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RESEARCH ARTICLE

Assessing nitrogen and phosphorus removal potential of five plant species in floating treatment wetlands receiving simulated nursery runoff

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Abstract

The feasibility of using floating treatment wetlands (FTWs) to treat runoff typical of commercial nurseries was investigated using two 8-week trials with replicated mesocosms. Plants were supported by Beemat rafts. Five monoculture treatments of *Agrostis alba* (red top), *Canna* × *generalis* 'Firebird' (canna lily), *Carex stricta* (tussock sedge), *Iris ensata* 'Rising Sun' (Japanese water iris), *Panicum virgatum* (switchgrass), two mixed species treatments, and an unplanted control were assessed. These plant species are used for ornamental, wetland, and biofuel purposes. Nitrogen (N) and phosphorus (P) removals were evaluated after a 7-day hydraulic retention time (HRT). N removal (sum of ammonium-N, nitrate-N, and nitrite-N) from FTW treatments ranged from 0.255 to 0.738 $g{\cdot}m^{-2}{\cdot}d^{-1}$ (38.9 to 82.4% removal) and 0.147 to 0.656 $g{\cdot}m^{-2}{\cdot}d^{-1}$ (12.9 to 59.6% removal) for trials 1 and 2, respectively. P removal (phosphate-P) ranged from 0.052 to 0.128 $g{\cdot}m^{-2}{\cdot}d^{-1}$ (26.1 to 64.7% removal) for trial 1, and 0.074 to 0.194 $g{\cdot}m^{-2}{\cdot}d^{-1}$ (26.8 to 63.2% removal) for trial 2. *Panicum virgatum* removed more N and P than any other FTW treatment and the control in both trials. Results show that species selection and timing of FTW harvest impact the rate and mass of nutrient remediation. FTWs can effectively remove N and P from runoff from commercial nurseries.

Keywords Biofuel · Nitrogen removal · Phosphorus removal · Biofilm

Introduction

Agricultural runoff can degrade water quality and contribute to eutrophication of downstream surface waters (Carpenter et al. 1998; Qin 2009). According to the U.S. Environmental Protection Agency (USEPA), agriculture is the leading contributor of impairments to streams and rivers (USEPA 2013) through nonpoint source pollution (NPS) due to erosion caused by tillage for crops, application of fertilizers and manures, and poor irrigation practices (Novotny 2003). Excess nutrients such as nitrogen (N) and phosphorus (P) released from chemical and manure fertilizer application can enter nearby water bodies through overland flow or groundwater leaching. Collectively, NPS from agriculture contributes to eutrophication of lakes, rivers, and estuaries worldwide (Anderson et al. 2002). One well-known example of a hypereutrophic water body is the Chesapeake Bay. To restore the health of the Chesapeake Bay estuary, a total maximum daily load (TMDL) was imposed by the USEPA to reduce N, P, and sediment loads entering the bay through upstream tributaries (USEPA 2010). The Chesapeake Bay TMDL requires reductions in N loading by 25% and P loading by 24% by the year 2025. This nutrient load reduction is apportioned to the municipal wastewater, stormwater, and agricultural sectors through a combination of required and voluntary actions. Agriculture makes up 24% of the land area in the Chesapeake Bay watershed, so significant reductions from this sector will be needed if the goal is to be reached.

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Agricultural reductions will most likely be accomplished by identifying and implementing suitable best management practices (BMPs) (Majsztrik and Lea-Cox 2013).

Nurseries and greenhouses use fertilizer and water to produce "container crops." Due to high plant densities, use of soilless substrates, high species diversity, and fast crop turnover per unit area per year, nurseries typically use more agrichemicals than row crops (White et al. 2010). Majsztrik (2011) reported average yearly container nursery N and P application rates of 680 kg·ha^{-1} and 129 kg·ha^{-1}, respectively. Well-drained and lightweight substrates are typically chosen for container operations to help prevent disease and reduce shipping costs, but the limited water retention capacity and space to accommodate roots leads to more frequent irrigation to maintain a viable and saleable plant (Majsztrik et al. 2011). The combination of well-drained substrates and frequent irrigation can cause water and nutrient loss through leaching or runoff. Studies conducted in the southeastern USA have shown average concentrations of N and P in nursery runoff can range from 8.27 to 21.7 mg·L^{-1} and 1.41 to 8.27 mg·L^{-1}, respectively (Taylor et al. 2006; White et al. 2010, 2011). Yeager et al. (2010) and Majsztrik et al. (2011) identified several BMPs used by the container nursery industry that serve to increase the efficiency of the plant production operation while simultaneously improving runoff water quality. BMPs such as vegetative buffer strips, constructed wetlands, and tailwater recovery basins (TRBs) remove both nutrients and sediment from runoff (Majsztrik et al. 2017). TRBs are large ponds used to intercept and treat runoff; they are often used to facilitate the reuse of irrigation runoff returns to supplement water supplies. TRBs remove sediment adequately but can be inefficient with regard to dissolved contaminant removal (Tanner and Headley 2011; Yeager et al. 2010).

Floating treatment wetlands (FTWs) are a relatively new technology that may enhance water treatment within TRBs. A FTW consists of a buoyant raft that holds emergent plants above the water surface while the plant roots extend below the water surface, as shown in Fig. 1 (Headley and Tanner 2006; Pavlineri et al. 2017; Shahid et al. 2018). Unlike traditional constructed wetlands, FTWs float and so can adjust to water level fluctuations (Headley and Tanner 2007; Lane et al. 2016). FTWs have been used and evaluated for treatment of urban stormwater (Borne et al. 2013; Li et al. 2017; Winston et al. 2013), overflows from combined sewage systems (Shen et al. 2018; Van de Moortel 2008), acid mine drainage (Smith and Kalin 2000), agricultural runoff, and other waste waters (Chen et al. 2016; Stewart et al. 2008). Benefits associated with FTWs include improved water quality, reduced shoreline erosion, and provision of wildlife habitat (Borne et al. 2015; Lynch et al. 2015; Wang et al. 2014). Studies have shown that installation of FTWs within ponds improves the nutrient removal capacity of the pond (Borne 2014; Borne et al. 2013; Chang et al. 2012). P removal occurs via sorption, particle entrapment, flocculation, and sedimentation; N removal occurs via assimilation and denitrification in the root biofilm zone (Borne et al. 2013; Jayaweera and Kasturiarachchi 2004). Borne et al. (2013) found that denitrification in FTWs contributed to more N removal than plant uptake, and that 10 to 50% of pond surface area coverage was required to maintain a low dissolved oxygen (DO) environment needed to facilitate these conditions. Borne et al. (2013) also observed TP reductions of 27% when FTWs were applied to ponds. Harvesting the vegetation on the FTWs at the end of each growing season, either by removing whole plants or the plant shoots, can also enhance the total nutrient load removed from the system (Chang et al. 2012; Wang et al. 2014).

Mesocosm (and microcosm) studies are popular for evaluating agricultural and ecological practices. Both offer the advantages of statistical replication and economy and provide a transition from the laboratory to the field. A summary of FTW mesocosm research detailing plant species and/or treatment, source water, hydraulic retention time (HRT), plant density, influent N and P concentrations, and N and P reductions in terms of % removal and unit area loading are provided in Table 1. Removal results vary widely by plant species and plant density; however, planting density is often unreported. As shown in Table 1, in terms of N reduction, performance ranged from 7.8% using *Polygonum barbatum* (Chua et al. (2012) to a high of 97–99.4% using *Rumex acetosa* (Zhou et al. (2012). P removal ranged from a low of 4% for *Juncus effusus* (Lynch et al. (2015) to 92% using *Iris pseudacorus*) (Keizer-Vlek et al. (2014). Nutrient removal is described in terms of units of nutrient mass per unit area of the raft and time, or g·m^{-2}·d^{-1}. Nutrient removal results across the studies

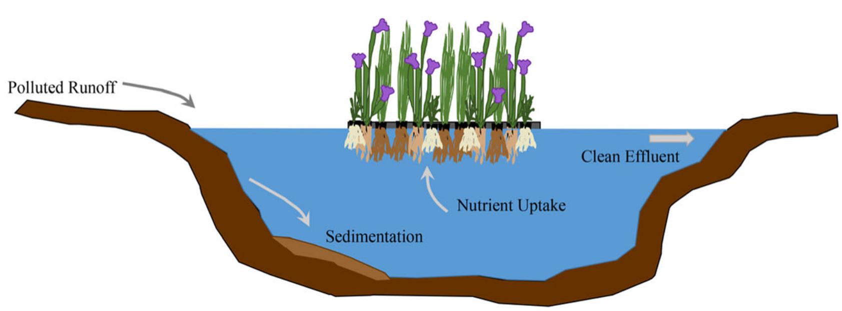


Fig. 1 The floating treatment wetland cross-section diagram

ranged from 0.008 to 66.3 g·m^{-2}·d^{-1} for N and from 0.002 to 1.8 g·m^{-2}·d^{-1} for P. While the variability of these numbers is influenced by plant species and water temperature, water source and quality, nutrient loading rate, and HRT also have significant influence on results. Of the studies referenced in Table 1, White and Cousins' study (2013) is the only work to date that addresses runoff from commercial nurseries; and these nutrient loadings were comparatively low, lower than the anecdotal observations of the authors. A key recommendation of White and Cousins (2013) was that additional nutrient concentrations and species be assessed to fully evaluate FTW technology for nursery runoff, including evaluating crops for resale, as suggested by Polomski et al. (2007).

In summary, few studies have been conducted that evaluate FTWs for treating container nursery runoff. The need for BMPs to reduce N and P in agricultural runoff is acute, especially in regions with nutrient load limitations such as the Chesapeake Bay watershed. Implementation of FTWs in TRBs could become an attractive alternative or enhancing treatment technology if FTW plants were also viable for sale. Thus, the goal of this research was to characterize efficacy of FTWs for nutrient remediation at commercial plant nursery operations. A secondary, but related objective, was to assess the potential viability of the FTW plants for sale.

