Greenhouse Culture and Production of Four Ornamental Native Wetland Plants

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ADDITIONAL INDEX WORDS. broadleaf sagittaria, *Sagittaria latifolia*, skyflower, *Hydrolea corymbosa*, cardinal flower, *Lobelia cardinalis*, string lily, *Crinum americanum*, habitat restoration, subirrigation

SUMMARY. Wetland restoration is an important way to improve ecosystem services, but many wetland nurseries lack the facilities that are traditionally used to produce large numbers of native plants used in these projects. Our goal was to evaluate growth and performance of four wetland species in a variety of substrates, fertilizer regimes, and irrigation methods under greenhouse conditions. Plants were grown in pots with drainage holes filled with one of four substrates (potting substrate, topsoil, sand, 50/50 mix of topsoil, and sand) amended with 0, 1, 2, or 4 g of 15N–3.9P–10K controlled-release fertilizer per liter of substrate. Irrigation was supplied via an overhead system or subirrigation. After 16 weeks of production, plants were scored for visual quality and plant height before a destructive harvest. Broadleaf sagittaria (*Sagittaria latifolia*) was mostly unaffected by substrate type but performed best when subirrigated and fertilized with 4 g·L⁻¹ of fertilizer. Growth of skyflower (*Hydrolea corymbosa*) and cardinal flower (*Lobelia cardinalis*) was best when fertilized with 2 or 4 g·L⁻¹ of fertilizer and grown using overhead irrigation. String lily (*Crinum americanum*) was unaffected by substrate type but produced the largest plants when subirrigated. These experiments provide guidance for cultivating these wetland species under greenhouse conditions, which may allow growers to efficiently produce plant material needed for the restoration market.

Aquatic and wetland restoration and mitigation has become an increasingly important activity that improves ecosystem services and provides habitat for native flora and fauna (Brix, 1994). This has created a growing market for wetland plants required for these projects, but many wetland nurseries lack the facilities and infrastructure to produce large numbers of plants. This problem could be addressed by developing methods to grow these wetland species using greenhouse and nursery

techniques similar to those used to culture other ornamental plants.

Habitat restoration and enhancement projects include a diversity of plant types and sizes to ensure that a heterogeneous architecture is created to attract an assemblage of native animals (Ma et al., 2010; Tews et al., 2004). Selecting ornamental plants for inclusion in these projects can satisfy multiple objectives, as the result can be aesthetically pleasing to stakeholders while providing habitat for native faunal denizens of aquatic and wetland environments. We focused our efforts on four ornamental native wetland species—broadleaf sagittaria, skyflower, cardinal flower, and string lily—for evaluation in these experiments. All four species are perennials native to the United States and are easily propagated via division (broadleaf sagittaria), twin

scaling (string lily), cuttings (skyflower), or seed (cardinal flower). These perennial native wetland plants were selected for inclusion in these experiments because they are “double-duty” species; they provide desirable characteristics such as habitat creation and bank stabilization in restoration projects and are also frequently included in water gardens and shoreline plantings because of their ornamental nature. Our goal was to identify optimum cultivation conditions for these wetland plants by evaluating their growth and performance in a variety of substrates, fertilizer regimes, and irrigation methods. These experiments were designed to provide insight into whether wetland plant nurseries could use existing facilities to increase production of desirable native wetland plants, with the aim of meeting market demands without costly infrastructure upgrades.

