% by volume of a hardwood biochar. Plants were automatically irrigated by one of the three irrigation schedules. The irrigation schedules were conventional irrigation, delivering 1.8 cm of water in one event each day, and two on-demand, need-based irrigation schedules. The first was based on the moisture characteristic curve for each of the three substrates developed via the evaporative method. Plants were irrigated when the volumetric water content (VWC) corresponding to a substrate water potential of -10 kPa, generally considered the highest tension for plant available water, was reached. The second was a plant physiology-based irrigation scheduling regime built on the relationship between photosynthesis and substrate moisture content. This schedule actuated irrigation at the VWC that was expected to maintain photosynthesis at 90% of the predicted maximum photosynthetic rate. Scheduling irrigation using a plant physiology or substrate physical properties basis, in combination with biochar, reduced the water requirement for ‘Silver Dollar’ hydrangea without any negative effect on plant dry weight by maintaining sufficient plant water status and gas exchange even just prior to irrigation. The 10% biochar amendment with substrate-based irrigation scheduling yielded the highest water use efficiency and low water use, making this the optimal irrigation scheduling and substrate combination in this study. Automated irrigation systems coupled with a plant physiology or substrate-based actuation and a water retentive substrate amendment have the potential to reduce nursery crops water use.

**Keywords:** Capacitance sensors, irrigation regime, gas exchange, Hyprop system, nursery crops, water-buffering capacity
3.2 Introduction

Inefficient use of irrigation can exacerbate water shortages not only in times of drought, but also during non-drought periods (Caron et al., 2005). Appropriate irrigation scheduling applies the correct amount of water when needed to support plant growth and avoids over- or under-watering (Nemali and Van Iersel, 2006). Integrating precise irrigation application systems with irrigation scheduling can increase water use efficiency in nursery production (Regan, 1999).

Scheduling irrigation based on estimated crop water use results in higher irrigation efficiency compared to relying on periodically adjusting irrigation volume and timing based on perceived water needs (van Iersel et al., 2013). Estimating crop water requirements by measurements derived from the physiological status of the plant (e.g., Cifre et al., 2005; Jones, 2004) can be used as an irrigation-scheduling basis. Irrigation based on the relationship between photosynthesis rate and substrate moisture content has been successfully used to improve crop water use efficiency (Fulcher et al., 2012; Hagen et al., 2014; Nambuthiri et al., 2017). However, visual indicators of physiological response to water deficit such as wilting cannot generally be used to schedule irrigation because plant growth is negatively affected at the water deficits associated with wilting (Jones, 2004; Slatyer, 1967).

Another irrigation scheduling technique, particularly suited for low water availability such as during water restrictions, is one in which irrigation actuation is based on substrate moisture availability derived from a moisture characteristic curve (Fields et al., 2016). Using substrate moisture sensors to implement water potential-based irrigation scheduling that maintains plant-available water in the range of -1 to -10 kPa can conserve water while also avoiding plant water stress (Arguedas Rodriguez, 2009). Recent research suggests further water savings are possible by exploiting the area beyond -10 kPa tension (Fields et al., 2016). Scheduling irrigation based on substrate water status or a calculated crop evapotranspiration model reduced water use without affecting plant growth and quality in comparison with timer-based irrigation (Incrocci et al., 2014).

Using amendments such as biochar can modify the average substrate particle size reducing the proportion of larger-sized components. Such substrate particle size manipulation increases the amount of available water, which can improve irrigation efficiency and plant growth (Caron et al., 2005). Biochar is produced from thermochemical decomposition of organic materials at high temperatures in an oxygen-limited atmosphere (Lehmann and Joseph, 2009). Biochar can improve nutrient use efficiency by increasing cation exchange capacity (CEC),
surface area and water retention of the soil/substrate (Altland and Locke, 2013; Glaser et al., 2002; Lehmann et al., 2006). Biochar also increases nutrient concentration and availability due to the initial nutrient concentration and high CEC (Headlee et al., 2014). These factors, either individually or in combination, can result in higher crop yields in soil systems (Major et al., 2010; Vaccari et al., 2011; Zhang et al., 2011).

Applications of 10% and 25% biochar amendment to pine bark substrate increased water-holding capacity and reduced water consumption of a high water use crop, *Hydrangea paniculata* (Pinky Winky® hardy hydrangea) (Basiri Jahromi et al., 2018). However, reduction of plant biomass in the 25% biochar treatment suggests that sufficient water might not be available to plants in this substrate. The lower irrigation frequency associated with 25% biochar amendment might have resulted in an insufficient portion of the water in each cycle being plant available and eventually exceeding the water buffering capacity (Basiri Jahromi et al., 2018). Further research was required to more fully understand the effect of biochar on plant water availability. This study was initiated to address this problem by using physiological parameters to monitor plant water status under different irrigation schedules that were designed to maximize plant available water. The objective of this research was to evaluate the impact of biochar and two on-demand, need-based irrigation schedules on gas exchange, plant water relations, and biomass gain of container-grown *Hydrangea paniculata* ‘Silver Dollar’ with the goal of reducing water use by exploiting the water buffering capacity while maintaining or shortening production cycles.

3.3 Materials and Methods

3.3.1 Plants and substrates

Rooted stem cuttings were obtained from a commercial nursery (Griffith Propagation Nursery Inc. Watkinsville, GA). ‘Silver Dollar’ hydrangea cuttings were transplanted into 7.6 L containers, filled with one-year-old pine bark and amended with 0%, 10% or 25% biochar by volume. The biochar (Proton Power Inc. Lenoir City, TN) was a mixed hardwood comprised of oak (*Quercus* spp.), hickory (*Carya* spp.) and yellow poplar (*Liriodendron tulipifera*) subjected to fast pyrolysis at ≈1000 °C with chemical and physical properties shown in Table 3.1.
Table 3.1. Chemical and physical properties of a hardwood biochar used as a substrate amendment for container nursery production.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
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<tbody>
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<td></td>
</tr>
<tr>
<td>EC</td>
<td>dS m⁻¹</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>%</td>
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<td></td>
</tr>
<tr>
<td>Nitrate</td>
<td>mg kg⁻¹</td>
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</tr>
<tr>
<td>Ammonia</td>
<td>mg kg⁻¹</td>
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</tr>
<tr>
<td>Phosphorus</td>
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</tr>
<tr>
<td>Potassium</td>
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<table>
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<th>Physical properties</th>
</tr>
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<tbody>
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<tr>
<td>Surface area</td>
</tr>
</tbody>
</table>

The results that are shown in Table 3.1 were obtained from Control Laboratories, Watsonville, CA.

One week after transplanting, all of the plants were top-dressed with 40 g per container of 18N-2.6P-9.9K controlled release fertilizer with micronutrients (Osmocote Classic, Everris, Marysville, OH), which included 10% NH₄-N and 8% NO₃-N. Substrates were also drenched twice with a surfactant (Aquagro L, Aquatrols, Paulsboro, NJ) at a rate of 600 ppm in order to prevent the substrate from becoming hydrophobic.

Substrate physical properties were determined for each substrate using a 15-cm tall porometer (694 cm³ volume), according to Fonteno and Harden (2010) with three replications (Table 3.2). In addition, particle size distribution was determined for three replications of each substrate by passing the substrate through seven sieves (6.30, 2.00, 0.71, 0.50, 0.25, 0.11 mm openings) and a lower catch pan, which was shaken for 5 minutes with a Ro-Tap shaker (Rx-29; W.S. Tyler, Mentor, OH).

### 3.3.2 Model development

Three substrate-specific moisture release curves were developed with the evaporative method to establish the substrate physical properties-based irrigation schedule set points. Moisture characteristic curves were developed using the Hyprop System (UMS, Munich, Germany). Samples and devices were prepared according to Fields et al. (2016). Each sample and device was placed on a scale and connected to a computer with Tensionview software (UMS, Munich, Germany). Water potential from the two tensiometers and total weight were recorded every 10 minutes. Data were fit using HypropFit software (UMS, Munich, Germany) to generate moisture characteristic curves describing the relationship between water potential and VWC.
Set points for the plant physiology-based irrigation schedule were established by determining the relationship between photosynthesis and substrate moisture content. Plants were potted in each substrate (0%, 10%, or 25% biochar by volume) and hand-watered until the roots reached the container sidewall. Just prior to initiating the experiment, plants were hand watered and soaked in water to evenly saturate the substrate, and drained to container capacity. Further irrigation was withheld. Photosynthesis was measured as the substrate dried for 14 days following Fulcher et al. (2012) using an infrared gas analyzer (LI-6400, LI-COR, Lincoln, NE, USA). Photosynthesis measurements were taken at 390 mg·L⁻¹ carbon dioxide (CO₂) and light intensity at 1500 µmol·m⁻²·s⁻¹ on the most fully expanded, recently matured leaf of five plants. Substrate VWC was estimated using capacitance sensors (ECHO-5, Decagon Devices Inc., Pullman, WA) connected to a data logger (CR1000, Campbell Scientific Inc., Logan, UT) and substrate weight was recorded concurrent to photosynthetic measurements. Each probe was calibrated for each of the three substrates. The relationship between photosynthetic rate and VWC of ‘Silver Dollar’ hydrangea plants characterized by a 3 parameter sigmoidal curve (SigmaPlot v 14, San Jose, CA). The experiment was in a complete randomized design with five replications.

3.3.3 Model evaluation

Following model development, model evaluation experiments were initiated. Eight week experiments were initiated on 20 July 2016 and 20 March 2017 at the University of Tennessee North Greenhouse Complex, Knoxville, Tennessee. Plants were hand-watered until the roots reached the container sidewall and just prior to initiating the experiment, plants were hand watered and soaked in water to evenly saturate the substrate and drained to container capacity. Then substrate moisture level was monitored and plants were irrigated by one of the three automatic irrigation schedules. Substrate VWC was estimated using capacitance sensors (ECHO-5, Decagon Devices Inc.) connected to a data logger (CR1000, Campbell Scientific Inc.) with multiplexer (AM16/32, Campbell Scientific Inc.). Each probe was calibrated for each of the three substrates at three moisture levels to determine VWC. Probes were installed halfway between the sidewall and the center of the container, perpendicular to the substrate surface so that the bottom of each probe was 9 cm below the substrate surface. Measurements from five sensors were used per irrigation and biochar rate combination to actuate irrigation for the eight plants in that treatment. A 16-channel relay controller (SDM-CD16AC, Campbell Scientific Inc.) was used to operate solenoid valves. When the average VWC estimated by the five sensors dropped below the irrigation set point, the data logger was programmed to supply power to the valve controlling
irrigation to those containers. Nine independent irrigation zones were constructed with one irrigation line per biochar rate and irrigation schedule combination. Each irrigation line irrigated eight plants with a 10 cm dribble ring (Dramm Corp, Manitowoc, WI) connected to a 3.8 L per hour emitter. Irrigation run time for each treatment was individually calculated based on the lower set points, upper irrigation set points and the flow rate of each line.

