



Research  
Watershed Ecology—Article

## A Floating Island Treatment System for the Removal of Phosphorus from Surface Waters



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### ABSTRACT

The goal of this project was to design, build, and test a pilot-scale floating modular treatment system for total phosphorus (TP) removal from nutrient-impaired lakes in central Florida, USA. The treatment system consisted of biological and physical–chemical treatment modules. First, investigations of prospective biological and physical–chemical treatment processes in mesocosms and in bench-scale experiments were conducted. Thirteen different mesocosms were constructed with a variety of substrates and combinations of macrophytes and tested for TP and orthophosphate ( $\text{PO}_4^{3-}$ ) removal efficiencies and potential areal removal rates. Bench-scale jar tests and column tests of seven types of absorptive media in addition to three commercial resins were conducted in order to test absorptive capacity. Once isolated process testing was complete, a floating island treatment system (FITS) was designed and deployed for eight months in a lake in central Florida. Phosphorus removal efficiencies of the mesocosm systems averaged about 40%–50%, providing an average uptake of  $5.0 \text{ g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  across all mesocosms. The best-performing mesocosms were a submerged aquatic vegetation (SAV) mesocosm and an algae scrubber (AGS), which removed 20 and  $50 \text{ mg}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ , respectively, for an average removal of 5.5 and  $12.0 \text{ g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  for the SAV and AGS systems. Of the absorptive media, the best performance was alum residual (AR), which reduced  $\text{PO}_4^{3-}$  concentrations by about 75% after 5 min of contact time. Of the commercial resins tested, the PhosX resin was superior to the others, removing about 40% of phosphorus after 30 min and 60% after 60 min. Under baseline operation conditions during deployment, the FITS exhibited mean  $\text{PO}_4^{3-}$  removal efficiencies of 53%; using the 50th and 90th percentile of  $\text{PO}_4^{3-}$  removal during deployment, and the footprint of the FITS system, yielded efficiencies for the combined FITS system of 56% and 86%, respectively, and areal phosphorus removal rates between  $8.9$  and  $16.5 \text{ g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$ .

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### 1. Introduction

In Florida, USA, as in many regions of the world, lake ecosystems are undergoing significant changes caused by human-induced alteration of watersheds, which have degraded water quality. There is increasing evidence that lake ecosystems, more so than other types of systems, may have ecological thresholds [1], which if exceeded make recovery exceptionally difficult and potentially a nonexistent alternative—due to alternative stable states and asymmetrical recovery trajectories (hysteresis) [2]. The ecological engineering of lacustrine recovery efforts must recognize these critical issues and adapt proactive approaches in

order to avoid ecosystem thresholds as well as to attempt restoration of those lakes that have already passed them.

At present, 157 lakes in Florida (totaling about  $1.42 \times 10^5 \text{ hm}^2$ ) are nutrient impaired and 116 lakes (totaling  $1.59 \times 10^5 \text{ hm}^2$ ) that are currently not impaired are degrading, leading to their questionable status in the future [3]. The recognition of impaired waters ultimately requires the adoption of total maximum daily loads (TMDLs) for the pollutants that have caused the impairment. If the lake is part of a Surface Water Improvement and Management (SWIM) Program, the development of pollution load reduction goals (PLRGs) is required by the water management districts that are responsible for the lake, and often provides the scientific basis for the TMDLs [4]. An integral part of the TMDL process is the development of the Basin Management Action Plan (BMAP) that lists each stakeholder's restoration strategies for meeting the required pollutant reductions.

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Some lakes represent nutrient sinks because they receive surface runoff from their watersheds and from the watersheds of all their tributaries. Because they have areas of low flow with high residence times, they tend to concentrate nutrients, thus representing interesting challenges for restoration. Wholesale removal of nutrients through lake bottom dredging is one alternative, albeit a costly one [5–7]. Furthermore, it lacks reduction of the external anthropogenic component that is defined by the TMDL process in the Clean Water Act and is almost universally required in order to maintain low levels of nutrient and sediment buildup within the lake. Restoration can also include construction of large-scale wetland treatment cells, where lake waters are pumped through the system to sequester nutrients and slowly reduce in-lake nutrient levels [8,9]. A popular alternative is the use of alum treatment systems, in which a chemical reaction precipitates the phosphorus (P) and sequesters the nutrient at the bottom of the water body or in an off-line flocculent holding pond. In all these cases, restoration requires a significant quantity of land in close proximity to the lake in question, either for the constructed wetland or for the disposal of sediments. The land surrounding many lakes is completely developed and therefore does not afford the opportunity for land-based restoration efforts. The use of floating island technology may be a solution to the lack of opportunity for land-based applications. However, simple biological treatment systems relying solely on plant uptake require too much surface area within the lake and/or its tributaries. Innovative alternatives combining plant components and adsorptive technology with minimal byproduct generation and small footprints may overcome many of the obstacles to nutrient reduction in urban watersheds with impaired lakes.

In this project, we designed a floating island water treatment technology that incorporated both a biological component (flow through wetland cells) and a physical–chemical component (fluidized beds of absorptive media) for the removal of total phosphorus (TP) and orthophosphate ( $\text{PO}_4^{3-}$ ) from lake water. We first tested various growing media and macrophyte combinations to determine the combinations under high volume flow conditions and several different absorptive media. To minimize the footprint of the treatment island and to maximize removal efficiency, we used solar photovoltaic (PV) panels to provide power for water pumps, since the island had to be portable and self-contained.

The overall objectives of the project were threefold. The first objective was to demonstrate at a pilot scale that one of several nutrient-removal processes can achieve efficient and sustainable TP reduction of lake water. The second objective was to assess the total yearly TP reduction in  $\text{kg}\cdot\text{a}^{-1}$  and in  $\text{kg}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  from each process tested, both at bench scale during optimization evaluation and through the floating island treatment system (FITS) that was eventually deployed. The third objective was to assess the cost of capital, operation, and maintenance that was required to upscale the process to meet Florida State effluent criteria based on the experimental pilot study. In addition, the FITS must be a moored or mobile floating platform without the need for an upland, tethered power source, and must not be a significant obstruction of navigation. The FITS cannot cause ecologically significant changes in water chemistry beyond reductions in nutrient concentrations between the influent and effluent, and there must be no chemicals in the effluent that were not in the influent; finally, there must be little loss of esthetics.

## 2. Methods

Six months of data were collected from biological mesocosms and bench-scale tests of absorptive media in preparation for the

design and deployment of the FITS. Methods for each component of the project are given next.

### 2.1. Biological mesocosm experiments

#### 2.1.1. Mesocosm design

The mesocosm-scale tests of biological treatment systems were conducted on the campus of the University of Florida (UF), in Gainesville, FL, USA. Fig. 1 shows an overview of the complete biological mesocosm experiment. A storage tank was necessary to control input concentrations of P to the mesocosms. In order to ensure a large quantity of water, which was necessary, the experiments used Gainesville's public water supply. An activated carbon filter was used to strip chlorine from the potable water prior to introduction to the mesocosms.

Figs. 2 and 3 provide construction details for four types of mesocosms: macrophytes, biofilm, algae scrubber (AGS), and vertical biofilter (VTF). The mesocosms were  $0.75 \text{ m}^3$  ( $0.5 \text{ m wide} \times 3.0 \text{ m long} \times 0.5 \text{ m deep}$ ), constructed from plywood, and lined with 40 mil (1 mil = 0.0254 mm) polyvinyl chloride (PVC) sheeting. Once constructed, each mesocosm was inoculated with water from the UF sewage treatment plant as well as water from Lake Alice on the UF campus to insure multi-organism seeding.

Mesocosm experiments were designed to quickly provide basic information regarding the selection of appropriate macrophytes and growing media. Because of space and equipment limitations, the mesocosm experiments were conducted in two phases. In all, 12 mesocosms were used in two phases, as follows:

#### First Phase:

- EMC: Emergent macrophyte mesocosm with recycled concrete (RC) as the substrate;
- EML: Emergent macrophyte mesocosm with lava rock as the substrate;
- VET: Vetiver grass (*Chrysopogon zizanioides*) mesocosm planted hydroponically within the mesocosm;
- SAV: Mesocosm containing the submerged aquatic plant *Ceratophyllum demersum*;
- BFJ: Biofilm mesocosm containing three PVC racks ( $0.5 \text{ m} \times 0.5 \text{ m}$ ) holding about 0.25 kg of jute fiber netting perpendicular to the direction of flow;
- BFB: Biofilm mesocosm containing three bales of coconut fiber ( $0.5 \text{ m} \times 0.5 \text{ m} \times 0.5 \text{ m}$ ) weighing approximate 0.5 kg, each installed perpendicular to the direction of flow;
- AGS: Algae scrubber mesocosm consisting of a shallow channel saturated with locally obtained algae.

#### Second Phase:

- PLM: Mesocosm containing emergent macrophytes (same six species used previously) planted in a plastic regrind substrate;
- PLV: Mesocosm containing vetiver grass planted in a plastic regrind substrate;
- BIB: Mesocosm containing Bioballs only; Bioballs are a commercially available high surface area plastic substrate designed to promote biofilm growth to treat high nutrient levels;
- PLO: Mesocosm containing plastic regrind without plants;
- VTF: Mesocosm containing a vertical trickling filter comprised of a plastic substrate in the mesocosm with a solar pump to provide water to hanging jute curtains ( $0.5 \text{ m} \times 0.5 \text{ m}$ ) holding about 0.25 kg of jute above the mesocosm.