Materials and methods

Broadleaf sagittaria and string lily experiments were started on 23 Dec. 2014 and 19 Feb. 2015, respectively, from field-collected material with foliage that was ≈30 cm tall. The skyflower experiment was started on 27 Jan. 2015 from well-rooted cuttings that were ≈25 cm in height. The cardinal flower study began on 29 Jan. 2015 from 6-month-old seedlings that were ≈5 cm tall with well-developed rosettes comprising a minimum of 20 leaves that were ≈8 cm long. A total of 128 plants of each species were transplanted into traditional 7–7/8-inch-diameter azalea pots (3.05 L) with drainage holes and filled with potting substrate [45% peat, 25% bark, 35% vermiculite (Fafard 4M; Sun Gro Horticulture, Anderson, SC)], topsoil [a regionally formulated mix of organic and mineral components comprising 35% to 50% organic matter (Timberline Top Soil; Oldcastle Lawn and Garden, Atlanta, GA)], sand [grain diameter 0.25–0.5 mm (Multi-Purpose Sand; Sakrete, Charlotte, NC)], or 50/50

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
10	%	g·L ⁻¹	0.1
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
28.3495	oz	g	0.0353
7.4892	oz/gal	g·L ⁻¹	0.1335
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

(v/v) mix of topsoil and sand (hereafter “mix”). Before planting, 15N–3.9P–10K controlled-release fertilizer (Osmocote Plus formulated for 6-month release in Florida; ICL Specialty Fertilizers, Dublin, OH) was placed in a layer ≈ 8 cm below the surface of the substrate at rates of 0, 1, 2, or 4 g of fertilizer per liter of substrate (0, 0.45, 0.91, or 1.83 g/pot N). Plants were divided into two groups that received either overhead irrigation or subirrigation. Plants receiving overhead irrigation were grown on nursery benches in a completely randomized design with respect to substrate and nutrient treatment combinations and irrigated at 10:00 AM and 4:00 PM daily with the equivalent of 0.5 inch of water per irrigation. Subirrigated treatments were placed in a completely randomized design in flood trays constructed from 2 $\times$ 6-inch lumber and lined with 6-mil clear poly sheeting; a constant water depth of 2 inches was maintained using a float system that automatically triggered the addition of water when the depth fell below 1.5 inches. All treatment combinations (substrate $\times$ nutrient $\times$ irrigation) were replicated four times for each species. Four flood trays were constructed for each species and one replication of each treatment combination was maintained in each flood tray. Plants were grown in an open-sided greenhouse exposed to ambient air temperatures and relative humidity located at the University of Florida Fort Lauderdale Research and Education Center in Davie, FL. Experiments were conducted from Jan. to June 2015; average daytime high temperatures ranged from 75 to 89 °F, average nighttime low temperatures ranged from 59 to 78 °F, and average relative humidity was 76%.

After 16 weeks of growth, plants were assigned a numerical value of 1 through 10 to indicate visual quality (1 = dead; 5 = fair quality, acceptable, somewhat desirable form and color, and little to no chlorosis or necrosis; 10 = excellent quality, perfect condition, healthy and robust, premium color and form, and very marketable). Plant height was recorded immediately before a destructive harvest of all live plant material. The plants were separated into aboveground shoots and belowground roots. Shoots were shaken to remove any soil particles or other debris, then placed in paper

bags and moved to a forced-air oven set for 65 °C. The roots were washed over aluminum screening [mesh size 18 $\times$ 16, aperture 0.0445 $\times$ 0.0515 inch (Insect Screen; ADFORS Saint-Gobain, Grand Island, NY)] attached to a frame constructed from 2 $\times$ 6-inch lumber and allowed to air-dry for ≈ 4 h. Any substrate remaining in the washed roots was removed by hand before the air-dried roots were transferred to paper bags and placed in a forced-air oven at 65 °C for a minimum of 1 week.

STATISTICAL ANALYSIS. Response data were analyzed by species using generalized linear mixed models methodology as implemented in SAS PROC GLIMMIX (SAS/STAT version 14.1; SAS Institute, Cary, NC). Irrigation regimen, substrate, and their interaction were treated as fixed effects. The response to fertilizer rate was modeled as a linear regression nested within each irrigation $\times$ substrate combination. Random effects were tray within irrigation and the residual error term, the latter serving as the experimental error for substrate, fertilizer rate, and all interaction terms. The primary purpose of this modeling was to determine the importance of interactions between the fixed effects; strong interactions indicate that optimal growing conditions are best characterized by specific combinations of the fixed effects because main effects are not additive.

