Water Research 159 (2019) 153–163

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Short- and long-term dynamics of nutrient removal in floating treatment wetlands

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ARTICLE INFO

Article history:
Received 12 February 2019
Received in revised form 30 April 2019
Accepted 4 May 2019
Available online 6 May 2019

Keywords:
Allocation
Rate
Pontederia
Juncus
Peak uptake

ABSTRACT

Floating treatment wetlands (FTWs) are a plant-based treatment technology shown to remove excess nutrients and metals from surface waters under a variety of conditions. Plants established in FTWs can accumulate and store nutrients within their tissues, but the amount of uptake and storage is dependent on plant species and nutrient influent concentration. This research was designed to quantify the influence of nutrient load and two plant species on nutrient uptake and partitioning patterns within plant tissues (shoots and roots) so that management recommendations for FTWs can be developed to better protect surface water quality. Treatments consisted of (1) two nutrient loads: a high concentration of 15 $mg \cdot L^{-1}$ nitrogen (N) and a low concentration of 5 $mg \cdot L^{-1}$ N supplied as water soluble fertilizer, and (2) four mesocosm treatments: (a) open water, (b) artificial mat only, no plants, (c) artificial mats planted with *Pontederia cordata* L., and (d) artificial mats planted with *Juncus effusus* L.. Plant growth, N, and phosphorus (P) uptake of both *P. cordata* and *J. effusus* were greater in the high nutrient treatment than in the low. *Pontederia cordata* facilitated the highest rates of N (0.31 $mg \cdot L \cdot day^{-1}$) and P (0.34 $mg \cdot L \cdot day^{-1}$) removal. The nutrient removal rates facilitated by *Juncus effusus* in the high nutrient treatment were much lower for both N (0.03 $mg \cdot L \cdot day^{-1}$) and P (0.02 $mg \cdot L \cdot day^{-1}$). Peak N and P accumulation in *J. effusus* occurred in September within both root (50 g N and 4.8 g P) and shoot tissues (98 g N and 12.5 g P). The uptake of N and P in *P. cordata* was highest in root tissues in August (307 g N and 30.5 g P) and in shoot tissues in September (1490 g N and 219.5 g P). In both species, shoots accumulated more N and P than the roots, resulting in a small root:shoot ratio at all stages of the experiment. Harvest of plants from FTWs should occur before plants senesce in the fall, which using *P. cordata* and *J. effusus* as model species, occurred from mid- to late-September in USDA Hardiness Zone 8a in the Southeastern United States.

1. Introduction

Constructed wetlands (CWs) are used by many industries to reduce nutrient contamination of water (Chung et al., 2008; Cui et al., 2010; Díaz et al., 2012, Gotschall et al., 2007). Floating treatment wetlands (FTWs) are an increasingly popular form of CW technology for nutrient remediation (Lynch et al., 2015; Stewart et al., 2008; Wang et al., 2015; White and Cousins, 2013). Floating treatment wetlands consist of emergent plants established on a buoyant mat with openings for plant insertion, suspended on the surface of a water body. In FTW systems, the shoots and crowns of the plants grow above the water level, while the roots extend down into the water column, developing an extensive below-mat root system (Pavlineri et al., 2017). Plants are an important component facilitating contaminant transformation and removal within FTWs (Akratos and Tsihrintzis, 2007; Headley and Tanner, 2012; Tanner et al., 1995; Van de Moortel et al., 2010).

Plants remove nutrients (e.g., nitrogen (N) and phosphorous (P)) from the water column and translocate them throughout the plant. Assimilation of nutrients within plant root and shoot tissues positively correlates with overall system treatment efficacy (Keizer-Vlek et al., 2014; Kyambadde et al., 2004; White and Cousins, 2013). Additionally, as plant biomass increases, accumulation and storage of N and P have been shown to increase (Keizer-Vlek et al., 2014; Kyambadde et al., 2004; Zhu et al., 2011). The presence of plants within a treatment system designed to remediate nutrients

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https://doi.org/10.1016/j.watres.2019.05.012

may not always prove beneficial. For example, if biomass is not harvested before the plant begins to senesce, it is possible for some of the nutrients sequestered within plant tissues to be released into the water column as plant tissues decay (Li et al., 2010; Zhao et al., 2012). Pavlineri et al. (2017) suggested that plant harvest in FTW applications is essential for removing nutrients completely from the water system and that whole plant harvesting needs to be further examined. Zhou and Wang (2010) also suggested regular harvesting to increase system efficacy and prevent decaying plant tissue from reentering the system.

Limited information is available regarding the uptake and translocation of nutrients within FTW vegetation. Kadlec and Reddy (2001) indicated that the influence of vegetation on contaminant removal is not based solely on temperature, but may also vary over the different seasons. Wang et al. (2015) observed seasonal changes in biomass and P accumulation in FTW plants, recommending harvest of above-ground vegetation be conducted during summer in June for maximum P removal or in September to prevent P release due to plant senescence. Wang et al. (2015) noted information is lacking with regard to plant growth rates and plant tissue capacity to accumulate and store nutrients within soilless environments, such as those that plants within FTWs inhabit.

This knowledge gap is in large part due to a lack of information on two factors; (1) species selection and (2) the rate of nutrient uptake/release over time. The biomass accumulation, nutrient storage capacity and allocation, root structure, microbial communities, and the growth cycle of the plant (e.g., annual, perennial) differ among plant species. Specifically, plants with high biomass accumulation potential can extract larger amounts of nutrients from their environment and store these nutrients in biomass and litter (Meuleman et al., 2002). Therefore, the nutrient removal efficacy of FTWs is highly dependent upon the species used within the system (Headley and Tanner, 2012; Li and Guo, 2017). Several researchers have demonstrated that increased influent nutrient concentration rates heighten removal efficacy by increasing vegetative growth and, subsequently, nutrient uptake by plants (Karnchanawong and Sanjitt, 1995; White and Cousins, 2013; Yang et al., 2008).

Species selection and rate of nutrient removal have been undertaken for free water surface and subsurface-flow CWs. The sampling periods during selected studies with CWs have varied from short-term, on the scale of hours or days, to long-term, multiple-year studies. These short and long-term studies have assisted with determination of peak nutrient uptake of the system (Schaafsma et al., 1999), duration of optimal performance (Al-Rubaei et al., 2016), and reactions of the system to variable influent loading rates (Dusek et al., 2008; Gebremariam and Beutel, 2008). Many FTW studies (Table S1) have been conducted that range in duration, sampling periods, and plant species trialed, yet few considered the changes in nutrient remediation rates over the experiment nor identified peak uptake. Understanding of nutrient remediation rates and, therefore, optimal harvest time, is imperative for FTW systems due to potential for release of nutrients back into the surface waters when plants senesce.

This experiment studied both the short- (weekly) and long-term (seasonal) nutrient remediation patterns of two aquatic plants at two levels of nutrient availability. Quantifying changes in nutrient uptake over time will help better explain species uptake efficiencies and FTW planting and harvest times to promote the greatest nutrient removal.

2. Material and methods

2.1. Experimental floating treatment wetland construction

The experiment was conducted from May–October 2015 (20-weeks), representative of a typical growing season for plants in USDA Hardiness Zone 8a. The experimental system was assembled at the Water Treatment Technology Laboratory at the South Carolina Water Resources Center at Clemson University (Pendleton, South Carolina, USA 34.640N, −82.773W) and consisted of 32, 378.5 L structural foam stock tanks or mesocosms (Rubbermaid, Atlanta, GA; Fig. 1). Each mesocosm had a surface area of 1.15 m^2 and a volume of 0.59 m^3. Mesocosms were equipped with a quarter turn valve at the outflow to control release of water. Holes were drilled 6 cm from the rim at one end of the mesocosm to regulate overflow and release of water. Each mesocosm held an average of 314 L of water. Mesocosms were arranged in a completely randomized block design. Each mesocosm could be filled from either of two, 5867 L black plastic storage stock tanks (Norwesco, St. Bonifacius, MN), depending on the treatment assigned. Each mesocosm was supplied with water from the stock tanks via PVC pipe and fittings with an inline pump (Little Giant, Fort Wayne, IN). Inlets to each mesocosm were equipped with a quarter-turn valve to control water volume and which stock tank filled each mesocosm. Once a mesocosm was assigned to a treatment, it consistently received

Fig. 1. Experimental layout showing thirty-two, 378.2 L mesocosms and two 5867 L stock tanks used to fill the mesocosms through water lines constructed using PVC piping and quarter turn valves.

water from the same stock tank.