The treatments were arranged in a $3 \times 3$ factorial with three substrates (100% pine bark with biochar at 0%, 10%, or 25% by volume) and three irrigation schedules (conventional irrigation, substrate physical properties-based and plant physiology-based). The experiment was a randomized complete block design with eight replications. Data were subjected to analysis of variance using mixed models (SAS v9.4, Cary, NC). Data were pooled across years, as there was no significant effect of experimental year on the measurements.

### 3.3.4 Data collection

Photosynthesis, stomatal conductance, transpiration, and vapor pressure deficit (VPD) were measured with an infrared gas analyzer (LI-6400, LI-COR) at 390 mg·L$^{-1}$ CO$_2$ and light intensity at 1500 µmol·m$^{-2}$·s$^{-1}$ on the most fully expanded, recently matured leaf of the five plants within each irrigation zone that contained capacitance sensors. These measurements were taken between 1 and 2 hours before and after-irrigation and when it was between 10 am and 3 pm to ensure light conditions supported maximum photosynthetic rates. Petiole water potential (hereafter referred to as leaf water potential) of the second most recently matured fully expanded leaf was measured immediately following photosynthetic measurements on five randomly selected plants per irrigation zone using a pressurized chamber (Soil Moisture Equipment Corp., Santa Barbara, CA).

Leachate samples were collected at the beginning (20 July 2016 and 20 March 2017) and the end (15 September 2016 and 15 May 2017) of each experiment using the pour through extraction method (Wright, 1986). Samples were stored in plastic vials, and were kept refrigerated for 48 to 72 hours, then analyzed. At the time of analysis, samples were filtered with a 0.45-µm syringe filter. The filtrate was then poured into 5-mL vials, capped, and analyzed on an ICS 1100 (Ion Chromatography System; Dionex, Bannockburn, IL) for concentrations of nitrate (NO$_3^-$), ammonium (NH$_4^+$), phosphate (PO$_4^{3-}$), and potassium (K$^+$). Electrical conductivity (EC) was measured with a portable EC meter (HI 9811-5, Hanna Instruments, Smithfield, RI, USA) and pH was measured with a pH meter (Denver Instrument, Bohemia, NY).

Time average application rate was calculated by total volume of applied water/time of
production (mL H₂O per h) as described by Fields et al. (2017). Growth index was determined at initiation and termination of the experiment using the formula [(plant width 1 + plant width perpendicular to width 1 + plant height)/3]. For dry weight measurements, the above ground portions of plants were harvested and hand-washed of substrate. Plant shoots and leaves were dried at 55 °C until weight no longer decreased to obtain dry weight at initiation and termination of the experiment. Water use efficiency (WUE) per plant was measured as increase in dry weight (g) per total irrigation volume applied (L) over the eight weeks. After drying, plant leaves and shoots were ground to pass a 1.0-mm screen 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 for analyses was prepared by acid digestion using concentrated nitric acid and analyzed by ICP-OES for phosphorus (P), K⁺, calcium (Ca²⁺), and magnesium (Mg²⁺) concentrations.

3.4 Results

3.4.1 Substrate physical properties

Container capacity increased and air space decreased as the amount of biochar increased. Application of 25% biochar caused a reduction in total porosity and bulk density compared to 0% biochar rate (Table 3.2). However, total porosity is on the upper end of the recommended range (Yeager et al., 2007) in all treatments. Increasing biochar rate to 25% also caused a decrease in large particles and a 96% increase in fine particles (Table 3.2).

3.4.2 Model development

Set points were established to actuate and terminate irrigation based on the moisture characteristic curves. Upper and lower set points for the substrate physical properties-based irrigation schedule were predicated on the generally accepted range of plant available water occurring between -1 kPa and -10 kPa tension (de Boodth and Verdonck, 1972). Irrigation was actuated once the substrate dried to the lower set point of 0.37, 0.34, and 0.34 cm³·cm⁻³ for 0%, 10% and 25% biochar amendment rate, respectively. Upper set points, which terminated irrigation, corresponded to -1 kPa tension and were 0.46, 0.44, 0.49 cm³·cm⁻³ for 0%, 10% and 25% biochar rate, respectively (Figure 3.1). Irrigation was applied once the lower set point was reached and consistently returned the substrate to the upper set points.
Table 3.2. Physical properties of pine bark substrate amended with 0%, 10%, or 25% by volume of hardwood biochar (n=3).

<table>
<thead>
<tr>
<th>Biochar amendment</th>
<th>Container capacity</th>
<th>Air space</th>
<th>Total porosity</th>
<th>Bulk density</th>
<th>Particle size distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(%)</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>g·cm⁻³</td>
<td>X-Large (&gt;6.3 mm)</td>
</tr>
<tr>
<td>0%</td>
<td>57.1c</td>
<td>30.0a</td>
<td>87.1a</td>
<td>0.24a</td>
<td>9.3a</td>
</tr>
<tr>
<td>10%</td>
<td>62.3b</td>
<td>26.0b</td>
<td>88.2a</td>
<td>0.23ab</td>
<td>7.5a</td>
</tr>
<tr>
<td>25%</td>
<td>65.7a</td>
<td>20.4c</td>
<td>86.2b</td>
<td>0.22b</td>
<td>7.2a</td>
</tr>
<tr>
<td>P-value</td>
<td>0.0005</td>
<td>0.0004</td>
<td>0.0167</td>
<td>0.0324</td>
<td>0.7495</td>
</tr>
</tbody>
</table>

*Means within a column followed by the same letter are not significantly different (α=0.05). Substrate physical properties were determined using a 15-cm tall porometer, according to the methods described by Fonteno and Bilderback (1993).

Figure 3.1. Moisture characteristic curves for pine bark with 0% biochar, pine bark with 10% by volume of biochar and pine bark with 25% by volume of biochar measured with the evaporative method using the Hyprop.
The plant physiology-based set points were developed using the sigmoidal relationship between substrate moisture content and crop photosynthetic rate. Irrigation was actuated at the VWC that was calculated to maintain photosynthesis at 90% of the predicted maximum photosynthetic rate as described by Fulcher et al. (2012). The lower set points were 0.25, 0.33 and 0.36 cm\(^3\)·cm\(^{-3}\) for 0%, 10% and 25% biochar rate, respectively (Figure 3.2).

The upper set point for each of the three substrates was the VWC at effective container capacity as determined following saturation and drainage as described in Hagen et al. (2015). Thus, upper set points terminated irrigation when the average probe measurement reached 0.46, 0.47 and 0.58 cm\(^3\)·cm\(^{-3}\) for 0%, 10% and 25% biochar rate, respectively (Figure 3.3). The traditional industry approach to irrigation served as the control, delivering 1.8 cm of water in one daily event.

A= 0% biochar rate under conventional irrigation, B= 10% biochar rate under conventional irrigation, C= 25% biochar rate under conventional irrigation, D= 0% biochar rate under physical properties-based irrigation, E= 10% biochar rate under physical properties-based irrigation, F= 25% biochar rate under physical properties-based irrigation, G= 0% biochar rate under plant physiology-based irrigation, H= 10% biochar rate under plant physiology-based irrigation and I= 25% biochar rate under plant physiology-based irrigation.

### 3.4.3 Gas exchange and plant water potential

Results were similar in both model evaluation experiments in terms of how biochar rate affected plant physiological parameters under the different irrigation systems so data were pooled across years. There was an interaction between biochar rate and irrigation system for photosynthetic rate \((P=0.0486)\), transpiration rate \((P=0.0163)\) and stomatal conductance \((P=0.0006)\). This was caused by increasing photosynthetic rate from 13.6 to 15.1 \(\mu\)mol CO\(_2\) m\(^{-2}\)·s\(^{-1}\), transpiration rate from 3.7 mmol to 4.5 mmol H\(_2\)O m\(^{-2}\)·s\(^{-1}\) and stomatal conductance from 0.25 to 0.37 mmol H\(_2\)O m\(^{-2}\)·s\(^{-1}\) under plant physiology-based irrigation regime as biochar rate went from 0% to 10%. However, photosynthetic rate, transpiration rate and stomatal conductance were similar in 0% and 10% biochar rate under the conventional and the physical properties-based irrigation regimes. The lowest photosynthetic rate (13.6 \(\mu\)mol CO\(_2\) m\(^{-2}\)·s\(^{-1}\)), transpiration rate (3.7 mmol H\(_2\)O m\(^{-2}\)·s\(^{-1}\)), and stomatal conductance (0.25 mmol H\(_2\)O m\(^{-2}\)·s\(^{-1}\)) were in 0% biochar treatment under plant physiology-based irrigation system (Table 3.3).
Figure 3.2. The relationship between photosynthetic rate and volumetric water content (VWC) of ‘Hydrangea paniculata’ ‘Silver Dollar’ plants with 0% biochar, 10% by volume of biochar and 25% by volume of biochar was characterized by a 3 parameter sigmoidal curve.