Visual quality, plant height, and dry weights (shoot, root, and total) were ranked from “best” to “worst” within each species. An overall ranking was calculated as the mean of these five values, which was then used to determine which substrate and irrigation combination produced the best growth by each wetland plant evaluated in these experiments.

Results

Fertilizer rate was fitted with a second-order polynomial nested within each of six irrigation $\times$ substrate level combinations; i.e., each combination had a separate intercept and slope. All species, except for string lily, had a significant second-order polynomial response to increasing fertilizer rate. We discuss irrigation $\times$ substrate interaction means at an intermediate fertilizer rate of 2 g·L⁻¹, which was optimal or near optimal for all species.

Irrigation $\times$ Fertilizer Interaction was not significant for broadleaf sagittaria and string lily for any response variable. For cardinal flower and skyflower, the interaction was significant ($P < 0.01$) for all traits but visual score.

Irrigation Main effect was significant for every response variable measured on broadleaf sagittaria but not for any other species evaluated.

Substrate Main effect was not significant for broadleaf sagittaria and string lily for any response variable. For cardinal flower and skyflower, the substrate main was significant ($P < 0.01$) for all traits but visual score.

Interaction means (specific combinations of irrigation and substrate) provide the most informative assessment of the response variables; each species will be discussed in detail.

BROADLEAF SAGITTARIA. There were no significant ($P < 0.05$) differences among substrates for any response variable when evaluated under overhead irrigation. With subirrigation, significant differences existed for root, shoot, and total dry weight, with potting substrate and topsoil having the largest and smallest response, respectively. Mean dry weights were 10.9 g (shoots), 6.9 g (roots), and 17.8 g (total) for subirrigated plants grown in potting substrate, whereas subirrigated plants grown in topsoil produced shoots, roots, and total biomass that weighed 4.6, 3.7, and 8.3 g, respectively. Subirrigation resulted in a numerically larger response for all response variables in all substrates and the four highest-ranked treatment combinations used subirrigation (Table 1). For some combinations, subirrigation resulted in a 2.5 to 4-fold increase. For example, mean shoots, roots, and total dry weights of plants grown in potting substrate with subirrigation were 10.9, 6.9, and 17.8 g, respectively. By contrast, plants grown in the same substrate with overhead irrigation produced shoots, roots, and total biomass that weighed 2.9, 2.1, and 5.0 g, respectively. A similar trend occurred with plants grown in sand. Based on these analyses, greenhouse production of broadleaf sagittaria should include ≥ 2 g·L⁻¹ of fertilizer and should use subirrigation, as that irrigation scheme yielded higher values for all parameters measured in these

Table 1. Interactive effect of substrate type $\times$ irrigation scheme on quality, height, and dry weight means of four wetland plants after 16 weeks of culture in substrate amended with $2 \text{ g} \cdot \text{L}^{-1}$ ($0.27 \text{ oz} \cdot \text{gal}^{-1}$) of controlled-release fertilizer. Values are the mean of four replications and are followed by the value's ranking within the eight treatment combinations in parentheses.