The floating mat used to hold plants above the water was a 2-cm thick, solid-core foam mat (Beemats, New Smyrna Beach, FL) cut to 60 cm × 30 cm and joined using 10-cm nylon connectors. Each mat section had 20 (7.5 cm) pre-cut holes spaced 12 cm on center. Holes allowed for the insertion of specially designed plastic aerator cups in which plants were placed, keeping the crown of the plant above the water surface, while permitting the plant roots to extend into the water column below the mat.

The experiment was designed as a 4 × 2 factorial with 4 plant/mat combinations and 2 nutrient exposure levels (Table 1). The 4 plant/mat treatments were 1) no plants, no mat; 2) no plants, with mat; 3) *Pontederia cordata* (pickerel weed) with mat and; 4) *Juncus effusus* (soft rush) with mat. These species were selected based upon their common use within FTW systems as well as their differences in growth cycle (deciduous vs evergreen). Plants were purchased as bareroot liners, 8–10 cm long (Florida Aquatic Nursery, Davie, FL) and washed using municipal water to remove any remaining residues or substrates prior to planting. Plants were planted at 10 plants per mat or 50% plant coverage to prevent crowding as the plants grew over the 20-week experiment.

2.2. Simulation of runoff containing nutrients

Mesocosms were filled with municipal water to which water-soluble fertilizer was added to simulate concentrations similar to either nursery irrigation runoff or stormwater runoff. Average total nitrogen (TN) levels were $14.6 \pm 5.2\ \mathrm{mg \cdot L^{-1}}$ N (high) or $4.88 \pm 1.75\ \mathrm{mg \cdot L^{-1}}$ N (low) and total phosphorus (TP) levels were $2.3 \pm 0.68\ \mathrm{mg \cdot L^{-1}}$ P (high) and $0.82 \pm 0.44\ \mathrm{mg \cdot L^{-1}}$ P (low) (Table 2). The $15\ \mathrm{mg \cdot L^{-1}}$ N solution was comparable to nursery irrigation runoff while the $5\ \mathrm{mg \cdot L^{-1}}$ N solution was comparable to stormwater runoff from an urban area (Leisenring et al., 2010; White, 2013). The simulated runoff was prepared by dissolving water-soluble fertilizer ($343\ \mathrm{g \cdot 5500\ L^{-1}}$ for the high treatment and $115\ \mathrm{g \cdot 5500\ L^{-1}}$ for the low treatment of 24N–8P–16K Nitrate Special Soluble Fertilizer, Southern Agricultural Insecticides, Inc., Hendersonville, NC) in water within the stock tanks, weekly. Following preparation, stock tanks were continuously mixed using the inline pump for 2 h prior to filling the mesocosms. Sixteen mesocosms were filled from the high N stock tank and 16 mesocosms were filled from the low N stock tank using the pump and PVC distribution system. Mesocosms were filled on Day 0 from the stock tanks and then drained on Day 7 to simulate a seven-day hydraulic retention time (HRT) throughout the 20-week experiment duration, for a total of 20 fills.

2.3. Water sampling and analysis

For each experimental mesocosm ($n = 32$), water samples were collected at Day 7 for all 20 weeks. All samples were taken at a 15-cm depth in the morning between 7:00 and 9:00 a.m. Every other week, samples were also collected on Day 3 and Day 5, beginning at Week 1, to better understand the short-term dynamics of the system. Water samples were also collected weekly from the stock tanks prior to filling the mesocosms to establish a baseline of the average concentration of nutrients in the two simulated runoff treatments (Table 2). Each water sample was analyzed using two analytical techniques: inductively coupled plasma emission spectrophotometry (ICP-ES) and a flow injection analysis (FIA). All ICP samples were immediately transferred to vials with no filtration or acidification and placed in a −25 °C freezer. The FIA samples were preserved by adding sulfuric acid to the sample until pH was <2.0 and placed in a −25 °C freezer. All samples were stored at appropriate temperatures until analysis.

Table 2
Physico-chemical characteristics of two treatment levels of nutrients characterizing simulated runoff from stormwater (low) and nursery production (high). Concentrations of simulated water were measured at Day 0 averaged across 20 weeks.

	LOW CONCENTRATION	HIGH CONCENTRATION
TN ($\mathrm{mg \cdot L^{-1}}$)	4.88 ± 1.75	14.6 ± 5.2
NH_4^+- N ($\mathrm{mg \cdot L^{-1}}$)	0.75 ± 0.30	1.33 ± 0.38
NO_3^- - N ($\mathrm{mg \cdot L^{-1}}$)	3.84 ± 0.31	9.62 ± 1.12
NO_2^- - N ($\mathrm{mg \cdot L^{-1}}$)	0.00 ± 0.00	0.0 ± 0.00
TP ($\mathrm{mg \cdot L^{-1}}$)	0.82 ± 0.44	2.3 ± 0.68
PO_4^{3-} - P ($\mathrm{mg \cdot L^{-1}}$)	0.73 ± 0.27	1.7 ± 0.43
pH	6.97 ± 0.22	6.81 ± 0.31
DO ($\mathrm{mg \cdot L^{-1}}$)	7.56 ± 0.21	7.54 ± 0.27
Temp (°C)	27.8 ± 3.23	27.7 ± 3.33

ICP-ES (ICP-ES, 61E Thermo Jarrell Ash, Franklin, MA) detected elemental concentrations including P, K, Ca, Mg, Zn, Cu, Mn, Mo, Ni, Fe, S, Na, B, and Al. FIA quantified total nitrogen (TN) and total phosphorus (TP) after persulfate digestion (QuickChem® Method 10-107-04-4B and 10-115-01-4B; Lachat Instruments, Loveland, CO, USA). All analyses were conducted using internal quality assurance/control procedures to ensure reliable and repeatable sample analysis. Following testing, all reusable sampling equipment was cleaned using a 10% hydrochloric acid-wash and rinsed with Milli-Q (18 MΩ cm resistivity) three times. Environmental parameters, including pH, dissolved oxygen (DO), and temperature, were measured on Day 0, 3, 5, and 7 for all 20 weeks using a calibrated handheld multi-meter, with individual sensors for each parameter, (YSI, Yellow Springs, OH). The sensors on the hand-held multimeter were allowed to stabilize prior to recording measurements.

2.4. Plant sampling and analysis

The roots (below-mat biomass) and shoots (above-mat biomass) of six representative plants per species (*Juncus effusus* and *Pontederia cordata*) were harvested at Day 0 of the experiment to establish baseline allocation and concentration of nutrients within the plant tissues. Plant size measurements were performed every 14 days on the same three plants per species per experimental mesocosm over the sampling period. Those plants were then harvested at the end of the 20-week period for final tissue

Table 1
Design of a 4 × 2 factorial experiment with four plant and floating treatment wetland mat combinations and two nutrient exposure levels. Abbreviations under Factor are combined to create letter designations under Treatment.