Photosynthetic rate = \frac{13.9783}{1+\exp\left(-\frac{(VWC - 0.1357)}{0.0672}\right)}, r^2 = 0.59 for 0% biochar.
Photosynthetic rate = \frac{13.1015}{1+\exp\left(-\frac{(VWC - 0.2354)}{0.0278}\right)}, r^2 = 0.55 for 10% biochar.
Photosynthetic rate = \frac{14.0009}{1+\exp\left(-\frac{(VWC - 0.2796)}{0.0507}\right)}, r^2 = 0.64 for 25% biochar.
Irrigation set points corresponded to 90% of maximum predicted photosynthetic rate and were 0.25, 0.33 and 0.36 cm$^3$·cm$^{-3}$ for 0%, 10% and 25% biochar amendment rate, respectively. Set points indicated by vertical bar (n=5).
Figure 3.3. Irrigation cycles of the six on-demand irrigation schedules in the third week; irrigation was triggered when the average probe reading reached the lower set point and remained on the time duration necessary to return the container to the upper set point.
Table 3.3. Photosynthesis and gas exchange measurements before irrigation for *Hydrangea paniculata* ‘Silver Dollar’ grown in substrates amended with 0%, 10%, or 25% by volume of hardwood biochar under three irrigation schedules (conventional irrigation, substrate physical properties-based and plant physiology-based irrigation systems (n=5) over 8 weeks.

<table>
<thead>
<tr>
<th>Irrigation System</th>
<th>Biochar Rate (%)</th>
<th>Photosynthetic Rates (μmol CO₂ m⁻² s⁻¹)</th>
<th>Transpiration Rates (mmol H₂O m⁻² s⁻¹)</th>
<th>Stomatal Conductance (mol H₂O m⁻² s⁻¹)</th>
<th>Vapor Pressure Deficit (kPa)</th>
<th>Leaf Petiole Water Potential (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>0</td>
<td>15.1ab&lt;sup&gt;z&lt;/sup&gt;</td>
<td>4.7ab</td>
<td>0.33ab</td>
<td>1.5bc</td>
<td>-0.33&lt;sup&gt;as&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15.0b</td>
<td>4.4ab</td>
<td>0.28bc</td>
<td>1.5bc</td>
<td>-0.32</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>15.2ab</td>
<td>4.9a</td>
<td>0.35a</td>
<td>1.5bc</td>
<td>-0.39</td>
</tr>
<tr>
<td>Substrate Physical Properties</td>
<td>0</td>
<td>15.4ab</td>
<td>4.4b</td>
<td>0.33ab</td>
<td>1.4c</td>
<td>-0.33</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15.2ab</td>
<td>4.7ab</td>
<td>0.32ab</td>
<td>1.6ab</td>
<td>-0.33</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>15.8a</td>
<td>4.8ab</td>
<td>0.32ab</td>
<td>1.6a</td>
<td>-0.34</td>
</tr>
<tr>
<td>Plant Physiology</td>
<td>0</td>
<td>13.6c</td>
<td>3.7c</td>
<td>0.25c</td>
<td>1.6ab</td>
<td>-0.33</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15.1ab</td>
<td>4.5ab</td>
<td>0.37a</td>
<td>1.4c</td>
<td>-0.32</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>15.0ab</td>
<td>4.7ab</td>
<td>0.36a</td>
<td>1.5bc</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

*P*-value

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochar</td>
<td>0.0474</td>
<td>0.0012</td>
<td>0.0939</td>
<td>0.7781</td>
<td>0.0393</td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>0.0023</td>
<td>0.0269</td>
<td>0.9199</td>
<td>0.1568</td>
<td>0.6603</td>
<td></td>
</tr>
<tr>
<td>Biochar*irrigation</td>
<td>0.0486</td>
<td>0.0163</td>
<td>0.0006</td>
<td>0.0082</td>
<td>0.1939</td>
<td></td>
</tr>
</tbody>
</table>

<sup>z</sup>Means within a column followed by the same letter were not significantly different (α=0.05).

<sup>as</sup>Values in same column followed by the ns letters are not significantly different (α=0.05).
There was an interaction \((P=0.0082)\) between biochar rate and irrigation system with respect to VPD. This interaction was likely the result of increasing VPD from 1.4 to 1.6 kPa under physical properties-based irrigation system as biochar rate went from 0 to 10%, while there was no difference from biochar rate in conventional irrigation. There was no interaction between biochar rate and irrigation system for leaf water potential \((P=0.1939)\), although biochar main effect was significant \((P=0.0393)\) and leaf water potential was highest in 25% biochar rate (Table 3.3).

The after-irrigation photosynthetic rate and stomatal conductivity were not different with respect to biochar rate or irrigation schedule (Table 3.4). All of the irrigation schedules had the same pattern of change over the week, thus there was no interaction between irrigation schedule and week in photosynthetic rate \((P=0.3090)\) and stomatal conductivity \((P=0.0817)\).

Table 3.4. Photosynthesis and gas exchange measurements after irrigation for Hydrangea paniculata ‘Silver Dollar’ grown in substrates amended with 0%, 10%, or 25% by volume of hardwood biochar under three irrigation schedules (conventional irrigation, substrate physical properties-based and plant physiology-based irrigation systems \((n=5)\) over 8 weeks.

<table>
<thead>
<tr>
<th>Week</th>
<th>Photosynthetic rates (µmol CO(_2) m(^{-2}) s(^{-1}))</th>
<th>Transpiration rates (mmol H(_2)O m(^{-2}) s(^{-1}))</th>
<th>Stomatal conductance (mol H(_2)O m(^{-2}) s(^{-1}))</th>
<th>Vapor pressure deficit (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.5bc(^2)</td>
<td>4.4c</td>
<td>0.30f</td>
<td>1.5bcd</td>
</tr>
<tr>
<td>2</td>
<td>15.6bc</td>
<td>5.1bc</td>
<td>0.33ef</td>
<td>1.6abc</td>
</tr>
<tr>
<td>3</td>
<td>14.8c</td>
<td>5.9a</td>
<td>0.34def</td>
<td>1.8a</td>
</tr>
<tr>
<td>4</td>
<td>16.9a</td>
<td>5.8a</td>
<td>0.40bcd</td>
<td>1.6ab</td>
</tr>
<tr>
<td>5</td>
<td>17.1a</td>
<td>5.3b</td>
<td>0.39cde</td>
<td>1.5bcd</td>
</tr>
<tr>
<td>6</td>
<td>16.6a</td>
<td>5.8a</td>
<td>0.44ab</td>
<td>1.4d</td>
</tr>
<tr>
<td>7</td>
<td>16.6ab</td>
<td>5.4ab</td>
<td>0.41abc</td>
<td>1.5cd</td>
</tr>
<tr>
<td>8</td>
<td>17.1a</td>
<td>5.2b</td>
<td>0.46a</td>
<td>1.3e</td>
</tr>
</tbody>
</table>

\(^{2}\)Means within a column followed by the same letter were not significantly different \((\alpha=0.05)\)
Photosynthetic rate, transpiration and stomatal conductance ultimately, over time, increased regardless of substrate or irrigation schedules. The irrigation schedule began to affect the after-irrigation photosynthetic rate and stomatal conductivity beginning week four. There was an interaction between irrigation schedule and week in after-irrigation transpiration rate \((P=0.0004)\) and VPD \((P=0.0021)\). The irrigation schedule began to affect after-irrigation transpiration from week two. An interaction was caused by increasing VPD from the first week to the third week and then decreasing over the time for the substrate physical-properties and conventional irrigation while the plant physiology-based irrigation was not different (Table 3.4).

### 3.4.4 Total water use, water use efficiency, final growth index and final dry weight

Total water use was the same in conventional irrigation (35 L), regardless of biochar amendment rate, as all of the treatments were irrigated with 1.8 cm of water every day. During the 8 weeks, total water use was lower in 0% biochar treatment irrigated by physical properties-based systems (28 L) and/or plant physiology-based (31.5 L) than the traditional industry irrigation practice. Total irrigation applied per container was reduced by 21% and 30% in 10% and 25% biochar rate, respectively, under physical properties-based irrigation and by 40% and 16% in 10% and 25% biochar rate, respectively, under plant physiology-based irrigation system. Time average application rate (data not presented) followed the same pattern as total irrigation applied. Increasing biochar application rate increased WUE under all of the irrigation systems \((P=0.0002)\) (Table 3.5).

Growth index was not affected by biochar rate \((P=0.3248)\). Growth index was highest for the plants under conventional irrigation, which was similar to the plants under substrate physical properties-based irrigation schedule \((P=0.0177)\).

Shoot dry weight was greatest in plants amended with 25% biochar rate \((P=0.0147)\). There was no difference between 0% and 10% biochar rate. Plant dry weight was not affected by irrigation system \((P=0.0817)\) (Table 3.5).
Table 3.5. Total irrigation applied per container, water use efficiency, final growth index and final dry weight for *Hydrangea paniculata* ‘Silver Dollar’ plants in substrates amended with 0%, 10%, or 25% by volume of hardwood biochar (n=8) over 8 weeks.

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>Biochar rate (%)</th>
<th>Total irrigation applied per container (L)</th>
<th>Water use efficiency (g·L⁻¹)</th>
<th>Final growth index (cm)</th>
<th>Final dry weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>2.1ns</td>
<td>55.6ns</td>
<td>87.3ns</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>35</td>
<td>2.6</td>
<td>58.3</td>
<td>86.2</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>35</td>
<td>2.3</td>
<td>65.6</td>
<td>92.1</td>
<td></td>
</tr>
<tr>
<td>Substrate physical properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>28</td>
<td>1.7</td>
<td>54.9</td>
<td>74.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>27.5</td>
<td>3.6</td>
<td>55.0</td>
<td>74.6</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>24.5</td>
<td>2.1</td>
<td>56.2</td>
<td>86.5</td>
<td></td>
</tr>
<tr>
<td>Plant physiology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>31.5</td>
<td>1.9</td>
<td>52.6</td>
<td>65.8</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>21</td>
<td>2.9</td>
<td>54.3</td>
<td>77.6</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>29.5</td>
<td>3.2</td>
<td>51.9</td>
<td>91.9</td>
<td></td>
</tr>
</tbody>
</table>

*P*-value

<table>
<thead>
<tr>
<th></th>
<th>Biochar</th>
<th>Irrigation</th>
<th>Biochar*irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochar</td>
<td>-</td>
<td>0.0002</td>
<td>0.3248</td>
</tr>
<tr>
<td>Irrigation</td>
<td>-</td>
<td>0.2676</td>
<td>0.0177</td>
</tr>
<tr>
<td>Biochar*irrigation</td>
<td>-</td>
<td>0.0638</td>
<td>0.3375</td>
</tr>
</tbody>
</table>

*ANOVA not conducted because there was only one solenoid valve for biochar*irrigation combination.

