High pH, Low Alkalinity Pond Water Used for Overhead Irrigation Does Not Affect Plant Growth of Select Flowering Shrubs[1]

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Abstract

In southeast U.S., pH of source water from ponds used for overhead-irrigating container crops can exceed the range (pH 5.8-7.0) for best management practices. Artificially maintaining this pH range is not common among producers using surface water for irrigation, nor is it known whether this would affect growth. Therefore, the objective was to test whether this source water affects growth of five flowering shrubs in nurseries in eastern North Carolina. Pond water at six nurseries with a pH range of 4.9-8.1 (control) was injected before irrigation with sulfuric acid (lower) or potassium bicarbonate (raise) onsite to maintain a pH of 5.8-6.2 (treatment). Ambient photosynthesis ($A_{ambient}$) and stomatal conductance (g_s) was measured in July, August, and September on leaves of forsythia (*Forsythia* x *intermedia* 'Mindor' ShowOff®) during irrigation runtime mini-experiments at three nurseries. For mini-experiments, pre- and post-treatment physiology was measured for plants receiving 0 (hand watered), 30, or 60 minutes of treated or nontreated overhead irrigation. Dry weight of all shrubs and gas exchange of forsythia was not affected by high pH, low alkalinity (<100 ppm) irrigation water. Southeastern producers using this source water for overhead irrigation may not need to adopt a system that reduces pH to improve growth.

Index words: Container-grown, plant physiology, photosynthesis, stomatal conductance, ornamental.

Chemicals used in this study: Potassium bicarbonate, sulfuric acid.

Species used in this study: fragrant abelia, *Zabelia tyaihyonii* (Nakai) Hisauti & H.Hara 'SMNAMDS' Sweet Emotion®; butterfly bush, *Buddleia* x 'Miss Molly'; border forsythia, *Forsythia* x *intermedia* 'Mindor' Show Off®; panicled hydrangea, *Hydrangea paniculata* Siebold 'SMHPLQF' Little Quick Fire®; landscape rose, *Rosa* x 'ChewPatout' Oso Easy®.

Significance to the Horticulture Industry

Pond surface water can exceed the best management practices (BMP) range for pH of 5.8 to 7.0 outlined for growing container ornamental crops in season. Elevated pH (>7.0) in ponds used for source water to irrigate is common among producers across the southeastern U.S. Remediation of pond water to properly improve quality within BMP guidelines consists of screens or finer filtration devices (e.g., sand or disc filters), monitoring pH and total alkalinity to determine the correct injection rate, then injecting an acid (e.g., sulfuric) followed by proper resonance time to thoroughly mix chemicals with water. Afterwards, within the irrigation system, monitoring equipment is used either in-line, which can automatically inform and adjust the upstream injection rate, or monitored manually at the point of trajectory (sprinkler head) using portable devices or litmus tests to ensure pH remains within recommended BMP ranges. This study suggests that irrigating container plants overhead with high pH, low alkalinity (<100 ppm total alkalinity) source water from ponds may not affect growth enough to warrant investment in an injection system simply to lower pH to meet BMPs. The range for pH stated in BMPs is still important for producers treating water with sanitizing chemicals to reduce microorganisms. If sanitizing chemicals are used, many systems benefit from reducing pH prior to chemical injection and therefore might feasibly justify an acid injection system.

Introduction

Many producers in the southeastern U.S. use surface water from ponds as a primary source water for irrigating container-grown crops. Water quality can change as both the growing season progresses and the nursery increases in size over time, especially if production runoff is recaptured and recycled for reuse. The pH and total alkalinity of surface waters in runoff containment basins (RCBs) on nurseries throughout the Southeast, Gulf states, and mid-Atlantic states tend to increase between February and October due to annual (monomictic) thermal stratification

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layers (Copes et al. 2017, Copes et al. 2018, Zhang et al. 2016). This increase occurs in the top layer of surface water where water withdrawal is accessed for irrigation application (Zhang et al. 2015). From February to July 2013 across 10 RCBs in MD, MS and VA, mean pH was 7.1 [±0.9 standard deviation (STD)] and total alkalinity (t-alk) was 28 ppm (±17 ppm STD) (Copes et al. 2018). Similarly, over a four year period during the growing season, reservoirs used for irrigation on three nurseries in VA had an average pH of 7.9 (±0.9 STD) (Zhang et al. 2016). In fact, Zhang et al. (2016) suggested using pH as an indicator of water quality because of the differences between winter and the summer stratification period where pH could decrease 4.16 units from the top to the bottom of the pond.

The combination of algae accumulation over the growing season with low t-alk in ponds leads to the increase in pH. Algae remove CO_2 for photosynthesis, which increases pH during the day, then releases it at night, thus lowering the pH in a daily cycle. Low t-alk present provides little buffering capacity to inhibit a large diurnal variation, therefore, mean pH can increase over the growing season (Tucker and D'abramo 2008) as algae concentrations increase (Zhang et al. 2015). Producers could simply treat for algae in ponds to lower pH by applying a number of best management practices. For example, copper sulfate both prevents (algastatic) and kills (algacidic) algae in ponds. At this time, however, copper sulfate is not recommended for ponds containing fish that have alkalinity below 50 ppm or above 250 ppm (Storlie 1995), and the average pond in the Southeast falls below this threshold for application and usually contains fish (e.g., 28 ppm mean t-alk in Copes et al. 2018). Adding barley bales to ponds, another algastatic method, may not be as effective in the Southeast due to the high water temperature and long growing season, which give algae the capacity to overwhelm barley's beneficial preventative properties (Lembi 2002). Pond dyes shade out algae, are nontoxic, and do not have any pond restrictions, but must be applied two to three times yearly before algae blooms occur. Floating wetlands work within the pond to remove nitrogen and phosphorous that algae use for photosynthesis and growth. These systems require yearly maintenance and replenishment, may not control all the algae within ponds, and can encourage other types of algae to grow (White et al. 2009, White et al. 2011). Water-lifting aerators increase the dissolved oxygen near the bottom of reservoirs to inhibit both nutrient release and algal growth (Ma et al. 2015). Another alternative is to channel production runoff through a wide, low-sloped, vegetative filter strip to remove all sediments, pesticides, and mineral nutrients (Zhang et al. 2010). This requires new land surveying, design, and perhaps loss of production area. While sediment, nutrients, and pesticides that reach the pond are reduced, however, this does not guarantee algae growth will be inhibited or pH will remain low. In fact, all of these techniques should be pursued as an integrated approach to fundamentally change the nursery production system and improve both the quality of production runoff and the source water used for irrigation. Mack et al. (2017) reported that growers are more likely to implement easy-to-install or low-cost BMPs and further hypothesized that when growers implement BMPs that require more than minimal inputs of cost, time, equipment, or knowledge, the reason is probably necessity. Whether or not high pH, low alkalinity water effects plant growth has not been studied widely in the Southeast to justify the necessity of adopting these BMPs, in addition to their already reported benefits, in the plant production process.