FACTOR	DESCRIPTION	REPLICATES	TREATMENT
H	High concentration influent	16	HN, HY, HYP, HYJ,
L	Low concentration influent	16	LN, LY, LYP, LYJ
N	No mat	8	HN, LN
Y	Mat	24	HY, HYP, HYJ, LY, LYP, LYJ
P	*Pontederia cordata*	8	HYP, LYP
J	*Juncus effusus*	8	HYJ, LYJ

concentrations. To determine plant nutrient accumulation and allocation over time, four separate mesocosms (two per species) were treated as harvest mesocosms and were used to harvest plants overtime during the experiment so as not to confound results from the experimental mesocosms. One mesocosm per plant species was exposed to the high nutrient treatment, and the other to the low nutrient treatment. The four 378.5 L structural foam mesocosms, identical in size to the 32 experimental mesocosms, were drained and filled in the same manner as the experimental units. Every four weeks, beginning at Week 4, two plants from each harvest mesocosm were harvested at random to quantify changes in nutrient composition and biomass over time, for a total of five harvests. Plant size measurement [shoot height (cm), longest root length (cm), and plant width (cm) in two directions (cm, widest and narrowest point)] were taken on the two harvest plants at each harvest interval. These measurements were then compared to the same measurements collected on plants within the experimental mesocosms.

For all harvested plants (experimental and harvest mesocosms), roots and shoots were separated, weighed (fresh weight, g), dried at 80 °C for a minimum of 72 h, weighed (dry weight, g), and ground in a Wiley Mini Mill (Thomas Scientific, Swedesboro, NJ) to pass through a 40-mesh screen (0.425-mm). Nitrogen concentration was determined using 100 mg of dried tissue and assayed using a combustion analyzer (Elementar Vario Macro Nitrogen, Mt. Laurel, NJ). Phosphorus, K, Ca, Mg, Zn, Cu, Mn Fe, S, Na, B, and Al concentrations in plant tissues were determined after sample digestion using ICP-ES with calibration standards rerun at midpoint and end of each analytical run (ICP-ES, 61E Thermo Jarrell Ash, Franklin, MA).

2.5. Data analysis

Using analytical methods as outlined by Chua et al. (2012), the time variation of concentration was estimated based on a first-order reaction:

$$\frac{(C - C_f)}{(C_i - C_f)} = e^{-kt} \quad (1)$$

where t is time (days), C is the sample concentration (mg/L) at time t, C_i is the initial concentration (mg/L), C_f is the final concentration (mg/L) and k is the rate constant (mg·L·day^{-1}). Estimates of k provide an indication of the rate constant at which nutrient uptake occurred.

Several steps were needed to quantify the effects of time and treatment (nutrient concentration and plant species) on nutrient removal efficacy and rate, plant nutrient uptake efficiency, and nutrient allocation within plant tissues. The first step determined if the weekly changes were best represented by an overall change

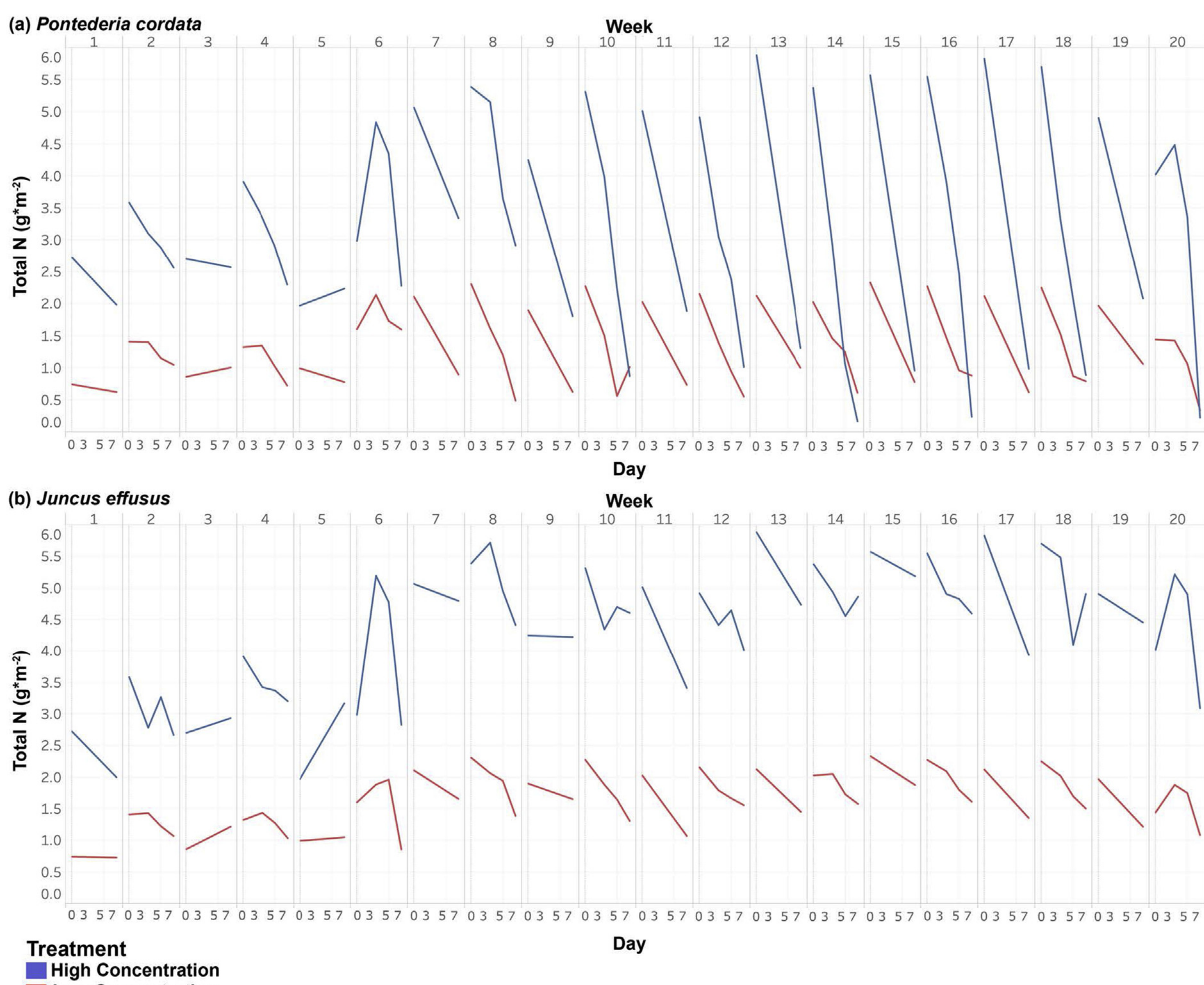

Fig. 2. Change in average total N load (g·m^{-2}) across days 0 (influent), 3, 5, and 7 for a series of 20 weeks using *Pontederia cordata* (a) and *Juncus effusus* (b) for high concentration (blue line) and low concentration (red line) ($n = 4$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

from Day 0 to Day 7, endpoints (Day 7 only), weekly slope (rate of change), etc. In the second step, we developed a model relating the weekly change to the overall effects of time and treatment. Analysis of Variance (ANOVA) was used to test the time and treatment effects of the model. In the third step, we developed a model determining the rate of change (rate constant) by treatment within each week and then ANOVA was used to test the effect of treatment in the models for each week. When treatment and week or their interaction were found to have a significant effect, the Fisher's Least Significant Difference test was used to further study the nature of these effects. For monthly effects, the monthly plant tissue concentration was plotted to determine visually when peak uptake occurs. An ANOVA was used to test the effect of treatment on the monthly plant nutrient concentration. Finally, in step four, we calculated nutrient budgets to quantify the overall change and efficacy of each treatment. All statistical calculations were conducted using JMP v13 (SAS Institute Inc. Cary, NC) and p-values <0.05 were considered evidence of statistical significance.