*Values within a column followed by the ns letters are not significantly different (α=0.05).

Water use efficiency per plant was estimated as [increase in dry weight over the course of the experiment (g)/total irrigation water volume applied (L)].
3.4.5 Substrate solution and foliar analysis

Substrate solution pH, EC and nutrient concentration were not affected by irrigation scheduling (Table 3.6). Biochar application rate affected substrate solution pH ($P<0.0001$). The 25% biochar-amended substrate resulted in the highest substrate solution pH with a 1.4 pH unit increase compared to 0% biochar rate. Substrate solution EC was not different in either biochar rate ($P=0.0942$) (Table 3.6). Additions of biochar resulted in higher NH$_4^+$ ($P=0.0151$) and K$^+$ ($P<0.0001$) concentration. The 25% biochar rate had 83% higher NH$_4^+$ and 175% higher K$^+$ concentration in leachate in comparison to 0% biochar amendment rate. However, NO$_3^-$, PO$_4^{3-}$, Ca$^{2+}$ and Mg$^{2+}$ concentration were not affected by biochar amendment rate or irrigation system (Table 3.6).

Foliar concentration of N, P and Ca$^{2+}$ were not affected by biochar rate ($P>0.4273$) or irrigation system. Foliar K$^+$ concentration increased with increasing biochar application rate ($P=0.0608$). The Mg$^{2+}$ concentration was higher in 0% and 10% biochar rate compared to 25% biochar application rate ($P<0.0001$) (Table 3.7).

### Table 3.6. Hydrangea paniculata ‘Silver Dollar’ substrate solution pH, electrical conductivity (EC), ammonium (NH$_4^+$), potassium (K$^+$), nitrate (NO$_3^-$), phosphorus (PO$_4^{3-}$), calcium (Ca$^{2+}$) and magnesium (Mg$^{2+}$) concentration in a pine bark substrate amended with either 0%, 10%, or 25% by volume of hardwood biochar (n=5) and a controlled release fertilizer (Osmocote, Everris, Marysville, OH. 18N-2.6P-9.9K at 40 g per container).

<table>
<thead>
<tr>
<th>Biochar rate (%)</th>
<th>pH</th>
<th>EC dS m$^{-1}$</th>
<th>NH$_4^+$ mg L$^{-1}$</th>
<th>K$^+$ mg L$^{-1}$</th>
<th>NO$_3^-$ mg L$^{-1}$</th>
<th>PO$_4^{3-}$ mg L$^{-1}$</th>
<th>Ca$^{2+}$ mg L$^{-1}$</th>
<th>Mg$^{2+}$ mg L$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.0c</td>
<td>2.0ns</td>
<td>18.5b</td>
<td>97.6b</td>
<td>320.1rn</td>
<td>2.6ns</td>
<td>5.1rn</td>
<td>3.2rn</td>
</tr>
<tr>
<td>10</td>
<td>5.7b</td>
<td>3.3</td>
<td>30.3a</td>
<td>206.2a</td>
<td>396.8</td>
<td>3.0</td>
<td>5.4</td>
<td>3.2</td>
</tr>
<tr>
<td>25</td>
<td>6.4a</td>
<td>1.9</td>
<td>33.8a</td>
<td>268.3a</td>
<td>344.2</td>
<td>2.8</td>
<td>5.4</td>
<td>3.5</td>
</tr>
<tr>
<td>P-value</td>
<td>&lt;0.0001</td>
<td>0.0942</td>
<td>0.0151</td>
<td>~0.0001</td>
<td>0.4957</td>
<td>0.4985</td>
<td>0.1265</td>
<td>0.3201</td>
</tr>
</tbody>
</table>

*Means within a column followed by the same letter are not significantly different ($\alpha=0.05$).

**Values within a column followed by ns are not significantly different ($\alpha=0.05$).

Samples were collected at the end (15 September 2016 and 15 May 2017) of the experiment with the pour through extraction method.
Table 3.7. Foliar nitrogen (N), phosphorus (P), calcium (Ca\(^{2+}\)), potassium (K\(^{+}\)), and magnesium (Mg\(^{2+}\)) concentration of Hydrangea paniculata ‘Silver Dollar’ grown in a pine bark substrate amended with either 0%, 10%, or 25% by volume of hardwood biochar (n=5) and a controlled release fertilizer (Osmocote 18N-2.6P-9.9K at 40 g per container).

<table>
<thead>
<tr>
<th>Biochar rate (%)</th>
<th>N (%)</th>
<th>P mg·kg(^{-1})</th>
<th>Ca(^{2+}) mg·kg(^{-1})</th>
<th>K(^{+}) mg·kg(^{-1})</th>
<th>Mg(^{2+}) mg·kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.0(^m)</td>
<td>128.7(^m)</td>
<td>915.1(^m)</td>
<td>462.3c(^c)</td>
<td>125.2a</td>
</tr>
<tr>
<td>10</td>
<td>3.0</td>
<td>133.4</td>
<td>889.1</td>
<td>507.6b</td>
<td>125.5a</td>
</tr>
<tr>
<td>25</td>
<td>2.9</td>
<td>129.9</td>
<td>882.6</td>
<td>564.5a</td>
<td>102.9b</td>
</tr>
<tr>
<td>P-value</td>
<td>0.4273</td>
<td>0.6744</td>
<td>0.8035</td>
<td>0.0608</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

\(^m\)Means within a column followed by the same letter are not significantly different (α=0.05).
\(^c\)Values within a column followed by the ns letters are not significantly different (α=0.05).

3.5 Discussion

Pine bark alone had the highest air space with a lowest percentage of fine particles. The fine particles of the biochar likely nested within the larger pores of the pine bark substrate, causing the increase in container capacity and decrease in air space (Table 3.2). Changes in container capacity and air space are consistent with other published studies (Altland and Locke, 2017; Bi and Evans, 2009; Vaughn et al., 2013). The biochar used in this study had lower bulk density (0.10 g·cm\(^{-3}\)) compared to the pine bark substrate (0.24 g·cm\(^{-3}\)). A composite material’s bulk density can be predicted by the weighted average of the substrate components’ bulk density (Altland and Locke, 2013; Pokorny et al., 1986). Increasing percentages of lower-density materials cause a reduction in 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).

Plant gas exchange parameters were relatively high when measured before irrigation events, which suggests each system maintained a sufficiently high plant water status between irrigation events using each irrigation scheduling treatment (Table 3.3; Fig 3.2). High gas exchange parameters both before (Table 3.3) and after-irrigation (Table 3.4) and leaf water potential indicated the plants were not stressed, and thus demonstrated on-demand irrigation schedules were an effective approach for irrigation.

After-irrigation plant gas exchange parameters were not depressed by irrigation systems, but in fact, increased over time. In this study, plants experienced low VWC prior to irrigation but not for an extended period of time so as to cause a drought response. Severity and
duration affect crop’s physiological responses to drought (Kim, 2011). For example, stomatal conductance and photosynthesis acclimation under mild drought were observed in petunia (Petunia hybrida) and loblolly pine (Pinus taeda). However, less or no acclimation was observed under severe drought (Kim, 2011; Watkinson et al., 2003). Also van Iersel and Dove (2005) reported that whole-plant photosynthesis was stable in abelia (Abelia grandiflora) and hydrangea (Hydrangea macrophylla) as VWC reduced from 0.25 cm$^3$·cm$^{-3}$ to 0.15 cm$^3$·cm$^{-3}$ in a bark-based substrate. However, pronounced reduction in photosynthesis was observed at lower VWC and photosynthesis did not recover to pre-drought levels following irrigation.

Plants had lower total water use under plant physiology-based and physical properties-based irrigation system compared to the conventional irrigation regardless of substrate (Table 3.5). Therefore, irrigation should be based upon an estimate of crop or substrate water status rather than static irrigation schedules in order to reduce water use. The 10% biochar-amended substrate under physical properties-based irrigation system yielded the highest WUE and low water use, which makes it a promising irrigation scheduling and substrate combination. Similar to our results, Beeson et al. (2004), Regan (1999) and van Iersel et al. (2013) reported that proper irrigation scheduling increased water use efficiency. And like previous research, irrigating on a physiological basis improved irrigation efficiency (Fulcher et al., 2012; Hagen et al., 2014; Nambuthiri et al., 2017).

The reduction of total irrigation applications seen in 10% and 25% biochar treatments, especially as the season progressed and as the crop size and atmospheric demand increased, did not negatively affect gas exchange metrics or leaf water potential, which suggests biochar not only increased substrate water holding capacity but also plant available water. The lowest photosynthetic rate, transpiration rate, and stomatal conductance were in 0% biochar treatment under plant physiology-based irrigation system, which had relatively high values but significantly lower than other treatments (Table 3.3). This is likely due to its lower irrigation set point (0.25 cm$^3$·cm$^{-3}$), which would cause the VWC to be lower at the measurement time compared to other treatments and possibly exceed the water buffering capacity. In another study of plant physiology-based irrigation scheduling, greater gas exchange and leaf water potential were reported for plants in the wetter irrigation treatments compared to the 0.22 cm$^3$·cm$^{-3}$ irrigation set point (Fulcher et al., 2012). The generally accepted lowest VWC with plant available water in soilless substrates is 0.20 cm$^3$·cm$^{-3}$ (Drzal et al., 1999; Milks et al., 1989), although this value varies among different substrates and species. For example, Hydrangea macrophylla ‘Fasan’ (0.28 cm$^3$·cm$^{-3}$) is less capable of extracting water from a drying substrate than Gardenia
jasminoides ‘Radicans’ (0.20 cm$^3$·cm$^{-3}$) (O’Meara et al., 2014).