Substrate ^a	Irrigation ^b	Quality [1–10 (rank)] ^{c,w}	Ht [cm (rank)] ^v	Shoot wt [g (rank)] ^v mean $\pm$ SD	Root wt [g (rank)]	Total wt [g (rank)]	Overall ranking ^w
Broadleaf sagittaria							
Potting	Sub	6.8 $\pm$ 1.7 (2)	36.0 $\pm$ 2.9 (2)	10.9 $\pm$ 2.1 (1)	6.9 $\pm$ 5.9 (1)	17.8 $\pm$ 7.4 (1)	1.4
Sand	Sub	7.8 $\pm$ 1.9 (1)	44.5 $\pm$ 12.1 (1)	5.4 $\pm$ 2.8 (3)	3.9 $\pm$ 2.0 (3)	9.3 $\pm$ 4.8 (3)	2.2
Mix	Sub	5.5 $\pm$ 3.1 (4)	34.3 $\pm$ 23.5 (4.5*)	6.6 $\pm$ 5.1 (2)	5.9 $\pm$ 5.4 (2)	12.5 $\pm$ 10.5 (2)	2.9
Topsoil	Sub	5.3 $\pm$ 2.9 (5)	34.3 $\pm$ 23.6 (4.5*)	4.6 $\pm$ 3.2 (4)	3.7 $\pm$ 4.1 (4)	8.3 $\pm$ 6.6 (4)	4.3
Mix	Over	6.5 $\pm$ 0.6 (3)	35.8 $\pm$ 2.3 (3)	4.0 $\pm$ 0.5 (5)	2.9 $\pm$ 0.3 (5)	6.9 $\pm$ 0.8 (5)	4.2
Potting	Over	5.0 $\pm$ 0.8 (6)	28.0 $\pm$ 1.9 (6)	2.9 $\pm$ 0.1 (6)	2.1 $\pm$ 0.1 (6)	5.0 $\pm$ 0.2 (6)	6.0
Sand	Over	4.0 $\pm$ 0.8 (7)	27.0 $\pm$ 6.0 (7)	2.3 $\pm$ 0.8 (7)	1.7 $\pm$ 0.6 (7)	3.9 $\pm$ 1.4 (7)	7.0
Topsoil	Over	3.3 $\pm$ 2.6 (8)	21.3 $\pm$ 11.8 (8)	2.0 $\pm$ 1.7 (8)	1.4 $\pm$ 1.3 (8)	3.4 $\pm$ 3.0 (8)	8.0
Cardinal flower							
Potting	Over	8.8 $\pm$ 1.3 (1.5*)	11.6 $\pm$ 2.9 (1)	8.0 $\pm$ 3.3 (1)	7.2 $\pm$ 3.6 (1)	15.2 $\pm$ 6.6 (1)	1.1
Mix	Over	8.8 $\pm$ 1.3 (1.5*)	9.9 $\pm$ 1.5 (3)	4.8 $\pm$ 1.4 (5)	6.2 $\pm$ 0.3 (2)	10.9 $\pm$ 1.4 (2)	2.7
Topsoil	Over	8.3 $\pm$ 1.0 (3)	9.8 $\pm$ 1.4 (4.5*)	6.0 $\pm$ 1.1 (2)	4.1 $\pm$ 1.8 (3)	10.1 $\pm$ 2.1 (3)	3.1
Sand	Over	7.5 $\pm$ 1.3 (5)	10.0 $\pm$ 2.7 (2)	4.4 $\pm$ 1.9 (6)	4.0 $\pm$ 2.3 (4)	8.4 $\pm$ 4.0 (4)	4.2
Sand	Sub	8.0 $\pm$ 1.4 (4)	9.8 $\pm$ 1.7 (4.5*)	5.1 $\pm$ 2.4 (3)	2.2 $\pm$ 1.0 (6)	7.3 $\pm$ 3.3 (6)	4.7
Potting	Sub	6.3 $\pm$ 2.2 (6)	9.4 $\pm$ 2.8 (6)	5.0 $\pm$ 2.8 (4)	3.2 $\pm$ 0.5 (5)	8.2 $\pm$ 2.9 (5)	5.2
Mix	Sub	4.8 $\pm$ 2.9 (7)	4.8 $\pm$ 3.4 (7)	1.0 $\pm$ 1.1 (7)	0.6 $\pm$ 0.6 (7)	1.6 $\pm$ 1.6 (7)	7.0