#### 2.1.2. Mesocosm operation

All mesocosms were operated using a daylight on/nighttime off cycle that was modified during the length of the experiment to match daylight hours. Each evening, the storage tank (Fig. 1) was filled with water and spiked with monopotassium phosphate ( $\text{KH}_2\text{PO}_4$ ) to raise the mesocosm influent  $\text{PO}_4^{3-}$  to match the

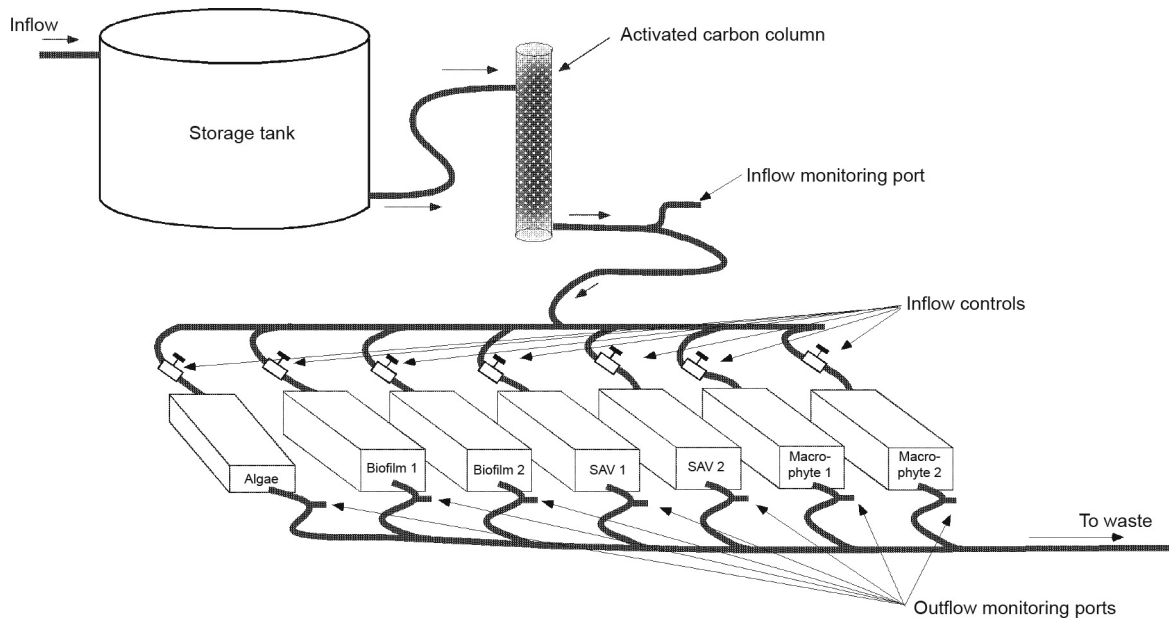


Fig. 1. Biological treatment mesocosm experimental design layout. The activated carbon column was used to remove chlorine from influent water.

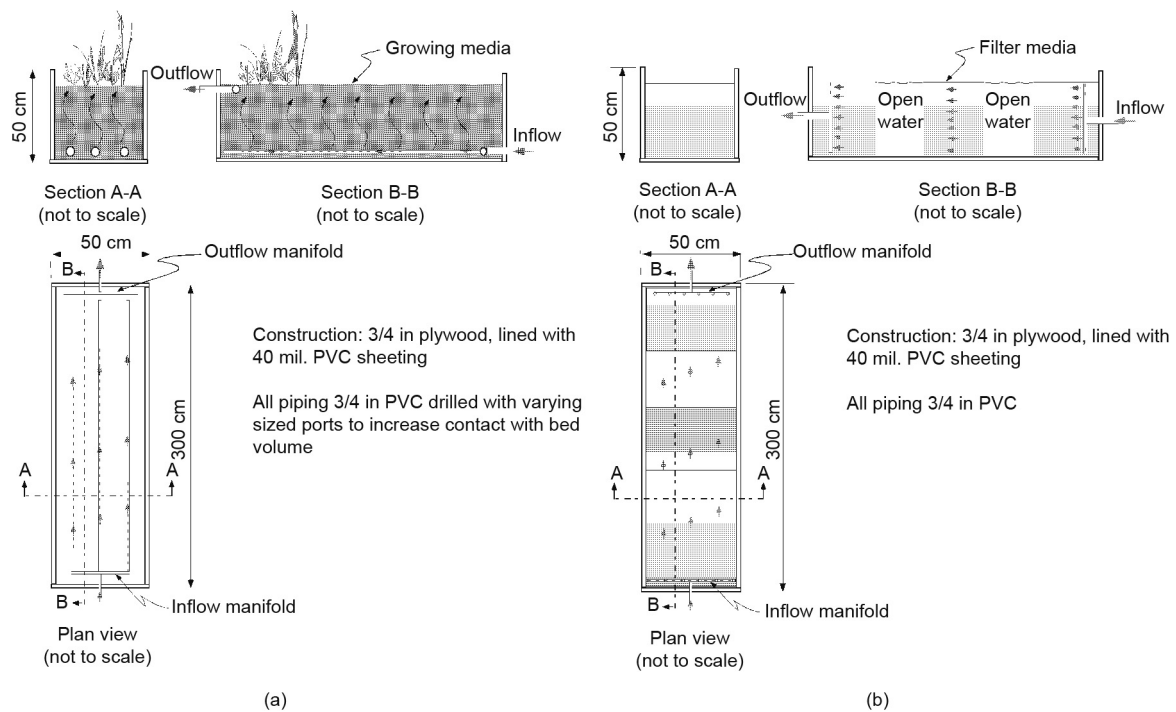


Fig. 2. Details of the construction of the mesocosms. (a) Macrophyte mesocosms (EMC, EML, VET, PLM, PLV, BIB, and PLO); (b) biofilm mesocosms (BFJ and BFB). 1 in = 2.54 cm.

expected level in central Florida lakes ( $220 \mu\text{g}\cdot\text{L}^{-1}$  of P). In addition, nitrate ( $\text{NO}_3^-$ ) levels were spiked to  $800 \mu\text{g}\cdot\text{L}^{-1}$  with sodium nitrate ( $\text{NaNO}_3$ ) to ensure that the system was not nitrogen limited. Since we maintained a constant concentration of P in the influent, mass loading of P was controlled in each mesocosm by hydraulic loading rates (HLRs). We varied the HLRs over a wide range (from 2.5 to  $60 \text{ cm}\cdot\text{d}^{-1}$ ) to test the response of vegetation and growing media; thus, the mesocosms experienced a wide range of mass loading and subsequent P uptake.

Mesocosm experiments were designed to quickly provide basic information regarding the selection of appropriate macrophytes

and growing media. Since a major concern in the long run was the esthetics of the floating islands, we selected macrophytes based on a combination of flowering and P uptake. Mesocosms containing emergent macrophytes were planted with an equal distribution (ten plants) of the following species: *Canna flaccida*, *Sagittaria lancifolia*, *Pontederia cordata*, *Peltandra virginica*, *Orontium aquaticum*, and *Hymenocallis* spp. In addition, we were interested in finding growing media with sufficient pore space that would accommodate relatively high HLRs of up to  $60 \text{ cm}\cdot\text{d}^{-1}$ .

The first set of mesocosms was operated from 24 April to 15 July 2009 and the second set was operated from 20 July to 15 December

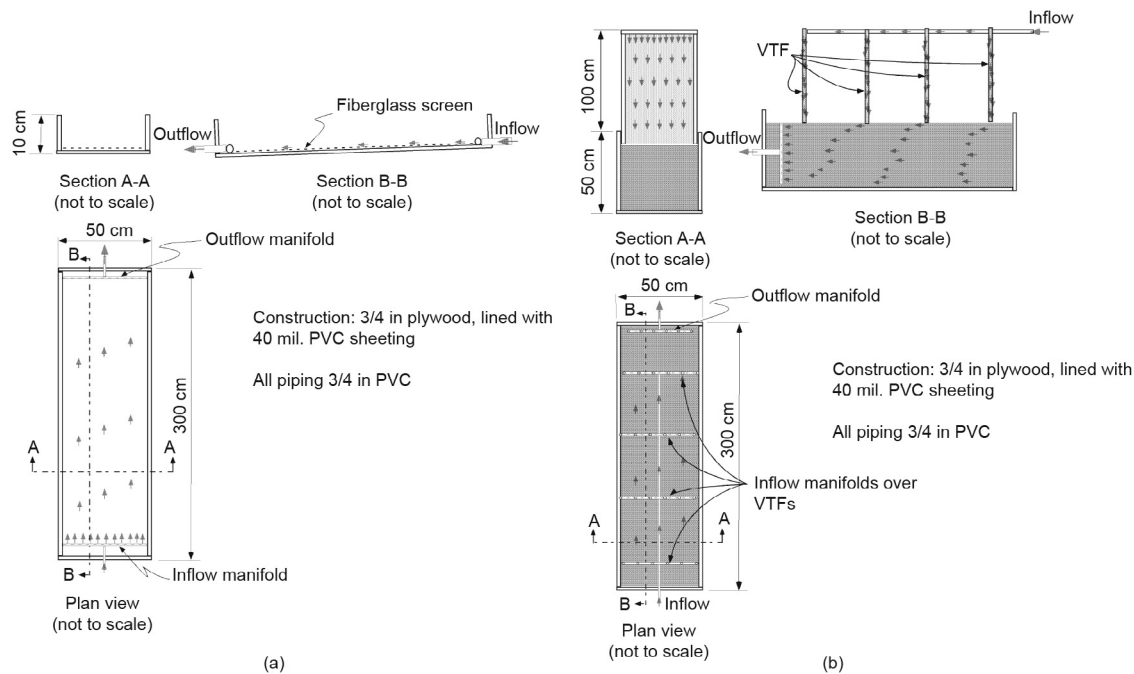


Fig. 3. Details of the construction of the mesocosm. (a) AGS; (b) VTF.

2009. During the operation of both sets, individual mesocosms were discontinued or were continued for longer than the operational phases given above, depending on their performance. During the operational phase of the first set of mesocosms, the length of operation varied for individual mesocosms. The mesocosm containing RC consistently exhibited a very high pH, the result of the concrete dust, and we discontinued its operation after four weeks. The highest P removal efficiency was found in the BFJ; however, as the jute degraded, the demand for oxygen increased, resulting in very low dissolved oxygen (DO) in effluent waters, a condition that would be unacceptable for a lake application. The BFB also suffered from low DO, and its operation was halted after eight weeks. The vegetation in the SAV mesocosm succumbed to temperature during the early summer, and we halted its operation after six weeks.

The second set of mesocosms was constructed based on the knowledge gained in the first trials, which were primarily intended to test different growing media. The new medium was a plastic regrind<sup>†</sup> that we obtained from a plastics manufacturer, which was destined for landfilling because of its poor quality for recycling. The chip size of the regrind was about 0.5 cm and afforded excellent hydraulic characteristics, with a cross-sectional flow through the medium that was high enough to meet our requirements of HLRs of up to 60 cm·d<sup>-1</sup>. In addition to the regrind, we tested a commercially available plastic substrate with a high surface area to promote biofilm growth (Bioballs, BIB), and a VTF. The VTF was designed as a drip biofilter composed of jute strips hung vertically with water discharged over them in order to overcome the anoxia of continuously inundated jute in the BFJ of the first set of mesocosms.