A high pH signal in leaves of plants may help moderate the plant's stress response to a water deficit by aiding in stomatal closure. In a review of the signaling pathways for stomatal closure, Davies et al. (2005) highlight the common theory that abscisic acid (ABA), a plant hormone, synthesized in the roots travels via xylem to the leaves to signal stomates to close when soil water is depleted. They also argue that ABA is produced in leaves and can be present there during non-drought conditions. ABA is available to signal stomatal closure when a high pH signal in the leaf tissue increases. The high pH signal is produced in the roots when the normally acidic xylem is alkalinized upon soil water depletion. The signal travels through the xylem to leaves that increase concentrations of ABA as a result (Davies et al. 2005 and other references therein). Stomates react to both the high pH xylem sap and the increased concentration of ABA to close and reduce transpiration (Geilfus and Muhling 2012). In a complement experiment, Wilkinson and Davies (2008) sprayed low alkalinity, high pH water on leaves of well-watered *Forsythia* x *intermedia* (forsythia) plants in a greenhouse over eight days, resulting in decreased stomatal conductance. Wilkinson and Davies (2008) argued that roots of the well-watered plants did not send a high pH signal to completely close stomates; plants instead reacted to the high pH water absorbed by the leaves, thus only a partial closure of stomates occurred. The solution sprayed on plants was pH 6.8, which is less than the mean pH calculated above for irrigation water across the southeast U.S. (Copes et al. 2018, Zhang et al. 2016). As a result of partially closed stomates, leaves of forsythia plants that received foliar applications of high pH water had smaller leaves than those that received applications of water with a pH of 5.0 or 5.8 (Wilkinson and Davies 2008).

The findings of Wilkinson and Davies (2008), as well as the water quality studies mentioned above, are the basis of the present study. Treating surface water to reduce pH before irrigation is not a common practice in nursery production. For example, producers of ornamental plants in eastern North Carolina use surface water from RCBs supplemented with well water to increase the capacity of source water to overhead irrigate container plants (LeBude, personal observations). Based on earlier discussion above (e.g., Zhang et al. 2015), it is safe to assume this source water at nurseries in eastern NC has a high pH with low alkalinity during the growing season, indicative of the southeastern and mid-Atlantic US. Irrigation days in the eastern part of NC range from 200-300 per year, meaning 0.4 ha (one acre) of container-grown plants may receive up to or more than 2.5 cm (an inch) of water [102,200 L (27,000 gallons)] applied by overhead irrigation each day.

Table 1. Descriptive statistics about production area, water sources, and irrigation technologies used for the production environments for each nursery (designated by code) included in the study.

Code	Container Production area (ha)	Field production area (ha)	Pond area (ha)	Recycled %	Filtration	Filter pore-size (µm)	Treatment system	Cycle start times	Cycle length (min)
A	3.6	3.5	0.16	100	sand, screen	>1000	Hydrogen peroxide, peroxyacetic acid	Manually operated as needed	90-120 (Left on until they remember to turn it off)
B	78.3	0.0	10.8	0	screen	>1000	Calcium hypochlorite	7:30 a.m. 11:00 a.m. 2:00 p.m. (syringe)	20
C	28.4	0.00	2.17	45	screen	>1000	Hydrogen peroxide, peroxyacetic acid	6:30 a.m. 11:00 a.m. 3:00 p.m.	20
D	6.6	0.0	1.10	35	screen	>1000	none	7:30 a.m. 10:30 a.m. 3:00 p.m.	15
E	17.5	24.0	0.29	40	sand, screen	>1000	none	9:00 a.m. 12:00 p.m.	20
F	11.1	0.0	0.05	0	screen	>1000	none	7:30 a.m. 10:30 a.m.	45

Plant leaves receiving this high pH irrigation water may perceive this as a signal that roots are slightly desiccated on a daily basis, reduce stomatal conductance partially as a result, and consequently result in a smaller plant over the 8 to 10 month growing season as suggested by Wilkinson and Davies (2008). There is no control comparison on a nursery for producers to determine if plant growth might be affected by lowering the pH of their source water. Growers by and large adopt new technologies from each other by watching nearby innovative growers experiment and succeed first (Bohlen et al. 1962). Thus, the experiment was conducted on six nurseries to both make use of existing water qualities found throughout the region and provide an experiential practice for growers to see any measured differences. The two-tiered objective was to first measure ionic properties of source water five years apart for many nurseries, then test whether irrigating overhead with high pH, low alkalinity source water affects growth of five common flowering shrubs in six container nurseries in eastern North Carolina.

Materials and Methods

Water quality. Individual water samples were collected randomly throughout the day from source water in ponds used for irrigation at 33 eastern North Carolina nurseries in January to March 2010, and then again August to September 2015. At both collection times, 473 ml (16 oz) of solution were obtained approximately 46 to 61 cm (18 to 24 in) below the pond surface as close to the intake for the irrigation pump system as possible. Electrical conductivity (EC) and pH were measured immediately using a portable meter (HI9813-6, HANNA® Instruments, Inc., Woonsocket, RI), then samples were plunged into a cooler with ice water before being submitted at the end of each day for solution analysis by the agronomic services division of the North Carolina Department of Agriculture and Consumer Services (NCDA&CS, Raleigh, NC). Samples were collected from several nurseries in 2015, which were not included in 2010, and some of those nurseries (3) were used in this study as representative of the range of water quality of the average nursery in southeast NC. Descriptions of production area and water quality technology among the six nurseries used in the present study for plant growth analysis are presented (Table 1).

Plants. On 16 April 2018, quick turn liners (1 qt, 946.4 ml) (Spring Meadow™ Nursery, Inc., Grandhaven, MI) of *Zabelia tyaihyonii* 'SMNAMDS' fragrant abelia (Sweet Emotion®), butterfly bush (*Buddleia* x 'Miss Molly'), border forsythia (*Forsythia* x *intermedia* 'Mindor' Show Off®), panicled hydrangea (*Hydrangea paniculata* Siebold 'SMHPLQF' Little Quick Fire®), and landscape rose (*Rosa* x 'ChewPatout' Oso Easy® Urban Legend®) were potted in 11.4 L (#3) containers (Nursery Supplies, Inc., Chambersburg, PA, PF1200, Proven Winner® white) filled with 100% pine bark [all-purpose potting mix (PM2), Pacific Organics, Inc., Henderson, NC] (Table 2) amended with 2.7 kg (6 lb) per 0.76 cu m (1 cu yd) ground dolomitic limestone (Rockydale Quarries Corporation, Roanoke, VA) and 0.68 kg (1.5 lbs) per 0.76 cu m (1 cu yd) micronutrients (Booster Plus, Harrell's LLC, Lakeland, FL). Potted plants were topdressed with 65 g (0.14 lbs) of an 8-9 mo controlled release fertilizer ($18N-4P_20_5-8K_20$ with minors, Harrell's LLC, Lakeland, FL) and 68 kg (150 lbs) per acre of the preemergence herbicide [Snapshot (Isoxaben +

Table 2. Select physical and chemical properties[z] of All-Purpose potting mix (PM2) obtained from Pacific Organics, Inc., Henderson, NC.

Substrate	Porosity	Container capacity	Airspace	Bulk density $g \cdot cm^{-3}$	Bulk density $lbs \cdot ft^{-3}$	pH	Electrical conductivity $mS \cdot cm^{-1}$
PM2	81%	46%	35%	0.18	11.5	4.3	0.23

[z] Data obtained from Pacific Organics, Inc., May 2018.

Table 3. Series D Ratio Feeder® (H.E. Anderson Company, Muskogee, OK) suitable up to 50 gal·min^{-1} (189.2 L·min^{-1}) for injecting sulfuric acid (reduce pH) or potassium bicarbonate (raise pH) into a small portion of nursery irrigation systems.

