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RESEARCH ARTICLE OPEN ACCESS

Utilizing a Two-Stage Constructed Wetland With Floating Plant Mats for Removing Phosphorus From Agricultural Drainage in Michigan

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ABSTRACT

A two-stage constructed floating wetland with a 0.7% ratio of wetland to drainage area was studied for removing phosphorus from subsurface agricultural drainage. This system consisted of two stages, the first being a floating wetland containing *Scirpus atrovirens, Carex vulpinoidea, Juncus effusus, Ranunculus hispidus*, and *Acorus americanus*, and the second containing a filter media of pea stone. It was found that total phosphorus (TP) in plant tissues was not statistically different across macrophyte species; however, total biomass did differ. Therefore, to obtain maximum TP removal, plant shoots should be removed when they reach their maximum biomass. *Scirpus* had the highest average dry mass (17.1 g) and average TP shoot mass and was significantly greater than the other species examined. Total P removal by plant shoots ranged between 0.89% and 19.3% of the soluble reactive phosphorus (SRP) entering the wetland, depending on the year. The average annual SRP and total phosphorus reductions from discharge entering and exiting the system equated to 65 and 36%, respectively. Additionally, the average SRP concentration across all 3 years during the growing season was reduced from 0.087 mg/L to 0.029 mg/L, and TP was reduced from 0.168 mg/L to 0.068 mg/L, keeping both SRP and TP effluent concentrations below maximum concentrations recommended for flowing waters to minimize eutrophication and harmful algal blooms.

1 | Introduction

Agricultural non-point source (NPS) runoff has been identified as a lead contributor to water quality impairment in the Western Lake Erie Basin (WLEB) (Stumpf et al. 2012; UNTC 2012; Kane et al. 2014). Historically, surface runoff has been the major focus of nutrient input to the WLEB. More recently, however, increased attention has been placed on nutrient loss through subsurface drainage (or tiling). As field studies have demonstrated, these tiling systems can disproportionately export large soluble reactive phosphorus (SRP) and nitrate ($N0_3$-N) loads relative to other surface and subsurface pathways (King et al. 2015; Miller and Lyon 2021), feeding harmful and nuisance algae and exacerbating harmful algal blooms within the WLEB.

To address excessive nutrients in subsurface drainage, increased participation in best management practice (BMP) adoption is needed to meet bi-national nutrient reduction goals guided by the Great Lakes Water Quality Agreement (GLWQA). Many BMPs, however, require added labor, equipment upgrades, or

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impose short-term yield risks to producers, which continue to prevent or slow their adoption. This is particularly concerning, as numerous studies have discussed that BMPs will need to be implemented at an unprecedented scale (Erickson 2016), with others demonstrating as much as a 100% adoption rate being needed to meet nutrient reduction goals in the WLEB (Scavia et al. 2017).

BMPs such as vegetated ditches, no-till or reduced tillage, and drainage water management are some of the techniques used today to help address P loss in subsurface drainage; but each presents unique challenges to achieving higher adoption rates. While vegetated ditches have demonstrated the ability to mitigate P under conditions of reduced flow (Erickson 2016), uncertainty remains about their effectiveness outside of these conditions. Additionally, while practices such as no-till or reduced tillage offer economic incentives (lower fuel expenses for operating tillage equipment), among numerous soil health benefits which help to retain nutrients (Scavia et al. 2017), debate remains surrounding the formation of preferential flow paths and their contributions to added P loss in subsurface drainage. Lastly, drainage water management, or controlled drainage, can reduce flow from subsurface drainage, allowing time for added nutrient retention within the field; but confusion remains about their effectiveness during the non-growing season, and frustrations can emerge regarding added labor and the costs to install them (Moore and Hunt 2012).

Floating treatment wetlands (FTWs) and constructed wetlands (CWs) offer an alternative means of nutrient remediation that could remove many of the common barriers to adoption mentioned above, while directly reducing subsurface nutrient loss in regions that rely on tile drainage to prevent flooding (King et al. 2015; Pease et al. 2017). These systems are most ideal when placed adjacent to working fields to avoid any lost opportunity costs, and taking care to ensure these areas are not deemed wetlands in the past. Additionally, these systems can bring aesthetic value to the farm, while providing added habitat for frogs and other aquatic species. Lastly, these systems do not require the purchase of equipment upgrades and need little to no maintenance once installed.