Materials and methods

Study location and equipment

The study was conducted in Virginia Beach, VA, at the Virginia Tech Hampton Roads Agriculture Research and Extension Center (HRAREC; 36° 53′ N, 76° 10′ W). Rainfall during the trial 1 and trial 2 study periods was 255 mm and 659 mm, respectively. The mean air temperature during the trial 1 and trial 2 study periods was 25.5 °C and 26.1 °C, respectively. Experiments were conducted using a specially built system of tanks, pumps, and piping. Two 5867 L (1550 gal) plastic storage tanks (Norwesco, St. Bonifacius, MN, USA), also referred to as the mix tanks, were used for the batch process makeup of the water and fertilizer solutions. One tank was capable of supplying water to half of the experimental mesocosms. Each tank drain was connected to the intake of an electric water pump (Model FH40-5500, Little Giant, Oklahoma City, OK, USA). The discharge of each pump consisted of a main supply line and a recirculation line. The recirculation line allowed for water circulation from the mix tank and drain back to the top of the mix tank. Thirty-two structural foam stock tanks (Rubbermaid Commercial Products, Winchester, VA, USA) were used as mesocosms. Each 378.5-L mesocosm was retrofitted with an overflow hole that allowed a maximum water volume of 302.8 L. Every mesocosm had a drain at the bottom that connected into a main drain line. The main drain line was connected to the intake of a Honda WX15 gas-powered water pump (Honda Power Equipment, Alpharetta, GA, USA). Water was discharged from the mesocosms through the main drain line and pumped through a series of 15.2-m (50 ft) sections of Goodyear 3.81-cm (1.5 in.) Spiraflex hose. The hoses conveyed the water to a nearby ditch to prevent flooding of the experiment area.

Experimental design

The experimental design was a randomized complete block that included four replications of eight treatments (Table 2). Treatments consisted of five monoculture plantings of *Agrostis alba*, *Carex stricta*, *Panicum virgatum*, *Iris ensata* 'Rising Sun', and *Canna* × *generalis* 'Firebird', one randomized planting with a uniform mixture of *Agrostis alba*, *Carex stricta*, and *Panicum virgatum* (grass and sedge mixture), a randomized planting with a uniform mixture of all five species, and a control with no plants or mat. Mesocosms were blocked by row with the northernmost row being block 1 and each subsequent row being blocks 2, 3, and 4 (see Fig. 2).

Each mesocosm had a volume of 302.8 L and water surface area of 0.79 m^2 at the operational depth of 47.3 cm. Beemats (Beemats LLC, New Smyrna Beach, FL, USA) were used as floating rafts, and biodegradable cups were inserted into the pre-cut holes in the mats per Beemat system installation protocol. The ends of each mat were trimmed to allow for proper fit in the mesocosms, leaving a total mat surface area of 0.64 m^2, which covered 80.3% of the water surface area. Plugs or bare root liners of the plant species were purchased. Before planting, the root balls of each plug were rinsed to remove the original planting media. The bare root liners were also rinsed. For this study, 20 plants were planted per mesocosm, or 31 plants/m^2.

After each 7-day HRT, the mesocosms were drained and refilled with a new batch of simulated runoff. The simulated runoff was created by adding water and 368 g of 24-8-16 (N:P:K) soluble fertilizer (Southern Agriculture Insecticides Inc., Hendersonville, NC, USA) to each mix tank. After allowing the solution to recirculate for 1 h, it was pumped to fill each mesocosm.

Water sampling and analysis

The start of each experimental week was designated as day 0. On day 0, samples were collected from each mix tank representing the initial nutrient concentration for the 7-day retention period. Each sample was collected in a 125-mL wide-mouth Nalgene bottle at a depth of 61 cm (24 in.) from the water surface. Water temperature (°C), pH, dissolved oxygen (DO, mg·L^{-1}), and electrical conductivity (EC, μS·cm^{-1}) measurements were taken *in situ* for both mix tanks using an

Table 1 Mesocosm studies evaluating nitrogen and phosphorus remediation aided by floating treatment wetlands

Source	Species/treatment	Location	Source water	HRT[1] (d)	Plant density (plants/m^2)	Influent concentration[2]		Reduction		Load reduction	
						N ($mg \cdot L^{-1}$)	P ($mg \cdot L^{-1}$)	N (%)	P (%)	N ($g \cdot m^{-2} \cdot d^{-1}$)	P ($g \cdot m^{-2} \cdot d^{-1}$)
Boonsong and Chansiri 2008	*Vetiveria zizanoides* (L.)	Thailand	Primary treated domestic wastewater	3–7	[3]	38.4–46.92	5.2–6.26	21.9–57.6	13.5–31.3	1.1–2.5	0.1–0.88
Bu and Xu 2013	*Canna indica*	China	River water	1.25	28–32	8.21	1.15	42.3	32.7	[3]	[3]
	Acorus calumus					8.21	1.15	38.4	28.9		
	Cyperus alternifolius					8.21	1.15	33.2	24.9		
	Vetiveria zizanoides (L.)					8.21	1.15	28.3	20.7		
Chang et al. 2012	*Canna flaccida* and *Juncus effusus* (mixed)	Florida, USA	Stormwater w/ added nutrients	30	[2]	4.25	2.81	61	53	10.64	7.47
Chua et al. 2012	*Chrysopogon zizanioides*	Singapore	Base flow of river	30	14.4	1.3	0.22	40.8	19.1	[3]	[3]
	Typha angustifolia			30	[2]			67.5	39.2	[3]	[3]
	Polygonum barbatum			15	[2]			7.8	46.0	[3]	[3]
Hubbard et al. 2004	*Typha latifolia*	Georgia, USA	Swine farm wastewater	14	20–40	160	30	[3]	[3]	1.11	0.16
	Juncus effusus							[3]	[3]	0.67	0.10
	Panicum hematomon							[3]	[3]	0.18–0.51	[4]
Keizer-Vlek et al. 2014	*Iris pseudacorus*	Netherlands	Groundwater w/ added nutrients	91	[3]	4.0	0.25	98	92	0.277	0.00932
	Typha angustifolia							[4]	[4]	[4]	[4]
	Control							[3]	[3]	0.00513	0.000932
Li et al. 2011	*Lolium perenne* 'Top One'	China	Urban pond water	20	[3]	2.99	0.56	49.8	87.5	0.013	0.004
	Lolium perenne 'Respect'							36.2	85.1	0.009	0.004
	Lolium perenne 'Top One' + immobilizing denitrifiers							57.4	88.1	0.014	0.004
	Lolium perenne 'Respect' + immobilizing denitrifiers							42.2	88.1	0.011	0.004
	Immobilizing denitrifiers							28.5	74.7	0.008	0.003
	Control							11.8	19.6	[3]	[3]
Li et al. 2012	*Geophila herbacea* O Kuntze	China	Refinery wastewater	35	15.6	59.3	51.2	[3]	[3]	0.057	0.002
	Loliurn perenne 'Caddieshack'					62.9	65.9	[3]	[3]	0.06	0.002
	Loliurn perenne L.					64.4	68.8	[3]	[3]	0.061	0.003
	Loliurn perenne 'Topone'					69.5	69.5	[3]	[3]	0.067	0.003
	Control					32.9	35.9	[3]	[3]	[3]	[3]
Lynch et al. 2015	*Juncus effusus*, Beemat	Virginia, USA	Agricultural pond	7	27	1.0	0.22	40	48	0.026	0.0076

Table 1 (continued)

Source	Species/treatment	Location	Source water	HRT[1] (d)	Plant density (plants/m^2)	Influent concentration[2]		Reduction		Load reduction	
						N (mg·L^{-1})	P (mg·L^{-1})	N (%)	P (%)	N (g·m^{-2}·d^{-1})	P (g·m^{-2}·d^{-1})
	Juncus effusus, BioHaven							25	4	0.025	0.0074
	Control							28	31	[3]	[3]
Sun et al., 2009	*Canna* spp.	China	River water	5	[3]	8.71	[3]	50.4	[3]	0.44	[3]
	Canna sp. and immobilizing denitrifiers									0.55	[3]
	Canna spp. and aeration									0.64	[3]
Van de Moortel et al. 2010	*Carex* spp. (dominant, > 95%)	Netherlands	Domestic wastewater	11	[3]	21.8	2.2	[3]	[3]	0.55	[3]
Van Oostrom, 1995	*Glyceria maxima*, normal flow	Netherlands	Meat processing wastewater	7	[3]	197	[3]	48.7	[3]	5.3	[3]
	Glyceria maxima, irrigated from top									5.2	[3]
	Glyceria maxima, 50% effluent recycled									5.5	[3]
Wang et al. 2012	*Phragmites australis*, *Typha latifolia* + biological ceramic filter substrate, 1–13 °C	China	River water	1–7	36	[3]	[3]	[3]	[3]	22.9	0.5
	Phragmites australis + *Typha latifolia* + biological ceramic filter substrate, 13–18 °C									66.3	1.8
	Phragmites australis, *Typha latifolia* without substrate, 1–13 °C									10.8	0.3
	Phragmites australis, *Typha latifolia* without substrate, 13–18 °C									52.2	0.9
	Phragmites australis + *Typhus latifolia* w/ fibrous filler substrate, 1–13 °C					[3]	[3]	[3]	[3]	11.8	0.3
	Phragmites australis + *Typhus latifolia* w/ fibrous filler substrate, 13–18 °C					[3]	[3]	[3]	[3]	61.6	0.8
Wang and Sample 2014	*Pontederia cordata*	Virginia, USA	Urban pond water	7	10.4	1.19	0.15	18.2	8.2	0.013–0.025	0.0002–0.0013
	Schoenoplectus tabernaemontani										
	Control							14.3	3.9		
White and Cousins 2013	*Canna flaccida*, 2008	South Carolina, USA	Lake water w/ added nutrients	3	27	0.85	0.08	83.5	75	0.22	0.014
	Juncus effusus, 2008							[3]	[3]	0.39	0.024
	Canna flaccida + *Juncus effusus* (mixed) 2008							[3]	[3]	1.05	0.04
	Canna flaccida, 2009		Lake water w/ added nutrients			1.88	0.22	58	45.5	0.22	0.014
	Juncus effusus, 2009							[3]	[3]	0.39	0.024