Topsoil	Sub	1.8 $\pm$ 1.0 (8)	1.3 $\pm$ 1.9 (8)	0.2 $\pm$ 0.2 (8)	0.1 $\pm$ 0.2 (8)	0.3 $\pm$ 0.4 (8)	8.0
Skyflower							
Potting	Sub	6.3 $\pm$ 2.1 (4.5*)	63.8 $\pm$ 17.6 (1)	6.8 $\pm$ 4.7 (1)	3.3 $\pm$ 2.0 (1)	10.1 $\pm$ 6.7 (1)	1.7
Topsoil	Over	8.0 $\pm$ 1.2 (1)	52.0 $\pm$ 5.5 (4)	6.2 $\pm$ 2.2 (2)	2.4 $\pm$ 1.2 (3.5*)	8.6 $\pm$ 3.2 (2)	2.5
Sand	Sub	6.3 $\pm$ 1.7 (4.5*)	61.8 $\pm$ 12.3 (2)	5.6 $\pm$ 3.5 (3)	2.6 $\pm$ 2.4 (2)	8.2 $\pm$ 5.8 (3)	2.9
Mix	Over	7.3 $\pm$ 1.0 (2)	57.0 $\pm$ 3.7 (3)	4.7 $\pm$ 2.5 (4)	1.5 $\pm$ 0.5 (5)	6.2 $\pm$ 2.9 (5)	3.8
Sand	Over	6.5 $\pm$ 0.6 (3)	50.8 $\pm$ 6.2 (5)	4.0 $\pm$ 1.9 (5)	2.4 $\pm$ 0.7 (3.5*)	6.4 $\pm$ 2.6 (4)	4.1
Potting	Over	5.3 $\pm$ 1.5 (6)	42.8 $\pm$ 14.0 (6)	2.2 $\pm$ 2.1 (6)	1.4 $\pm$ 1.3 (6)	3.6 $\pm$ 3.4 (6)	6.0
Mix	Sub	2.3 $\pm$ 2.5 (7)	26.3 $\pm$ 17.1 (7)	0.8 $\pm$ 1.0 (7)	0.4 $\pm$ 0.7 (7)	1.2 $\pm$ 1.7 (7)	7.0
Topsoil	Sub	1.0 $\pm$ 0.0 (8)	0.0 $\pm$ 0.0 (8)	0.0 $\pm$ 0.0 (8)	0.0 $\pm$ 0.0 (8)	0.0 $\pm$ 0.0 (8)	8.0
String lily							
Topsoil	Sub	7.8 $\pm$ 1.7 (1)	55.4 $\pm$ 8.3 (1)	6.5 $\pm$ 3.2 (1)	5.1 $\pm$ 2.1 (1.5*)	11.6 $\pm$ 5.1 (1)	1.1
Mix	Sub	6.5 $\pm$ 3.1 (2)	42.1 $\pm$ 19.6 (2)	5.8 $\pm$ 2.0 (2)	5.1 $\pm$ 2.4 (1.5*)	10.9 $\pm$ 4.3 (2)	1.9
Potting	Sub	5.5 $\pm$ 3.5 (4)	34.6 $\pm$ 26.4 (3)	4.7 $\pm$ 2.1 (3)	4.0 $\pm$ 1.2 (3)	8.7 $\pm$ 3.2 (3)	3.2
Topsoil	Over	6.3 $\pm$ 3.1 (3)	22.1 $\pm$ 12.8 (4)	2.2 $\pm$ 0.8 (6)	2.8 $\pm$ 0.7 (5)	5.0 $\pm$ 1.0 (5)	4.6
Sand	Over	4.3 $\pm$ 2.2 (6)	14.4 $\pm$ 9.2 (8)	2.3 $\pm$ 1.5 (5)	3.3 $\pm$ 2.6 (4)	5.6 $\pm$ 4.0 (4)	5.4
Sand	Sub	3.0 $\pm$ 1.2 (8)	14.5 $\pm$ 7.0 (7)	2.4 $\pm$ 0.4 (4)	2.5 $\pm$ 0.5 (7)	4.9 $\pm$ 0.5 (6)	6.4
Mix	Over	3.5 $\pm$ 1.9 (7)	15.1 $\pm$ 7.7 (5.5*)	1.9 $\pm$ 0.4 (7.5*)	2.7 $\pm$ 1.1 (6)	4.6 $\pm$ 1.3 (7)	6.6
Potting	Over	4.8 $\pm$ 3.1 (5)	15.1 $\pm$ 11.5 (5.5*)	1.9 $\pm$ 0.7 (7.5*)	2.0 $\pm$ 0.4 (8)	3.9 $\pm$ 1.1 (8)	6.8