3. Results and discussion

3.1. Nutrient removal over time

Plant nutrient uptake, facilitated by the presence of plants and FTWs, was evaluated over both the short-term (7 days) and long-term (20 weeks). When assessing changes in concentration on a weekly basis after each seven-day exposure to *P. cordata* or *J. effusus* with high and low TN (Fig. 2) and TP (Fig. 3) loads, results were clustered by plant species and separated by influent nutrient concentrations. Data are presented as loading rates to account for mass of nutrients per unit surface area of the water covered by FTWs ($g \cdot m^{-2}$). Initial nutrient loads were variable by week as adjustments to stock tanks resulted in fluctuations during the first six weeks of the experiment. *P. cordata* consistently removed TN and TP between Days 0, 3, 5, and 7, beginning in week 7. Nutrient removal by *J. effusus* was inconsistent throughout the experiment, with fluctuations in TN and TP concentrations during Days 3 and 5 (Figs. 2 and 3). In most cases, the nutrient load on Day 7 was lower than the load on Day 0, indicating net removal. Instances occurred in the beginning of the study in which nutrient load at Day 7 was higher than at Day 0, indicating release of N and P. This occurred in Week 5 for both species (TN and TP) and Week 3 for *J. effusus* (TN). During Weeks 4 and 9, the TN load measured at Day 7 was lower than on Day 0 for both plant species; however, the load of TP increased over the course of the week for *J. effusus*, while decreasing in the presence of *P. cordata* (Figs. 2 and 3). This initial period of fluctuation (Week 1–6) could indicate transplant shock, root and shoot dieback and adaptation to a new environment, followed by increased growth beginning in Week 7 (Fig. 4). These findings align with previous research with wetland plants, where

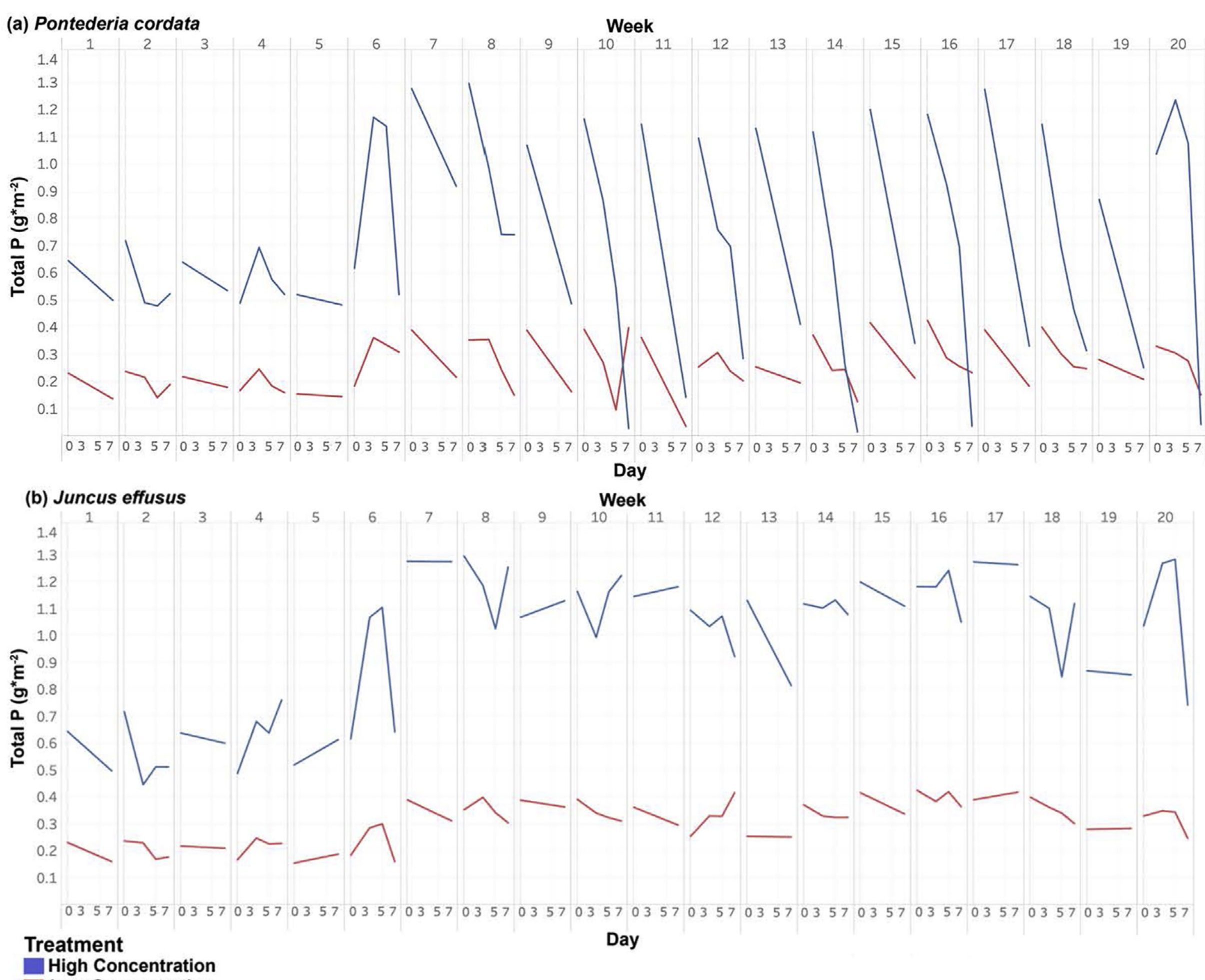

Fig. 3. Change in average total P load ($g \cdot m^{-2}$) across days 0 (influent), 3, 5, and 7 for a series of 20 weeks using *Pontederia cordata* (a) and *Juncus effusus* (b) for high concentration (blue line) and low concentration (red line) ($n = 4$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

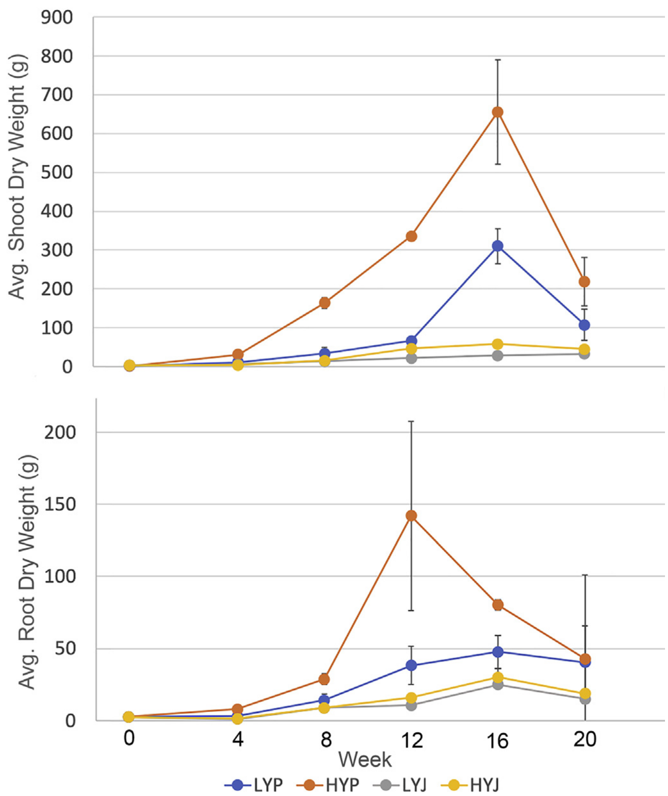

Fig. 4. Plant mass for shoots and roots over 20 weeks by plant species (*Pontederia cordata* and *Juncus effusus*) and nutrient treatment (low and high) ($n = 4$). Low (L) or high (H) nutrient treatments in the presence of FTWs (Y) established either with *Pontederia cordata* (P) or *Juncus effusus* (J).

once plants were established, N removal stabilized (Heffernan and Fisher, 2012; Spangler et al., 2019) (see Fig. 2).