The substrate physical properties-based irrigation scheduling likely maintained matric potential in the range of plant-available water. Readily available water (-1 to -10 kPa) includes easily available water (-1 to -5kPa) and water buffering capacity (-5 to -10 kPa) (de Boodth and Verdonck, 1972). Plants can exploit the water buffering capacity but we hypothesize that treatments do not exceed it during irrigation cycles in the substrate physical properties-based irrigation, which provides an ideal opportunity to maintain crop growth while conserving water. The 0% biochar rate under plant physiological-based irrigation had the lowest irrigation set point (0.25 cm$^3$·cm$^{-3}$) compared to other treatments. Substrate in this treatment may dry below the water-buffering capacity, which would explain the low plant dry weight. Plant biomass metrics did not decrease correspondingly with decreases in photosynthetic rates except for the 0% biochar rate under plant physiological-based irrigation. In general, shoot dry weight were similar under different irrigation schedules and greater in 25% biochar rate. Results were the same as a previous study that reported a plant physiology-based irrigation schedule with set point of 0.33 cm$^3$·cm$^{-3}$ reduced water use with no negative effect on oakleaf hydrangea (Hydrangea quercifolia ‘Alice’) and slender deutzia (Deutzia gracilis) photosynthetic rate or on biomass compared to daily water use irrigation system (Hagen et al., 2014; Nambuthiri et al., 2017). Plant growth is more dependent on changes in water relations than photosynthetic rate (Taiz and Zeiger, 2006). By maintaining photosynthetic rate at 90% or greater of the maximum rate, growth was not reduced but substantial water savings could be achieved.

Biochar application increased substrate solution pH but did not affect EC. Substrate solution pH, EC and nutrient concentration were not affected by irrigation schedule (Table 3.6). Likewise Incrocci et al. (2014) found that substrate water status and evapotranspiration-based irrigation scheduling did not affect leachate nutrient, EC and pH compared to timer controlled irrigation. Leachate EC levels in all of the treatments were in the recommended range of 1.0 to 3.5 dS·m$^{-1}$ for greenhouse crops as measured by the pour-through method (Cavins et al., 2000), but higher than the recommended range of 0.5 to 1.0 dS·m$^{-1}$ for container substrate via pour through extraction method (Yeager et al., 2007). Addition of biochar has increased soil pH in acidic soils, as biochar tends to have a neutral to alkaline pH, contingent upon feedstock type, soil type and application rate (Jeffery et al., 2011). An increase in pH was also reported in other biochar amended soilless substrates (Conversa et al., 2015; Kaudal et al., 2016).

Biochar amended at 25% increased NH$_4^+$ and K$^+$ in substrate solution compared to non-amended pine bark (Table 3.6) and foliar K$^+$ increased with increasing biochar amendment in
containers (Table 3.6) indicating biochar was a source of K⁺ for the crops. Similarly, Vaughn (2013) reported that wood biochar had low levels of NO₃⁻, acceptable levels of P (between 3 and 5 mg·kg⁻¹) and Ca²⁺, and high levels of K⁺. In another study, application of 10% gasified rice hull biochar increased K⁺ concentration in leachate compared to 0% or 1% biochar rate, and similar NO₃⁻ concentrations were observed across all treatments (Altland and Locke, 2013). Application of up to 25% switchgrass biochar to sand-based substrate increased K released into pore water (Brockhoff et al., 2010). A meta-analysis of 114 studies concluded that addition of biochar to mineral soils caused an increase in plant tissue K concentration but did not affect plant tissue N and P concentration (Biederman and Harpole, 2013). Biochar may be a more important source of K in soilless substrate (Altland and Locke, 2013). As the effect of biochar depends on its chemical and physical properties, which are derived from feedstock type, the production conditions, and the ecosystem or cropping system (Sohi et al, 2009), different nutrient concentration could occur following biochar application. Biochar products produced from different feedstocks may have different chemical properties even under the same manufacturing process (Evans et al. 2017). Thus, biochar amendments could be produced and prescribed based on meeting the nutrient needs of a specific crop.

### 3.6 Conclusion

This research demonstrated that improvements to status quo nursery irrigation can be achieved by adopting substrate moisture probe technology to actuate novel on-demand irrigation schedules and by using a moisture retentive substrate amendment. Two different on-demand irrigation schedules that apply the appropriate amount of water when needed as determined by plant physiological status or substrate physical properties, reduced water use over the traditional practice of applying 1.8 cm of water per day in all of the treatments. These on-demand irrigation schedules reduced water use without a negative effect on plant dry weight by maintaining sufficient plant water status and gas exchange even just prior to irrigation, the driest point in the irrigation cycle. However, the very low set point in 0% biochar rate under plant physiology-based irrigation likely exceeded the water buffering capacity. The 10% biochar-amended substrate with a substrate-based irrigation schedule yielded the highest WUE and high water saving, making it a promising irrigation scheduling and substrate combination. Biochar provided a source of K by increasing K concentration in substrate solution and in plant foliage. Future work should focus on maximizing the plant biomass metrics by maintaining high plant water status and gas exchange without a negative effect on plant biomass metrics.
Acknowledgements

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3.7 References


Chapter 4
Evaluating on-demand irrigation systems for container-grown woody plants grown in biochar-amended pine bark
This chapter is a reformatted version of a paper, by the same name, accepted in the HortScience journal 53(12): 1891-1896 by Nastaran Basiri Jahromi, Amy Fulcher, Forbes Walker, James Altland, Wesley Wright and Neal Eash.

4.1 Abstract

Controlling irrigation using timers or manually operated systems are the most common irrigation scheduling methods in outdoor container production systems. Improving irrigation efficiency can be achieved by scheduling irrigation based on plant water needs and the appropriate use of sensors rather than relying on periodically adjusting irrigation volume based on perceived water needs. Substrate amendments such as biochar, a carbon-rich by-product of pyrolysis or gasification, can increase the amount of available water and improve irrigation efficiency and plant growth. Previous work examined two on-demand irrigation schedules in controlled indoor (greenhouse) environments. The goal of this study was to evaluate the impact of these on-demand irrigation schedules and hardwood biochar on water use and biomass gain of container-grown Hydrangea paniculata ‘Silver Dollar’ in a typical outdoor nursery production environment. Eighteen independently controlled irrigation zones were designed to test three irrigation schedules on ‘Silver Dollar’ hydrangea grown in pine bark amended with 0% or 25% hardwood biochar. The three irrigation schedules were conventional irrigation and two on-demand schedules, which were based on substrate physical properties or plant physiology. The conventional irrigation delivered 1.8 cm of water in one event each day. The substrate-based irrigation scheduling was based on the soilless substrate moisture characteristic curve, applying water whenever the substrate water content decreased to the driest point at which there was plant available water, or -10 kPa. The plant-based irrigation schedule was based on a specific substrate moisture content derived from a previously-defined relationship between substrate moisture content and photosynthetic rate, maintaining the volumetric water content (VWC) to support photosynthesis at 90% of the maximum predicted photosynthetic rate. Total water use for the substrate-based irrigation was the same as for the conventional system, while the plant-based system was significantly lower. However, plant dry weight was 22% and 15% greater, water use efficiency (WUE) was 40% and 30% greater, and total leachate volume was 25% and 30% lower for the substrate-based and plant-based irrigation scheduling systems, respectively, than for the conventional irrigation. The 25% biochar amendment rate reduced leachate volume per irrigation event and leaching fraction but did not affect total water use nor plant dry weight. This research demonstrated that on-demand irrigation scheduling with plant-based or substrate-based could be
an effective approach to increase WUE for container-grown nursery crops without negatively affecting plant growth.

**Keywords:** Automatic irrigation system, nursery crops, overhead irrigation, plant-based irrigation, substrate-based irrigation

### 4.2 Introduction

Overhead irrigation controlled by timers or manually operated systems are the most common irrigation methods for container nursery production systems. Using a fixed irrigation rate in a timer-based or manual system can result in over- or under-watering (Warsaw et al., 2009), which might cause an increase in crop vulnerability to disease (Chappell et al., 2013), a decrease in nursery crop growth due to human error (Belayneh et al., 2013; Million et al., 2007; Warsaw et al., 2009; Welsh and Zajicek, 1993), and/or an increase in leachate volume which can cause an increase in nutrient losses. Improving irrigation efficiency can be achieved by scheduling irrigation with the appropriate use of sensors rather than relying on periodically adjusting irrigation volume based on plant or substrate visual appearance (van Iersel et al., 2013). Overhead irrigation generally has an application efficiency (amount of water retained in the container / total water applied) of about 25% to 37%, so a demand-based irrigation system reduced the overhead irrigation water loss by reducing the frequency of irrigation (Beeson, 2006).

Soil and substrate volumetric water content measurement or use of models to predict crop water use can both be used as tools for plant-demand based irrigation scheduling (e.g., Bauerle et al., 2002; Kim et al., 2011). Determining the correct substrate moisture content at which to irrigate can be done in one of two ways. The simplest method (hereafter called the “substrate-based” method) is to assume a range of plant available water tensions, usually defined as -1 kPa and -10 kPa (Arguedas-Rodriguez, 2009), though this can be extended beyond -10 kPa tension to achieve greater water savings (Fields et al., 2016). A more recently-established method of predicting crop water use by plant physiological status (Cifre et al., 2005; Jones, 2004) can be based on the relationship between photosynthetic rate and substrate moisture content before the plant photosynthesis rate is reduced by water stress (Fulcher et al., 2012; Hagen et al., 2014; Nambuthiri et al., 2017). This method will hereafter be termed the “plant-based” approach. Using either of these approaches, the on-demand irrigation systems schedule water application based on substrate moisture measurements.

In addition to examining the water and crop effects of irrigation scheduling techniques, this study also addressed the use of substrate amendments. Amendments such as biochar, a
carbon-rich by-product of pyrolysis, can reduce substrate pore size by nesting between larger particles of pine bark and providing greater water-holding capacity. This reduction in substrate pore size has been demonstrated to increase the amount of available water and improve irrigation efficiency and plant growth (Caron et al., 2005). Biochar improves soil fertility in the long term by changing soil physiochemical properties and can act as a fertilizer itself (Glaser et al., 2002; Lehmann et al., 2006) since the concentration of nutrients in biochar products are higher than the feedstock (raw material) (Altland and Boldt, 2018; Judd, 2016). Biochar products vary widely in mineral element concentration. The reason may be due to biochar being produced from a wide range of biomass material which may affect the final product characteristics. Biochar products produced from different feedstocks can have different chemical properties even using the same manufacturing process (Evans et al. 2017).