The HLRs of the flow through the mesocosms in the second set were changed approximately every 30 d during the 148 d of oper-

ation. They were started at 30 cm·d<sup>-1</sup>, then increased to 45 cm·d<sup>-1</sup>, increased again to 70 cm·d<sup>-1</sup>, decreased to 45 cm·d<sup>-1</sup>, and were finally decreased to 20 cm·d<sup>-1</sup>. The VTF mesocosm was operated at 55 cm·d<sup>-1</sup> with variation in the HLR resulting from the fact that water was pumped over the vertical jute via a solar pump.

### 2.1.3. Sampling procedure for mesocosm experiments

Water samples were collected every other day during the first two months of operation and every fourth day thereafter. All water samples were collected and composited as daily samples in brown (opaque) Nalgene bottles that were specific to each mesocosm. A drip-sampling orifice at the outflow of each system was adjusted to provide a 500 mL sample every 12 h. Sample bottles were washed three times with sample water before being placed on the drip line. At the end of each sample day, samples were refrigerated at 4 °C for PO<sub>4</sub><sup>3-</sup> analysis. Phosphorus analyses were performed within three days of sample collection, in accordance with EPA Method 365.1 [10].

Flow rates through the mesocosms were adjusted every morning and measured twice a day in order to ensure constant rates using a stopwatch and a 1000 mL graduated plastic cylinder. DO, temperature, and pH were measured daily in each mesocosm.

## 2.2. Bench-scale jar tests and column experiments

### 2.2.1. Materials

Two classes of materials were evaluated in this work: adsorbents and ion-exchange resins. The adsorbents evaluated in this work consisted of waste byproducts and natural materials, as described in Table 1. The adsorbents, drinking water treatment alum residual (AR), iron slag (IS), and steel slag (SS) were crushed with a mortar and pestle and sieved through US Standard sieves 30 and 40, to yield a particle size range of 420–595 μm. Drinking water treatment ferric residual (FR), RC, and limestone (LS) were dried under ambient laboratory conditions before being crushed as described above. Class F fly ash (FA) was received in powdered form and was used in its original state. The ion-exchange resins

<sup>†</sup> Plastic regrind is ground or chopped flash, runners, sprues, and non-contaminated rejected parts from plastic manufacturing that are produced by a mold in initial molding processes. These materials are crushed to smaller size and recycled with virgin materials. Regrind applies to post-industrial (pre-consumer) waste.

**Table 1**  
Adsorbents used in jar tests and column experiments.

Adsorbent	Source	Description
Drinking water treatment AR	Peace River Manasota Regional Water Supply Authority, Arcadia, FL	Surface water treatment plant that uses aluminum sulfate to treat water from the Peace River
Drinking water treatment FR	David L. Tippin Water Treatment Facility, Tampa, FL	Surface water treatment plant that uses ferric sulfate to treat water from the Hillsborough River
Granulated blast furnace IS	Civil & Marine Inc., Cape Canaveral, FL	Non-metallic byproduct from iron production
Basic oxygen furnace SS	Levy Enterprises, Valparaiso, IN	Byproduct of manufacturing steel from pig iron
FA	Boral Materials Technologies, Tampa, FL	Combustion byproduct of coal
RC	Florida Concrete Recycling Inc, Gainesville, FL	Concrete aggregate collected from demolition sites
LS	Florida Rock Industries Inc., Gainesville, FL	Natural rock mined from various locations

used in this work are described in Table 2, and were used as received.

### 2.2.2. Test waters

Since the quantity of test water for jar and column tests was relatively small, we used water collected from two central Florida locations. The first location was Sanford Avenue Canal, a tributary to Lake Jesup, near Sanford Florida; the second source was Lake Alice on the campus of the UF in Gainesville. Table 3 shows the water quality for Sanford Avenue Canal and Lake Alice taken from January through August 2009.

### 2.2.3. Jar tests

Jar tests were conducted to investigate the effectiveness of the adsorbents and ion-exchange resins in removing TP and  $\text{PO}_4^{3-}$  from the test waters. The adsorbents were dosed gravimetrically ( $0.5\text{--}8\text{ g}\cdot\text{L}^{-1}$ ) and the ion-exchange resins were dosed volumetrically ( $0.5\text{--}4\text{ mL}\cdot\text{L}^{-1}$ ). A Phipps and Bird PB-750 Jar Tester equipped with either 2 L or 500 mL jars were used. The baseline experimental protocol was as follows: Add adsorbent or ion-exchange resin to test water, rapidly mix at  $100\text{ r}\cdot\text{min}^{-1}$  for 60 min, and allow to settle for 30 min. The FR, IS, SS, RC, and LS were rapidly mixed at  $200\text{ r}\cdot\text{min}^{-1}$  because these materials were denser than the AR,

FA, and ion-exchange resins. Samples were taken after 5 and 30 min of mixing, and after 60 min of mixing and 30 min of settling. Samples were analyzed for TP,  $\text{PO}_4^{3-}$ , pH, turbidity, ultraviolet absorbance at 254 nm ( $\text{UV}_{254}$ ), total organic carbon (TOC), and total nitrogen (TN).  $\text{UV}_{254}$  and TOC are commonly measured surrogates for organic matter.

### 2.2.4. Column experiments

The column experiments were conducted using a column with an inner diameter of 0.7854 cm and a height of 2 cm, and with  $25\text{ }\mu\text{m}$  pore size polyethylene frits on each end. The column was then filled with 1 mL of wet adsorbent or ion-exchange resin. By definition, 1 bed volume (BV) was equal to 1 mL. Tubing was connected to allow for an up-flow direction. The flow rate used was  $2\text{ mL}\cdot\text{min}^{-1}$  or  $2\text{ BV}\cdot\text{min}^{-1}$ . Before a column experiment was started, the system was flushed by pumping 120 BV of deionized (DI) water through the column. Water to be treated was filtered through a Whatman GF/A filter ( $1.6\text{ }\mu\text{m}$  pore size) to control the clogging of frits. Two scenarios were tested: continuous flow and intermittent flow (12-h-on/12-h-off), where 1 h long samples were taken every 3 h and left to flow without sampling for 12 h or left to rest for 12 h during the night, respectively. A predetermined breakthrough  $\text{PO}_4^{3-}$  concentration was set at 50% removal, after which one extra sample was taken at the next sample point to confirm the end of an experiment. Water samples were analyzed for the same parameters as the jar tests.

**Table 2**  
Ion-exchange resins used in jar tests and column experiments.

Ion-exchange resin	Manufacturer	Structure
PhosX	SolmeteX	Macroporous polymer resin impregnated with iron oxide particles
MIEX	Orica Watercare	Macroporous, polyacrylic anion-exchange resin with strong-base, type II functional groups
Dowex22	Dow Chemical	Macroporous, polystyrene anion-exchange resin with strong-base, type II functional groups

**Table 3**  
Water quality of test waters used in jar tests and column experiments.

Location	Sample	Month of 2009	pH	Turbidity (NTU)	$\text{PO}_4^{3-}$ ( $\text{g}\cdot\text{L}^{-1}$ of P)	TP ( $\text{g}\cdot\text{L}^{-1}$ )	Chloride ( $\text{mg}\cdot\text{L}^{-1}$ )	Sulfate ( $\text{mg}\cdot\text{L}^{-1}$ )	TOC ( $\text{mg}\cdot\text{L}^{-1}$ )	$\text{UV}_{254}$ ( $\text{cm}^{-1}$ )
Sanford Avenue Canal	Raw	April	7.6	4	222	329	185	33	14	0.641
	Filtered <sup>a</sup>	April	7.7	—	215	250	185	33	15	0.593
	Raw	June	6.9	—	107	195	55	6	34	1.63
	Filtered <sup>a</sup>	June	7.6	—	107	143	55	6	31	1.64
Lake Alice	Raw	July	7.7	—	421	482	14	19	7.2	0.228
	Filtered <sup>a</sup>	July	7.7	—	387	423	14	18	7.1	0.219
	Raw	August	7.6	—	507	529	16	21	8.3	0.225
	Filtered <sup>a</sup>	August	7.5	—	272	327	—	—	8.1	0.228

NTU: nephelometric turbidity unit; TOC: total organic carbon;  $\text{UV}_{254}$ : ultraviolet absorbance at 254 nm.

<sup>a</sup> Whatman GF/A filter.

## 2.3. Floating island treatment system

### 2.3.1. Materials

Fig. 4 is a drawing of the “as-built” FITS. The design utilized a Hobie Cat<sup>®</sup> haul and framework with additional floatation added to support the weight of the treatment systems (estimated at about 1100–1200 lb (1 lb = 0.4536 kg) when full of water). The additional floating structure utilized Styrofoam dock “billets” that were placed between the two hauls of the Hobie Cat<sup>®</sup>.



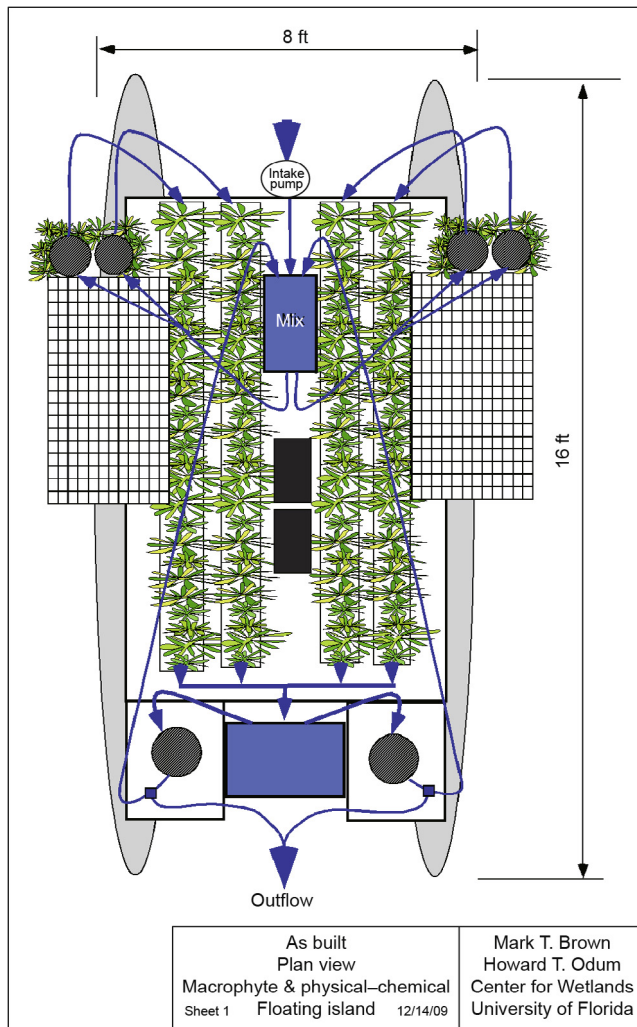


Fig. 4. Plan view of the final FITS design. Blue arrows indicate flow direction of water through the FITS. 1 ft = 0.3048 m.