Table 1 (continued)

Source	Species/treatment	Location	Source water	HRT[1] (d)	Plant density (plants/m^2)	Influent concentration[2]		Reduction		Load reduction	
						N ($mg \cdot L^{-1}$)	P ($mg \cdot L^{-1}$)	N (%)	P (%)	N ($g \cdot m^{-2} \cdot d^{-1}$)	P ($g \cdot m^{-2} \cdot d^{-1}$)
	Canna flaccida + *Juncus effusus* (mixed) 2009							[3]	[3]	3	0.17
Xian et al. 2010	*Lolium multiflorum* Lam. 'Dryan'	China	Swine farm wastewater	35	80	18.0	2.29	84	90.4	0.13	0.018
	Lolium multiflorum Lam. 'Waseyutaka'					24.6	1.49	79.6	89.9	0.092	0.011
	Lolium multiflorum Lam. 'Tachimasari'					19.5	1.75	80.3	88.3	0.134	0.013
	Control					17.4	2.16	69.2	71.3	0.103	0.013
Xin et al. 2012	*Oenanthe javanica*	China	Eutrophic water	15	[2]	18.32	0.8	91.3	57.5	0.34	0.01
Yang et al. 2008	*Oenanthe javanica*	China	River water w/ added nutrients	3	100	3.76	1.25	31.1	6.4	0.21	0.01
				2		4.57	1.35	43.3	14.1	0.44	0.06
				1		7.94	1.54	46.0	13.0	2.74	0.11
Zhao et al. 2012	*Zizania caduciflora*	China	Urban pond water	16	61	5.6	0.48	37.5	43.8	0.05	[3]
	Triarrhena lutarioriparia									0.15	[3]
	Thalia dealbata									0.13	[3]
	Vetiveria zizanioides									0.15	[3]
	Miscanthus sinensis Anderss sp.									0.16	[3]
	Acorus calamus									0.18	[3]
	Control									0.14	[3]
Zhou and Wang 2010	*Oenanthe javanica* 'Blume'	China	River water	35	50	12.58	0.68	90.78	76.47	0.0465	0.0021
	Control					12.58	0.68	65.42	33.82		
Zhou et al. 2012	*Rumex acetosa* 'Linn.', summer	China	River water	48	8–10	14.8–15.12	[3]	97–99.4	[3]	0.06	[3]
	Rumex acetosa 'Linn.', winter									0.057	[3]

[1] Hydraulic retention time

[2] Reported value, average or median

[3] Not available

[4] Neglible

Table 2 Treatments for the 2016 floating treatment wetland study conducted from June 2016 to September 2016

Treatment	Mat	Plants	Species	Replications
1	Yes	Yes	*Agrostis alba*	4
2	Yes	Yes	*Canna* × *generalis* 'Firebird'	4
3	Yes	Yes	*Carex stricta*	4
4	No	No	N/A	4
5	Yes	Yes	*Iris ensata* 'Rising Sun'	4
6	Yes	Yes	Mixed: all plants	4
7	Yes	Yes	Mixed: partial (*Agrostis alba*, *Carex stricta*, and *Panicum virgatum*)	4
8	Yes	Yes	*Panicum virgatum*	4

YSI Professional Plus multi-probe meter (Yellow Springs International Inc. Ohio, USA) at the same depth.

Day 0 of each experimental week was also day 7, as the tanks were drained and refilled on the same day. On day 7, before the mesocosms were drained, a 125-mL grab sample was collected from each of the 32 mesocosms, and water temperature, pH, DO, and EC measurements were taken *in situ* at a depth of 30.5 cm (12 in.). These samples reflect the post treatment nutrient concentration for the retention period. The depth from the water surface to the bottom of the mesocosms was recorded to estimate evapotranspiration and convert concentration data to mass.

After collection, all water samples were kept on ice in a cooler until other necessary fieldwork was completed, then transported to the lab. Each water sample was filtered through a 0.2-μm Thermo Scientific™ Target2 30-mm PVDF Syringe Filter into a Thermo Scientific™ Dionex AS-AP Auto Sampler Vial. The samples were frozen until analysis using ion chromatography (Thermo Scientific™ Dionex ICS2100 for anion and ICS1600 for cation; Waltham, MA, USA) for nitrate, nitrite, ammonium, and phosphate with Dionex columns AS19 (anion) and CS12 (cation) (Dionex, Sunnyvale, CA) and eluents potassium hydroxide and 20 mM sulfuric acid, respectively.

Plant tissue sampling and analysis

Three plant tissue samples were collected at the end of each trial from each monoculture mesocosm, and three plant tissue samples were collected for each species in the mixed planting mesocosms. The plants were kept in a walk-in cooler at 8.9 °C until initial measurements and processing were complete. Each plant was rinsed with deionized water prior to measuring

Fig. 2 The schematic layout and experimental design

Table 3 Scale rating plant visual quality and viability after transplant from floating treatment wetlands

Rating	Description
1	Little (< 25%) plant growth observed
2	> 25% plant growth observed
3	> 50% plant growth observed
4	> 75% plant growth observed
5	100% of the plant is in growth, little to no dead tissue observed

root and shoot length. After taking measurements, the roots and shoots were separated at the crown.

Plant tissue samples were dried in a forced air oven at 58 °C until a consistent sample weight was attained. Tissue samples were then ground to 0.5-mm particle size using a 3379-K35 Variable Speed Digital ED-5 Wiley Mill set to 900 RPM (Thomas Scientific, Swedesboro, NJ, USA). For the monoculture mesocosms, each of the three root and shoot tissue samples were processed individually. For the mixed planting mesocosms, the three shoot samples from each species were ground into a composite sample; the same process was used for the roots. All plant tissue samples were analyzed by the U.S. Department of Agriculture Horticultural Research Laboratory (Ft. Pierce, Florida). Tissue samples were analyzed for N content by dynamic flash combustion (Thermo Scientific™ FLASH 2000 Elemental Analyzer; Waltham, MA, USA). P was analyzed using ICP-OES (Thermo Scientific™ iCAP 6500 Duo view ICP-OES; Waltham, MA, USA).

Six plants from each monoculture mesocosm were harvested at the end of each trial to evaluate the effects of transplanting into a soil or soilless media on plant quality. Three of the six plants were transplanted into high-density polyethylene containers (Nursery Supplies Inc. ®, Chambersburg, PA, USA) filled with 11.4-L Sun Gro Metro-Mix® 852 soil (Sun Gro Horticulture, Agawam, MA, USA). The remaining three samples from each monoculture mesocosm were planted into the ground in a 5.2-m by 7.6-m plot at the HRAREC. The plot was covered with 7.5 cm (3 in.) of woodchip mulch for weed control. The biodegradable Beemat cups were left intact on the plant roots during planting. No fertilizer was added. Plants in the plot were hand watered immediately after planting. Transplants in containers received daily irrigation. Both container and field transplant studies were designed as serial repeated measures designs (RMD). Plant viability was rated on a scale of 1–5 (see Table 3 for definition of each rating) based upon visual

Table 4 The mean cumulative nitrogen (N) and phosphorus (P) removals (g and %) by treatment for floating treatment wetland studies (trial 1 and trial 2) conducted from June 2016 to September 2016 ($n = 4$)

	Cumulative removal after 8 weeks			
Treatment	P (g)[1]	(%)	N (g)[1]	N (%)
Trial 1				
Agrostis alba	2.18[cd]	29.8	10.6[d]	41.5
Canna × *generalis* 'Firebird'	1.92[d]	26.1	11.2[d]	43.7
Carex stricta	2.09[d]	28.3	10.0[d]	38.9
Control	1.59[d]	21.9	1.21[e]	4.8
Iris ensata 'Rising Sun'	3.57[b]	48.6	12.9[cd]	50.4
Mixed: all plants	3.28[bc]	44.2	16.3[bc]	63.4
Mixed: partial[2]	3.27[bc]	44.2	17.4[b]	67.7
Panicum virgatum	4.88[a]	64.7	21.6[a]	82.4
ANOVA F ratio, p value	20.5, < 0.0001		47.6, < 0.0001	
Trial 2				
Agrostis alba	2.00[b]	26.8	3.44[b]	12.9
Canna × *generalis* 'Firebird'	2.75[b]	37.1	7.74[b]	29.2
Carex stricta	2.24[b]	29.6	7.09[b]	26.2
Control	2.53[b]	34.6	3.77[b]	14.4
Iris ensata 'Rising Sun'	3.19[b]	42.9	5.84[b]	22.0
Mixed: all plants	2.50[b]	33.3	7.01[b]	26.1
Mixed: partial[2]	2.65[b]	35.1	9.64[b]	35.8
Panicum virgatum	4.86[a]	63.2	16.3[a]	59.6
ANOVA F ratio, p value	11.70, < 0.0001		8.84, < 0.0001	

[1] Means with different letters differ significantly from other means with for the same trial at $p < 0.05$

[2] Partial mixed treatments included *Agrostis alba*, *Carex stricta*, and *Panicum virgatum*