Model	Max ratio	Min ratio	Pumper size	L per stroke	ml injected per stroke	Strokes per min at max flow
DD1000	1:1000	1:10000	A3-VCP	3	3	63

Trifluralin), Dow AgroSciences LLC, Zionsville, IN]. After potting, plants were watered by hand, then irrigated overhead as needed, and grown for approximately 3 weeks at the NC State University Horticultural Field Lab (USDA Plant Hardiness Zone 7b, Raleigh, NC) before being distributed to the six nurseries.

pH treatments. A series D Ratio Feeder® (DD1000, H.E. Anderson Company, Muskogee, OK) was installed at each of the six nurseries near the end of a rectangular container pad within an irrigation zone (Table 3). Existing irrigation pipe [ranging from 1.9 to 5.1 cm diameter (0.75 to 2 in)] located near the pad was excavated and fitted with a PVC extension (Gra-Mac Distributing Co., Mocksville, NC) that directed water through the injection system, then back into the underground irrigation system to be delivered through the existing overhead impact sprinkler heads to experimental plots. This ensured that only a small volume of water used for irrigation was treated, rather than the entire volume for the nursery. Additionally, by placing the injection system within an irrigation zone, this ensured the same frequency and duration of irrigation for both control and treatment plots. After injection, the aqueous solution passed through a mixing vessel [9.9 L (603.2 cu in)] that increased homogenization prior to application to plants. A small structure was built to house the injection system and protect it from extreme weather, secure the vessel containing diluted chemical, and provide a ready power supply. To maintain a pH of 6.0 in the treated plots, sulfuric acid (93% technical grade, Griffin Greenhouses & Nursery Supplies, Knoxville, TN) (reduce pH) or potassium bicarbonate (99.5%, J.R. Peters, Inc., Allentown, PA) (raise pH) (nursery F only) were diluted with distilled water to 20% sulfuric acid or 5% potassium bicarbonate then stored in plastic containers with lids (PN400-5 gal blue HDPE square and MO82T-¾” vented lid, Industrial Container and Supply Co., Salt Lake City, UT) that had a knockout hole in the center for inserting a siphon.

Two treatments at each nursery were the control (nontreated) and treated to maintain a pH of 6.0. Plants in the control were irrigated with nontreated pond water at each nursery. This pH ranged from 4.9 (Nursery F was only nursery below pH 6.0) to 9.3 depending on the nursery (Table 4), fluctuated throughout the experiment, and was not treated to maintain any actual pH, rather to reflect status quo at each nursery. The treated plot consisted of the same pond water treated with either diluted sulfuric acid or potassium bicarbonate (Nursery F only) to maintain a pH of 6.0 based on manual calibration every two weeks using a portable pH meter (HI9813-6, HANNA® Instruments, Inc., Woonsocket, RI). The control and treatment plots at individual nurseries received the same frequency and duration of irrigation (with the exception of nursery B where the two plots were in different irrigation zones, but were operated sequentially), but among nurseries, plots did not receive the same frequency, cycle, or volume of irrigation water daily (Table 5).

Irrigation runtime mini-experiment. These one-day experiments at three select nurseries were conducted to

Table 4. Summary statistics of water quality measurements from pond water of six nurseries included in the study collected 46-61 cm (18-24 in) below the surface of ponds used for irrigation in summer 2015.

		Nursery					
Water quality variables[Z]	Units	A[Y]	B	C	D	E	F
NH$_4$-N	mg·L^{-1}	0.03	3.16	0.42	0.01	0.11	0.03
NO$_3$-N	mg·L^{-1}	1.32	4.10	0.24	0.23	0.08	4.83
Total-P	mg·L^{-1}	0.69	1.96	0.59	0.04	0.24	0.01
K	mg·L^{-1}	9.10	13.45	18.11	5.21	5.41	4.32
Ca	mg·L^{-1}	22.98	21.33	18.37	7.49	5.50	3.32
Mg	mg·L^{-1}	9.77	8.31	9.57	2.87	3.38	1.70
S	mg·L^{-1}	9.40	16.7	3.73	2.25	3.79	2.68
B	mg·L^{-1}	0.02	0.03	0.21	0.02	0.04	0.03
Cu	mg·L^{-1}	0.01	0.01	0	0	0	0
Fe	mg·L^{-1}	0.09	0.14	0.23	0.19	0.28	0.02
Mn	mg·L^{-1}	0.03	0.04	0	0.02	0.01	0.06
Zn	mg·L^{-1}	0.01	0.02	0	0	0	0
Na	mg·L^{-1}	12.32	7.52	20.11	6.13	9.52	2.03
pH	SU	8.6	6.9	7.3	8.8	9.3	4.9
EC	mS·cm^{-1}	0.28	0.32	0.35	0.13	0.14	0.08
T-Alk	mg·L^{-1}	85.0	35.0	125.0	40.0	25.0	0

[Z] Water analysis consisted of the determination of ammonium–nitrogen (NH$_4^+$-N), nitrate–nitrogen (NO$_3$-N), total-phosphorus (Total-P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), sodium (Na), pH, electrical conductivity (EC), and total alkalinity (T-Alk), performed by the North Carolina Department of Agriculture & Consumer Services, Raleigh, NC.

[Y] Samples were collected once per day at each nursery but different times of day for the different nurseries.

Table 5. Application rate (AR) using catch cans for the Treatment (T) and Control (C) plot and resulting leaching fractions (LF) during an irrigation event.

Nursery Code	AR_T in·hr^{-1} (cm·hr^{-1})	AR_C in·hr^{-1} (cm·hr^{-1})	LF_T %	LF_C %	Pressure PSI	Mean AR for both In·hr^{-1} (cm·hr^{-1})
A	0.23 (0.58)	0.24 (0.61)	33	27	37	0.24 (0.61)
B	0.34 (0.86)	0.15 (0.38)	8.7	11.5	42	0.25 (0.64)
C	0.91^z (2.31)	0.30 (0.76)	42	10.6	55	0.60 (1.52)
D	0.43 (1.09)	0.46 (1.17)	12	4.5	37	0.45 (1.37)
E	0.44 (1.12)	0.44 (1.12)	5.2	10.7	35	0.44 (1.12)
F	0.35 (0.89)	0.25 (0.64)	8.3	7.2	29	0.30 (0.76)

^{z}The treatment area was a small experimental area set aside close to the pumphouse that had higher pressure and closer sprinkler design than the control plot in the general nursery, therefore it received more volume than the rest of the nursery.

determine if overhead irrigation with control or treated irrigation water affected plant gas exchange directly after application. Because all three nurseries were not measured on the same day, measurement date during the summer was coded as 1 (29 June; 3 July; 19 July), 2 (5 August; 6 August; 9 August.), or 3 (5 September; 11 September; 19 September). On each run-time experiment day, between 7:00 a.m. and 9:00 a.m., at nurseries A, D, and E only, plants of *Forsythia* Show Off® in the control and treatment plots of a single nursery were hand watered to container capacity and allowed to set for 30 minutes. Plants had not yet received overhead irrigation for that day. Gas exchange measurements were collected randomly from two leaves on opposite sides of each plant (two leaves per plant). Plants in each plot were then divided randomly into 3 runtime treatments containing two plants each and placed back in their original control or treatment plot. Irrigation run time treatments were 1) 0 min irrigation (plants received no overhead irrigation but were hand watered again); (2) 30 min overhead irrigation (plants were removed from irrigation after 30 minutes); or 3) 60 min overhead irrigation. After foliage dried on all plants (approximately 15-30 min after irrigation ceased), physiology measurements were collected again randomly from two different leaves per plant. After mini-experiments were concluded at each measurement day, plants received their normal frequency and duration of irrigation they had been receiving since the main experiment began as noted in Table 5.