Overall, the treatment system was organized with the biological treatment component first in the treatment train, followed by the physical-chemical component (P-C Treatment Columns). The biological treatment was designed with two stages: First, there were six VTFs, with water trickling from top inflow through biofilter media, being collected at the bottom, and then being introduced to four parallel wetland linear treatment cells (WLTCs) containing aquatic macrophytes and vetiver grass planted in a recycled, reground plastic media. The WLTCs were constructed from 12 in (1 in = 2.54 cm) diameter PVC pipe cut lengthwise, and the ends were sealed so that each pipe resembled a trough. The total volume of the WLTCs was 450 L, and they had an area equal to 3.7 m<sup>2</sup>. Eighty herbaceous wetland plants and 80 vetiver plants were planted in the WLTCs. The species planted were chosen based on the mesocosm experiments, as the species that exhibited best survival, and included: *Canna flaccida*, *Sagittaria lancifolia*, and *Pontederia cordata*. Second, the P-C Treatment Columns was composed of two up-flow fluidized beds; the volume of each bed was 12 L. The treatment columns contained either AR or PhosX resin, which were shown to be the most effective materials for TP removal based on the previous laboratory work. The fluidized beds could be operated with a contact time of 0.5–5 min.

The water inflow was at the bow (i.e., the front end, which faced south) and the outflow port was at the stern (back) of the Hobie Cat®. The pumping system consisted of four 12 V solar-powered

bilge pumps—two on the inflow and two to pump water through the P-C Treatment Columns. The size and power requirements of the pumps were as follows: Attwood-Tsunami T800 Bilge Pump rated at 800 gal·min<sup>-1</sup> (1 gal·min<sup>-1</sup> = 3.785 L·min<sup>-1</sup>) at 2.5 A. While these pumps were not rated for continuous use, the manufacturer considered that they would last several months operating under the conditions of the FITS. Their cost (under 20 USD each) justified their subsequent use.

Inflow water was applied first to the VTFs and then, through gravity, to the horizontal wetlands. A storage tank followed the wetland treatment, from which water was pumped through the P-C Treatment Columns. In December 2009, after three months of deployment, some redesign of the original FITS configuration was undertaken. A second storage tank was added to allow mixing of treated water with inflowing lake water, so that we could test a wider range of inflow concentrations. After the redesign, the FITS consisted of the following unit processes: a mixing chamber, VTFs, horizontal wetlands, and P-C Treatment Columns. The mixing chamber blended water from Lake Alice with treated water recycled from the FITS P-C Treatment Column. This blended water with lower phosphorus concentrations was then used as the influent to the FITS biological treatment.

The electrical system consisted of two 100 W (18 V) solar panels and two deep-cycle, 12 V marine batteries with appropriate switches and relays to turn pumps on and off depending on the time of day and water levels. Calculations suggested that with the electrical configuration, system operation could be sustained even with two days of cloudy weather.

### 2.3.2. FITS deployment

On Friday, 18 September 2009, the FITS was deployed into Lake Alice on the campus of the UF. During the first deployment, the FITS was operated with a flow of 1 gal·min<sup>-1</sup>; therefore, each of the P-C Treatment Columns was tested under flows of 0.5 gal·min<sup>-1</sup>. One P-C Treatment Column contained PhosX resin and the second contained recycled AR.

After the redesign of the original FITS configuration was undertaken in December 2009, the FITS was relaunched for a second deployment on 24 March 2010. While the objective of the first deployment was proof of concept, the objective during the second deployment was to evaluate the operating conditions in greater detail and to lower the input P concentration to levels more characteristic of central Florida lakes. Table 4 lists the various operational conditions of the FITS during both the initial and second deployment.

The VTFs and WLTCs were operated under constant flow conditions (1 gal·min<sup>-1</sup>) during daylight hours for the entire deployment, excluding Run 2–4, when flow rates were increased to 1.5 gal·min<sup>-1</sup>. P-C Treatment Column 1 was also operated under constant flow conditions during the entire deployment, while P-C Treatment Column 2 was operated under different conditions, as shown in Table 4.

Within each of these two deployments, several sub-objectives were completed. The objectives of Runs 1–2, 1–3, and 1–6 were to compare PhosX resin and AR. Runs 1–4, 1–5, 1–7, and 1–8 evaluated the performance of regenerated PhosX resin. After the first deployment, attention was focused on PhosX resin because it was the better performing material relative to AR. During the second deployment, the first run (Run 2–1) was used to verify that both treatment columns performed identically. This was important because it showed that the treatment units can be easily replicated. The objective of Run 2–2 was to evaluate the effect of doubling the amount of PhosX resin, which at the baseline flow rate was equivalent to doubling the contact time. The objective of Run 2–3 was to evaluate PhosX resin that had been regenerated four times. This batch of PhosX resin was previously tested and regenerated three times during the first deployment. The objective of Run 2–4 was to evaluate the effect of doubling the volume of

**Table 4**  
FITS operating conditions during the entire deployment.

Test	Dates	Infl.	VTFs		Horizontal wetlands		Column 1			Column 2		
			Operational	Q (gal·min <sup>-1</sup> )	Operational	Q (gal·min <sup>-1</sup> )	Material	V (mL)	Q (gal·min <sup>-1</sup> )	Material	V (mL)	Q (gal·min <sup>-1</sup> )
1-1	22 Sep 2009–1 Oct 2009	LA	No	—	Yes	1.0	PhosX	950	0.5	—	—	—
1-2	2 Oct 2009–8 Oct 2009	LA	No	—	Yes	1.0	PhosX	950	0.5	AR	950	0.5
1-3	10 Oct 2009–19 Oct 2009	LA	No	—	Yes	1.0	PhosX	950	0.5	AR	950	0.5
1-4	3 Nov 2009–13 Nov 2009	M.	No	—	Yes	1.0	PhosX	950	0.5	R1PX	950	0.5
1-5	18 Nov 2009–30 Nov 2009	M.	No	—	Yes	1.0	PhosX	950	0.5	R1PX	950	0.5
1-6	1 Dec 2009–12 Dec 2009	M.	No	—	Yes	1.0	PhosX	950	0.5	AR	950	0.5
1-7	15 Dec 2009–21 Dec 2009	M.	No	—	Yes	1.0	PhosX	950	0.5	R2PX	950	0.5
1-8	13 Jan 2010–20 Jan 2010	M.	Yes	1.0	Yes	1.0	PhosX	950	0.5	R3PX	950	0.5
2-1	24 Mar 2010–10 Apr 2010	M.	Yes	1.0	Yes	1.0	PhosX	950	0.5	PX	950	0.5
2-2	14 Apr 2010–6 May 2010	M.	Yes	1.0	Yes	1.0	PhosX	950	0.5	2VPX	1900	0.5
2-3	11 May 2010–28 May 2010	M.	Yes	1.0	Yes	1.0	PhosX	950	0.5	R4PX	950	0.5
2-4	2 Jun 2010–23 Jun 2010	M.	Yes	1.5	Yes	1.5	PhosX	950	0.5	2V2QPX	1900	1.0
2-5	25 Jun 2010–30 Jul 2010	M.	Yes	1.0	Yes	1.0	PhosX	950	0.5	3VPX	2850	0.5

Infl.: Influent to FITS; LA: Lake Alice; M: mixture of Lake Alice and treated effluent from FITS; Q: flow rate; V: volume of material in treatment column; R1PX: 1st regenerated PhosX; R2PX: 2nd regenerated PhosX; R3PX: 3rd regenerated PhosX; 2VPX: doubled volume of PhosX; R4PX: 4th regenerated PhosX; 2V2QPX: twice the volume and twice the flow rate using PhosX; 3VPX: three times the volume of PhosX.

PhosX resin and doubling the flow rate. The objective of Run 2-5 was to evaluate the effect of tripling the volume of PhosX resin, which at the baseline flow rate is equivalent to tripling the contact time. In addition, the columns were changed out on weekly intervals during this run as an optimization experiment.

It is important to note that the operating conditions used in P-C Treatment Column 1 were the same operating conditions that were tested throughout the entire deployment. Hence, these operating conditions serve as a baseline performance to aid in optimizing the process.

### 2.3.3. Sample collection

The following samples were collected from the FITS: untreated Lake Alice water (LA Infl.), which served as the influent to the FITS; mixed Lake Alice water and FITS-treated water (M. infl.), which served as the influent to the FITS for a majority of the study; effluent from the VTFs (Vert. effl.); effluent from the horizontal wetlands (Bio. effl.); effluent from Treatment Column 1 (PX effl.), and effluent from Treatment Column 2 (either RPX effl. or OPX effl.) (see Tables 2 and 3). The italicized description in parentheses is used in subsequent sections to identify the sample locations. Samples were initially collected as grab samples (for about two weeks) and then collected by the “drip” method used in the mesocosms, which collects a composite daily sample.

Water samples were collected approximately every other day. At the end of each sample day, the composite samples were refrigerated at 4 °C for PO<sub>4</sub><sup>3-</sup> analysis. Phosphorus analyses were performed within 3 d of sample collection, in accordance with US EPA Method 365.1 [10].

The composite samples were then analyzed for PO<sub>4</sub><sup>3-</sup> and TP, yielding one data point for TP and PO<sub>4</sub><sup>3-</sup> each sample day for the inflow and outflow of each sampling location within the FITS. Water samples were also analyzed for pH, TN, and TOC.

To monitor for possible changes in water quality as a result of the physical–chemical treatment system, pH, UV<sub>254</sub>, TOC, chloride, and sulfate were monitored in each of the daily pooled samples of the FITS outflow. Water samples were analyzed in the lab of the UFs Center for Wetlands with random samples (totaling about 10% of total samples) sent to a certified lab (UF/IFAS Analytical Services Laboratory) for analysis as a check for in-house analysis methods.