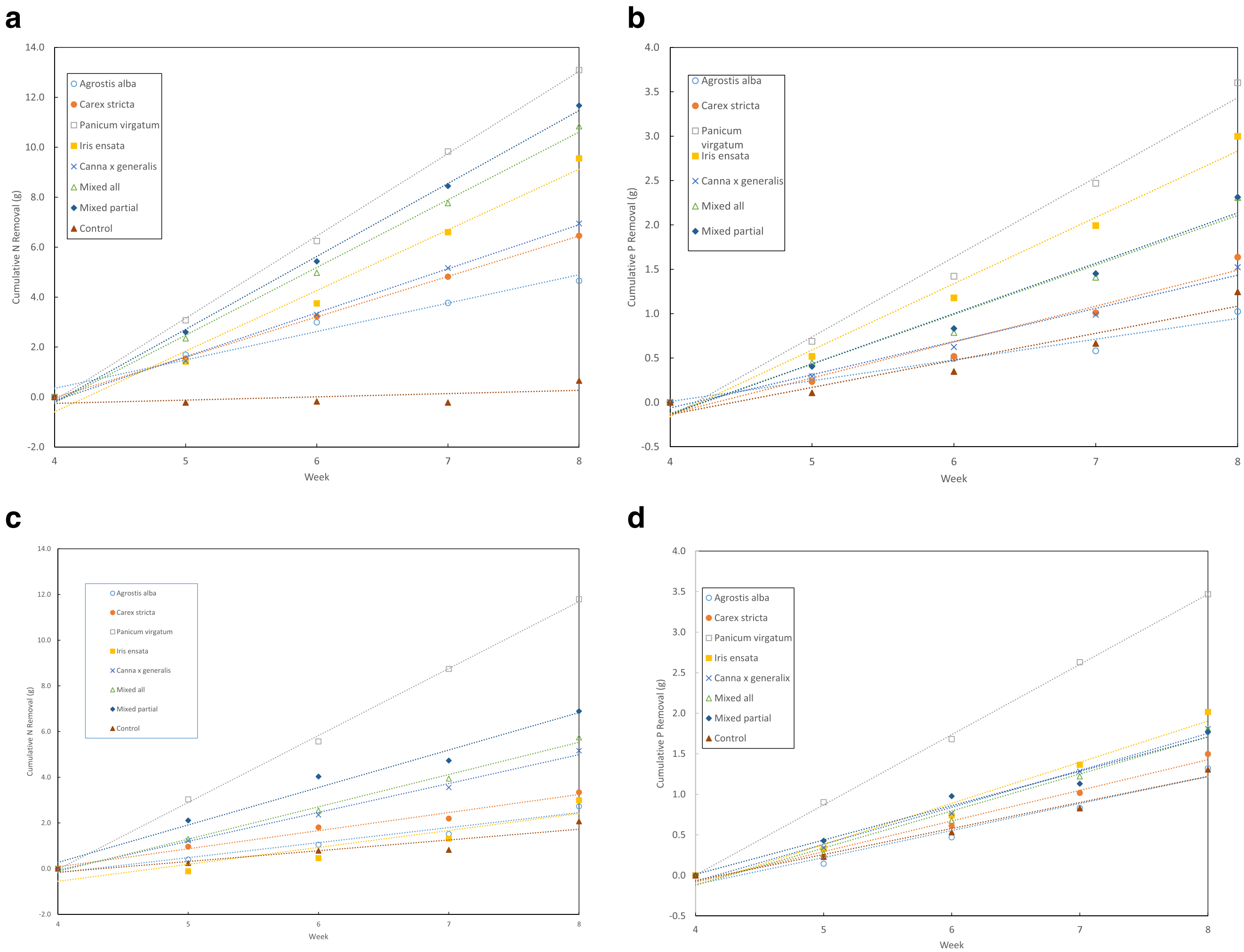


Fig. 3 The mean cumulative removal of nitrogen in trial 1 (**a**) and trial 2 (**c**) and mean cumulative removal of P in trial 1 (**b**) and trial 2 (**d**) by treatment. Fitted linear regression lines represent operational rates after 3-week plant establishment phase

observation once per week for a total of 4 weeks after transplant. For consistency, one person performed the ratings.

Data analysis

N values reported are the sum of ammonium-N, nitrate-N, and nitrite-N. *p* values reported are phosphate-P. Water sample results were converted from units of concentration to mass using depth measurements and a correlation between volume and depth of the mesocosms. All values are reported as the mean and the standard error (±) of the mean unless otherwise noted. SAS JMP® Pro 13.0.0 (SAS Institute Inc. Cary, NC, USA) was used to perform statistical analyses. Statistical analyses were used to determine whether treatments differed from each other or the control in terms of N or P removals or differed in other physiochemical properties. Normality assumptions were tested both visually using the histogram and residuals and using the Shapiro-Wilk goodness-of-fit test, and suggested guidelines for skew and kurtosis were compared. Normally distributed data were analyzed using analysis of variance (ANOVA). Treatment differences were identified using the ANOVA *F* ratio for data with equal variance; Welch's ANOVA *F* ratio was used to determine treatment differences for data with unequal variance. The Student *t* test was used for pairwise comparisons, and Tukey's honestly significant difference (HSD) test was used for multiple comparisons ($p < 0.05$). When data were non-normal, the nonparametric Wilcoxon/Kruskal-Wallis tests (rank sums) were used treatment comparison ($p < 0.05$).

Results and discussion

Aqueous nitrogen and phosphorus removals

The mean N load at the start of each 7-day HRT for trial 1 and trial 2 was 10.4 ± 0.15 mg·L^{-1} (3.28 g mass load), and the mean P load was 2.96 ± 0.10 mg·L^{-1} (0.93 g mass load). N values reported for water samples for our study are the sum of nitrate-N, nitrite-N,

Table 5 The mean nitrogen (N) and phosphorus (P) loads ($g{\cdot}m^{-2}{\cdot}d^{-1}$) removed and associated correlation (load × time) statistics (R^2) for floating treatment wetland studies (trial 1 and trial 2) conducted from June 2016 to September 2016 ($n = 4$)

Treatment	P ($g{\cdot}m^{-2}{\cdot}d^{-1}$)	P (R^2)	N ($g{\cdot}m^{-2}{\cdot}d^{-1}$)	N (R^2)
Trial 1				
Agrostis alba	0.052	0.926	0.255	0.973
Canna × *generalis* 'Firebird'	0.084	0.985	0.394	0.998
Carex stricta	0.091	0.958	0.362	0.999
Control	0.068	0.923	0.029	0.307
Iris ensata 'Rising Sun'	0.167	0.984	0.544	0.984
Mixed: all plants	0.125	0.964	0.607	0.997
Mixed: partial[1]	0.127	0.972	0.653	0.998
Panicum virgatum	0.200	0.987	0.738	0.999
Trial 2				
Agrostis alba	0.074	0.966	0.147	0.956
Canna × *generalis* 'Firebird'	0.102	0.992	0.283	0.995
Carex stricta	0.085	0.986	0.177	0.983
Control	0.072	0.981	0.105	0.868
Iris ensata 'Rising Sun'	0.113	0.979	0.166	0.834
Mixed: all plants	0.102	0.980	0.316	0.994
Mixed: partial[1]	0.095	0.978	0.367	0.980
Panicum virgatum	0.194	0.999	0.656	0.999

[1] Partial mixed treatments included *Agrostis alba*, *Carex stricta*, and *Panicum virgatum*

and ammonium-N, which can approximate, but are not exactly total N. The *p* values reported reflect phosphate-P, a major component of total P. This approximation is considered acceptable because the nutrients were added via commercial fertilizer to create the applied load in solution. These concentrations fall within the range 0.39 to 36.81 $mg{\cdot}L^{-1}$ of N and 0.07 to 6.77 $mg{\cdot}L^{-1}$ P, respectively, used by Polomski et al. (2007) and are greater than those used previously by White and Cousins (2013) (Table 1).

Table 6 The mean nitrogen (N) and phosphorus (P) contents (roots + shoots) per plant by treatment and trial for floating treatment wetland studies conducted from June 2016 to September 2016

Treatment	Trial 1		Trial 2	
	P (g)[1]	N (g)[1]	P (g)[1]	N (g)[1]
Agrostis alba[2]	0.07^{e}	0.53^{cde}	0.020^{b}	0.13^{c}
Agrostis alba, mixed all[3]	0.10^{cde}	0.64^{cde}	0.001^{b}	0.05^{bc}
Agrostis alba, mixed partial[3,4]	0.07^{de}	0.49^{cde}	0.003^{b}	0.05^{bc}
Canna × *generalis* 'Firebird'[2]	0.10^{de}	0.52^{cde}	0.063^{b}	0.29^{bc}
Canna × *generalis* 'Firebird', mixed all[3,4]	0.04^{e}	0.21^{e}	0.018^{b}	0.08^{bc}
Carex stricta[2]	0.09^{e}	0.82^{bc}	0.048^{b}	0.40^{bc}
Carex stricta, mixed all[3]	0.08^{de}	0.77^{bcde}	0.041^{b}	0.42^{bc}
Carex stricta, mixed partial[3,4]	0.09^{cde}	0.84^{bcde}	0.052^{b}	0.44^{bc}
Iris ensata 'Rising Sun'[2]	0.16^{bcd}	0.79^{cd}	0.067^{b}	0.44^{b}
Iris ensata 'Rising Sun', mixed all[3]	0.05^{e}	0.25^{de}	0.041^{b}	0.25^{bc}
Panicum virgatum[2]	0.22^{ab}	1.48^{ab}	0.196^{a}	1.12^{a}
Panicum virgatum, mixed all[3]	0.31^{a}	1.83^{a}	0.177^{a}	1.03^{a}
Panicum virgatum, mixed partial[3,4]	0.21^{abc}	1.35^{a}	0.259^{a}	1.29^{a}
Welch's ANOVA *F* ratio, *p* value	9.54, < 0.0001	14.4, < 0.0001	27.6, < 0.0001	18.1, < 0.0001

[1] For each column, means not connected by the same letter differ significantly at $p < 0.05$

[2] $n = 12$

[3] $n = 4$

[4] Partial mixed treatments included *Agrostis alba*, *Carex stricta*, and *Panicum virgatum*