Pontederia cordata reduced the load of TN in the HYP from 4.5 ± 1.2 g m^{-2} TN to 1.6 ± 0.92 g m^{-2}, similar to the final TN load of the low solution, 1.8 ± 0.51 g m^{-2} ($p \leq 0.0001$) (Fig. 2). This may indicate that *P. cordata* has a lower limit of remediation in these conditions of approximately 0.86 g m^{-2} TN. Further, in situations where initial nutrient loads fall within the low nutrient range, *P. cordata* may not be the most suitable plant selection for use in FTWs. Research from other studies indicate plants such as *Canna* 'Bengal Tiger' and *Peltandra virginica* can perform well when exposed to low nutrient conditions (Polomski et al., 2007). Within the HYP treatment, the load of TP remaining in solution at Day 7 were more variable than for TN (0.02 g m^{-2} TP to 0.92 g m^{-2} TP). For many weeks, TP removal, in HYP, was at or below the Day 0 load of the LYP treatment at Day 7 (Fig. 3). This continued TP removal was not seen within the LYJ treatment. *Juncus effusus* is a comparatively slower growing plant with low minimum nutrient requirements (McCorry and Renou, 2003), as evidenced by the similar amount of nutrients removed in both the high and low nutrient treatments, an average of 0.58 ± 0.35 g m^{-2} for HYJ and 0.54 ± 0.26 g m^{-2} for LYJ ($p > 0.05$).

These changes can be further assessed by observing the rate constant in TN and TP over the course of the seven days (Figs. 5 and 6). While *J. effusus* had a consistent, low weekly rate of change (rate constant; mg·m^{-2}·day^{-1}) over the duration of the experiment, the rate for *P. cordata* increased over time, peaking around Week 14 for high concentrations of TN and TP ($p \leq 0.001$) and Week 12 for low concentrations of TN and TP ($p \leq 0.005$). The initial concentration of nutrients in simulated runoff did not influence the nutrient removal rate of HYJ or LYJ ($p = 0.238$ for TN and $p = 0.623$ for TP). Initial concentration was important for *P. cordata* ($p \leq 0.005$ for TN and TP), with the HYP treatment facilitating faster removal rates than the LYP treatment (Figs. 5 and 6). These differences are most likely attributable to differences in the growth characteristics of *J. effusus* and *P. cordata* and are consistent with other published findings (Gettys and Dumroese, 2009; Godfrey and Wooten, 1979). Both species are herbaceous perennials. However, in USDA hardiness zone 8a, *Juncus effusus* is also evergreen, this means there is potential for year-round accumulation of nutrients within plant tissues; whereas, *Pontederia cordata,* vegetation grew rapidly until it flowered during August and September. Thereafter, the vegetative growth of *Pontederia cordata* slowed and nutrient uptake declined as the plant entered dormancy and tissues began to senesce in late October to mid-November (Fig. 4).

The species of plant established within the FTW greatly influenced removal of both TN and TP. Compared with *J. effusus*, *P. cordata* consistently reduced the effluent nutrient concentration by 37% TN and 42% TP in high treatments and by 34% TN and 22% TP in low concentrations ($p \leq 0.0001$) (Table 3).

3.2. Plant nutrient accumulation and partitioning

An important component when assessing the rate of removal of P and N in FTWs is the mass of nutrients accumulated within the plants in comparison to other removal processes (Table 3). Nitrogen accumulation within *P. cordata* [35.4 g m^{-2} (high) and 10.5 g m^{-2} (low)] was higher than *J. effusus* [4.89 g m^{-2} (high) and 2.89 g m^{-2} (low); $p \leq 0.0001$ for both high and low treatments]. Phosphorus assimilation trends were similar for high and low nutrient treatments with *P. cordata* accumulating 4.36 g m^{-2} and 1.25 g m^{-2}, respectively; compared to *J. effusus* accumulating 0.53 g m^{-2} g and 0.27 g m^{-2}, respectively ($p \leq 0.0001$ for both high and low treatments; Table 3). The N accumulation values correlate with plant growth and plant mass data at harvest ($p \leq 0.0001$; Fig. 7). Data show that on a per m^2 basis, *P. cordata* was able to remove 3.6 to 7.2 times more N and between 4.6 and 8.2 time more P than *J. effusus*, depending on treatment.

Peak uptake of both N and P was in September for both *P. cordata* and *J. effusus* in the high nutrient treatments; uptake of N and P ($p \leq 0.0001$ for *P. cordata*, $p \leq 0.002$ for *Juncus*) was similarly consistent in low nutrient treatments, peaking in September for all except the LYP treatment, which demonstrated continued accumulation of P in root and shoot tissues (Fig. 7). The peak in nutrient accumulation may be an indicator of ideal harvest time to prevent the majority of nutrient release back into the water as plant tissues senesce. Temperature did not influence accumulation patterns ($p \leq 0.324$) during the experiment. However, multiple iterations of the experiment, performed over different years and locations would help to better understand if time to peak accumulation is temperature related or seasonally driven. For example, had the experiment been initiated one month earlier would peak removal shift back a month to August, or if September were hotter than the 2015 average of 24.8 °C would this delay time to peak? Also, physiological (senescence initiation) and morphological (flowering) changes within plants in FTWs may be more pertinent drivers of peak accumulation than time planted or temperature (Keizer-Vlek et al., 2014; Kyambadde et al., 2004; Zhu et al., 2011). Mamolos et al. (2011) found that wetland species typically have a delayed peak in biomass production and accumulation in comparison to upland species due to a longer growing period. Furthermore, Mamolos et al. (2011) determined a delay in peak of biomass by one month from peak of nutrient accumulation. In this study, biomass decreased the month accumulation peak, but could be attributed to senescence from cooler weather and preparation for dormancy (Fig. 4).