Gas exchange. Gas exchange was measured at nurseries A, D, and E three times during summer 2018 during the irrigation run-time mini-experiments. Measurements were collected on bright, sunny days using the same ambient conditions in the cuvette to ensure comparisons effectively among nurseries and measurement dates. Net photosynthesis at ambient conditions ($A_{ambient}$) and stomatal conductance (g_s) was measured using a portable photosynthesis system (Li-6400XT, Open 6.3.4; LI-COR® Biosciences, Lincoln, NE) fitted with a standard 2 × 3 cm cuvette, absolute, open-path, non-dispersive infrared gas analyzers for both CO_2 and H_2O, a 6400-02B Red/Blue LED Light Source, and a 6400-01 CO_2 injector. Average ambient environmental conditions were maintained for all measurements. Carbon dioxide (CO_2) level was set to 400 μmol·m^{-2}·s^{-1}, photosynthetically active radiation (PAR) was 1700 μmol·m^{-2}·s^{-1}, block temperature 32 C (89.6 F), and water vapor scrubbed from incoming air to maintain relative humidity between 63% and 74%, depending on the time of day and measurement date during summer. Before logging data, $A_{ambient}$ and g_s were monitored for 1 to 5 min while the total coefficient of variation was $<0.5\%$.

Plant growth. After approximately 140 days at all nurseries, growth index (GI) was calculated for all species by adding height, the widest canopy measurement, and the width perpendicular to that measurement then dividing by 3 [GI=(Ht. + W1 + W2)/3]. Leaf length and width of the widest part of the blade was measured on four recently expanded leaves on three plants per plot for all species. The entire above ground portion of the plant (stems plus leaves) was bagged separately for each plant, dried for 72 hours at 70 C (158 F), and then weighed to the nearest gram.

Data analysis. The experimental design for growth was a split plot design with nursery as the main-plot and pH of irrigation water applied as the sub-plot. In the treated irrigation plot, Nursery F received potassium bicarbonate to increase the pH to 6.0, while all other nurseries received sulfuric acid to lower the pH to 6.0. The objective of the experiment was not to test various chemical additives, but rather to test whether or not irrigating overhead with water maintained at a pH of 6.0 continuously through the season affected plant growth and physiology. Therefore, Nursery F was included in all applicable analyses. Species were considered separate experiments though grown within the same plots. Within each sub-plot of irrigation, each species was replicated six times. Within each nursery, these replications represented pseudo-plots for each irrigation treatment because there were only single plots of each irrigation treatment. For gas exchange measurements in the irrigation runtime mini-experiment, the design was a split, split-plot with nursery as the main plot, pH of irrigation water on the sub-plot, and irrigation runtime on the sub-

Table 6. Summary statistics of water quality measurements collected 46-61 cm (18-24 in) below the surface of ponds (n=46) used for irrigation at the same 33 nurseries in southeastern North Carolina collected winter 2010 and summer 2015.

		Preferred	Winter 2010			Summer 2015		
Water quality variables[Z]	Units	Range[Y]	Mean[X]	Min.	Max.	Mean	Min.	Max.
NH_4-N	mg·L^{-1}	NL[W]	0.23	0.01	0.40	0.10	0.00	0.78
NO_3-N	mg·L^{-1}	0-10.0	0.73	0.00	4.16	0.53	0.00	5.57
Total-P	mg·L^{-1}	0-1.0	0.17	0.00	1.12	0.21	0.01	2.34
K	mg·L^{-1}	1.0-10.0	2.88	0.00	12.23	6.09	1.19	19.55
Ca	mg·L^{-1}	40-100	5.75	1.52	18.71	8.35	1.08	35.48
Mg	mg·L^{-1}	5.0-25.0	2.61	0.75	6.08	3.68	1.00	9.77
S	mg·L^{-1}	25-200	3.54	1.13	16.64	3.02	0.42	9.40
B	mg·L^{-1}	0.2-0.5	0.02	0.00	0.15	0.04	0.00	0.54
Cu	mg·L^{-1}	0.05-0.15	0.01	0.00	0.04	0.00	0.00	0.02
Fe	mg·L^{-1}	1.0-3.0	0.14	0.02	0.57	0.51	0.04	3.28
Mn	mg·L^{-1}	0.2-1.0	0.03	0.00	0.18	0.03	0.00	0.32
Zn	mg·L^{-1}	0-0.2	0.01	0.00	0.08	0.00	0.00	0.03
Na	mg·L^{-1}	0-30	5.42	1.11	41.72	8.43	1.17	62.01
pH	SU	5.2-6.8	6.44	4.70	7.57	8.08	6.55	9.88
EC	mS·cm^{-1}	0-0.30	0.10	0.03	0.30	0.15	0.05	0.35
T-Alk	mg·L^{-1}	0-140	15.65	0.00	45.00	41.63	5.00	150.00

[Z] Water analysis consisted of the determination of ammonium–nitrogen (NH_4^+-N), nitrate–nitrogen (NO_3-N), total-phosphorus (Total-P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), sodium (Na), pH, electrical conductivity (EC), and total alkalinity (T-Alk), performed by the North Carolina Department of Agriculture & Consumer Services, Raleigh, NC.

[Y] Robbins (2018).

[X] Samples were collected once per day at each nursery in both years, but different times of day for the different nurseries.

[W] NL=not listed.

sub-plot. The two plants for each irrigation runtime by pH treatment interaction served as pseudo replications of those treatments at each nursery.

Data were subjected to a mixed model analysis of variance using PROC MIXED METHOD=REML [residual (restricted) maximum likelihood] with the term location, as well as its interactions, designated as a random effect. PROC MIXED and the model statement, which reflected the split-plot treatment structure at each nursery, constructed error terms used to determine the significance of main effects (SAS® software, v. 9.4, SAS Institute, Cary, NC). The REML method accounts for unbalanced data when estimating variance components since all runtime treatments were not represented equally at the third measuring sequence at all locations when physiology data were collected because of plant death. The correction ddfm=KR2 (Kenward-Roger2) was used as the method for computing denominator degrees of freedom for the F ratio when testing fixed main effects (measuring sequence, pH treatment, and runtime) and interactions because of small sample approximations, which also improves the estimation of the LSMEANS error (SAS 2019). Paired comparisons within main effects were made using LSMEANS with adjustment of p values for paired comparisons using Tukey's test ($P<0.05$). Data for stomatal conductance were not normally distributed nor had equal variance, therefore data were natural log transformed, which improved both metrics, so transformed data were used in subsequent analyses, but nontransformed data are reported.

Results and Discussion

Water quality. Between winter 2010 and summer 2015, the ionic properties of source water of ponds used for irrigation generally increased for the same 33 nurseries (Table 6). This is to be expected when making descriptive surface measurements only between winter and summer because ponds experience monomictic thermal stratification in summer that increases pH, as well as other variables at the surface (Zhang et al. 2016, 2015). Additionally, the slight increase in many mean mineral concentrations in summer 2015 could be the result of increased irrigation use lowering overall pond volume, increased production runoff containing mineral nutrients from previous applications, or both. With the exception of mean high pH (8.1), all of the water quality measurements for both dates are either below or within preferred ranges (Robbins 2018), and are similar to other nurseries in the southeast U.S. (Copes et al. 2018). This is also true of the subset of six nurseries used in the study (Table 1). For one nutrient at Nursery B, sulfur (S) was 16.7 mg·L^{-1}, which was 7.3 mg·L^{-1} higher than the highest value measured for the other 33 nurseries (Table 4); however, as stated above, these values for S are actually lower than the lowest preferred value (25 mg·L^{-1}) for water quality in nurseries (Robbins 2018).