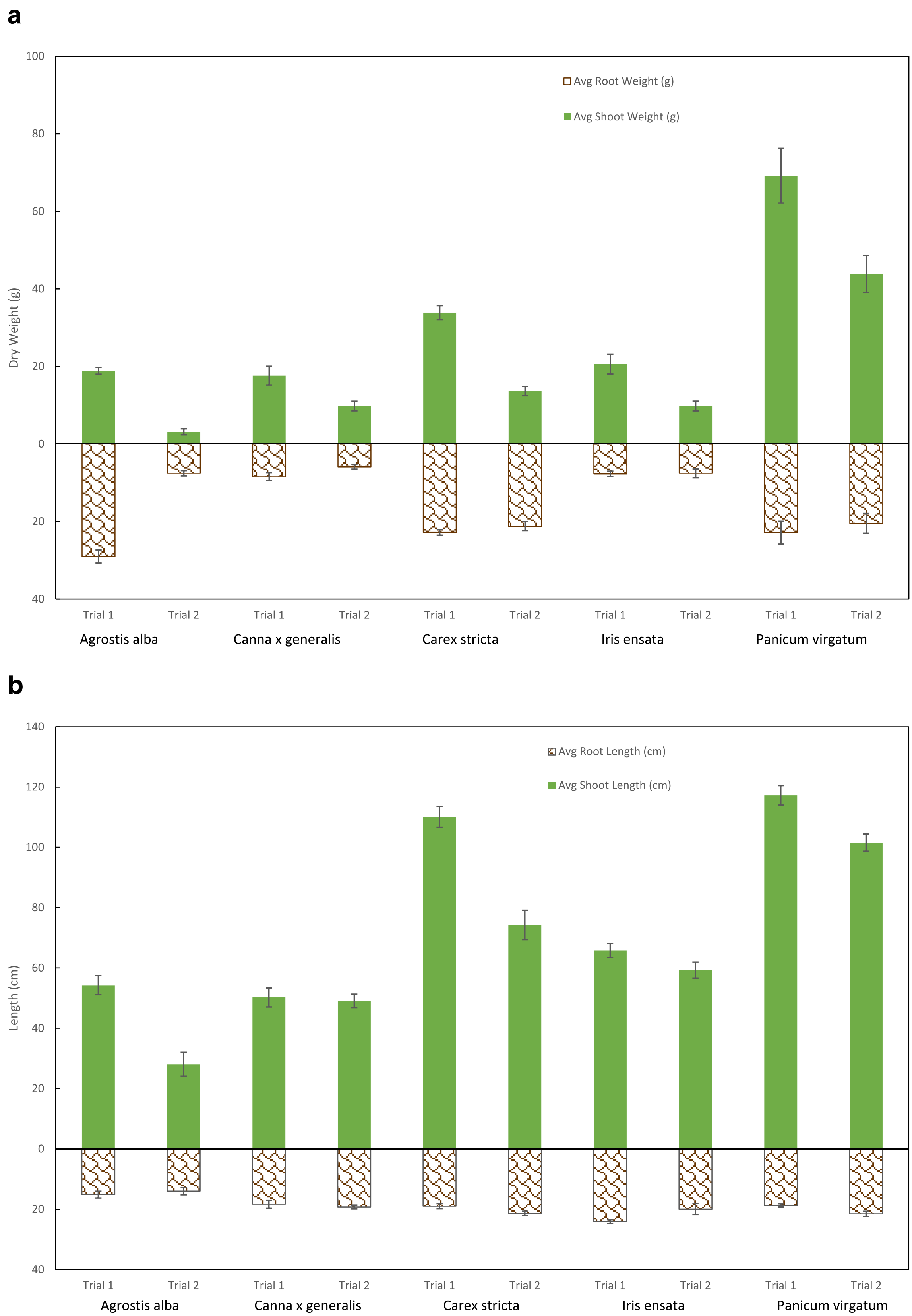
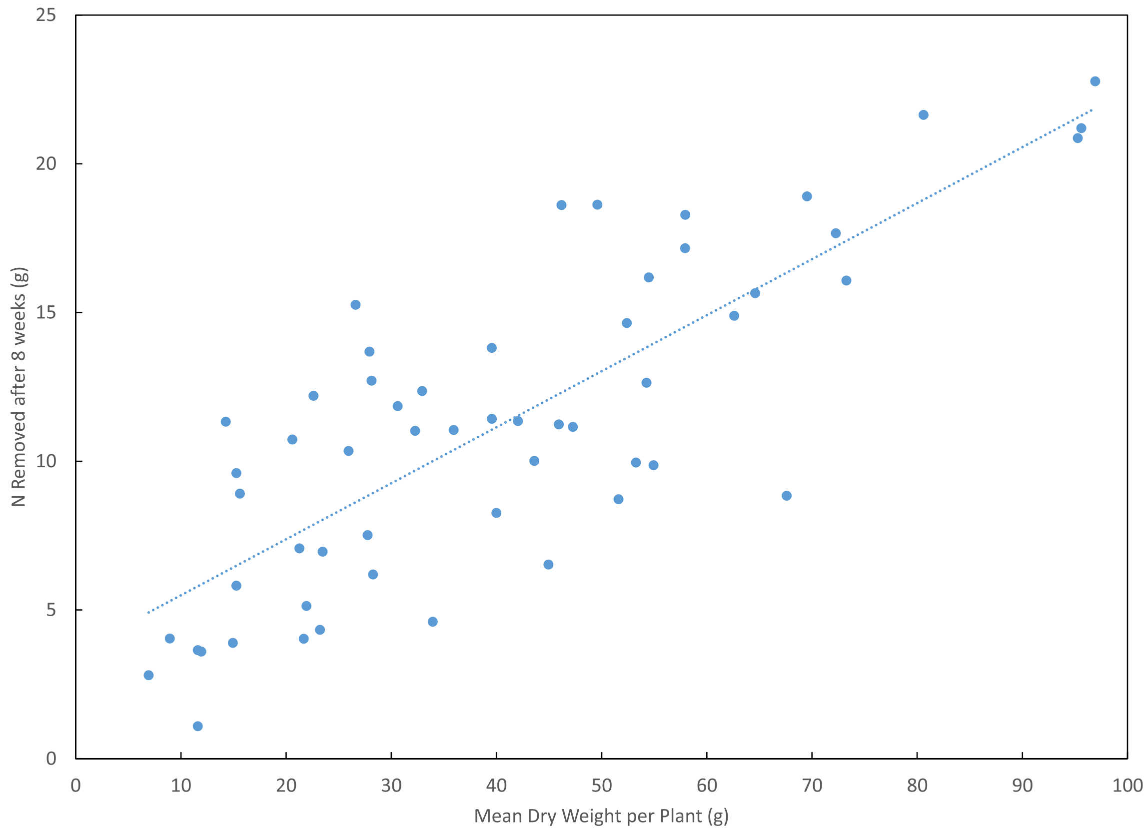
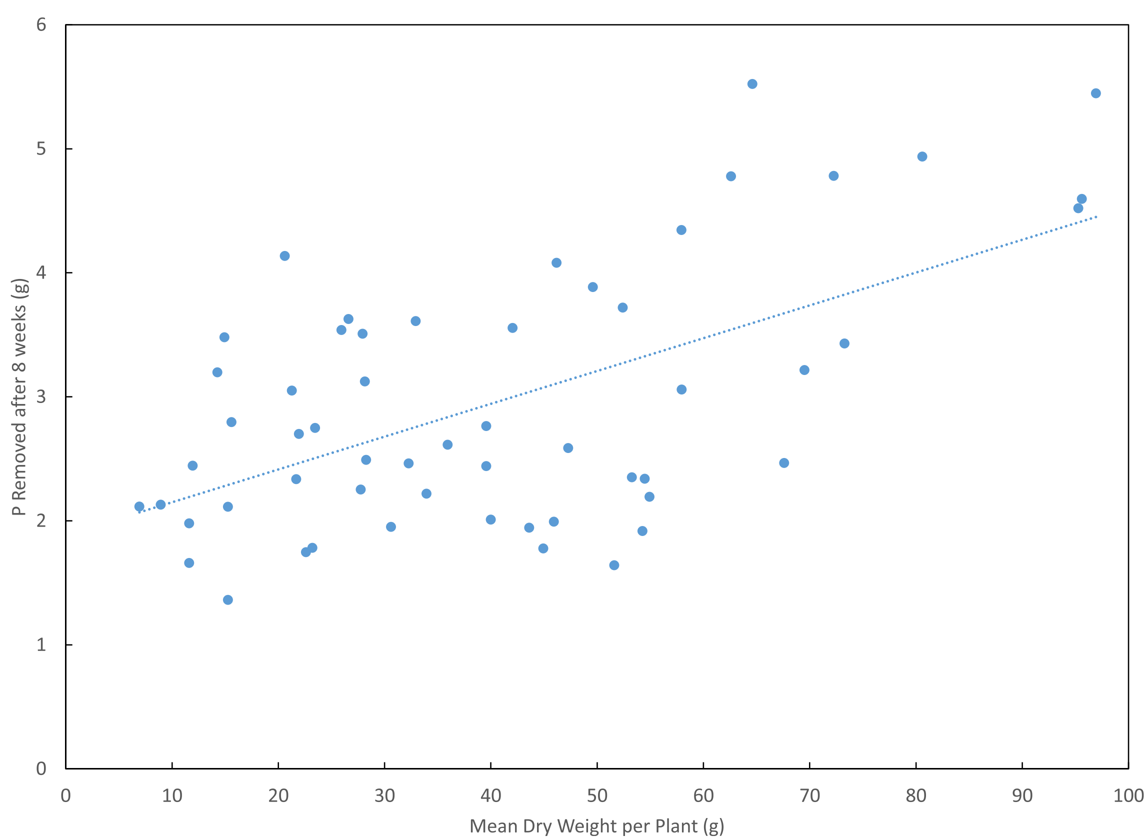


Fig. 4 Root and shoot dry weights (**a**) and lengths (**b**) by trial for monoculture mesocosms after 8 weeks of growth in the floating treatment wetland study conducted during the 2016 growing season [$n = 12$]

a


25
20
15
10
5
0
N Removed after 8 weeks (g)
0
10
20
30
40
50
60
70
80
90
100
Mean Dry Weight per Plant (g)

b


6
5
4
3
2
1
0
P Removed after 8 weeks (g)
0
10
20
30
40
50
60
70
80
90
100
Mean Dry Weight per Plant (g)

◀ **Fig. 5** Cumulative nitrogen (**a**) and phosphorus (**b**) removed from water after 8 weeks (trials 1 and 2) as a function of the mean dry weight per plant [$n = 8$. Nitrogen: $R^2 = 0.644$, F ratio = 97.9, $p < 0.0001$; phosphorus: $R^2 = 0.34$, F ratio = 27.8, $p < 0.0001$]

The mean cumulative P and N removals for trial 1 and trial 2 by species are presented in Table 4. During trial 1, removal efficiencies ranged from 21.9 to 64.7% for P and 4.8 to 82.4% for N. *Panicum virgatum* removed more N and P than all other treatments ($p < 0.0001$), with a cumulative mean removal of 21.6 ± 0.42 g N and 4.88 ± 0.21 g P. The mixed plantings generally removed more nutrients than the monoculture plantings, possibly due to the inclusion of *Panicum virgatum*, which comprised 20% and 30% of the complete mix and partial mix plantings, respectively. Sometimes, mixed plantings of flowering plants are desired for diversity and aesthetic reasons (Headley and Tanner 2012). In such cases, choosing the proper ratio of high nutrient removal species to other, less efficient species should be considered to maximize remediation effectiveness of the FTW system. The control treatment was least effective at N (1.21 ± 1.27 g) and P (1.59 ± 0.25 g) removals. *Agrostis alba*, *Canna* × *generalis*, and *Carex stricta* did not remove more P than the control treatment, but all species removed more N than the control treatment in trial 1 (Table 4).