## 2.4. Analytical methods

Table 5 summarizes all the chemical measurements and analytical methods used in this work [9–14]. Calibration standards were

prepared by dissolving American Chemical Society (ACS)-grade chemicals in DI water, or were used as provided by the manufacturer. Samples requiring filtration were vacuum-filtered through 0.45 µm membrane filters.

## 3. Results and discussion

### 3.1. Biological mesocosm experiments

Table 6 summarizes the HLRs, P mass loading, and P removal in the mesocosms. Overall, the mesocosms that were operated over the entire ten weeks of the first set exhibited mean removal efficiencies between 18% and 45% and an annualized (240-day growing season) P mass removal of between 2.2 and 12.0 g·m<sup>-2</sup>·a<sup>-1</sup>. The BFJ exhibited a mean uptake efficiency of 71.6%, resulting in an annualized P mass removal of 12.6 g·m<sup>-2</sup>·a<sup>-1</sup>. However, as the jute decayed, the DO of the effluent dropped to zero, a condition that was unacceptable for the FITS, so its operation ceased after approximately six weeks. The same drop in DO occurred with the coconut fiber biofilter; although its removal efficiency was 44% (7.4 g·m<sup>-2</sup>·a<sup>-1</sup>), its operation was terminated after eight weeks.

As they were operated at higher HLRs than the first set, the second set of mesocosms exhibited lower removal efficiencies (with a mean between 5.5% and 19.2%) and annualized P mass removal (with a mean between 1.4 and 6.9 g·m<sup>-2</sup>·a<sup>-1</sup>). These lower mean efficiencies and removal rates were partly due to senescence of the vegetation and to cold temperatures during the latter part of the experimental operation (November and December).

### 3.2. Bench-scale jar tests and column experiments

#### 3.2.1. Jar tests

Fig. 5(a) shows the concentrations of PO<sub>4</sub><sup>3-</sup>, TP, UV<sub>254</sub>, and TOC at 60 min, normalized by the respective concentrations in the raw water. FA was not included in Figs. 3–6 because it added PO<sub>4</sub><sup>3-</sup> to the treated water. All of the materials in Figs. 3–6 removed PO<sub>4</sub><sup>3-</sup> to some extent, as shown in the figures. The FR and AR resulted in a measureable increase in the TP concentration of the treated water relative to the raw water. This increase in TP is likely a result of attrition of the adsorbents during the jar tests, which is evidenced by the fact that the turbidity of all treated waters was greater than the turbidity of the raw water. The FR also increased the concentrations of UV<sub>254</sub> and TOC in the treated water. There

**Table 5**  
Chemical measurements and analytical methods.

Chemical measured	Analytical method	Filtered
TP and PO <sub>4</sub> <sup>3-</sup>	Samples for TP and PO <sub>4</sub> <sup>3-</sup> were sent to the UF/IFAS Analytical Services Laboratory in 20 mL scintillation vials, and were analyzed following US EPA Method 365.1 [10]. Samples for TP analysis were acidified in the laboratory to pH < 2 with sulfuric acid for preservation, after which autoclave digestion using ammonium persulfate and sulfuric acid was performed at the UF/IFAS Analytical Services Laboratory	TP (No) PO <sub>4</sub> <sup>3-</sup> (Yes)
PO <sub>4</sub> <sup>3-</sup>	PO <sub>4</sub> <sup>3-</sup> was measured using a Hach DR-850 colorimeter using an ascorbic acid method equivalent to US EPA Method 365.2 [11], and was checked periodically for its accuracy by measuring 50, 100, and 200 g·L <sup>-1</sup> standard solutions of P	No
PO <sub>4</sub> <sup>3-</sup>	Mesocosm PO <sub>4</sub> <sup>3-</sup> was measured using a Lamontt SMART 2 colorimeter. The colorimeter was calibrated four times from April 2009 to December 2009. No appreciable drift (> 10%) was noted in any calibration. Phosphorus analysis was done using the SMART 2, phosphorus, low-range, ascorbic acid reduction method (Lamontt Code #:3653-SC)	No
pH	pH was measured using an Accumet AP71 pH meter with an Ag/AgCl reference probe. The pH meter was calibrated before each use with pH 4, 7, and 10 buffer solutions Mesocosm pH was measured using a HANNA pH meter, calibrated weekly with pH solutions obtained from Fischer Scientific	No
Turbidity	Turbidity was measured using a LaMotte 2020e portable turbidity meter. The instrument was calibrated before each use using the 1.0 NTU turbidity standard	No
TOC and TN	TOC and TN were measured using a Shimadzu TOC-V <sub>CPH</sub> total organic carbon analyzer, as described in Ref. [9]. The instrument uses a high-temperature combustion method to measure non-purgeable organic carbon (i.e., TOC) and chemiluminescence to measure TN, similar to that described in Standard Method 5310B High-Temperature Combustion [12]. Calibration points were prepared the day of analysis from standard TOC and TN solutions. All samples were measured in duplicate with average values reported. The acceptance criterion for duplicate samples was a relative difference of < 20%	No
UV <sub>254</sub>	UV <sub>254</sub> was measured on a Hitachi U-2900 spectrophotometer using a 1 cm quartz cell	Yes
Chloride, nitrate, and sulfate	Chloride, nitrate, and sulfate were measured on a Dionex ICS-3000 ion chromatograph equipped with an AG22 guard column and an AS22 analytical column, as described in Ref. [13] and following US EPA Method 300.0 [14]. All samples were measured in duplicate with average values reported. The acceptance criterion for duplicate samples was a relative difference of < 20%	Yes
DO	Mesocosm DO and temperature were measured using an Oakton 110 DO meter, calibrated weekly using a zero-dissolved-oxygen solution obtained from Oakton. The temperature sensor was also calibrated weekly using a mercury glass thermometer from Fischer Scientific	

was a minor change in the UV<sub>254</sub> and TOC for waters treated by IS, LS, SS, and RC. AR was the only material to show measurable removal of UV<sub>254</sub> and TOC.

Fig. 5(b) shows the results for the ion-exchange resins. All ion-exchange resins showed removal of PO<sub>4</sub><sup>3-</sup>, TP, UV<sub>254</sub>, and TOC to some extent. The order of removal for PhosX and Dowex22 was PO<sub>4</sub><sup>3-</sup> > TP > UV<sub>254</sub> and TOC, with PhosX showing greater removal of all parameters relative to Dowex22. The order of removal for MIEX was UV<sub>254</sub> > TOC > PO<sub>4</sub><sup>3-</sup> > TP.

### 3.2.2. Column experiments

Fig. 6 shows the results for column experiments using Sanford Avenue Canal water and the materials AR and PhosX. For a majority of the column experiment, the PO<sub>4</sub><sup>3-</sup> concentration in AR-treated water was reduced from 107 to 35–50 µg·L<sup>-1</sup> of P,

while the TP concentration was reduced from 153 µg·L<sup>-1</sup> to 80–90 µg·L<sup>-1</sup>. The results for PhosX were very similar to the results for AR. There is a general trend of decreasing removal over time for both of the materials. Fig. 7 shows the results for column experiments using Lake Alice water and the materials AR and PhosX. The Lake Alice water had nearly three times the concentration of TP and PO<sub>4</sub><sup>3-</sup> as the Sanford Avenue Canal water. The PO<sub>4</sub><sup>3-</sup> and TP treatments by AR and PhosX were similar; however, the decreasing removal over time was more pronounced with the higher influent concentrations.

The potential for extending the removal capacity by pulsing the influent water is shown in Fig. 8. The graph compares TP results for column experiments using Lake Alice water and PhosX in which continuous-flow operation and intermittent flow operation (12-h-on/12-h-off) occurred. The graph shows the normalized effluent concentration (i.e., treated water divided by raw water)

**Table 6**  
HLR, P mass loading, and P removal rates for the mesocosm experiments.

Mesocosm	Dates of operation	Mean HLR (cm·d <sup>-1</sup> )	Mean P loading (mg·m <sup>-2</sup> ·d <sup>-1</sup> )	Mean P removed (mg·m <sup>-2</sup> ·d <sup>-1</sup> )	Efficiency (P <sub>remove</sub> /P <sub>load</sub> )
First Set (24 Apr 2009–15 Jul 2009)					
EMC	Apr 24–May 15	54.5 (±38.8)	34.42 (±37.1)	24.43 (±34.1)	–
VET	Jun 13–Aug 1	18.3 (±5.3)	41.7 (±12.3)	9.05 (±6.7)	18.2% (±8.5%)
EML	Apr 24–Aug 1	35.3 (±28.0)	51.07 (±24.6)	16.2 (±19.4)	37.1% (±25.0%)
VET	May 3–Aug 1	17.2 (±3.4)	39.0 (±8.7)	15.2 (±8.1)	38.3% (±20.5%)
SAV	May 13–Jun 28	22.0 (±4.9)	49.6 (±13.2)	23.1 (±11.9)	44.4% (±19.1%)
BFJ	Apr 24–Jun 2	45.1 (±12.7)	67.3 (±51.1)	52.4 (±42.5)	71.6% (±29.1%)
BFB	Apr 24–Jun 28	47.2 (±27.0)	69.3 (±35.1)	30.1 (±25.38)	44.0% (±26.9%)
AGS	Apr 24–Dec 15	60.9 (±29.3)	116.06 (±44.0)	49.8 (±25.0)	45.4% (±20.0%)
Second Set (20 Jul 2009–15 Dec 2009)					
PLM	July 20–Dec 15	40.8 (±18.5)	92.9 (±49.47)	13.5 (±15.7)	16.9% (±17.0%)
PLV	July 20–Dec 15	41.1 (±17.8)	92.7 (±43.0)	11.7 (±9.3)	13.5% (±9.1%)
BIB	July 20–Dec 15	40.8 (±21.2)	91.5 (±53.5)	7.1 (±8.2)	9.5% (±8.9%)
PLO	July 20–Dec 15	42.89 (±21.1)	96.4 (±53.3)	5.7 (±13.2)	5.5% (±10.1%)
VTF	July 20–Dec 15	55.8 (±19.4)	127.7 (±55.1)	28.6 (±34.0)	19.2% (±17.1%)



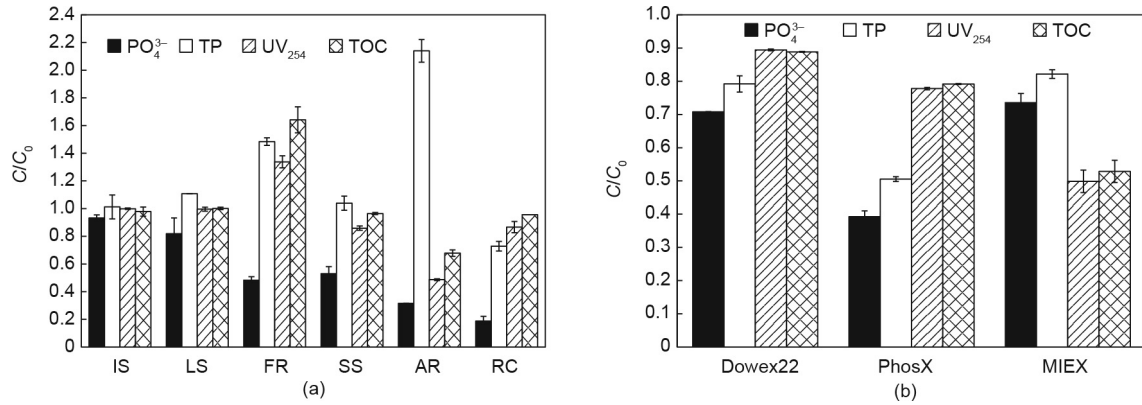


Fig. 5. Final normalized concentrations (C) for (a) adsorbents and (b) ion-exchange resins, after 60 min jar tests of Sanford Avenue Canal water. Initial concentrations ( $C_0$ ) are given in Table 3.