^aPotting = 45% peat, 25% bark, 35% vermiculite (Fafard 4M Mix; Sun Gro Horticulture); topsoil = regionally formulated mix of organic and mineral components comprising 35% to 50% organic matter (Timberline Top Soil; Oldcastle Lawn and Garden); sand = Multi-Purpose Sand; Sakrete; mix = 50/50 (v/v) mix of topsoil and sand.

^bSub = subirrigation via flood trays maintained at a depth of 4 cm (1.6 inch); over = 0.5 inch of overhead irrigation twice daily (1 inch/d); 1 inch = 2.54 cm.

^c1 = dead; 5 = fair quality, acceptable, somewhat desirable form and color; little to no chlorosis or necrosis; 10 = excellent quality, perfect condition, healthy and robust, premium color and form, and very marketable.

^w1 = best, 8 = worst, * = tied ranking; overall ranking = mean of rankings of the five characters evaluated for each treatment combination.

^v1 cm = 0.3937 inch, 1 g = 0.0353 oz.

studies. Although substrate did not affect plant height or visual score, growth (measured as shoot, root, and total dry biomass) was consistently highest in subirrigated plants grown in potting substrate and lowest in plants cultured in topsoil.

CARDINAL FLOWER. There were no significant ($P < 0.05$) differences among substrates for any response variable when evaluated under overhead irrigation, except for root dry biomass. With subirrigation, significant differences existed for all response variables, except visual rating, with sand and topsoil having the largest and smallest response, respectively. Plant height averaged 11.6 cm and mean dry weights were 8.0 g (shoots), 7.2 g (roots), and 15.2 g (total) for overhead irrigated plants grown in potting substrate, whereas subirrigated plants in potting substrate averaged 9.4 cm tall and produced shoots, roots, and total biomass that weighed 5.0, 3.2, and 8.2 g, respectively. The response to irrigation was always larger for overhead irrigation than for subirrigation and the four highest ranked treatment combinations used overhead irrigation (Table 1). For example, plants that were overhead irrigated and grown in topsoil generated shoots, roots, and total biomass that weighed an average of 6.0, 4.1, and 10.1 g, respectively; this represents a more than 20-fold increase in dry weights compared with subirrigated plants grown in topsoil. Although irrigation as a main effect was not significant, cardinal flower grown using overhead irrigation performed equally well in all substrates, except root dry biomass was lowest in plants grown in topsoil. By contrast, the strong interaction between irrigation and substrate type produced subirrigated plants cultured in topsoil that were shorter and accumulated less root, shoot, and total dry biomass, whereas subirrigated plants cultured in potting substrate or sand were taller and gained larger amounts of shoot, root, and total dry biomass. These data suggest that greenhouse production of cardinal flower will likely be most successful when plants are cultured with ≥ 2 g·L⁻¹ of fertilizer and grown using overhead irrigation.