During trial 2, removal efficiencies ranged from 26.8 to 63.2% for P and 12.9 to 59.6% for N. As in trial 1, *Panicum virgatum* removed more N and P than all other treatments (Table 4). N and P removals were similar among all the remaining treatments. Collectively, the trial 1 plants removed more N ($p < 0.0003$) than the trial 2 plants, but cumulative P removal was similar between the two trials. Differences between trial results could be influenced by variability in initial plant uniformity and the time of the growing season the trials were conducted. Sun et al. (2009) observed a 44% removal rate of N (ammonium-N, nitrate-N, and nitrite-N) with *Canna* established in floating beds; this removal rate is similar to the removal rate observed for the *Canna* × *generalis* treatment in trial 1 (43.7%) of our study. The mean initial concentrations of N in our study were 4.45 mg·L^{-1} higher than those used by Sun et al. (2009) and the HRT 2 days longer.

At week 4 of each trial, an inflection in the slopes of cumulative nutrient removal data was noted. Therefore, the time from initiation until week 4 was defined as the plant establishment phase, after which the plants likely reached their optimal nutrient removal potential. The cumulative N and P removals during the active nutrient uptake phase of growth (weeks 4 to 8) for trials 1 and 2 are shown in Fig. 3. The linear trend lines fitted through the mean cumulative removal rates represent the removal rate in g·week^{-1} for each treatment. The rates were converted to g·m^{-2}·d^{-1} by dividing the weekly rates by the mat area and the 7-day HRT. The mean N and P removal rates for each treatment and associated correlation values (R^2) for N removal by week are provided in Table 5. N removal rates were the highest for the *Panicum virgatum* treatment for trial 1 (0.738 g·m^{-2}·d^{-1}) and trial 2 (0.656 g·m^{-2}·d^{-1}). *Panicum virgatum* also had the highest P removal rates at 0.200 g·m^{-2}·d^{-1} and 0.194 g·m^{-2}·d^{-1} for trials 1 and 2, respectively. Tanner and Headley (2011) used the sedge, *Carex virgata*, in a FTW study and measured P removal rates of up to 0.027 g·m^{-2}·d^{-1}. P removal by *Carex stricta* in our study was three times higher than those reported by Tanner and Headley (2011). The higher P removal rates in our study could be attributed to the higher initial P loading or that the Tanner and Headley (2011) study focused upon the first 3 days.

Plant growth

Plant uptake of N and P content followed a similar pattern to cumulative nutrient removal. The mean N and P content per plant by species and trial are provided in Table 6. For trials 1 and 2, *Panicum virgatum* whether in monoculture or mixed treatments fixed more N in its tissues than all other monoculture treatments. Keizer-Vlek et al. (2014) reported 18.6 g·m^{-2} N removal and 0.51 g·m^{-2} P removal after a 91-day study using *Iris ensata*. These N removal results fall within the range of N removed by *Iris ensata* in our study (24.8 g·m^{-2} for trial 1 and 13.6 g·m^{-2} for trial 2). P removal by *Iris ensata* in our study was four to ten times higher than that reported by Keizer-Vlek et al. (2014), ranging from 2.09 to 5.03 g·m^{-2}. One difference between the two studies that could contribute to such a large difference in total removed N and P is the initial nutrient load. Our study had an initial N concentration 2.5 times higher and an initial P concentration 12 times higher than the Keizer-Vlek et al. (2014) study, which could be attributed to much longer (3-12X) HRTs in comparison with our study.

Plant dry weights (mean ± standard error) and root and shoot length (mean ± standard error) for the monoculture treatments are shown in Fig. 4. Total plant weight differed by plant species ($p < 0.0001$) for both trial 1 and trial 2. *Panicum virgatum* had the largest mean total dry weight at 92.1 ± 9.01 g (69.2 g for shoots and 22.9 g for roots) for trial 1 and 64.4 ± 6.89 g (43.9 g for shoots and 20.5 g for roots) for trial 2. The root weights of *Panicum virgatum*, *Carex stricta*, and *Agrostis alba* did not differ for trial 1. For trial 2, *Panicum virgatum* and *Carex stricta* had similar root weights, but shoot mass differed ($p < 0.001$). No differences in the total weight, root weight, or shoot weight were detected between *Iris ensata* and *Canna* × *generalis* for trial 1 or trial 2.

In trial 1, the mean root length of *Iris ensata* (24.1 ± 0.6 cm) was longer than all other monoculture species. *Panicum virgatum* and *Carex stricta* had consistently taller shoots than the other species for both trials 1 and 2; this height difference is partly due to the growth habits of those two species. For trial 2, *Agrostis alba* had significantly lower root lengths and shoot lengths than all other

Table 7 The mean physicochemical responses for floating treatment wetlands after a 7-day hydraulic retention time for a study conducted from June 2016 to September 2016 ($n = 32$)

Treatment	DO ($mg \cdot L^{-2}$)	EC ($\mu S \cdot cm^{-1}$)	pH	Temperature (°C)
Trial 1				
Agrostis alba	0.44[1]	274	6.10[1]	27.1
Canna × generalis 'Firebird'	0.39[1]	257	6.05[1]	26.8
Carex stricta	0.99[1]	258	5.36[1]	27.4[1]
Control	8.31	281	8.07	25.9
Iris ensata 'Rising Sun'	0.87[1]	240[1]	5.46[1]	26.9
Mixed: all plants	0.61[1]	238[1]	5.64[1]	26.9
Mixed: partial[2]	0.70[1]	236[1]	5.68[1]	26.9
Panicum virgatum	0.63[1]	211[1]	5.29[1]	26.7
Chi Square, *p* value	109, < 0.0001	97.5, < 0.0001	152, < 0.0001	8.71, 0.271
Trial 2				
Agrostis alba	1.20[1]	250	5.68[1]	25.9
Canna × generalis 'Firebird'	1.27[1]	235	5.63[1]	25.8
Carex stricta	1.54[1]	246	5.26[1]	26.2[1]
Control	8.28	247	7.37	24.8
Iris ensata 'Rising Sun'	1.62[1]	240	5.20[1]	25.9
Mixed: all plants	1.29[1]	234	5.48[1]	26.0
Mixed: partial[2]	1.20[1]	229	5.27	26.0
Panicum virgatum	1.31[1]	208[1]	4.97[1]	26.0
Chi Square, *p* value	89.9, < 0.0001	23.4, 0.0015	97.9, < 0.0001	9.51, 0.218

[1] Means differ significantly from the control using Dunn's method for joint ranking at $p < 0.05$

[2] Partial mixed treatments included *Agrostis alba*, *Carex stricta*, and *Panicum virgatum*

species, which was not the case for trial 1. *Agrostis alba* did not acclimate well during the trial 2 study, and nearly 50% of the plants died, which likely accounted for the slower growth observed.

Correlations between the mean dry weight of the plant tissue ($g \cdot plant^{-1}$) and the cumulative N and P removed (g) after 8 weeks are shown in Fig. 5. Cumulative N removed was correlated to plant dry weight ($p < 0.0001$) with a linear fit R^2 value of 0.64. The P removal after 8 weeks also correlated with plant dry weight ($p < 0.0001$) with a linear fit R^2 value of 0.34. While the linear correlation between plant dry weight and cumulative N or P fixed within the plant is not close to 1.0, indicating that variability in the model is influenced by factors not included in the analysis, the general trends represented still hold true in that plants with larger biomass accumulated more N and P; this is consistent with results reported by Wang et al. (2014). Furthermore, the correlations observed in our study are similar to those observed by Wang et al. (2014). Wang et al. (2014) showed total nutrient removal from the FTW treatment as opposed to the plant uptake portion of removal alone; correlating plant dry mass to total N and P removals within the FTW microcosm permitted estimation of unaccounted for nutrient removal.

Physicochemical properties

The mean DO, EC, pH, and water temperature for trials 1 and 2 are presented in Table 7. The mean DO for the control treatment during trial 1 was 8.31 ± 0.32 $mg \cdot L^{-1}$, higher than all other treatments which ranged from 0.39 to 0.99 $mg \cdot L^{-1}$. Trial 2 showed similar results where the control treatment had a mean DO level of 8.28 ± 0.23 $mg \cdot L^{-1}$ and all other treatments ranged from 1.20 to 1.62 $mg \cdot L^{-1}$. The lower DO levels of the FTW treatments increased the potential for formation of anoxic conditions. If the primary goal of the FTW is to remove N, lower DO levels would encourage denitrification. However, if the goal of the FTW is nutrient removal and wildlife habitat, then FTWs should not cover more than 50% of the pond surface area, to minimize risk of DO concentration declining to less than 4.0 $mg \cdot L^{-1}$, reducing potential for impairment of aquatic ecosystem health (Borne et al. 2015; Garcia Chance and White 2018). The pH for the control treatments in trials 1 and 2 was 8.07 ± 0.12 and 7.37 ± 0.85, respectively. All FTW treatments had lower mean pH levels than the control. Similar observations were reported in the study conducted by the author from June 2015 to October 2015 (Spangler 2017). The lower pH could be attributed to the release of root exudates that may include organic acids,

Table 8 Rainfall and temperature for the transplant observation periods

Study period date range	Total rainfall (mm)	Mean air temperature (°C)	Max air temperature (°C)	Min air temperature (°C)
Trial 1: July 27, 2016–August 24, 2016	265	27.1	35.9	17.5
Trial 2: September 21, 2016–October 19, 2016	424	20.8	30.3	10.4

phenolic compounds, and sugars from the rhizosphere (Blossfeld et al. 2011; Marschner 1995). Water temperature did not differ substantially between the treatments in trials 1 or 2. The EC was the lowest for treatments that performed the highest with regard to removal of N and P.