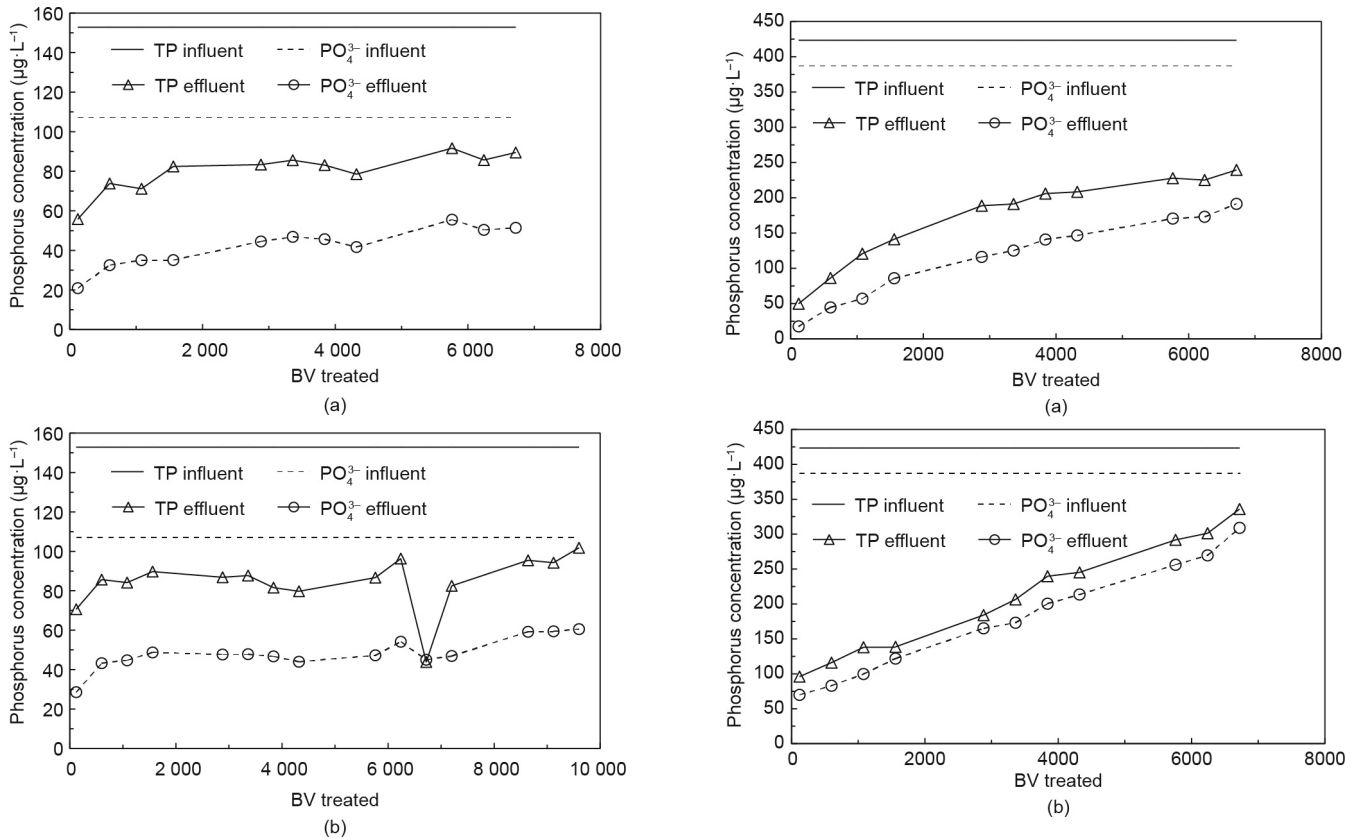


Fig. 6. Results from column experiments using Sanford Avenue Canal water (collected June 2009) and the materials (a) AR and (b) PhosX. Experimental conditions: 1 BV = 1 mL of wet settled material, continuous flow, flow rate = 2 BV·min<sup>-1</sup>, influent water filtered through a Whatman GF/A filter, TP influent (solid line) = 153  $\mu\text{g}\cdot\text{L}^{-1}$ ,  $PO_4^{3-}$  influent (dashed line) = 107  $\mu\text{g}\cdot\text{L}^{-1}$  of P.

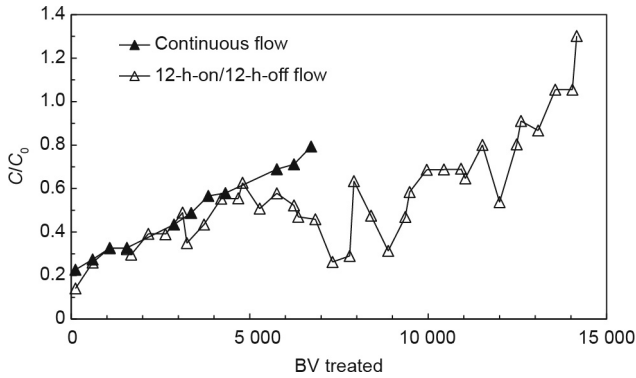
Fig. 7. Results from column experiments using Lake Alice water (collected July 2009) and the materials (a) AR and (b) PhosX. Experimental conditions: 1 BV = 1 mL of wet settled material, continuous flow, flow rate = 2 BV·min<sup>-1</sup>, influent water filtered through a Whatman GF/A filter, TP influent (solid line) = 423  $\mu\text{g}\cdot\text{L}^{-1}$ ,  $PO_4^{3-}$  influent (dashed line) = 387  $\mu\text{g}\cdot\text{L}^{-1}$  of P.

because experiments were conducted with two different batches of water from Lake Alice. The results show that the removal capacity of PhosX is extended by operating in intermittent flow mode (i.e., 12-h-on/12-h-off) relative to continuous flow.

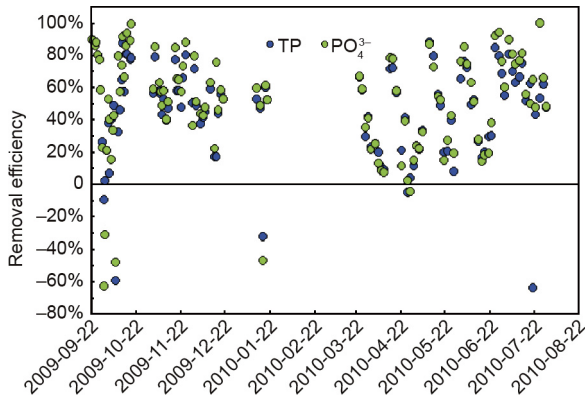
### 3.3. Deployment of the FITS

The FITS was deployed for a total of eight months in Lake Alice on the campus of the UF in two separate deployments. The first

deployment (22 September 2009 to 22 January 2010) was used as a proof of concept. The second deployment (24 March 2010 to 30 July 2010) was designed to evaluate various operating conditions of the FITS, which were mostly related to the P-C Treatment Columns. There was a hiatus in the deployment between 22 January 2010 and 24 March 2010. Fig. 9 summarizes the performance of the FITS, showing sustained removal efficiencies of about 60%. Since the FITS was operated to test the life of PhosX resin and the AR, removal efficiencies show a cyclic pattern as the adsorbents were used to near exhaustion. This is especially evident in the second half of the deployment (Fig. 9), where in an effort to determine



**Fig. 8.** Normalized ( $C/C_0$ ) TP results from column experiments using Lake Alice water (collected July 2009 for continuous flow and August 2009 for 12-h-on/12-h-off flow) and PhosX resin. Experimental conditions: continuous flow and 12-h-on/12-h-off flow, 1 BV = 1 mL of wet settled material, flow rate = 2 BV·min<sup>-1</sup>, influent water filtered through a Whatman GF/A filter.



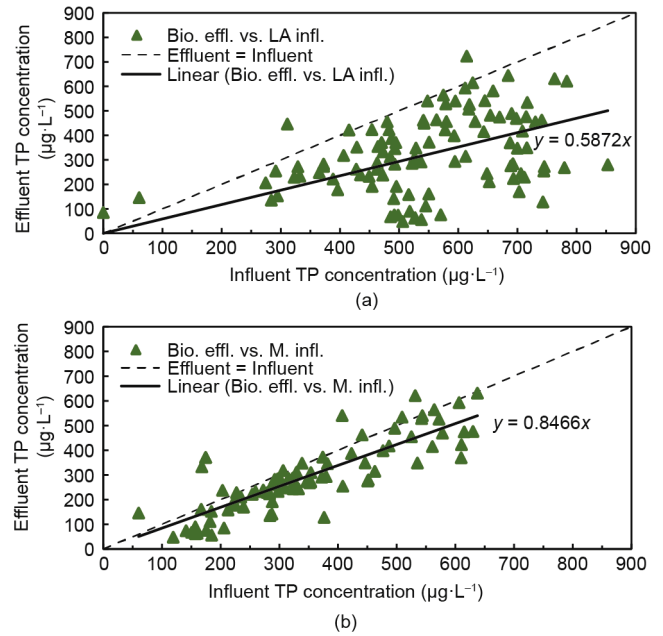
**Fig. 9.** Removal of TP and  $PO_4^{3-}$  of the FITS operating at baseline conditions using PhosX resin (see Tables 2 and 3).

resin lifespan and treatment efficiency under operating conditions, the resins were not changed out until their treatment capacity had been almost completely exhausted.