At nurseries A through E, treatment integrity between the nontreated control (pH 7.4-8.1) and acid-treated irrigation water (pH 5.8-6.2) was maintained over the length of the experiment (Fig. 1). Nursery F was chosen because source water pH was already close to 6.0 and it remained so during the experiment. The pH was monitored manually at each nursery when visited randomly throughout the day rather than continuously by in-line technology, therefore not all fluctuations in pH throughout the day or over the entire growing season were reflected in observed values; nevertheless, high pH of similar ponds across the southeast with measurements collected either continuously or more methodically remained consistently high throughout the growing season despite diurnal fluctuations (Zhang

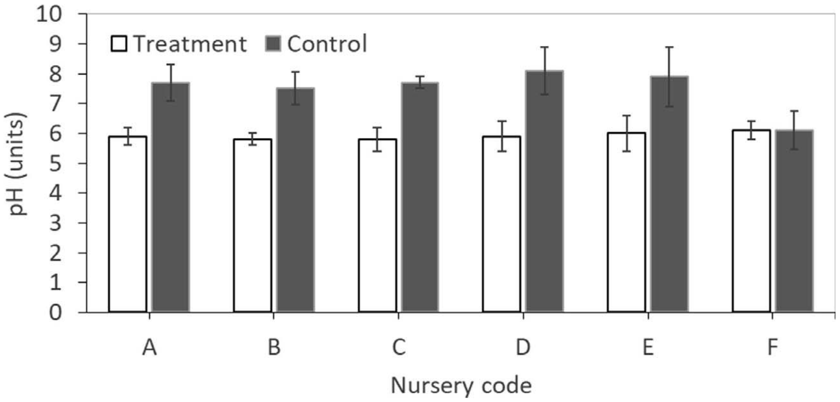

Fig. 1. Mean pH (± SEM) of pond water at six nurseries in southeast NC used for irrigation. Water was nontreated, control (unfilled bars), or treated (filled bars) with either sulfuric acid (reduce pH) (Nurseries A-E) or potassium bicarbonate (increase pH) (Nursery F) to maintain a pH of 6.0. Data points are means of single, biweekly measurements (6-10 total measurements for each nursery) collected randomly throughout the day at each physiology measurement date or nursery visit between May and September 2018. With the exception of Nursery F, there was a significant difference ($P<0.05$) between the control and treatment for each nursery.

et al. 2016; Copes et al. 2018). Moreover, diurnal fluctuations in source water in this experiment would still maintain treatment integrity because the same source water used for the nontreated control (pH 7.4-8.1) was used to produce the treatment injected with sulfuric acid (pH 6.0).

Dry weight. Maintaining the pH at 6.0 by adding sulfuric acid or potassium bicarbonate to the source water from ponds used for irrigation did not affect the dry weight (DW) of any of the species tested in this experiment (Table 7). Location affected DW ($P\leq0.10$) for three species; however, the location by treatment interaction was also significant ($P\leq0.06$) for all species tested. None of the six nursery locations applied the same volume of water to plants during the experiment, nor was the application time of day similar (Table 5). This was intentional because the effect of the treatment needed to be averaged over many nursery conditions and species and be visible to nursery producers before advising them to adopt such technology for all plants being grown. Unfortunately, there was no effect of irrigating with either high or low pH water. There was variation in DW, however, associated with nurseries. Therefore, an adhoc regression of dry weight on total alkalinity (ppm) by treatment averaged over all species revealed that this ionic property could be used as a proxy for location to explain the variation in DW (Fig. 2). This suggests that total alkalinity in water is beneficial in regards to crop growth up to approximately 100 ppm across locations. Even though this experiment is essentially neutralizing alkalinity to change pH, total alkalinity was not controlled for as an independent variable, therefore, these ad hoc findings are simply a suggestion for future research, addressing liming recommendations of crops based on total alkalinity in irrigation water, and also to perhaps investigate liming agricultural ponds as an alternative to or in addition to adding lime to substrates. Moreover, reduced growth due to high alkalinity stress is more common in ornamentals than simply high pH stress (Albano et al. 2017, Chen et al. 2003, Valdez et al. 2007, Valdez and Reed 2009). In the event that source water used for irrigation might have total alkalinity above 100 ppm, producers may consider neutralizing it with the addition of sulfuric acid. Otherwise, simply irrigating with high pH water with total alkalinity less than 100 ppm doesn't seem to affect plant growth significantly enough to install an injection system.

Leaf length at the end of the experiment was not affected by maintaining the pH of irrigation water at 6.0 (data not shown). Forsythia leaf elongation rate over eight days was reduced for plants irrigated daily with foliar sprays of pH 6.7 compared to sprays of water (pH not reported), pH 5.0, or pH 5.8 (Wilkinson and Davies 2008). In the current experiment, daily leaf lengths were not measured for any species, therefore, any differences that might have been

Table 7. Analysis of variance for dryweight (DW) (g) and leaf length (LL) (cm) for five species grown at six nurseries (LOC) receiving irrigation treatments (TRT) of either nontreated source water with pH 7.4 to 8.1 or source water treated with either sulfuric acid (reduce pH) or potassium bicarbonate (raise pH) to maintain pH 5.8 to 6.2.

		ABE		BUD		FOR		HYD		ROSE[z]	
		DW	LL	DW	LL	DW	LL	DW	LL	DW	LL
Source	df	*P* value									
LOC (L)	5	0.60	0.01	<0.01	0.01	0.25	0.34	0.06	0.06	0.10	0.25
TRT (T)	1	0.98	0.06	0.21	0.63	0.84	0.32	0.97	0.75	0.55	0.89
T(L)	6	<0.01	0.59	0.06	0.61	0.01	0.26	<0.01	<0.01	<0.01	0.01

[z] ABE=fragrant abelia, *Abelia mosanensis* 'SMNAMDS' Sweet Emotion®; BUD= butterfly bush, *Buddleia* x 'Miss Molly'; FOR=border forsythia, *Forsythia* x *intermedia* 'Mindor' Show Off®; HYD=panicled hydrangea, *Hydrangea paniculata* Siebold 'SMHPLQF' Little Quick Fire®; ROSE=landscape rose, *Rosa* x 'ChewPatout' Oso Easy® Urban Legend®.

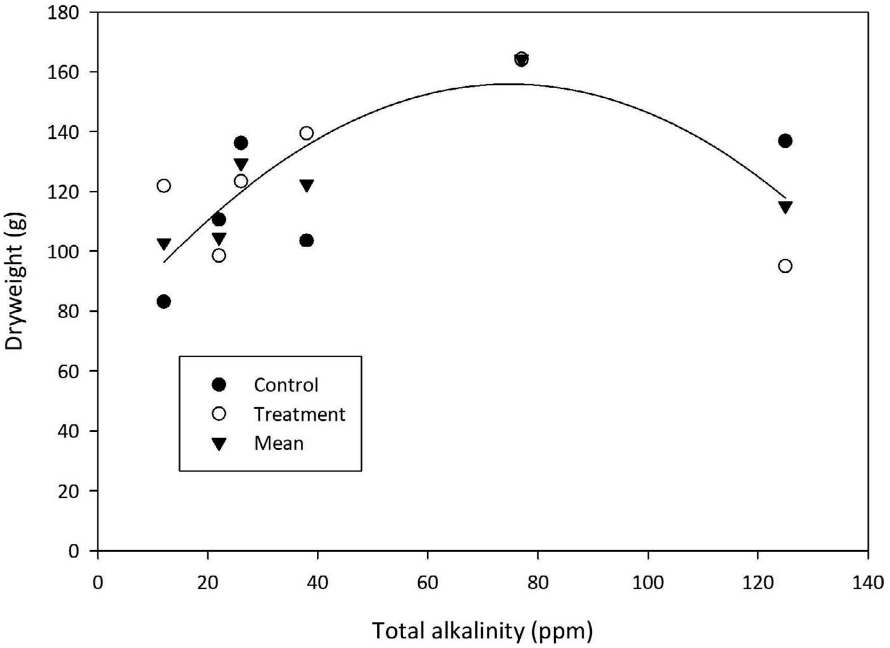

Fig. 2. **Dry weight (g) for five species grown receiving irrigation treatments of either nontreated source water with pH 7.4 to 8.1 (Control, filled circle) or source water treated with either sulfuric acid (reduce pH) or potassium bicarbonate (raise pH) to maintain pH 5.8 to 6.2 (Treatment) (unfilled circle) at six nurseries with increasing total alkalinity (ppm). Data points are means of five species in each treatment. Each treatment had one plot at each nursery with six plants in each plot as replication. Total alkalinity was not an independent variable in the experiment, but averaged over 3-4 samples collected from the source water during the experiment. Regression equation for Mean (filled triangle) DW= $71.1 + 2.28x - 0.02x^2$, $P<0.01$, $r^2=0.71$.**

apparent had leaf length been measured during leaf expansion earlier in the experiment, rather than after growth completed, may have been masked, or not occurred at all.