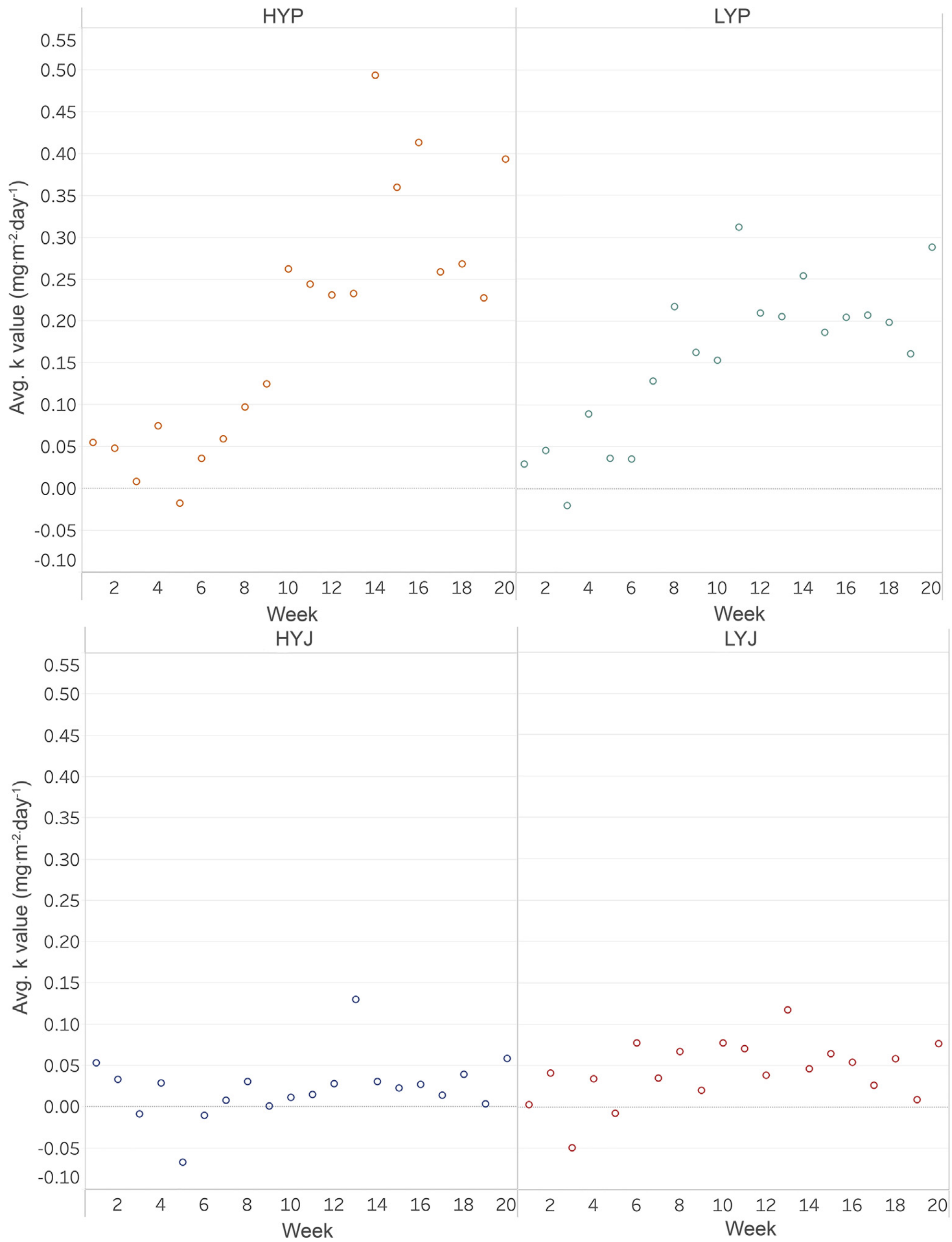

Fig. 5. Weekly rate constant (k) between influent and effluent N concentration over 20 weeks of floating treatment wetlands (FTWs) exposed to two nutrient treatments and two plant species. Low (L) or high (H) nutrient treatments in the presence of FTWs (Y) established either with *Pontederia cordata* (P) or *Juncus effusus* (J).

Determining the pattern of nutrient partitioning within plants is important for understanding which portion of the plant to harvest to remove the largest mass of nutrients (Edwards et al., 2006; Karathanasis et al., 2003; Zhu et al., 2011). Initial N and P allocations for *J. effusus* were concentrated in the shoot with 66.9% of N and 64.6% of P for both high and low nutrient concentrations (Fig. S1). During the growing season, the majority of N allocation was in the *J. effusus* shoots, with an average root:shoot ratio of 0.31 : 0.69 for HYJ and 0.33 : 0.67 for LYJ. Phosphorus partitioning trends were similar to N for *J. effusus* ($p > 0.05$), with root:shoot allocations of 0.29 : 0.71 for HYJ and 0.32 : 0.68 for LYJ. While N ratios were similar for *P. cordata* and *J. effusus*, P ratios differed ($p = 0.034$), with a greater allocation of P within shoot tissues for *P. cordata*. While *P. cordata* initially (in May, at transplant) had more N and P within root tissues than shoot tissues (0.66 : 0.34 N and 0.51 : 0.49 P), by June, N and P partitioning had shifted, and N and P were predominantly stored in shoot tissues (0.16 : 0.84 N and 0.08 : 0.92 P). Nitrogen and P partitioning mainly within shoot tissues persisted for the remainder of the growing season, with some variability between months ($p = 0.004$; Fig. S1).

The changes in nutrient allocation were correlated with biomass production ($R = 0.83$; Fig. 4 a). Both *Pontederia cordata* and *Juncus effusus* had a greater increase in shoot biomass throughout the growing season than root biomass ($p = 0.0032$ *Pontederia* and $p = 0.029$ *Juncus*). Therefore, a greater proportion of nutrients were accumulated in the actively growing tissues (the shoots). Diminution of nutrients within tissues following peak uptake in September were most likely regulated by metabolic processes in the shoots.

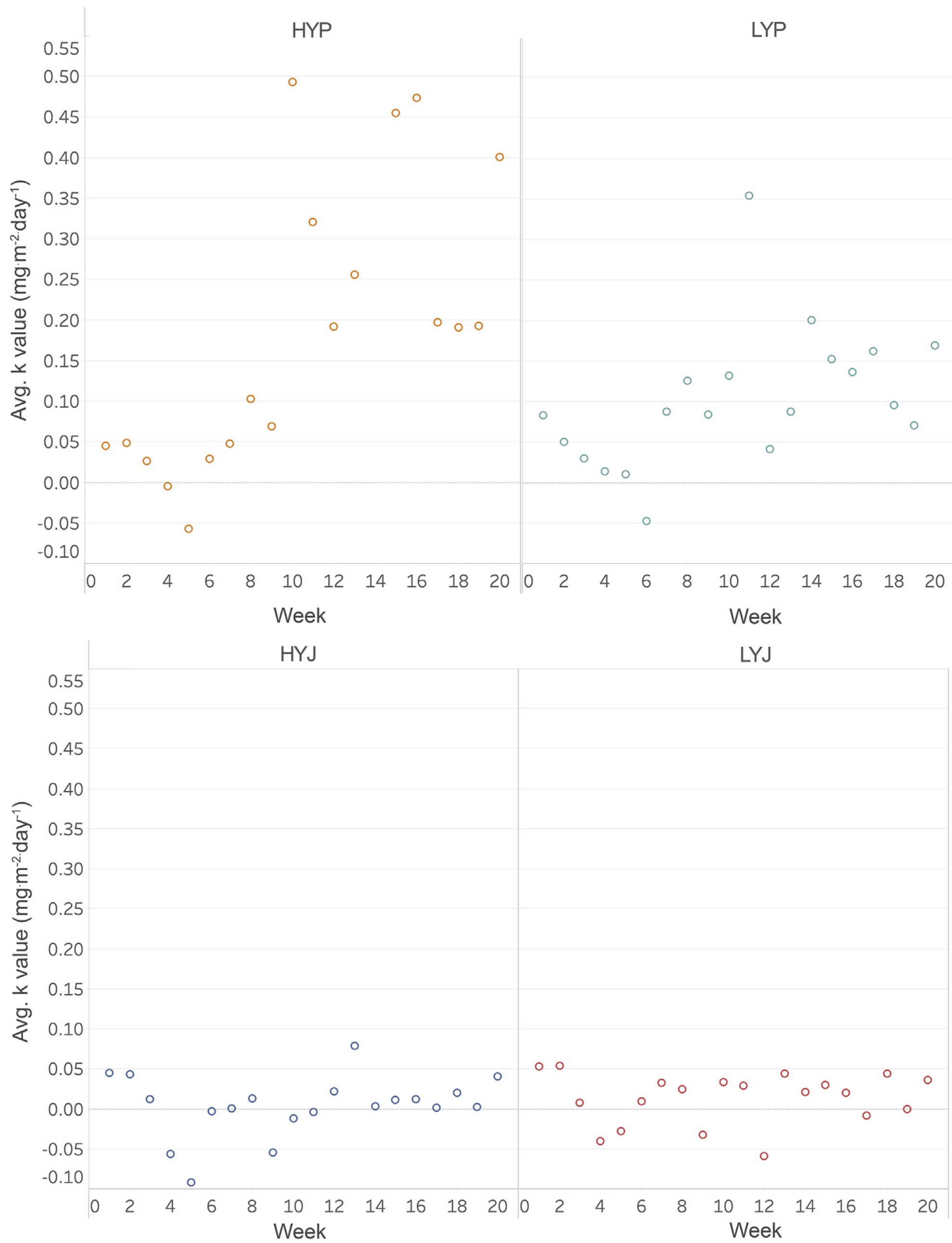

Fig. 6. Weekly rate constant (k) between influent and effluent P concentration over 20 weeks of floating treatment wetlands (FTWs) exposed to two nutrient treatments and two plant species. Low (L) or high (H) nutrient treatments in the presence of FTWs (Y) established either with *Pontederia cordata* (P) or *Juncus effusus* (J).