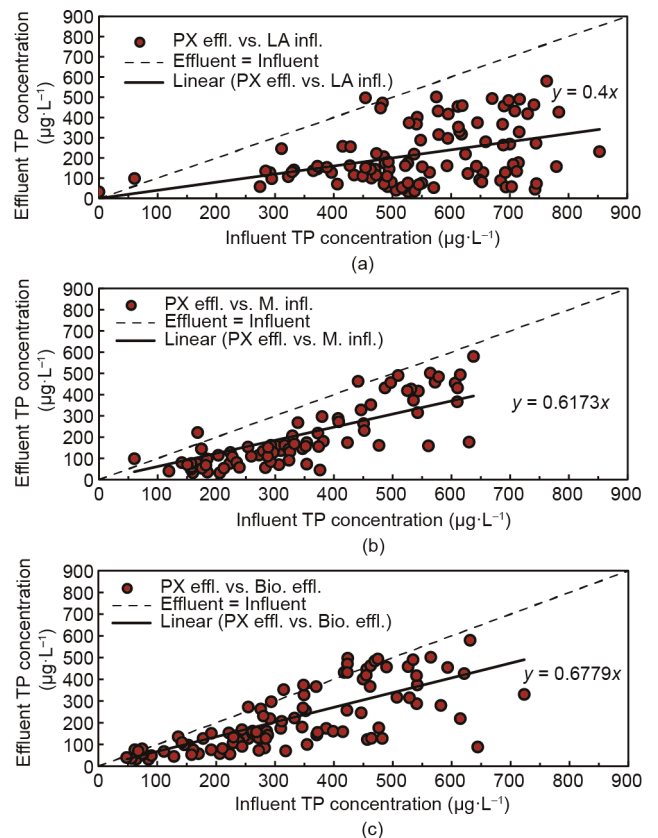
### 3.3.1. FITS treatment efficiency

Figs. 10 and 11 show the TP removal efficiencies for the FITS biological treatment and physical–chemical treatment processes, respectively. The removal efficiency is displayed as the effluent concentration on the y-axis and as the influent concentration on the x-axis. For example, “Bio. effl. vs LA infl.” (Fig. 10(a)) is the concentration of TP in the effluent from the biological treatment versus the concentration of TP in Lake Alice water, which served as the influent to the FITS in the first deployment. Fig. 10(b) shows the treatment efficiency of the biological treatment versus the mixed influent; it is evident that at lower inflow concentrations, the treatment efficiencies are lower. Overall, the linear regression line shows treatment efficiencies of 42% at the higher influent TP concentrations (Fig. 10(a)) and of about 15% at the lower concentrations.

The graphs in Fig. 11 show the TP removal efficiencies for the FITS PhosX resin column (Column 1: see Table 4). Fig. 11(a) shows the overall FITS treatment efficiency, comparing the effluent of the resin column to Lake Alice water; thus, it includes both biological and resin column treatment. The treatment efficiency in Fig. 11(b) is for the FITS system (again including both the biological and physical–chemical components versus the mixed influent); Fig. 11(c) shows the treatment efficiency of the resin column versus



**Fig. 10.** TP removal efficiency for (a) Bio. effl. vs. LA infl. to FITS and (b) Bio. effl. vs. M. infl. The solid black line shows a scenario in which the effluent concentration is equal to the influent concentration (i.e., no removal).



**Fig. 11.** TP removal efficiency for (a) PX effl. vs. LA infl. to FITS, effluent from a PhosX resin column operating at baseline conditions, (b) PX effl. vs. M. infl. to FITS, and (c) PX effl. vs. Bio. effl. The dash line shows a scenario in which the effluent concentration is equal to the influent concentration (i.e., no removal).

the effluent of the biological treatment. It is evident that the resin column adds to the treatment capacity of the FITS, especially when compared with the biological component alone.

The graphs in Figs. 12 and 13 show the  $\text{PO}_4^{3-}$  removal efficiencies for the FITS biological treatment and physical-chemical treatment processes, respectively. Treatment efficiencies for  $\text{PO}_4^{3-}$  within the biological component of the FITS were slightly lower than they were for TP, while, as might be expected, they were higher in the resin column. With the lower  $\text{PO}_4^{3-}$  concentrations that resulted from the mixed influent, treatment efficiencies were slightly lower than the raw Lake Alice influent.

Table 7 summarizes the performance of the FITS for the entire 8-month deployment, and gives the mean TP and  $\text{PO}_4^{3-}$  removal for the biological component and the resin columns as stand-alone units and for the entire system. The input to the biological component was both Lake Alice water (four weeks) and mixed effluent (28 weeks), and the input to the PhosX resin columns was the output from the biological component. The combined system was calculated using the Lake Alice and mixed influent versus the PhosX effluent. Obviously, the variation in input sources and removal by each component results in very high efficiency. However, the mean efficiency of removal of TP and  $\text{PO}_4^{3-}$  by the biological component was 20.2% and 17.6%, respectively, during the period of operation, while that of the PhosX was 35.3% and 42.5%, respectively. Overall, the FITS removal efficiency for TP and  $\text{PO}_4^{3-}$  was 45.5% and 53.3%, respectively. Assuming a 240-day growing season,  $3.7 \text{ m}^2$  in the biological treatment component, and the mean P removal for the biological component given in Table 7 results in a TP uptake by the biological treatment component of  $12.1 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$  and a  $\text{PO}_4^{3-}$  uptake of  $8.3 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$  of P.

### 3.3.2. FITS biomass

Biomass was harvested at two times during deployment. Plant material was harvested from the horizontal wetlands in December 2009, after a hard freeze that caused dieback of the aboveground wetland macrophytes, and again in June 2010. The data in Table 8 show the results of the analysis of harvested vegetation. The concentration of TP in the combined above- and below-ground wetland macrophyte biomass was about  $3.99 \text{ g P per kg dry weight}$

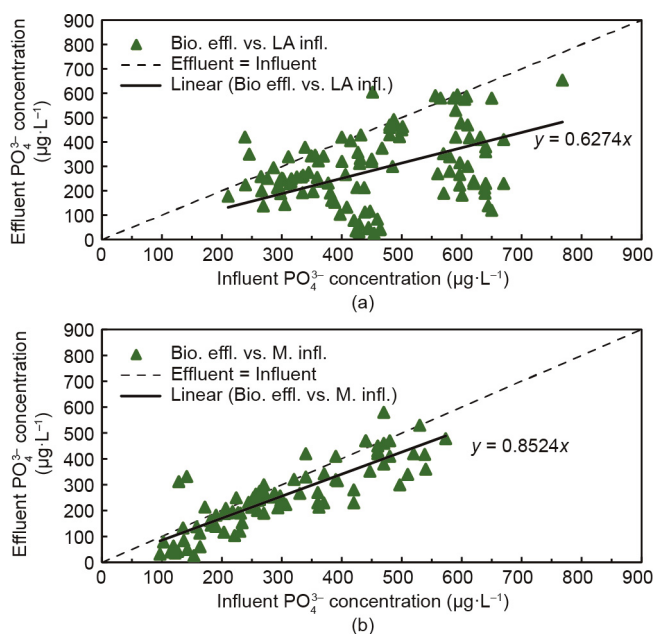


Fig. 12.  $\text{PO}_4^{3-}$  removal efficiency for (a) Bio. effl. vs. LA infl. to FITS and (b) Bio. effl. vs. M. infl. The dash line shows a scenario in which the effluent concentration is equal to the influent concentration (i.e., no removal). Data that fall below the "Effluent = Influent" line illustrate removal.

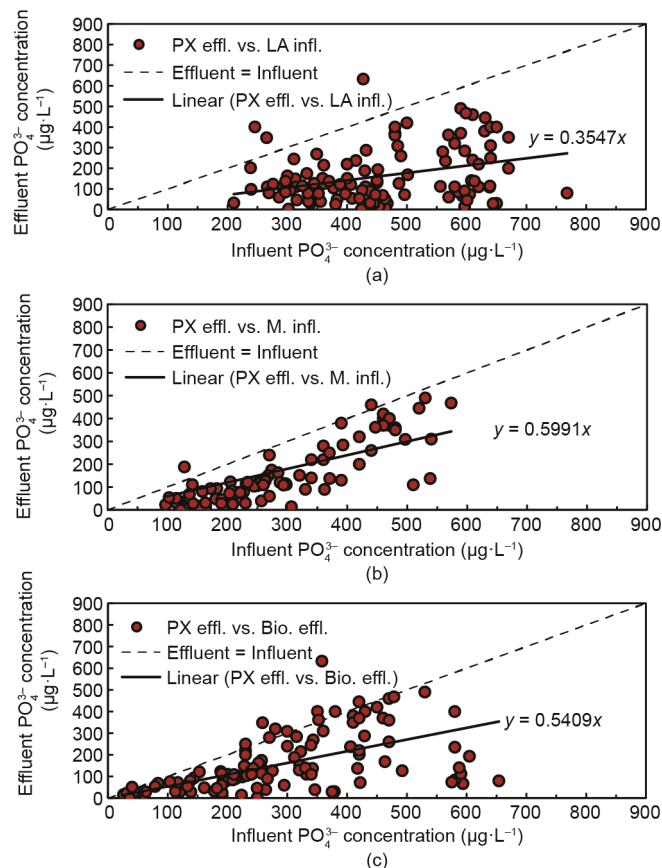


Fig. 13.  $\text{PO}_4^{3-}$  removal efficiency for (a) PX effl. vs. LA infl. to FITS, effluent from a PhosX resin column operating at baseline conditions, (b) PX effl. vs. M. Infl. to FITS, and (c) PX effl. vs. Bio. effl. The dash line shows a scenario in which the effluent concentration is equal to the influent concentration.

of organic matter (OM) after three months of growing. The vetiver, on the other hand, had tissue concentrations of about  $1.75 \text{ g P per kg OM}$  and  $1.4 \text{ g P per kg OM}$  in above- and below-ground biomass, respectively. In the three months of the first deployment before the freeze, the wetland macrophytes had stored  $2.3 \text{ g} \cdot \text{m}^{-2}$  of P in above- and below-ground biomass. The vetiver, which was not affected by the freeze and which stores most of its phosphorus in the large quantity of below-ground biomass, had stored  $2.8 \text{ g} \cdot \text{m}^{-2}$  of P in eight months.