SKYFLOWER. There were no significant ($P < 0.05$) differences among substrates for any response variable when evaluated under overhead irrigation, except for shoot dry weight

and visual rating. With subirrigation, significant differences existed for all response variables, with mix and topsoil having the poorest response; plants grown in either of these substrates performed much better under overhead irrigation compared with subirrigation (Table 1). For example, plants that were overhead irrigated and grown in mix were 57 cm tall on average and had shoots, roots, and total dry weights of 4.7, 1.5, and 6.2 g, respectively. By contrast, subirrigated plants grown in mix were only 26.3 cm tall and produced shoots, roots, and total dry biomass that weighed 0.8, 0.4, and 1.2 g, respectively. Also, plants grown in topsoil with overhead irrigation were an average of 52.0 cm tall and had shoots, roots, and total dry weights of 6.2, 2.4, and 8.6 g, respectively, whereas all subirrigated skyflower plants grown in topsoil died before the end of these experiments. Similar to cardinal flower, irrigation as a main effect was not significant. As with cardinal flower, a strong interaction between irrigation and substrate type resulted in poor performance (in the case of skyflower, plant death) of subirrigated plants cultured in topsoil, whereas subirrigated plants cultured in potting substrate or sand were taller and gained more shoots, roots, and total dry biomass. The four highest overall rankings found that growth was best when plants were subirrigated and grown in potting substrate or sand (overall rankings 1.7 and 2.9, respectively) or when plants were overhead irrigated and grown in topsoil or mix (overall rankings 2.5 and 3.8, respectively). As such, greenhouse production of skyflower will likely be most successful when plants are cultured with ≥ 2 g·L⁻¹ of fertilizer and grown in potting substrate or sand with subirrigation or in topsoil or mix with overhead irrigation.

STRING LILY. There were no significant ($P < 0.05$) differences among substrates for any response variable when evaluated under overhead irrigation and fertilizer rate had no effect on growth of string lily. With subirrigation, significant differences existed for all response variables, except for visual rating, with potting substrate and sand having the poorest response. Subirrigation generally resulted in healthier plants compared with overhead. For example, plants

that were overhead irrigated and grown in potting substrate were 15.1 cm tall on average and had shoots, roots, and total dry weights of 1.9, 2.0, and 3.9 g, respectively. By contrast, subirrigated plants grown in potting substrate were 34.6 cm tall and produced shoots, roots, and total dry biomass that weighed 4.7, 4.0, and 8.7 g, respectively. The three highest ranked treatments used subirrigation (Table 1), so greenhouse production of string lily will be most successful when plants are cultured with any amount of fertilizer, grown under subirrigated conditions, and any substrate except sand.

Discussion

These experiments revealed several commonalities among optimum culture conditions for broadleaf sagittaria, skyflower, cardinal flower, and string lily. With the exception of cardinal flower, best growth (measured as plant height and biomass accumulation) was realized when plants were subirrigated. There was a consistent preference among these species for higher [i.e., 2 or 4 g·L⁻¹ (0.91 and 1.83 g/pot N)] fertilizer rates. We would expect plant growth to increase as fertilizer rate increased. Moore et al. (2006) reported that buttonbush (*Cephalanthus occidentalis*), water mint (*Mentha aquatica*), skyflower, and lizard's tail (*Saururus cernuus*) shoot dry weight for plants watered three times per day using an overhead system (50 mL of water per irrigation) and fertilized with 5.25 g of N per 3.3-L pot (almost twice the highest nutrient rate in our studies) was greater than for plants watered three times per day and fertilized with 1.8 g/pot N.

Broadleaf sagittaria and string lily showed no substrate preference, whereas skyflower and cardinal flower did not grow well in topsoil. Broschat and Moore (2001) suggested that greater salvia (*Salvia splendens*), marigold (*Tagetes patula*), bell pepper (*Capsicum annuum*), impatiens (*Impatiens wallerana*), and begonia (*Begonia × semperflorens-cultorum*) growth in a commercial peat/perlite/vermiculite substrate [75% to 85% peat, 15% to 25% perlite, and vermiculite (Pro-Mix BX; Premier Tech Horticulture, Quakertown, PA)] compared with pine bark mix might have been due to the greater water-holding capacity of the peat/perlite/vermiculite substrate.