Physiology. Ambient photosynthesis ($A_{ambient}$) was not affected by reducing the pH of irrigation water, but $A_{ambient}$ was affected by the main effect of irrigation runtime (ANOVA not shown). Generally $A_{ambient}$ was reduced more for plants receiving 60 minutes (-4.9 $\mu molCO_2m^{-2}s^{-1}$) of overhead irrigation than for plants receiving either 0 (-1.9 $\mu molCO_2m^{-2}s^{-1}$) or 30 minutes (-3.8 $\mu molCO_2m^{-2}s^{-1}$) regardless of pH of the irrigation water (Fig. 3). The g_s was not affected by treatment or runtime.

Overall the experiment tested the hypothesis that irrigating with high pH water normally found in nurseries in the southeastern U.S. reduces plant growth by reducing stomatal conductance and thus photosynthesis. The internal runtime by treatment experiments at three locations tested whether predicted differences in growth of all species at the end of the experiment could be attributed to reduced gas exchange of forsythia; however, there was no acute dose response effect of high pH irrigation water on either stomatal conductance, photosynthesis, or DW of forsythia. Simply irrigating for 60 minutes continuously decreased $A_{ambient}$ slightly. Plants in the entire experiment were not grown under these irrigation runtimes daily over the length of the experiment (Table 1) because of variation in frequency and volume of irrigation applied at each nursery (Table 5). These runtime treatments were applied directly only on the days physiology was measured. If a one-time, 60 minute, daily cycle treatment was used at every nursery, however, it's not clear that plants in the control (high pH) would be smaller than plants grown under an artificially lower pH. Many reports state that dividing the total volume of water applied from one entire application into several separate, but equal volumes saves water and mineral nutrients from being leached into production runoff; however, growth of plants in these cyclic treatments is similar to plants in onetime application treatments (Tyler et al. 1996; Beeson 1998; Warren and Bilderback 2002). Additionally, when the entire irrigation volume was applied at one time, but treatment volumes were reduced by either a percentage of the control volume (set at 19 mm) (Beeson 2006) or a percentage of daily water used by each plant (Warsaw et al. 2009), growth was similar to the control for many species. More growers are adopting cyclic irrigation practices to conserve applied mineral nutrients (5 of 6 growers in the present study irrigated cyclically), sensor networks are available for monitoring substrate-available water content to make more informed decisions about irrigation frequency and duration (Bayer et al. 2015, Lichtenberg et al. 2013), and production practices are moving away from one-time, 60 minute irrigation applications toward targeted, measured, efficient systems (Fulcher et al. 2016, Stanley 2013), especially if water is recycled and of poor quality (Bortolini et al. 2018). Moreover, microirrigation application of this high pH source water delivered directly to pine bark soilless substrates would be neutralized easily by the inherent acidity (Lopez et al. 2010). Given current production practice adoption trends, testing whether or not daily 60 minute applications of high pH, low alkaline irrigation water reduces growth may not

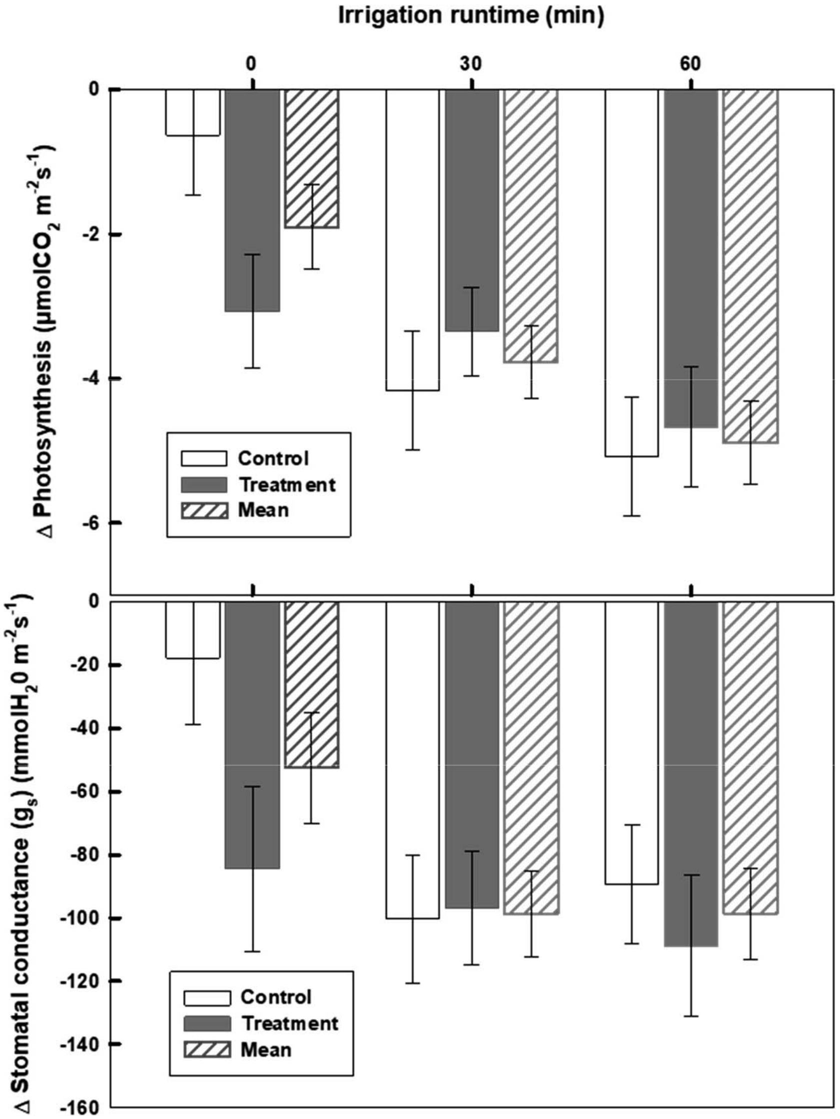

Fig. 3. Difference (pre- and post-irrigation) in (top) photosynthetic rate ($A_{ambient}$) and (bottom) stomatal conductance (g_s) of well-watered plants of *Forsythia* ShowOff® after receiving either 0, 30, or 60 minutes of overhead irrigation runtime using pond water with a pH ranging from 7.6-8.1 (control) or maintained at 6.0 (treatment) using sulfuric acid (lower pH) or potassium bicarbonate (raise pH). Photosynthetic rate at ambient conditions ($A_{ambient}$) and g_s were measured at the average environmental conditions estimated for the entire experiment and were held constant among all measurements at each nursery and measuring periods over the experiment. See text for rates of individual variables. All plants were hand watered to container capacity first, then physiology measurements were collected approximately 30 minutes later. Irrigation treatments were applied after these "preirrigation" readings were completed. Then physiology measurements were repeated approximately 30 minutes after irrigation treatments were completed. Data points are means of two plants (two leaves measured per plant) in each irrigation runtime at three nurseries (A, D, and E) measured three times during summer 2018 (n=18 for each data point). Means (±SEM) with different letters are significantly different at $P<0.05$. There was no difference between the control and treatment at any runtime for either $A_{ambient}$ or g_s.

be informative on an applied level nor would it decrease growth.