### 3.4. Synthesis of biological mesocosm experiments, bench-scale jar tests and column experiments, and FITS

The biological mesocosm experiments showed, on average, 40%  $\text{PO}_4^{3-}$  removal across a wide range of biological systems. The  $\text{PO}_4^{3-}$  removal efficiency decreased to about 20% when the mesocosms were scaled down and the hydraulic retention times (HRTs) were increased in the second set of mesocosms, which was intended to more closely simulate the FITS. From the biological mesocosm experiments, it was determined that emergent macrophytes and vetiver grass grown in plastic regrind media would be the most appropriate biological unit process for FITS. A limitation of the biological mesocosm experiments was the composition of the test water—tap water spiked with phosphate and nitrate. It is likely that the test water did not contain the micronutrients necessary for optimum performance of the biological system. In addition, the test water did not contain natural organic matter, which can affect the speciation of TP. Nevertheless, the biological mesocosm

**Table 7**  
Summary of TP and  $\text{PO}_4^{3-}$  removal by the FITS during 8-month deployment.

Component	TP			$\text{PO}_4^{3-}$		
	P loading ( $\text{mg}\cdot\text{d}^{-1}$ )	P removal ( $\text{mg}\cdot\text{d}^{-1}$ )	Efficiency ( $P_{\text{remove}}/P_{\text{load}}$ )	P loading ( $\text{mg}\cdot\text{d}^{-1}$ )	P removal ( $\text{mg}\cdot\text{d}^{-1}$ )	Efficiency ( $P_{\text{remove}}/P_{\text{load}}$ )
Biological	1042.4 ( $\pm 433.9$ )	187.2 ( $\pm 163.7$ )	20.2% ( $\pm 18.3\%$ )	844.9 ( $\pm 340.0$ )	127.7 ( $\pm 146.4$ )	17.6% ( $\pm 32\%$ )
PhosX	873.9 ( $\pm 419.1$ )	290.5 ( $\pm 290.1$ )	35.3% ( $\pm 25.9\%$ )	722.3 ( $\pm 352.0$ )	282.6 ( $\pm 254.6$ )	42.5% ( $\pm 29.6\%$ )
Combined	1042.4 ( $\pm 433.9$ )	455.4 ( $\pm 318.0$ )	45.5% ( $\pm 26.3\%$ )	844.9 ( $\pm 340.0$ )	409.6 ( $\pm 247.3$ )	53.3% ( $\pm 30.0\%$ )

**Table 8**  
Biomass and phosphorus in harvested vegetation.

Vegetation	December harvest		June harvest		Phosphorus storage ( $\text{g}\cdot\text{m}^{-2}$ )
	Biomass (g)	Phosphorus ( $\text{g}\cdot\text{kg}^{-1}$ )	Biomass (g)	Phosphorus ( $\text{g}\cdot\text{kg}^{-1}$ )	
Wetland macrophytes <sup>a</sup>	1082.2	3.994	—	—	2.32
Vetiver (above ground) <sup>b</sup>	—	—	872.2	1.757	0.82
Vetiver (below ground)	—	—	2656.8	1.401	2.00

<sup>a</sup> Total of above- and below-ground biomass after three months (September 22–December 22) harvested from 1.86 m<sup>2</sup> horizontal wetlands.

<sup>b</sup> Vetiver harvested after approximately eight months from 1.86 m<sup>2</sup> horizontal wetlands.

experiments provided a realistic range of treatment efficiencies for  $\text{PO}_4^{3-}$  removal that could be expected by FITS.

The bench-scale jar tests and column experiments demonstrated that AR and PhosX resin were the best-performing materials for TP removal. Although the FR, SS, and RC removed  $\text{PO}_4^{3-}$  and TP during the jar tests, the FR leached organic matter into the treated water, while the SS and RC increased the pH of the treated water. As a result, these materials would require subsequent post-treatment to correct the changes in water quality, which would add another unit process to the treatment system. Thus, the focus of the column experiments was to evaluate AR and PhosX resin under continuous-flow conditions that would more closely simulate the FITS. The removals of  $\text{PO}_4^{3-}$  and TP by AR and by PhosX resin in both Sanford Avenue Canal and Lake Alice water were very similar. This was an important result because AR and PhosX could not be quantitatively compared in the jar tests, as AR was dosed on a mass basis while PhosX was dosed on a volume basis. However, the same volume of AR and PhosX resin was used in the column experiments to allow for quantitative comparisons.

The FITS combined biological treatment (emergent macrophytes and vetiver grass grown in plastic regrid media) with physical–chemical treatment (up-flow columns containing either AR or PhosX resin) to maximize P removal. PhosX was used for a majority of the deployment because it showed greater P removal than AR. This was in contrast to the bench-scale experiments, and is likely a result of the difficulty of making the AR into particles. The AR was received in large, irregular pieces, and it was a challenge to grind the AR particles to a consistent particle size rather than to powder. The PhosX resin did not require any adjustment in particle size.

It should be emphasized that the average removal efficiencies (Table 7) represent periods of time when the PhosX resin was run to near exhaustion as well as times with fresh PhosX, so the overall average must be used with caution. For the entire duration of the FITS deployment in the lake, the biological unit processes reduced TP by about 20%, while the PhosX resin reduced TP by an additional 35%. The overall efficiency of the FITS was between 45% and 50% (Table 7). When operated under optimum conditions, the efficiencies were much higher. If we assume an operation that results in efficiencies within the 90th percentile of all measured results, the FITS removes about 863  $\text{mg}\cdot\text{d}^{-1}$  of TP and 259  $\text{mg}\cdot\text{d}^{-1}$  of  $\text{PO}_4^{3-}$ , with a resulting overall removal efficiency of 78% for TP and 85% for  $\text{PO}_4^{3-}$ .

Differences in the removal efficiency of TP and  $\text{PO}_4^{3-}$  by the biological treatment component confirmed our initial assumptions that the biological component would not only reduce  $\text{PO}_4^{3-}$ , but also reduce TP through filtration of phytoplankton as lake water passes through the growing medium of the WLTCs. Average TP removal was higher (20.2%) than  $\text{PO}_4^{3-}$  removal (17.6%) (Table 7). We expected this filtration action, and this was a primary reason for placing the biological component first in the treatment train, and thus reducing clogging of the physical–chemical component.

Using the footprint of the biological component (3.7 m<sup>2</sup>) and the footprint of the total area of the FITS (including solar cells and resin columns, approximately 10 m<sup>2</sup>), it is possible to determine the P removal per unit area for comparison with other technologies. Assuming a growing season of 240 d and the average mass removal of P given in Table 7, the FITS biological component can remove about 12.1  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  as TP and 8.3  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  of P as  $\text{PO}_4^{3-}$ . Overall, the combined biological and chemical components of the FITS can remove 10.9  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  as TP and 9.8  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  of P as  $\text{PO}_4^{3-}$ .

These removal rates compare favorably with other biological and engineered treatment systems. In a wetland system designed to filter particulate phosphorus, extrapolated average annual P removal rates were 2.2  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  [15]. Four free-water constructed wetlands in Sweden were capable of removing between 1 and 4  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  of P depending on inflow concentrations [16]. The average TP removal over a five year period in large-scale treatment wetlands in the Everglades (FL, USA) was 1.2  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  [17]. The long-term average P removal rate for 13 natural SAV-dominated lake and river systems in Florida was 1.2  $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  [18].

During FITS deployment, other water quality parameters were monitored. There was generally less than a 20% difference between Lake Alice water and FITS effluent (i.e., “PX effl.”) for pH, chloride, and sulfate. Although the turbidity in Lake Alice was relatively low (on average, about 4 nephelometric turbidity unit (NTU)), the effluent turbidity was reduced by approximately 50%, which is expected to translate to reductions in particulate phosphorus. The TOC, UV<sub>254</sub>, and TN were all lower in the FITS effluent relative to Lake Alice and the mixed influent, with average removals of 30%. There were no clear removal trends for nitrate because concentrations were near the lowest calibration standard used by the instrument. Overall, monitoring of other water quality parameters showed that the FITS is highly selective for  $\text{PO}_4^{3-}$  and TP treatment when compared with other water



chemistry, and that it does not introduce any treatment byproducts into the water column.

The spent PhosX resin can be regenerated multiple times, which allows for the resin to be reused [19]. We regenerated the resin in this study three times without appreciable reduction in absorptive capacity. In addition, it is possible to recover the phosphate from the waste regeneration solution by precipitating the phosphate with calcium and separating it from the solution through filtration. This creates a beneficial product (e.g., struvite) and allows for the waste regeneration solution to be reused for another cycle of resin regeneration.

#### 4. Conclusions

The following conclusions can be drawn from the design and operation of the FITS:

- The  $\text{PO}_4^{3-}$  removal efficiencies of mesocosms under moderate HLRs averaged between 40% and 50%, providing an average uptake of  $5.0 \text{ g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  of P across all mesocosms. At higher HLRs equivalent to the operational flows of the FITS, the mesocosms averaged about 15% removal efficiencies.
- The bench-scale jar tests and column experiments demonstrated that AR and PhosX resin were the best-performing materials for TP removal.
- PhosX was used for the majority of the deployment because it showed greater TP removal than AR; this is likely because PhosX did not require any particle size adjustment.
- Regenerated PhosX was shown to perform as effectively as virgin PhosX.
- The FITS was highly selective for  $\text{PO}_4^{3-}$  and TP treatment when compared with other water chemistry parameters, and it did not introduce any treatment byproducts into the water column.
- An important mechanism of TP removal was filtration of suspended algae in the WLTCs, as evidenced by the difference in removal efficiencies between  $\text{PO}_4^{3-}$  and TP of the biological component during deployment of the FITS.
- After just three months in the late growing season of 2009, the wetland macrophytes had stored on average  $2.3 \text{ g}\cdot\text{m}^{-2}$  of P in above- and below-ground biomass.
- Using the 50th and 90th percentiles of  $\text{PO}_4^{3-}$  removal and the footprint of the FITS system yields efficiencies for the combined FITS system of 56% and 86%, respectively, and areal P removal rates of between  $8.9$  and  $16.5 \text{ g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$  during the period of record.

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#### Compliance with ethics guidelines

Mark T. Brown, Treavor Boyer, R.J. Sindelar, Sam Arden, Amar Persaud, and Sherry Brandt-Williams declare that they have no conflict of interest or financial conflicts to disclose.

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