A previous study developed and evaluated two on-demand, need-based irrigation scheduling systems in two consecutive seasons in a greenhouse (Basiri Jahromi et al., 2017). These systems were based on plant physiology (plant-based) and substrate physical properties (substrate-based), as described above. The current study was an outdoor experiment established to validate the models in an outdoor production environment using more commonly-used overhead irrigation system rather than the micro-irrigation used in the greenhouse experiment. The goal of this study was to evaluate the impact of on-demand irrigation scheduling and hardwood biochar amendment on plant water use and biomass gain of container-grown *Hydrangea paniculata* ‘Silver Dollar’ grown outdoors.

### 4.3 Material and Methods

The experiment was initiated by filling 7.6 L plastic containers with aged pine bark amended with 0% or 25% biochar by volume. The biochar (Proton Power Inc. Lenoir City, TN) was a mixed hardwood comprised of oak (*Quercus* spp.), hickory (*Carya* spp.), and yellow poplar (*Liriodendron tulipifera*) subjected to fast pyrolysis at \( \approx 1000 \) °C with chemical and physical properties shown in Table 4.1. ‘Silver Dollar’ hydrangea rooted cuttings (Griffith Propagation Nursery Inc. Watkinsville, GA) were transplanted into the containers on 15 July 2016 and 5 May 2017.
Table 4.1. Chemical and physical properties of the hardwood biochar used as a substrate amendment for container nursery production.  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>10.5</td>
</tr>
<tr>
<td>EC</td>
<td>dS m⁻¹</td>
<td>4.6</td>
</tr>
<tr>
<td>Carbon</td>
<td>%</td>
<td>88.6</td>
</tr>
<tr>
<td>Nitrate</td>
<td>mg kg⁻¹</td>
<td>0.8</td>
</tr>
<tr>
<td>Ammonia</td>
<td>mg kg⁻¹</td>
<td>14.5</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>%</td>
<td>0.1</td>
</tr>
<tr>
<td>Potassium</td>
<td>%</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Physical properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density</td>
<td>g cm⁻¹</td>
<td>0.1</td>
</tr>
<tr>
<td>Surface area</td>
<td>m² g⁻¹</td>
<td>366</td>
</tr>
</tbody>
</table>

*The results shown in Table 4.1 were obtained from Control Laboratories, Watsonville, CA.*

The plants were top-dressed with controlled release fertilizer (18N-2.6P-9.9K) at a rate of 40 g per container (Osmocote Classic, Everris, Marysville, OH) one week after transplanting. A wetting agent (Aquagro L, Aquatrols, Paulsboro, NJ) was applied as a drench of 600 mg·L⁻¹ to ensure even wetting of the substrate. Plants were hand watered until the roots reached the container sidewall. Just prior to initiating the experiment, the containers were soaked in water once to evenly saturate the substrate and then drained to container capacity.

Treatments were arranged in a 2×3 factorial with two substrates (100% pine bark amended with biochar at 0% or 25% by volume) and three irrigation schedules (conventional irrigation, substrate-based, and plant-based irrigation system). The experiment was arranged in a randomized complete block design with three replications and three subsamples in the 2016 experiment and eight subsamples in the 2017 experiment. All data were analyzed using mixed models analysis of variance (SAS v9.4, Cary, NC). Data taken in both years was pooled, as early analysis found no significant effect of experimental year on the measurements.

Substrate physical properties were determined for each substrate using a 15-cm tall porometer (694 cm³ volume), according to Fonteno and Harden (2010), with three replications for each container (Table 4.2). In addition, particle size distribution was determined for three replications of each substrate by passing the substrate through seven sieves (6.30, 2.00, 0.71, 0.50, 0.25, 0.11 mm openings) and a lower catch pan shaken for 5 minutes with a Ro-Tap shaker (Rx-29; W.S. Tyler, Mentor, OH).

Outdoor experiments were initiated on 15 Aug. 2016 and 15 June 2017 at the University
of Tennessee, Knoxville, TN. Square irrigation zones of 135 cm by 135 cm were delineated by a grid of 1.9 cm diameter polyvinyl chloride pipe with 220 cm space between irrigation zones. Irrigation was applied to each zone by four overlapping sprinklers, each providing 5.5 L·h⁻¹ (Toro® 570 Shrub Spray, The Toro Co., Riverside, CA). The sprinklers were installed on 1.3 cm diameter risers at a height of 66 cm above ground level. Each zone utilized a single irrigation scheduling technique. Because the irrigation system was replicated as well, three replicate primary containers for a specific irrigation x biochar treatment were placed in the center of the zone. In the 2017 study these were augmented by an additional five supplementary containers not used for the water measurements but used for the biomass estimates. In 2017, these were in turn surrounded by an additional 8 border containers to minimize edge effects. Since each zone represented a single replicate of a unique irrigation x biochar treatment combination, and there were three zone replicates, there were a total of 18 irrigation zones.

The control irrigation treatment was the traditional industry of delivering 1.8 cm of water in one daily application. The on-demand substrate-based irrigation treatment was based on soilless substrate moisture characteristic curves developed using the evaporative method and the Hyprop system (UMS, Munich, Germany) (Basiri Jahromi et al., 2017). The lower set points (for irrigation to be actuated) corresponded to the -10 kPa tension and upper set points (for irrigation to be turned off) corresponded to -1 kPa tension. The lower set points corresponded to VWC values of 0.37 and 0.34 cm³·cm⁻³ for 0% and 25% biochar amendment treatments, respectively, and the upper set points corresponded to 0.46 and 0.49 cm³·cm⁻³ for 0% and 25% biochar treatments, respectively.

For the plant-based irrigation system, set points were developed based on a relationship developed in a previous study (Basiri Jahromi et al., 2017) between substrate moisture content and photosynthetic rate of ‘Silver Dollar’ hydrangea plants, characterized by a 3-parameter sigmoidal curve (SigmaPlot v 14, San Jose, CA) based on five replicates. The lower set point was the VWC expected to maintain photosynthesis at 90% of the predicted maximum photosynthetic rate, resulting in 0.25 and 0.36 cm³·cm⁻³ for 0% and 25% biochar rate, respectively. The upper set point for this method was the effective container capacity, defined as the VWC following substrate saturation and drainage of gravitational water but before evaporation losses occurred (Hagen et al., 2015). Effective container capacity values were 0.46 and 0.58 cm³·cm⁻³ for 0% and 25% biochar rate, respectively.

Substrate moisture levels within an irrigation zone were monitored with a moisture sensor in each of three containers as described previously. There were no sensors in the five
supplementary or eight border containers in the 2017 study. The moisture sensors (GS1, Meter Devices Inc. Pullman, WA) were connected to a data logger (CR1000, Campbell Scientific Inc. Logan, UT) via a multiplexer (AM16/32, Campbell Scientific Inc.). Each moisture sensor was calibrated for its substrate type at three moisture levels to determine VWC. Two 16-channel relay controllers (SDM-CD16AC, Campbell Scientific Inc.) were used to operate solenoid valves controlling irrigation for each zone. A rain gauge was wired to the datalogger to measure local precipitation, allowing irrigation scheduling to take natural rainfall into account.

There were three sensors per irrigation zone. For the two on-demand irrigation systems, when the average VWC estimated by the three sensors in a zone decreased below the lower set point, the data logger opened the valve controlling irrigation to all containers in that zone. The irrigation “on” time for the zone was individually calculated based on the difference between the lower and upper set points and the flow rate for that zone.

Leachate volume was measured daily one to two hours after each irrigation event for the three containers in the zone with probes. The leachate collection pans were shielded from the overhead irrigation by an inverted 7.6 L plastic container with the bottom removed. Leaching fraction was calculated as [100 * leachate volume (mL) / total irrigation volume (mL)].

At the beginning (15 Aug. 2016 and 15 June 2017) and end (25 Oct. 2016 and 25 Sep. 2017) of each experiment, substrate nutrient samples were collected using the pour-through extraction method (LeBude and Bilderback, 2009) from three pots with probes in each zone. Samples were filtered with a 0.45 um syringe filter and then analyzed on an ICS 1100 (Ion Chromatography System; Dionex, Bannockburn, IL) for concentrations of nitrate (NO₃⁻), phosphate (PO₄³⁻), and potassium (K⁺). Electrical conductivity (EC) was measured with a portable EC meter (HI 9811-5, Hanna Instruments, Smithfield, RI, USA), and pH was measured with a benchtop pH meter (Denver Instrument, Bohemia, NY).

More measurements were taken during the 2017 experiment. This included plant size index [(plant width 1 + plant width perpendicular to width 1 + plant height) /3] for all of the plants at initiation (from identically treated extra plants) and termination of the experiment. Leaf chlorophyll content was measured using a SPAD chlorophyll meter (SPAD-502Plus, Konica Minolta, Tokyo, Japan), taking a measurement on most recent fully developed leaves of three plants per pot and recording the mean for the three primary pots in each zone. All of the plant shoots and leaves were harvested and hand-washed at initiation and termination of the experiment and dried at 55 °C for 72 h. The dried material of three plants of each zone was ground using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Plant tissue nitrogen (N) was determined using
combustion CHNS/O analyzer (CE Elantech, Lakewood, NJ) from the three primary plants in each zone. Plant tissue used for analysis was prepared by acid digestion using concentrated nitric acid and analyzed by ICP-OES for phosphorus (P), potassium, calcium (Ca), and magnesium (Mg\(^2+\)) concentrations. WUE for each plant was calculated as \([\text{increase in dry weight (g)} / \text{total water applied (L)}]\) for all measured plants in each zone.

### 4.4 Results and Discussion

#### 4.4.1 Substrate physical properties

Container capacity increased while air space, total porosity, and bulk density decreased with application of 25% biochar to pine bark substrate (Table 4.2). Physical properties of pine bark substrate amended with 0% or 25% biochar were in the range recommended by Bilderback et al. (2013). Biochar addition also decreased the percentage of coarse particles by 39% and increased the percentage of fine particles by 96% (Table 4.2). Biochar application may improve water relations by increasing the container capacity, changing particle size distribution, and rearrangement of the substrate structure. Pine bark has a high pore space and low water holding capacity because of the large macro pores which cannot hold water due to low matric potential, while biochar has a high surface area that allows the substrate to hold a greater quantity of water. Soilless substrate water retention characteristics can be affected by pore size and number (Handreck and Black, 2002). Biochar application alters pore characteristics by nesting within the larger pores of pine bark and increasing the portion of the finer particle size and smaller pores, which causes an increase in container capacity and a decrease in the air space and total porosity. Increased container capacity and a reduction in air space were reported in other studies following biochar application to soilless substrates (Altland and Locke, 2017; Vaughn et al., 2013).