The treated irrigation water in the present study was pH 5.8-6.2, while the control was pH 7.4-8.1. Wilkinson and Davies (2008) found that well-watered forsythia receiving 8 single day applications of water with pH 6.7 had reduced g_s on average by 90.8 mmol $H_20{\cdot}m^{-2\cdot}\ s^{-1}$ (photosynthesis was not measured) at ambient conditions compared to plants receiving solutions of water (pH not given) or pH 5.0. Moreover, in that study, forsythia treated with pH 5.8 or pH 6.7 had a mean g_s of 200 or 100 mmol $H_2O{\cdot}m^{-2\cdot}\ s^{-1}$, respectively, regardless of light intensity or leaf temperature, whereas plants treated with pH 5.0 water had a negative linear relationship with those factors from 300 to 100 mmol $H_2O{\cdot}m^{-2\cdot}\ s^{-1}$. Higher pH water, the authors argued, absorbed by the foliage, uncoupled the relationship between g_s, light, and leaf temperature so that g_s remained continuously low despite changes to those variables and as a result growth was decreased. In the present study, the pH of the control and the treatment would both be considered high compared to pH 5.0 in Wilkinson and Davies (2008), and, therefore, might explain no difference in g_s between our treatments. In fact, the mean pre-irrigation g_s for both the control and treatment plants in the 30 and 60 minute runtimes was 211.1 mmol $H_2O{\cdot}m^{-2\cdot}\ s^{-1}$ (data not shown) and was reduced to 98.6 mmol $H_2O{\cdot}m^{-2}\ {\cdot}s^{-1}$ after irrigation (data not shown), similar to the 90.8 mmol $H_2O{\cdot}m^{-2}{\cdot}s^{-1}$ reduction in Wilkinson and Davies (2008) for pH 6.7. In the present study, both control and treatment pH and the cuvette conditions used to measure g_s was high compared to Wilkinson and Davies (2008) [pH 5.8-6.0 (treated) and pH 7.4-8.1 (control) vs. 5.0, light 1700 vs. 1200 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$, and leaf temp 32 C vs. 34 C; present study vs. Wilkinson and Davies (2008), respectively], so this might explain why there were no treatment differences for g_s of forsythia and no growth differences over the length of the experiment. The growing environment in the southeastern U.S. is stressful because of high light, heat, and humidity, which depresses g_s chronically, yet our reduced pH treatment did not alleviate the reduction in g_s. Alternatively, the plants chosen for the experiment are robust, generally, and represent some of the highest revenue producing genera in nursery production, probably because they grow well across many environmental conditions despite the inherent stress.

The plant growth stage when physiology was measured might also explain the lack of treatment differences. In Thetford et al. (1995), mean net photosynthesis (net P) of untreated *Forsythia* x *intermedia* 'Spectabilis' (15.2 $\mu mol\ CO_2{\cdot}m^{-2}{\cdot}s^{-1}$) was similar to mean $A_{ambient}$ of treated and control forsythia preirrigation in the present study (12.8 $\mu mol\ CO_2{\cdot}m^{-2}{\cdot}s^{-1}$) (data not shown) when days after potting (DAP) were aligned [84-150 DAP with 55, 77, 120 days after treatment (DAT) were used from Thetford et al. (1995)] between studies in an attempt to normalize growth stages. Physiology measurements in that study were recorded in more stressful environments in the afternoon (1:00 to 3:00 p.m.) than in the present study and Thetford et al. (1995) did not have the ability to control cuvette conditions (e.g., light or CO_2). When plants were smaller and expanding rapidly in Thetford et al. (1995), net P was 19.9 $\mu mol\ CO_2{\cdot}m^{-2}{\cdot}s^{-1}$ (80 and 86 DAP or 49 and 77 DAT), indicating that treatment differences in the present study might have been recorded had physiology measurements been collected before plants matured in size. For example, exposure to residual herbicides in irrigation water reduced growth and physiology in newly expanded leaves of *Hydrangea paniculata*; however, when exposure ceased, plants recovered quickly from damage (Poudyal et al. 2020). The robustness of popular genera grown in ornamental horticulture to overcome minor setbacks in gas exchange and growth seem to outweigh any reductions perceived in the present study.

To test the hypothesis that high pH water uncouples correlation between g_s, light, and leaf temperature, future experiments might include a pH 5.0 treatment and measure g_s over a series of light and leaf temperatures. Additionally, the volume of water applied among nurseries needs to be monitored more regularly with sensors. If growth differences are found, however, irrigating with pH 5.0 water might not be adopted because such a low pH is below best management practices outlined for southeastern U.S. nursery production (Bilderback et al. 2013, Robbins 2018). Moreover, the mean total alkalinity in pond water is generally <50 ppm (see Table 6 herein) (Copes 2018), so stabilizing pH 5.0 on nurseries might be difficult because little buffering capacity remains after more than 80% of the alkalinity is neutralized. In the present experiment, the authors had difficulty initially setting the correct injection concentration on site because once 80% alkalinity was neutralized the pH would quickly decrease to a pH of 3 or 4. Unfortunately, container producers may not purchase the in-line post injection monitoring equipment necessary to determine if target levels are consistently stable and instead may rely on portable testing kits at the irrigation sprinkler heads (De Hayr et al. 1994). All irrigation remediation treatments benefit from filtering organic matter and sediment first before injecting chemicals to lower pH, reduce pathogens, or increase nutrition. Therefore, if producers were to adopt acid injection, increased filtration would improve efficiency. Cost analysis of water treatment technologies must account for the price of equipment, installation, consumables such as sulfuric acid, sanitizing chemicals, electricity, and labor cost for maintenance over the system's useful life (Raudales et al. 2017). To access reduced pH irrigation water in the pond's profile, if possible with deep ponds, producers could simply lower the intake pipe below the thermal stratification layer where lower pH has been recorded (Zhang et al. 2015). Unless producers are also chlorinating to sanitize irrigation water and reduce microorganisms, it might not be feasible to install acid injection to lower pH given the small growth increases hypothesized, but as yet unseen.

Literature cited

Albano, J.P., J. Altland, D.J. Merhaut, S.B. Wilson, and P. C. Wilson. 2017. Irrigation water acidification to neutralize alkalinity for nursery crop production: substrate pH, electrical conductivity, nutrient concentrations, and plant nutrition and growth. Hortscience 52:1401–1405.

Bayer, A., J. Ruter, and M.W. van Iersel. 2015. Automated irrigation control for improved growth and quality of *Gardenia jasminoides* 'Radicans' and 'August Beauty.' HortScience 50:78–84

Beeson, R.C., Jr. 1998. Effect of cyclic overhead irrigation on the growth of ten species of woody ornamentals grown in #1 containers. Proc. Southern Nursery Assoc. Res. Conf. 43:502–505.

Beeson, R.C., Jr. 2006. Relationship of plant growth and actual evapotranspiration to irrigation frequency based on management allowed deficits for container nursery stock. J. Amer. Soc. Hort. Sci. 131:140–148.