Transplant effects

After each trial, three plants from each monoculture mesocosm were planted in a field and three were planted in containers to evaluate transplant viability. The study period and ambient weather conditions during the evaluation are shown in Table 8. Plants were observed weekly and given a rating from 1 to 5 based on the plant viability definitions provided in Table 3. A photograph of *Carex stricta* exhibiting the classification range (from 1 to 5) is provided in Fig. 6.

The mean viability ratings by week for trials 1 and 2 for each plant species are shown in Fig. 7a for field and Fig. 7b for containers, respectively. For the field plantings, trial 2 had better ($p < 0.0001$) viability ratings than trial 1. This difference can be explained by ambient conditions during transplant and the evaluation period for trial 1. The temperature reached 36.7 °C on the day plants were transplanted in trial 1, and the evaluation period had a higher mean temperature and less total rainfall; causing stressful field growing conditions during which no supplemental irrigation was supplied other than irrigation upon initial transplant. For both trials, differences between plant species were notable ($p < 0.0001$), and plant viability decreased between the time of transplant and the fourth week of evaluation. *Agrostis alba* and *Panicum virgatum* generally did not transition from FTW to field as well as the other species.

Fig. 6 Visual example of the rating scale used for the evaluation of plants (*Carex stricta*) during two, 4-week FTW transplant studies. From left to right, the ratings are 5, 3, and 1. Plant viability was rated on a scale of 1–5 (see Table 3 for definition of each rating) based upon visual observation

Agrostis alba was not included in the container transplant evaluation due to insufficient plant numbers. For the container transplants, overall plant aesthetic ratings were higher than field ratings. The mean rating for the container transplants was 3.6 in comparison to the 3.2 mean rating of the field transplants. Container ratings were higher in trial 1 than trial 2 ($p < 0.0001$). Plant responses over time were similar in both container trials ($p < 0.0001$). *Carex stricta* is the only species that performed better with an earlier seasonal transplant time.

Evaluation data indicate that transplanting materials harvested from a FTW into containers under irrigation is the better option for plant viability; successful transplant into containers can occur at different times of the growing season. Transplanting from a FTW directly to the field would most likely mean the plants are going into a general landscape or a specific practice such as bioretention cell, vegetated buffer, or constructed wetland. To reduce stress factors and maximize survival, plants should be transplanted later in the growing season or into locations where adequate water will be available during their establishment phase. While *Panicum virgatum* has ornamental uses, it has also been the subject of much study as a source of cellulosic biofuel (Gu and Wylie 2017). It is possible that these plants could be harvested from FTWs to serve as cellulosic feedstock rather than for transplant.

Conclusions

FTWs are a viable option for nutrient remediation in nursery tailwater recovery basins. Specific N and P removal rates and masses vary by plant species, but FTW systems are capable of handling the frequent and high nutrient loads in runoff generated by commercial nursery production practices. The top-performing species in this study was *Panicum virgatum*, which removed up to 64.7% P and up to 82.4% N. Other species remediation rates ranged from 26.1 to 48.6% P and 12.9 to 50.4% N. *Panicum virgatum* would be the recommended species for use as a monoculture or in mixed plantings. While FTWs with mixed plantings performed well that performance was impacted by the specific species and plant ratios used. Regardless of species, a minimum 3-week

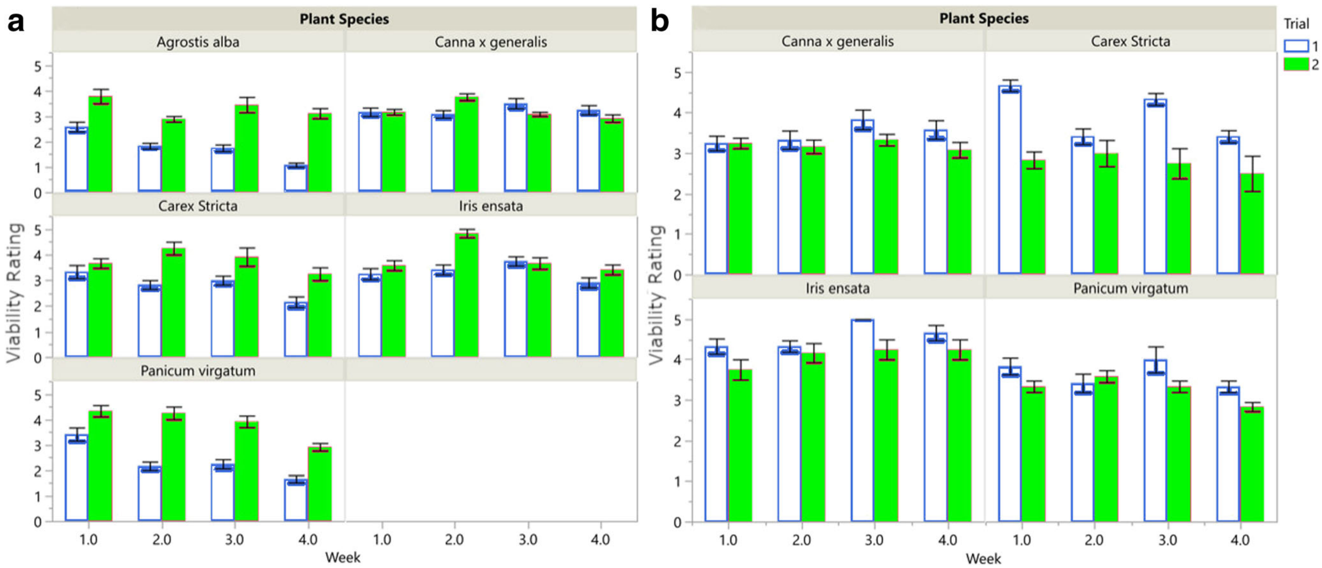


Fig. 7 Field (**a**) and container (**b**) transplant viability ratings (mean ± standard error) by week for trial and plant species during two, 4-week floating treatment wetland transplant studies. Plant viability was rated on a scale of 1–5 (see Table 3 for definition of each rating) based upon visual observation

establishment period was needed before plant-aided nutrient remediation was significant.

The presence of FTWs can enhance remediation regulated by microbial processes. The pond surface area covered by FTWs impacts the amount of DO in the water column. Lower DO favors denitrifying conditions; this could synergistically increase N removal with microbial transformation complementing plant uptake.

Installing and maintaining FTW systems can be expensive and labor intensive. To offset the costs, FTWs could be utilized as additional production space. Plants could be harvested (possibly multiple times during the growing season) and used for a variety of purposes such as being sold directly, potted up for future sale, composted and used as an amendment to a soilless substrate, or sold for biofuel (as in the case of *Panicum virgatum*). FTW plants were successfully transplanted into containers at two different times during the growing season. Selling plants for direct transplant into the ground requires scheduling for transplant later in the growing season when temperatures are cooler for the best survivability.

In this study, biomass per plant correlated with overall nutrient removal by plant. If biomass could be used to estimate removal performance, including plant uptake and other removal processes, it would be a much less intensive and expensive way to predict FTW performance. More research is needed to evaluate specific plant species' nutrient remediation abilities and to quantify the removal rates in full-scale nursery retention pond settings. Using harvested FTWs for production remains an opportunity; however, evaluation and market analysis is needed.

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References

Anderson DM, Glibert PM, Burkholder JM (2002) Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries 25:704–726

Blossfeld S, Gansert D, Thiele B, Ouml RN, Kuhn AJ (2011) The dynamics of oxygen concentration, pH value, and organic acids in the rhizosphere of Juncus spp. Soil Biol Biochem 43:1186–1197

Boonsong K, Chansiri M (2008) Domestic waste water treatment using vetiver grass cultivated with floating platform technique. Assumption University Journal of Technology 12:73–80

Borne K, Fassman-Beck E, Winston R, Hunt W, Tanner C (2015) Implementation and maintenance of floating treatment wetlands for urban stormwater management. J Environ Eng-ASCE 141:04015030

Borne KE (2014) Floating treatment wetland influences on the fate and removal performance of phosphorus in stormwater retention ponds. Ecol Eng 69:76–82

Borne KE, Tanner CC, Fassman-Beck EA (2013) Stormwater nitrogen removal performance of a floating treatment wetland. Water Sci Technol 68:1657–1664

Bu FP, Xu XY (2013) Planted floating bed performance in treatment of eutrophic river water. Environ Monit Assess 185:9651–9662

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Issues in Ecology:1–1

Chang NB, Islam MK, Wanielista MP (2012) Floating wetland mesocosm assessment of nutrient removal to reduce ecotoxicity in stormwater ponds. Int J Environ Sci Technol 9:453–462

Chen Z, Cuervo DP, Müller JA, Wiessner A, Köser H, Vymazal J, Kästner M, Kuschk P (2016) Hydroponic root mats for wastewater treatment—a review. Environ Sci Pollut Res 23:15911–15928

Chua LHCC, Tan SBKK, Sim CH, Goyal MK (2012) Treatment of baseflow from an urban catchment by a floating wetland system. Ecol Eng 49:170–180

Garcia Chance LM, White SA (2018) Aeration and plant coverage influence floating treatment wetland remediation efficacy. Ecol Eng 122:62–68