Nutrient concentration did not contribute to changes in nutrient storage location (low vs. high nutrient treatments and partitioning differences in roots and shoots). The nutrient levels in this experiment may have been higher than those previously shown to affect partitioning and biomass distribution (Wang et al., 2015). Despite relatively lower mass of nutrients fixed within root tissues, root tissues still contribute considerable nutrient removal; thus our recommendation concurs with that of Pavlineri et al. (2017), according to which the whole plant should be harvested to prevent release of nutrients back into the water column. Maintenance costs and feasibility of harvest for nutrient removal are debated based on whether FTWs are actively or passively managed. If the ultimate purpose of a FTW installation is nutrient management, then active management, including harvest is needed to remove plant-absorbed nutrients and better prevent and short-circuit internal nutrient cycles in natural waters. If FTWs are installed as a best management practices for mitigation of nutrients in watersheds as part of basin-wide nutrient management plans, then harvest of the whole plant is critical as nutrient credits are based on total biomass removed and tissue concentrations. Additional research, in different geographic locations and expanding start of the experiment and harvest through additional months would enhance understanding of the effect of seasonality and plant growth/decay on nutrient partitioning.

3.3. *Role of the FTW mat in remediation of N and P*

Previously, some studies have assessed how the FTW mat used influences the remediation capacity of FTWs (Hu et al., 2010; Wang and Sample, 2014; Zhao et al., 2013). Results from the these studies

Table 3
Nitrogen and phosphorus mass balance calculations indicating both average and cumulative removal by concentration and load as influenced by two treatments (plant species (*Juncus effusus* and *Pontederia cordata*) and nutrient concentration) over a 20-week experiment evaluating floating treatment wetland nutrient removal efficacy. Total load reduction is divided into plant uptake and other removal processes.

Average Concentration	Total Nitrogen (mg L^{-1})				Total Phosphorus (mg L^{-1}			
	HYJ†	HYP	LYJ	LYP	HYJ†	HYP	LYJ	LYP
	(mg L^{-1})				(mg L^{-1})			
Influent	14.6 (5.15)	14.6 (5.15)	4.88 (1.75)	4.88 (1.75)	2.30 (0.68)	2.30 (0.68)	0.82 (0.44)	0.82 (0.44)
Effluent	13.0 (4.69)	6.41 (4.69)	4.05 (4.19)	2.38 (1.46)	2.29 (0.68)	1.34 (0.93)	0.71 (0.20)	0.53 (0.30)
Reduction in Concentration	*1.60*	*8.19*	*0.83*	*2.50*	*0.01*	*0.96*	*0.11*	*0.29*
% Concentration Reduction	11.0%	57.3%	17.0%	51.2%	0.0%	41.7%	13.4%	35.4%
Daily Load	(g m^{-2}day^{-1})				(g m^{-2} day^{-1})			
Influent	4.53 (1.19)	4.53 (1.19)	1.81 (0.51)	1.81 (0.51)	0.98 (0.27)	0.98 (0.27)	0.31 (0.09)	0.31 (0.09)
Effluent	3.94 (0.91)	1.60 (0.92)	1.31 (0.30)	0.82 (0.36)	0.93 (0.30)	0.37 (0.31)	0.28 (0.09)	0.19 (0.16)
Reduction in Daily Load	*0.59*	*2.93*	*0.5*	*0.99*	*0.05*	*0.61*	*0.03*	*0.12*
% Daily Load Reduction	13.0%	64.7%	27.6%	54.7%	5.1%	62.2%	9.7%	38.7%
Mass Balance	(g m^{-2}experiment^{-1})				(g m^{-2}.experiment^{-1})			
Total Influent Load	90.7 (5.83)	90.7 (5.83)	36.3 (2.31)	36.3 (2.31)	78.5 (1.28)	78.5 (1.28)	24.8 (0.42)	24.8 (0.42)
Total Effluent Load	82.7 (4.91)	33.5 (2.92)	27.6 (1.66)	17.2 (1.60)	74.6 (1.30)	29.7 (1.03)	22.6 (0.41)	15.4 (0.39)
Total Load Reduction	*8.0*	*57.5*	*8.7*	*19.1*	*3.9*	*48.8*	*2.2*	*9.4*
Plant Uptake	4.89	35.4	2.89	10.5	0.53	4.36	0.27	1.25
% Plant Uptake	61.1%	61.7%	33.2%	55.0%	13.6%	8.9%	12.3%	13.3%
Other Removal Processes	3.11	22.1	5.81	8.90	3.37	44.4	1.93	8.15
% Other Removal Processes	38.9%	38.3%	66.8%	45.0%	86.4%	91.1%	87.7%	86.7%

† HYJ = High nutrient treatment, with a floating treatment wetland established with *Juncus effusus;* HYP = High nutrient treatment, with a floating treatment wetland established with *Pontderia cordata;* LYJ = low nutrient treatment, with a floating treatment wetland established with *Juncus effusus;* LYP = low nutrient treatment, with a floating treatment wetland established with *Pontderia cordata*.

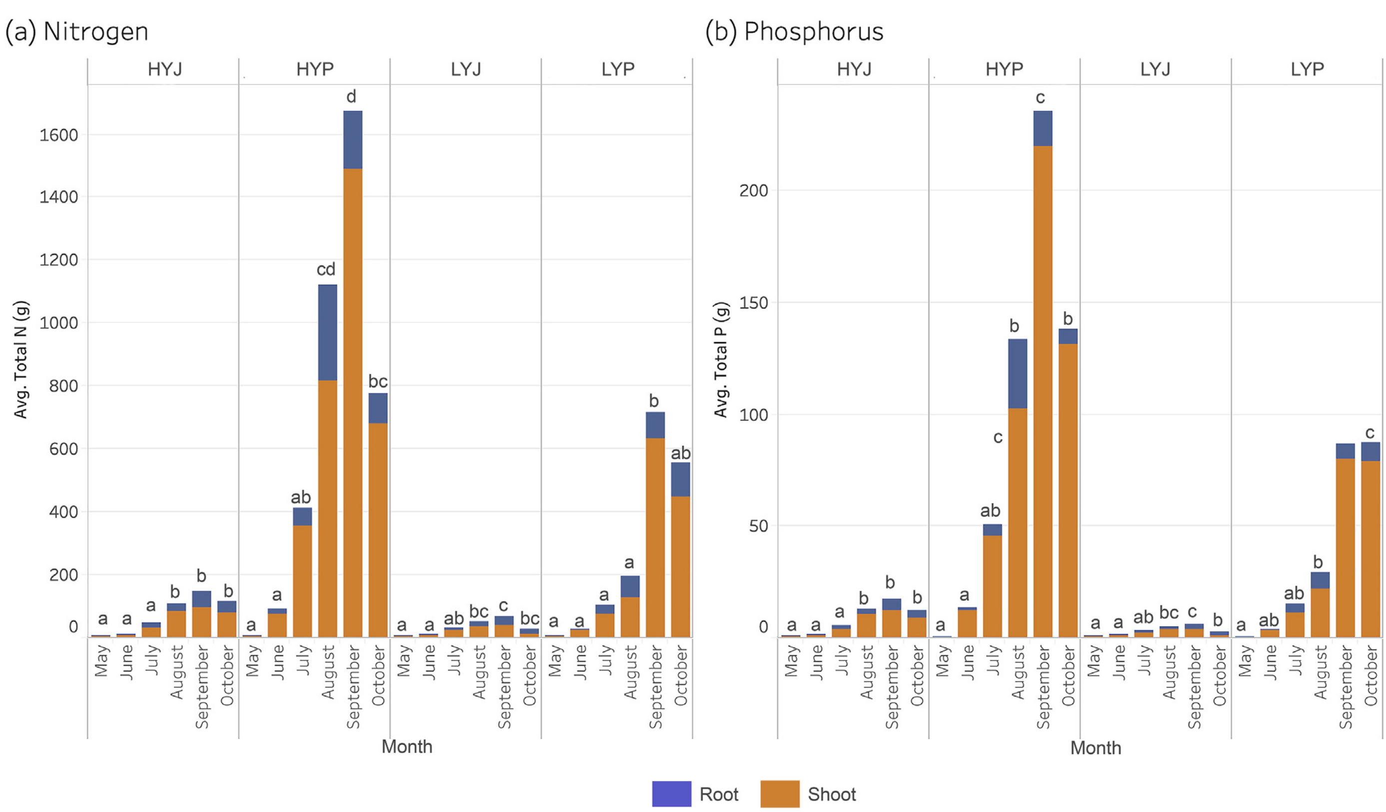

Fig. 7. Total accumulation and distribution of (a) nitrogen and (b) phosphorus within the roots and shoots of plants established in floating treatment wetlands. Data are presented as the monthly averages of four treatments using two plant species (*Pontederia cordata* and *Juncus effusus*) and two nutrient treatments (high and low). Low (L) or high (H) nutrient treatments in the presence of FTWs (Y) established either with *Pontederia cordata* (P) or *Juncus effusus* (J).