Bilderback, T., C. Boyer, M. Chappell, G. Fain, D. Fare, C. Gilliam, B.E. Jackson, J. Lea-Cox, A.V. LeBude, A. Niemiera, J. Owen, J. Ruter, K. Tilt, S. Warren, S. White, T. Whitewell, R. Wright, and T. Yeager. 2013. Best management practices: Guide for producing nursery crops. 3rd ed. South. Nurs. Assoc., Acworth, GA.

Bohlen, J., C.M. Coughenour, H.F. Lionberger, E.O. Moe, and E.M. Rogers. 1962. Adoption of new farm ideas: characteristics and communications behavior. North Central Regional Publication No. 13. 12 p.

Bortolini, L., C. Maucieri, and M. Borin. 2018. A tool for the evaluation of irrigation water quality in the arid and semi-arid regions. Agronomy 8:doi:10.3390/agronomy8020023.

Chen, J., R.C. Beeson, T.H. Yeager, R.H. Stamps, and L.A. Felter. 2003. Evaluation of captured rainwater and irrigation runoff for greenhouse foliage and bedding plant production. HortScience 38:228–233.

Copes, W.E., A. Ristvey, P.A. Richardson, B.E. Belayneh, H. Zhang, J. Lea-Cox, and C. Hong. 2018. Monthly levels and criteria considerations of nutrient, pH, alkalinity, and ionic variables in runoff containment basins in ornamental plant nurseries. HortScience 53:360–372.

Copes, W.E., H. Zhang, P.A. Richardson, B.E. Belayneh, A. Ristvey, J. Lea-Cox, and C. Hong. 2017. Nutrient, pH, alkalinity, and ionic property levels in runoff containment basins in Alabama, Louisiana, Maryland, Mississippi, and Virginia ornamental plant nurseries. HortScience 52:641–648.

Davies, W.J., G. Kudoyarova, and W. Hartung. 2005. Long-distance ABA signaling and its relation to other signaling pathways in the detection of soil drying and the mediation of the plant's response to drought. J. Plant Growth Regul. 24:285–295.

De Hayr, R., K. Bodman, and L. Forsberg. 1994. Bromine and chlorine disinfestation of nursery water supplies. Comb. Proc. Int. Plant Prop. Soc. 44:60–66.

Fulcher, A., A.V. LeBude, J.S. Owen, Jr., S.A. White, and R.C. Beeson. 2016. The next ten years: strategic vision of water resources for nursery producers. HortTechnology 26:121–132.

Geilfus, C.-M. and K. H. Muhling. 2012. Transient alkalinization in the leaf apoplast of Vicia faba L. depends on NaCl stress intensity: an in situ ratio imaging study. Plant, Cell and Environment 35:578–587.

Lembi, C. 2002. Aquatic plant management: barley straw for algae control. Purdue Extension APM-1-W. p. 1–8.

Lichtenberg, E., J. Majsztrik, and M. Saavoss. 2013. Profitability of sensor-based irrigation in greenhouse and nursery crops. HortTechnology 23:770–774.

Lopez, R.G., M.V. Mickelbart, and C. Pasian. 2010. Alkalinity management in soilless substrates. Purdue Extension HO-242-W. https://www.extension.purdue.edu/extmedia/ho/ho-242-w.pdf. Accessed October 23, 2020.

Mack, R., J.S. Owen, A.X. Niemiera, and J. Latimer. 2017. Virginia nursery and greenhouse grower survey of best management practices. HortTechnology 27:386–292.

Ma, W.-X., T.-L. Huang, and X. Li. 2015. Study of the application of the water-lifting aerators to improve the water quality of a stratified, eutrophicated reservoir. Ecological Engineering 83:281–290.

Poudyal, S., J.S. Owen, Jr., R.T. Fernandez, and B. Cregg. 2020. Sensitivity of *Hydrangea paniculata* plants to residual herbicides in recycled irrigation varies with plant growth stage. Water 12:1402.

Raudales, R.E., P.R. Fisher, and C.R. Hall. 2017. The cost of irrigation sources and water treatment in greenhouse production. Irrig. Sci. 35:43–54.

Robbins, J. 2018. Irrigation water for greenhouses and nurseries. Univ. Arkansas Coop. Ext. Ser. Agr. Nat. resources Bull. FSA6061-PD-5-2018RV. p. 1–6.

SAS/STAT User's Guide 15.1. 2019. Kenward-Roger degrees of freedom approximation. SAS Institute Inc., Cary, NC, USA. Reprinted with permission. All rights reserved.

Stanley, J. 2013. Using leaching fractions to maximize irrigation efficiency. Acta Hortic. 1014:331–334. DOI: 10.17660/ActaHortic.2013.1014.74.

Storlie, C. 1995. Controlling bacteria, algae, and weeds in irrigation ponds. Rutgers Extension FS796. p. 1–2.

Thetford, M., S.L. Warren, F.A. Blazich, and J. Thomas. 1995. Response of *Forsythia* x *intermedia* 'Spectabilis' to Uniconazole II: leaf and stem anatomy, chlorophyll, and photosynthesis. J. Amer. Soc. Hort. Sci. 120:983–988.

Tucker, C.S. and L.R. D'Abramo. 2008. Managing high pH in freshwater ponds. Southern Region Aquaculture Center Pub. No. 4604. p. 1–5.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Cyclic irrigation increases irrigation application efficiency and decreases ammonium losses. J. Environ. Hort. 14:194–198.

Valdez-Aguilar, L.A., C.M. Grieve, J. Poss, and M.A. Mellano. 2009. Hypersensitivity of *Ranunculus asiaticus* to salinity and alkaline pH in irrigation water in sand cultures. HortScience 44:138–144.

Valdez-Aguilar, L.A. and D.W. Reed. 2007. Response of selected greenhouse ornamental plants to alkalinity in irrigation water. J. Plant Nutrition 30(3):441–452.

Warren, S.L. and T.E. Bilderback. 2002. Timing of low pressure irrigation affects plant growth and water utilization efficiency. J. Environ. Hort. 20(3):184–188.

Warsaw, A.L., R.T. Fernandez, B.M. Cregg, and J.A Andresen. 2009. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. Hortscience 44:1308–1318.

White, S.A., B. Seda, M. Cousins, S.J. Klaine, and T. Whitwell. 2009. Nutrient remediation using vegetated floating mats. Proc. South Nur. Assoc. Research Conference 54:39–43.

White, S.A., M.D. Taylor, R.F. Polomski, and J.P. Albano. 2011. Constructed Wetlands: A How to Guide for Nurseries. Environmental Resource Management Research Group, Floriculture and Nursery Research Initiative, United States Department of Agriculture-Agricultural Research Service, Horticulture Research Institute, SCA #58-6618-7-216. p. 1–30.

Wilkinson, S. and W.J. Davies. 2008. Manipulation of the apoplastic pH of intact plants mimics stomatal and growth responses to water availability and microclimatic variation. Exp. Bot. 59:619–631.

Zhang, H., P.A. Richardson, B.E. Belayneh, A. Ristvey, J. Lea-Cox, W.E. Copes, G.W. Moorman, and C. Hong. 2015. Characterization of water quality in stratified nursery recycling irrigation reservoirs. Agriculture Water Management 160:76–83.

Zhang, H., P.A. Richardson, B.E. Belayneh, A. Ristvey, J. Lea-Cox, W.E. Copes, G.W. Moorman, and C. Hong. 2016. Recycling irrigation reservoir stratification and implications for crop health and production. J. Amer. Water Resources Association 52:620–631.

Zhang, X., X. Liu, M. Zhang, R.A. Dahlgren, and M. Eitzel. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. J. Environ. Qual. 39:76–84.