The bulk density of a composite material can be predicted by the weighted average of the substrate component’s bulk density (Altland and Locke, 2013; Pokorny et al., 1986). Therefore, the reduction of bulk density in the 25% biochar amendment rate is due to the addition of biochar, which is a lower-density material (0.10 g·cm\(^{-3}\)) compared to the pine bark substrate (0.24 g·cm\(^{-3}\)). 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).
Table 4.2. Physical properties of pine bark substrate amended with 0% or 25% by volume of hardwood biochar (n=3).

<table>
<thead>
<tr>
<th>Biochar rate (%)</th>
<th>Container capacity (%)</th>
<th>Air space (%)</th>
<th>Total porosity (%)</th>
<th>Bulk density (g·cm⁻³)</th>
<th>Particle size distribution %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Coarse (&gt;2 mm)</td>
</tr>
<tr>
<td>0</td>
<td>57.1b²</td>
<td>30.0a</td>
<td>87.1a</td>
<td>0.24a</td>
<td>52.1a</td>
</tr>
<tr>
<td>25</td>
<td>65.7a</td>
<td>20.4b</td>
<td>86.2b</td>
<td>0.22b</td>
<td>32.0b</td>
</tr>
<tr>
<td>P-value</td>
<td>0.0008</td>
<td>0.0002</td>
<td>0.0213</td>
<td>0.0395</td>
<td>0.0242</td>
</tr>
</tbody>
</table>

²Means within a column followed by the same letter are not significantly different (α = 0.05).
Substrate physical properties were determined using a 15-cm tall porometer, according to the methods described by Fonteno and Harden (2010).

4.4.2 Irrigation scheduling systems

The upper and lower set points of the substrate-based irrigation system were predicated on the generally accepted range of plant available water occurring between -1 kPa and -10 kPa tension (de Boodt and Verdonck, 1972). Irrigation was actuated when the average sensor reading fell below the VWC corresponding to a substrate water potential of -10 kPa, generally considered the highest tension for plant available water. Plant-based irrigation was developed with the hypothesis that by maintaining VWC that corresponds to a predicted maximum photosynthetic rate at 90% or greater of the maximum photosynthetic rate, growth would not be reduced but substantial water savings could be achieved. Ninety percent of the maximum photosynthetic rate was observed at a higher VWC in 25% biochar treatment (0.36 cm³·cm⁻³) compared to 0% biochar rate (0.25 cm³·cm⁻³). Substrates with 25% biochar rate had a higher VWC at lower tension (-1 kPa), 0.49 cm³·cm⁻³, and lower VWC, 0.34 cm³·cm⁻³, at greater tension (-10 kPa) compared to those with 0% biochar. Therefore, biochar application increased the plant available water, which is defined as the VWC between -1 kPa and -10 kPa. An increase in available water following biochar application was also reported by Rogovska et al. (2014).

4.4.3 Total water use, final dry weight, final size index and water use efficiency

Rainfall was well-distributed during the 2017 experiment, but there were dry periods in 2016. Total rainfall for the experiment time frame was 70 mm in 2016 and 370 mm in 2017. There was no significant effect of biochar amendment rate nor any significant interaction between biochar rate and irrigation system for the measured parameters of total irrigation applied, final dry
Plant-based irrigation used significantly less water than the two other irrigation systems while still supplying the plants with sufficient water. The total amount of water used over the experiment was reduced by 16% using this system compared to the conventional system (Table 4.3). However, there was no difference in the total water use between conventional irrigation and the system based on substrate physical properties.

Although the total water use was unaffected or lower in the two on-demand irrigation systems, plant dry weight ($P=0.0272$) and size index ($P=0.0324$) were higher in on-demand irrigation systems compared to the traditional industry practice of applying 1.8 cm of water per day (Table 4.3). Plant dry weight was 22% and 15% higher and size index was 9% and 6% higher in substrate-based and plant-based irrigation scheduling systems, respectively, compared to the conventional irrigation. One reason might be that the on-demand irrigation system prevented the over- or under-watering that typically occurs with traditional non-sensor irrigation systems (Warren and Bilderback, 2005) and that has been demonstrated to decrease nursery crop growth (Belayneh et al., 2013; Million et al., 2007; Warsaw et al., 2009; Welsh and Zajicek, 1993). Another reason might be that on-demand irrigation scheduling shortens the periods of low VWC between irrigation events, which may affect plant growth. The moisture deficit in traditional irrigation systems might approach or exceed the water buffering capacity, which results in little to no plant available water (Nambuthiri et al., 2017). This appears to somewhat contradict Warsaw et al. (2009) who found that even moderate moisture deficit has little to no effect on plant growth. However, that research was conducted in a Northern location with lower ET crop demand.

The set point (0.25 cm$^3$·cm$^{-3}$) in 0% biochar rate with plant-based irrigation scheduling went beyond the water buffering capacity (-5 to -10 kPa) resulting in water saving and higher plant biomass metrics, which suggests that the range of plant available water can be extended beyond -10 kPa tension, and range of plant available water potential can be different in different substrates. Similar to our results, other recent studies also reported an extended range of plant available water potential (Fields et al., 2017; Montesano et al., 2018) and also that the range of plant available water potential may be somewhat dynamic due to a plant species and substrate effect on hydraulic conductivity (Fields et al., 2017; O’Meara et al., 2014).
Table 4.3. Total irrigation applied per container (L), final dry weight (g), final size index (cm), water use efficiency (g · L⁻¹) (n=8) and total leachate volume (L) (n=3) for Hydrangea paniculata ‘Silver Dollar’ plants in substrates amended with 0% or 25% by volume of hardwood biochar.

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>Total irrigation applied per container (L)</th>
<th>Final dry weight (g)</th>
<th>Final size index (cm)</th>
<th>Water use efficiency (g · L⁻¹)</th>
<th>Total leachate volume (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>48.8a⁺</td>
<td>96.9b</td>
<td>55.7b</td>
<td>1.0b</td>
<td>22.2a</td>
</tr>
<tr>
<td>Substrate-based</td>
<td>47.9a</td>
<td>117.9a</td>
<td>60.6a</td>
<td>1.4a</td>
<td>16.6b</td>
</tr>
<tr>
<td>Plant-based</td>
<td>40.8b</td>
<td>111.5a</td>
<td>59.2a</td>
<td>1.3a</td>
<td>15.5b</td>
</tr>
</tbody>
</table>

⁺Means in each column followed by the same letter were not significantly different (α = 0.05).

Total irrigation applied and total leachate volume were measured both in 2016 and 2017. Data presented in this table is the average of both years. Final dry weight, final size index and water use efficiency were measure only in 2017.

Our results are consistent with other published studies that reported scheduling irrigation based on substrate water status or crop water requirements reduced water use without negative effects on plant growth and quality in comparison to conventional nursery irrigation system (Basiri Jahromi et al., 2018c; Basiri Jahromi et al., 2017; Grant et al., 2009; Incrocci et al., 2014; Stoochnoff et al., 2018; Warsaw et al., 2009). Increase or no changes in plant growth after biochar application was reported in different studies during container production (Dumroese et al., 2011; Graber et al., 2010; Headlee et al., 2014; Vaughn et al., 2013).

WUE was greater in the two on-demand irrigation schedules (P=0.0442). It increased by 40% and 30% in substrate-based and plant-based irrigation schedules, respectively, compared to conventional irrigation (Table 4.3). Irrigation schedules increased WUE over the traditional industry practice of applying 1.8 cm per day by applying the appropriate amount of water based on plants needs. Similar results are reported in other studies (Beeson et al., 2004; Regan, 1999; van Iersel et al., 2013). Nambuthiri et al. (2017) reported that the moderate moisture deficit created by on-demand irrigation systems improved WUE by reducing the water use and leachate volume without a negative effect on plant growth. A plant-based irrigation schedule improved irrigation efficiency in Hibiscus rosa-sinensis ‘Cashmere Wind’, oakleaf hydrangea (Hydrangea quercifolia ‘Alice’) and slender deutzia (Deutzia gracilis) (Fulcher et al., 2012; Hagen et al., 2014; Nambuthiri et al., 2017).

This outdoor experiment was intended to validate the water use models and greenhouse
experiments (Basiri Jahromi et al., 2017) in an outdoor production environment using an overhead irrigation system. The results showed that on-demand irrigation schedules performed even better outside compared to the greenhouse experiments. On-demand irrigation scheduling improved plant biomass metrics and WUE when used outdoors. While there were no differences in plant biomass metrics or WUE with on-demand irrigation compared to conventional irrigation in the greenhouse experiments (Basiri Jahromi et al., 2017).

4.4.4 Total leachate volume, leachate volume per irrigation event and leaching fraction

Total leachate volume was 25% lower in substrate-based and 30% lower in plant-based irrigation scheduling compared to the conventional irrigation system (Table 4.3). The substrate-based and conventional irrigation systems used the same amount of water, but the conventional irrigation system had a greater leachate volume. Both on-demand schedules may prevent the substrate from becoming hydrophobic by minimizing the length of time a substrate dries between irrigation events (Nambuthiri et al., 2017), reducing channeling of water and thus leachate volume and associated fertilizer leaching (Hoskins et al., 2014). The tendency of water to channel through the substrate increases when applied to the dry substrate (Hoskins et al., 2014). Similarly, Fulcher et al. (2012) reported that estimating plant water use using sensors tied to the physiological status of the plant can conserve water and minimize leachate.

Total water applied and total leachate volume were not affected by biochar amendment rate ($P>0.05$) (Table 4.3). However, leachate volume per irrigation event ($P=0.0038$) and leaching fraction ($P=0.0001$) were lower in 25% biochar amended substrates (Table 4.4). Leachate volume was reduced by 16% and leaching fraction reduced by 26% in 25% biochar rate compared to 0% biochar treatment. Leaching fraction was above the recommended guideline of 15% for all treatments (Bilderback et al., 2013). The previous greenhouse studies had also shown a reduction of leachate volume per irrigation event and leaching fraction as a result of 25% biochar application to pine bark substrate (Basiri Jahromi et al., 2018b; Basiri Jahromi et al., 2016).