Table 4
Nitrogen and phosphorus mass balance calculations indicating average and cumulative removal by concentration and load and the effect of an open control with no floating treatment wetland mat or with a mat in place and nutrient level.

A verage Concentration	Total Nitrogen				Total Phosphorus			
	HNO†	HYO	LNO	LYO	HNO	HYO	LNO	LYO
	(mg L^{-1})				(mg·L^{-1})			
Influent	14.6 (5.15)	14.6 (5.15)	4.88 (1.75)	4.88 (1.75)	2.30 (0.68)	2.30 (0.68)	0.82 (0.44)	0.82 (0.44)
Effluent	10.1 (3.96)	13.2 (4.33)	2.81 (2.13)	4.46 (2.28)	2.16 (0.62)	2.30 (0.84)	0.74 (0.42)	0.82 (0.43)
Reduction in Concentration	*4.50*	*1.4*	*2.07*	*0.42*	*0.14*	*0.00*	*0.08*	*0.00*
% Concentration Reduction	30.8%	9.6%	42.4%	9.2%	6.1%	0.0%	9.8%	0.0%
Daily Load	(g m^{-2} day^{-1})				(g m^{-2} lay^{-1})			
Influent	4.53 (1.19)	4.53 (1.19)	1.81 (0.51)	1.81 (0.51)	0.98 (0.27)	0.98 (0.27)	0.31 (0.09)	0.31 (0.09)
Effluent	3.07 (0.82)	4.00 (1.09)	0.97 (0.49)	1.65 (0.65)	0.87 (0.29)	1.00 (0.45)	0.28 (0.18)	0.33 (0.18)
Reduction in Daily Load	*1.46*	*0.53*	*0.84*	*0.16*	*0.11*	*−0.02*	*0.03*	*−0.02*
% Daily Load Reduction	32.5%	11.7%	46.4%	8.8%	11.2%	−2.0%	9.7%	−6.5%
Mass Balance	(g m^{-2} experiment^{-1})				(g m^{-2} experiment^{-1})			
Total Influent Load	90.7 (5.83)	90.7 (5.83)	36.3 (2.31)	36.3 (2.31)	78.5 (1.28)	78.5 (1.28)	24.8 (0.42)	24.8 (0.42)
Total Effluent Load	62.0 (4.33)	81.6 (5.21)	20.5 (1.65)	33.2 (2.33)	69.5 (1.30)	80.3 (1.56)	22.7 (0.60)	25.6 (0.58)
Total Load Reduction	*28.7*	*9.10*	*15.8*	*3.10*	*9.00*	*−1.80*	*2.10*	*−0.80*

† HNO = High nutrient treatment, with no floating treatment wetland mat; HYO = High nutrient treatment, with a floating treatment wetland mat; LNO = Low nutrient treatment, with no floating treatment wetland mat; LYO = Low nutrient treatment, with a floating treatment wetland mat.

conflicted with each other. Hu et al. (2010) found no difference with or without the FTW mat, in an ecological sludge floating-bed artificial eco-system. Wang and Sample (2014) determined their mat, a 20-cm thick blended-fiber matrix, facilitated removal of a similar mass of nutrients as those treatments established with both plants and the mat (indicating a substantial role of microorganisms). Zhao et al. (2013) reported that once established, the mat (plastic trays with 12 holes filled with mixed media in rhizo-bags) performed better than the control (no FTW mat), but worse than a planted mat. Results from this study add another scenario, as the control (no mat) outperformed the mat-only treatment in removal of both TN and TP, at both nutrient levels (Table 4). Furthermore, the control facilitated removal of a greater mass of both N and P in comparison to HYJ treatments ($p \leq 0.05$) and N compared to LYJ ($p \leq 0.05$). However, mats planted with *Pontederia cordata* outperformed the control for both N and P removal ($p \leq 0.05$; 57.5 g m^{-2} N and 48.8 g m^{-2} P compared to 28.7 g m^{-2} N and 9.00 g m^{-2} P for high fertilizer) (Table 3). No measurements were collected quantifying the mass of algae and chlorophyll A present in the system, which would have been beneficial. However, based on observations, larger amounts of algae grew in the mesocosms with no mat in comparison to those with a mat. This could be one explanation for the higher remediation levels achieved by the no mat control. Algal communities in the no-mat control may have contributed to some removal of nutrients, while mesocosms covered with a mat were shaded, leaving the system with little surface area open to the sunlight needed by the algal communities for energy production and growth.

Dissolved oxygen concentration plays an important role in nitrification and denitrification of a system as nitrification is an aerobic process (DO > 2.0 mg/L) while denitrification is an anaerobic process (DO < 1.0 mg/L) (DeBusk, 1999; Tallec et al., 2008). Dissolved oxygen levels in the water column of mesocosms with mats were lower than those without mats ($p < 0.05$; Fig. S2). Furthermore, mats planted with *P. cordata* and *J. effusus* further reduced the DO levels within the water column of the mesocosms from those without mats ($p < 0.05$). The change in DO likely impacted N removal processes; however, the system never reached anaerobic levels (DO < 1 mg/L; Fig. S2). It is possible that were algal growth controlled, results would be similar to Hu et al. (2010) or Zhao et al. (2013); however, neither Hu et al. or Zhao et al. discussed the role/presence of algae within their systems. Based upon our findings, the plant species used within FTWs in combination with a mat is highly important to facilitate removal of nutrients, however the mat itself is not the major contributor to nutrient removal.

4. Conclusions

- *P. cordata* proved more efficient than *J. effusus* at accumulation of both N and P.
- *P. cordata* facilitated the highest rates of N (0.31 mg·L·day^{-1}) and P (0.34 mg·L·day^{-1}) removal from water. Nutrient removal rates facilitated by *J. effusus* in the high nutrient treatment were much lower for both N (0.03 mg·L·day^{-1}) and P (0.02 mg·L·day^{-1}) compared with *P. cordata.*
- Peak N and P accumulation in *J. effusus* occurred in September within both root (50 g N and 4.8 g P) and shoot tissues (98 g N and 12.5 g P). The uptake of N and P in *P. cordata* was highest in root tissues in August (307 g N and 30.5 g P) and in shoot tissues in September (1490 g N and 219.5 g P).
- In both species, shoots accumulated more N and P than the roots, resulting in a small root:shoot ratio at all stages of the experiment.
- The presence of the mat only within a water body (i.e., shade only impact) did not enhance nutrient remediation within the system, as little to no N or P removal occurred in this treatment.
- If mitigation of nutrient impairment of a water body is the goal, harvest of plants from FTWs should occur before plants senesce in the fall, which using *P. cordata* and *J. effusus* as model species occurred from mid- to late- September in USDA Hardiness Zone 8a in the Southeastern United States.
- Further studies should consider the role of algae within the system and lengthen the study until decline in plant growth (senescence and dormancy) is confirmed. Validation of these results, especially with regard to timing of harvest is needed across a range of hardiness zones, as in colder regions the growing seasons are shorter; potentially impacting the performance and management of these FTW systems.

Funding

Technical Contribution No. 6743 of the Clemson University Experiment Station. This work was supported by the National

Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2014-51181-22372 and project number SC-1700539.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeaed to influence the work reported in this paper.

Acknowledgements

The authors wish to thank Julie Brindley, Dr. Dil Thavarajah, and the Clemson Agricultural Services Laboratory for contributions to laboratory work. A special thanks as well to the reviewers of *Water Research* for their comments and feedback.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2019.05.012.

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