Coarse-textured soils often do not saturate efficiently when using subirrigation because they lack sufficient small pore spaces to allow for capillary water uptake (Biernbaum, 1993; Newman, 1999). In most cases, cardinal flower and skyflower grew best when watered via overhead irrigation, although several plants grown in potting substrate and maintained under subirrigation performed well. By contrast, broadleaf sagittaria and string lily grew better under subirrigation. Most subirrigation substrates tend to be fine textured with abundant micropores (Biernbaum, 1993). Klock-Moore and Broschat (2001) reported that pentas (*Pentas lanceolata*), crossandra (*Crossandra infundibuliformis*), and philodendron (*Philodendron* 'Hope') were larger in pots filled with a peat/perlite/vermiculite substrate and subirrigated daily than in a commercial bark/vermiculite/peat substrate [40% to 50% composted pine bark, 20% to 35% vermiculite, 12% to 22% peat (Metro-Mix 500; Scotts, Marysville, OH)] or a pine bark/sedge peat/sand substrate [50% pine bark, 40% Florida sedge peat, and 10% sand (Atlas Peat and Soil, Boynton Beach, FL)]. However, the largest areca palms (*Dypsis lutescens*) were in pots filled with the bark/vermiculite/peat substrate and watered daily via overhead irrigation.

Several large interaction effects (i.e., responses to specific treatment combinations that were not well predicted by the main treatment effects) were noted in these studies. One of the most important was detected in skyflower, which performed best when subirrigated and grown in potting substrate amended with 4 g·L⁻¹ controlled-release fertilizer (1.8 g/pot N) and when watered overhead in topsoil amended with the same amount of fertilizer. Skyflower plants that were grown in topsoil and subirrigated died, but growth (i.e., quality and height) of plants in topsoil watered via overhead irrigation was excellent. The reason for this is unclear but could be due in part to the highly variable nature of topsoil, which is often locally sourced from whatever materials are convenient and can vary considerably from batch to batch. Topsoil was purchased from a local "big-box" supplier as needed for these experiments; substrate (and by

extension, topsoil) had no effect on broadleaf sagittaria (planted 23 Dec. 2014) or string lily (planted 19 Feb. 2015). By contrast, best growth of skyflower and cardinal flower, planted on 27 and 29 Jan. 2015, respectively, occurred when plants were cultured in substrates that did not contain topsoil. It is possible that the topsoil purchased for the skyflower and cardinal flower experiments had an unspecified contaminant. This would also explain why skyflower grown in topsoil with overhead irrigation performed well, as overhead irrigation could serve to leach contaminants from the substrate. Further research should be conducted to determine the presence and nature of contaminants in commercial topsoils such as the one used in these studies, as growers would be interested in which contaminants cause problems in greenhouse culture and which topsoils should be avoided.

These studies revealed that although there was no "one size fits all" method for optimum culture of all four wetland species, greenhouse production of these perennials should be fairly straightforward without significant modifications or changes to existing infrastructure. This confirms previous reports that some wetland species, in addition to swamp rosemallow (*Hibiscus grandiflorus*), pickernelweed (*Pontederia cordata*), and pond apple (*Annona glabra*), are easily cultured under greenhouse conditions (Gettys and Sutton, 1999, 2001; Gettys et al., 2001, 2013). Good quality and growth were realized using standard commercially available containers, substrates, controlled-release fertilizer, and inexpensive flood trays easily constructed to provide subirrigation when appropriate. It can be tempting to use the least-expensive materials available for greenhouse production of wetland plants to maximize profits; of the substrates examined in these experiments, topsoil is likely the least expensive. However, as evidenced in the topsoil × subirrigation interaction noted in skyflower, sometimes efforts to reduce production costs can backfire and cause loss of sellable plant material. Therefore, it would be wise for growers to evaluate production methods on a species-by-species trial before gearing up for large-scale

greenhouse production of wetland plants.

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