4.4.5 Substrate solution and foliar nutrient analysis

Substrate solution pH was not affected by irrigation system ($P>0.05$), but was affected by biochar application ($P=0.0009$) (Table 4.4). Substrate pH was higher in 25% biochar application rate (Table 4.4) because of the high pH (pH 10.5) of the biochar (Table 4.1). Biochar (pH=10.5)
application has been reported to increase soilless substrate pH in tomato (*Solanum lycopersicum* L.) and geranium (*Pelargonium × hortorum*) plants grown in a biochar amended peat moss-based substrate (Altland and Locke, 2017). An increase in pH was also reported in biochar (pH=10.7) amended peat (Conversa et al., 2015) and biochar (pH=7.5) amended pine bark (Kaudal et al., 2016). Many biochars have a high pH (Bi and Evans, 2009; Headlee et al., 2014; Tian et al., 2012), which is due to the temperatures at which they were produced. Increasing pyrolysis temperatures is known to increase biochar cation exchange capacity and pH (Zhang et al., 2017).

Substrate solution EC was not affected by biochar rate nor irrigation system (*P* > 0.05) (Table 4.4). Electrical conductivity was in the range of 0.5 to 1.0 dS·m⁻¹, which is the recommended range for EC in container substrate via pour-through extraction method (Bilderback et al., 2013). Substrate solution nutrient concentrations at the end of the experiment were not affected by biochar rates or irrigation systems (*P* > 0.05) (Table 4.5). Incrocci et al. (2014) reported similar results indicating that substrate water status and irrigation scheduling did not affect leachate nutrient concentrations, EC, and pH.

Foliar chlorophyll (SPAD) readings and plant tissue nutrient concentration were not affected by biochar rates nor irrigation system (*P* > 0.05) (Table 4.6). Similar to our results, Rogovska et al. (2014) reported no effect of hardwood biochar on plant tissue N, K, and Mg²⁺ concentrations. The results of a meta-analysis of 114 published studies showed that concentration of plant tissue N and P did not show any effect from biochar application (Biederman and Harpole, 2013). As the effect of biochar depends on the type of feedstock, the pyrolysis conditions, and the ecosystem or cropping systems to which biochar is applied (Altland and Boldt, 2018; Sohi et al., 2009), different nutrient concentration could be reported following biochar application. Biochar chemical properties may vary with source material even with the same production techniques (Evans et al., 2017). Thus, biochar amendments could be produced and prescribed based on meeting the nutrient needs of a specific crop.
Table 4.4. Leachate volume per irrigation event (ml), total leachate volume (L), leaching fraction (%), substrate solution pH and electrical conductivity (EC) for *Hydrangea paniculata* ‘Silver Dollar’ plants in substrates amended with 0% or 25% by volume of hardwood biochar over 13 weeks (n=3).

<table>
<thead>
<tr>
<th>Biochar rate (%)</th>
<th>Leachate volume per irrigation event (ml)</th>
<th>Total leachate volume (L)</th>
<th>Leaching fraction (%)</th>
<th>pH</th>
<th>EC (dS·m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>298.4a</td>
<td>18.6⁺⁺⁺⁺</td>
<td>51.9a</td>
<td>6.2b</td>
<td>0.5⁺⁺⁺⁺</td>
</tr>
<tr>
<td>25</td>
<td>249.9b</td>
<td>17.6</td>
<td>38.2b</td>
<td>6.6a</td>
<td>0.6</td>
</tr>
<tr>
<td><em>P</em>-value</td>
<td>0.0038</td>
<td>0.4211</td>
<td>0.0001</td>
<td>0.009</td>
<td>0.0909</td>
</tr>
</tbody>
</table>

⁺Means in same column followed by the same letter are not significantly different (α =0.05).
⁺⁺Values in same column followed by the ns letters are not significantly different (α =0.05).
Values presented in this table were measured in both 2016 and 2017 and are the average of both years.

Table 4.5. *Hydrangea paniculata* ‘Silver Dollar’ substrate solution potassium (K⁺), nitrate (NO₃⁻), phosphorus (P) or PO₄³⁻, calcium (Ca) and magnesium (Mg²⁺) concentration in a pine bark substrate amended with 0% or 25% by volume of hardwood biochar (n=3) and a controlled release fertilizer (Osmocote, Everris, Marysville, OH. 18N-2.6P-9.9K at 40 g per container).

<table>
<thead>
<tr>
<th>Biochar rate (%)</th>
<th>NO₃⁻ (mg·L⁻¹)</th>
<th>PO₄³⁻ (mg·L⁻¹)</th>
<th>K⁺ (mg·L⁻¹)</th>
<th>Ca (mg·L⁻¹)</th>
<th>Mg²⁺ (mg·L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>81.2⁺⁺⁺⁺</td>
<td>6.1⁺⁺⁺⁺</td>
<td>41.3⁺⁺⁺⁺</td>
<td>47.3⁺⁺⁺⁺</td>
<td>14.4⁺⁺⁺⁺</td>
</tr>
<tr>
<td>25</td>
<td>87.2</td>
<td>4.7</td>
<td>43.4</td>
<td>44.2</td>
<td>10.9</td>
</tr>
<tr>
<td><em>P</em>-value</td>
<td>0.1578</td>
<td>0.9782</td>
<td>0.8356</td>
<td>0.4450</td>
<td>0.1447</td>
</tr>
</tbody>
</table>

⁺⁺Values in same column followed by the ns letters are not significantly different (α =0.05).
Values presented in this table were measured in both 2016 and 2017 and are the average of both years. Samples were collected at the end (15 June 2016+ 25 September 2017) of the experiment with the pour through extraction method.

Table 4.6. Foliar nitrogen (N), chlorophyll (SPAD) readings, phosphorus (P), calcium (Ca), potassium (K), and magnesium (Mg²⁺) concentration of *Hydrangea paniculata* ‘Silver Dollar’ grown in a pine bark substrate amended with either 0% or 25% by volume of hardwood biochar (n=3) and a controlled release fertilizer (Osmocote 18N-2.6P-9.9K at 40 g per container).

<table>
<thead>
<tr>
<th>Biochar rate (%)</th>
<th>SPAD</th>
<th>N (%)</th>
<th>P (%)</th>
<th>K⁺ (%)</th>
<th>Ca²⁺ (%)</th>
<th>Mg²⁺ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.4⁺⁺⁺⁺</td>
<td>2.4⁺⁺⁺⁺</td>
<td>0.01⁺⁺⁺⁺</td>
<td>0.04⁺⁺⁺⁺</td>
<td>0.12⁺⁺⁺⁺</td>
<td>0.01⁺⁺⁺⁺</td>
</tr>
<tr>
<td>25</td>
<td>2.5</td>
<td>2.5</td>
<td>0.01</td>
<td>0.03</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td><em>P</em>-value</td>
<td>0.6162</td>
<td>0.3704</td>
<td>0.2841</td>
<td>0.0608</td>
<td>0.0616</td>
<td>0.6809</td>
</tr>
</tbody>
</table>

⁺⁺⁺Values in same column followed by the ns letters are not significantly different (α =0.05).
Values presented in this table were measured only in 2017.
4.5 Conclusion

This study demonstrated that water savings were achieved in some on-demand irrigation scheduling regimes in outdoor environments compared to the traditional practice of applying 1.8 cm of water per day in all of the treatments. On-demand irrigation regimes work even better outside with sprinkler-applied water than in an earlier greenhouse experiment with micro-irrigation. Plant-based irrigation used less water than the two other irrigation systems while still meeting crop demand, which makes it the optimal irrigation scheduling system in this experiment. Both on-demand irrigation-scheduling regimes had greater plant biomass metrics and WUE and smaller leachate volume compared to conventional irrigation. The 25% biochar amendment rate also reduced the leachate volume per irrigation event and leaching fraction. This research demonstrated that on-demand irrigation scheduling with a plant-based or substrate-based irrigation regime could be an effective approach to increase WUE for container-grown nursery crops without negatively affecting plant growth. Nursery industry professionals should consider adopting plant based on-demand irrigation systems in order to increase water savings potential or expand production on existing and/or limited water supplies.

Acknowledgements

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4.6 References


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Chapter 5

Conclusion

Adopting substrate moisture probe technology to actuate irrigation in combination with biochar amendment increased substrate water-holding capacity, reduced the water requirement for hydrangea and reduced leachate volume of both hydrangea and boxwood. 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. Reduction of total water use in hydrangea did not affect the plant dry weight in 10% biochar application rate but reduced plant dry weight in 25% biochar rate.

Using on-demand irrigation schedules based on plant physiological status or substrate physical properties, reduced water use over the traditional practice of applying 1.8 cm of water per day in all of the treatments when used in the greenhouse without a negative effect on plant dry weight. These on-demand irrigation schedules maintained sufficient plant water status and gas exchange even just prior to irrigation, the driest point in the irrigation cycle. However, the very low set point in 0% biochar rate under plant physiology-based irrigation likely exceeded the water buffering capacity. On-demand irrigation work even better outside with sprinkler irrigation than in earlier greenhouse experiments with micro-irrigation. Plant-based irrigation used less water than the two other irrigation systems while still meeting crop demand when used outdoors. Both on-demand irrigation-scheduling regimes had greater plant biomass metrics and water use efficiency and smaller leachate volume compared to the traditional practice of applying 1.8 cm of water per day in all of the treatments when used outdoors. The 25% biochar amendment rate also reduced the leachate volume per irrigation event and leaching fraction in outdoor experiment.

Application of up to 25% switchgrass biochar increased the concentration of P and K in both hydrangea and boxwood plant tissues and substrate. Hardwood biochar provided a source of K by increasing K concentration in substrate solution and in hydrangea plant foliage in greenhouse experiments. These results suggested that biochar might be able to replace fertilizer requirements if used commercially. This research also demonstrated that on-demand irrigation scheduling with a plant-based or substrate-based could be an effective approach to increase water use efficiency for container-grown nursery crops without negatively affecting plant growth. Nursery industry professionals should consider adopting on-demand irrigation systems in order to increase water savings potential or expand production on existing and/or limited water supplies.
and using biochar amendment to minimize leaching, reduce nutrient losses and increase nutrient use efficiency.
Vita

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