Gu Y, Wylie BK (2017) Integrating future scenario-based crop expansion and crop conditions to map switchgrass biofuel potential in eastern Nebraska, USA. GCB Bioenergy 1:1–8. https://doi.org/10.1111/gcbb.12468

Headley TR, Tanner CC (2006) Application of floating wetlands for enhanced stormwater treatment: a review. Auckland Regional Council, Hamilton

Headley TR, Tanner CC (2007) Floating wetlands for stormwater treatment: removal of copper, zinc and fine particulates. In: Prepared by NIWA for Auckland Regional Council. Auckland Regional Council. Available at: https://www.niwa.co.nz/sites/niwa.co.nz/files/tr2008_030_-_floating_vegetative_islands_for_stormwater_treatment_removal_of_copper_zinc_and_fine_particulates.pdf

Headley TR, Tanner CC (2012) Constructed wetlands with floating emergent macrophytes: an innovative stormwater treatment technology. Crit Rev Environ Sci Technol 42:2261–2310

Hubbard RK, Gascho GJ, Newton GL (2004) Use of floating vegetation to remove nutrients from swine lagoon wastewater. Trans ASAE 47: 1963–1972

Jayaweera MW, Kasturiarachchi JC (2004) Removal of nitrogen and phosphorus from industrial wastewaters by phytoremediation using water hyacinth (*Eichhornia crassipes* (Mart.) Solms). Water Sci Technol 50:217–225

Keizer-Vlek HE, Verdonschot PFM, Verdonschot RCM, Dekkers D (2014) The contribution of plant uptake to nutrient removal by floating treatment wetlands. Ecol Eng 73:684–690

Lane S, Sample D, Andy Lazur A, Ryan Winston R, Streb C, Ferrier D, Linker L, Brittingham K, Schueler T, Lane C, Wood D (2016) Recommendations of the expert panel to define removal rates for floating treatment wetlands in existing wet ponds: final report. Annapolis, Maryland. Available at:https://www.chesapeakebay.net/documents/FINAL-FTW-EXPERT-PANEL-REPORT-072716-LONG.pdf

Li H, Hao H, Yang X, Xiang L, Zhao F, Jiang H, He Z (2012) Purification of refinery wastewater by different perennial grasses growing in a floating bed. J Plant Nutr 35:93–110

Li H, Zhao HP, Hao HL, Liang J, Zhao FL, Xiang LC, Yang XE, He ZL, Stoffella PJ (2011) Enhancement of nutrient removal from eutrophic water by a plant-microorganisms combined system. Environ Eng Sci 28:543–554

Li YC, Zhang DQ, Wang M (2017) Performance evaluation of a full-scale constructed wetland for treating stormwater runoff. CLEAN - Soil, Air, Water. John Wiley & Sons, Ltd, 45(11):1600740. https://doi.org/10.1002/clen.201600740

Lynch J, Fox LJ, Owen JS Jr, Sample DJ (2015) Evaluation of commercial floating treatment wetland technologies for nutrient remediation of stormwater. Ecol Eng 75:61–69

Majsztrik JC 2011 Modeling nitrogen, phosphorus and water dynamics in greenhouse and nursery production systems. ProQuest Dissertations Publishing

Majsztrik JC, Fernandez RT, Fisher PR, Hitchcock DR, Lea-Cox J, Owen JS Jr, Oki LR, White SA (2017) Water use and treatment in container-grown specialty crop production: a review. Water Air Soil Pollut 228:151

Majsztrik JC, Lea-Cox JD (2013) Water quality regulations in the Chesapeake Bay: working to more precisely estimate nutrient loading rates and incentivize best management practices in the nursery and greenhouse industry. HortSci 48:1097–1102

Majsztrik JC, Ristvey AG, Lea-Cox JD (2011) Water and nutrient management in the production of container-grown ornamentals. Hortic Rev 38:253

Marschner H (1995) Mineral nutrition of higher plants. Academic Press, London; San Diego

Novotny V (2003) Water quality: diffuse pollution and watershed management. Wiley, Hoboken

Pavlineri N, Skoulikidis NT, Tsihrintzis VA (2017) Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. Chem Eng J 308:1120–1132

Polomski RF, Bielenberg DG, Whitwell T, Taylor MD, Bridges WC, Klaine SJ (2007) Nutrient recovery by seven aquatic garden plants in a laboratory-scale subsurface-constructed wetland. HortSci 42: 1674

Qin BQ (2009) Lake eutrophication: control countermeasures and recycling exploitation. Ecol Eng 35:1569–1573

Shahid MJ, Arslan M, Ali S, Siddique M, Afzal M (2018) Floating wetlands: a sustainable tool for wastewater treatment. CLEAN - Soil, Air, Water. 46(10):1–13. https://doi.org/10.1002/clen.201800120

Shen X, Huang D, Zhang C, Hu K (2018) Performance evaluation of constructed wetlands treating wastewater treatment plant effluent in Taihu Lake, China. CLEAN - Soil, Air, Water. John Wiley & Sons,Ltd, 46(1):1600442. https://doi.org/10.1002/clen.201600442

Smith MP, Kalin M (2000) Floating wetland vegetation covers for suspended solids removal. Quebec 2000: Millennium Wetland Event (selected papers), Treatment wetlands for water quality removal, Quebec City, Quebec, Canada, pp 143-148

Spangler JT (2017) An assessment of floating treatment wetlands for reducing nutrient loads from agricultural runoff in Coastal Virginia. Virginia Polytechnic Institute and State University, Blacksburg, p 98

Stewart FM, Mulholland T, Cunningham AB, Kania BG, Osterlund MT (2008) Floating islands as an alternative to constructed wetlands for treatment of excess nutrients from agricultural and municipal wastes – results of laboratory-scale tests. Land Contamination & Reclamation 16:25–33

Sun LP, Liu Y, Jin H (2009) Nitrogen removal from polluted river by enhanced floating bed grown Canna. Ecol Eng 35:135–140

Tanner CC, Headley TR (2011) Components of floating emergent macrophyte treatment wetlands influencing removal of stormwater pollutants. Ecol Eng 37:474–486

Taylor MD, White SA, Chandler SL, Klaine SJ, Whitwell T (2006) Nutrient management of nursery runoff water using constructed wetland systems. HortTechnology 16:610–614

USEPA (2010) Chesapeake Bay total maximum daily load for nitrogen, phosphorus, and sediment. In: USEPA Region III. Philadelphia, PA. Available at: https://www.epa.gov/chesapeake-bay-tmdl/chesapeakebay-tmdl-document

USEPA (2013) National summary of state information. U.S. Environmental Protection Agency, Washington, D.C.

Van de Moortel AMK (2008) Use of floating macrophyte mats for treatment of CSOs, 11th International Conference on Urban Drainage, Edinburgh, Scotland

Van de Moortel AMK, Meers E, De Pauw N, Tack FMG (2010) Effects of vegetation, season and temperature on the removal of pollutants in experimental floating treatment wetlands. Water Air Soil Pollut 212: 281–297 van Oostrom AJ (1995) Nitrogen removal in constructed wetlands treating nitrified meat processing effluent. Water Sci Technol 32: 137–147

Wang CY, Sample DJ (2014) Assessment of the nutrient removal effectiveness of floating treatment wetlands applied to urban retention ponds. J Environ Manag 137:23–35

Wang C-Y, Sample DJ, Bell C (2014) Vegetation effects on floating treatment wetland nutrient removal and harvesting strategies in urban stormwater ponds. Sci Total Environ 499:384–393

Wang D, Bai S, Wang M, Xie Q, Zhu Y, Zhang H (2012) Effect of artificial aeration, temperature, and structure on nutrient removal in constructed floating islands. Water Environ Res 84:405–410

White SA, Cousins MM (2013) Floating treatment wetland aided remediation of nitrogen and phosphorus from simulated stormwater runoff. Ecol Eng 61(Part A):207–215

White SA, Taylor MD, Albano JP, Whitwell T, Klaine SJ (2011) Phosphorus retention in lab and field-scale subsurface-flow wetlands treating plant nursery runoff. Ecol Eng 37:1968–1976

White SA, Taylor MD, Chandler SL, Whitwell T, Klaine SJ (2010) Remediation of nitrogen and phosphorus from nursery runoff during the spring via free water surface constructed wetlands. J Environ Hortic 28:20–217

Winston RJ, Hunt WF, Kennedy SG, Merriman LS, Chandler J, Brown D (2013) Evaluation of floating treatment wetlands as retrofits to existing stormwater retention ponds. Ecol Eng 54:254–265

Xian Q, Hu L, Chen H, Chang Z, Zou H (2010) Removal of nutrients and veterinary antibiotics from swine wastewater by a constructed macrophyte floating bed system. J Environ Manag 91:2657–2661

Xin ZJ, Li XZ, Nielsen SN, Yan ZZ, Zhou YQ, Jia Y, Tang YY, Guo WY, Sun YG (2012) Effect of stubble heights and treatment duration time on the performance of water dropwort Floating Treatment Wetlands (FTWS). Ecological Chemistry and Engineering S 19:315–330

Yang ZF, Zheng SK, Chen JJ, Sun M (2008) Purification of nitrate-rich agricultural runoff by a hydroponic system. Bioresour Technol 99: 8049–8053

Yeager T, Million J, Larsen C, Stamps B (2010) Florida nursery best management practices: past, present, and future. HortTechnology 20:82

Zhao FL, Yang WD, Zeng Z, Li H, Yang XE, He ZL, Gu BH, Rafiq MT, Peng HY (2012) Nutrient removal efficiency and biomass production of different bioenergy plants in hypereutrophic water. Biomass Bioenergy 42:212–218

Zhou XH, Wang GX (2010) Nutrient concentration variations during *Oenanthe javanica* growth and decay in the ecological floating bed system. J Environ Sci 22:1710–1717

Zhou XH, Wang GX, Yang F (2012) Nitrogen removal from eutrophic river waters by using *Rumex acetosa* cultivated in ecological floating beds. Fresenius Environ Bull 21:1920–1928