Another form of treatment is a combination of an FTW and a CW, or a constructed floating wetland (CFW). These are particularly effective for treating water bodies impacted by eutrophication due to their use of strategically placed floating mats, which allow for the uptake of nutrients and the growth of biofilms that assist in filtering sediment. Additional benefits of a CFW include the flexibility to construct them in agricultural settings where they will most optimally reduce nutrients from sub-surface drainage. Furthermore, there is the option of making these into hybrid systems, as done in this study. The added benefit of this includes a second pond or cell that the treated water can flow into and undergo further treatment. In this study, we employ a floating wetland in pond one, equipped with floating mats where four native plant species could provide the uptake of nutrients, while the second pond contained a pea stone substrate for further filtering of sediment.

Identifying appropriate macrophytes (native to northern climates) and substrate combinations, which will both reduce P while requiring minimal maintenance or land removal from producers, will play an important role in the future adoption of treatment wetland systems. Numerous substrates have been scored for their P-removal abilities, but limited studies exist on their performance in on-farm trials (Ballantine and Tanner 2010). Furthermore, substrates that are low cost and readily available, such as the pea stone (or pea gravel) used in this study, need further exploration.

Lastly, a constructed wetland is scaled according to its treatment drainage area, with the standard being within the 0.5% to 2.0% range (Tyndall and Bowman 2016). Sizing is also dependent on nutrient loading to the wetland, nutrient removal goals, available land, and budget (Borne 2014). Ideally, the treatment drainage area ratio would be small enough to not inhibit opportunity costs, but large enough to avoid saturation and becoming a source of phosphorus over time. Limited on-farm trials, however, explore the risk of saturation using this typical scaling range after multiple years of having an FTW or CFW installed.

In this study, we measured P retention over approximately 3 years (January of 2020 to October of 2022) and P percentage in plants over 4 years (June 2019–October 2022) in a two-stage constructed floating wetland (Figure 2) growing five species of northern plant species: Dark Green Bulrush (*Scirpus atrovirens*), Fox Sedge (*Carex vulpinoidea*), Common Rush (*Juncus effusus*), Hispid Buttercup (*Ranunculus hispidus*), and American sweet flag (*Acorus americanus*). These plants were grown on floating mats in pond one, while pea stone (a limestone-sand mixture was tried first but caused clogging) provided additional P removal within cell two. Our main study questions were: (1) which native northern plant species most effectively removed P, and (2) how effectively did the entire treatment system retain P from subsurface drainage?

2 | Materials and Methods

2.1 | Site Description

The two-stage wetland was constructed within the Western Lake Erie Basin (WLEB) in southeast Michigan, which has a cold temperate climate with an average annual rainfall of 972 mm (38.3 in.) (Ann Arbor, MI, GLISA 2024). Michigan's growing season is variable; however, for the purpose of this study, it was defined from mid-March to mid-November. Additionally, the wetland was positioned on the edge of a conventionally managed field under a crop rotation of soybean, alfalfa, and corn. Water flows from the field into the first and then second wetland and exits into the south branch of the River Raisin (Figure 1).

2.2 | Construction of the Two-Stage Wetland

The two wetlands were constructed with a 3:1 slope and lined with a commercially available impermeable Ethylene Propylene Diene Monomer pond liner to provide a research-grade wetland treatment that prevented both groundwater discharge and recharge. The liner would not be needed for this purpose for standard edge-of-field practices. Additional berms were created to divert surface runoff from entering the wetlands. Trees

around the wetlands were removed to allow sunlight to reach the wetlands and minimize the quantity of leaves entering them. Any exposed soil on the wetland bank and in the surrounding areas was planted with a cereal rye and grass mixture for erosion prevention. At the start of the project in June 2019, surface discharge collected from water and sediment control basins (WASCOBs) and subsurface discharge from subsurface drain tiles from the adjacent fields to the south were combined and directed to the wetland system via a 20.3 cm (8 in.) PVC pipe. During the first year of operation, heavy rains produced large volumes of surface runoff directed from three WASCOBs, causing the wetlands to overflow. At the end of 2019, the surface water was separated from the subsurface drainage and only subsurface drainage entered the treatment train. The discharge from the field was diverted to flow in a series from the field to wetland one, then to wetland two, and finally discharged into the south branch of the River Raisin. Floating mats with plants were placed in wetland one at the start of the project, and a filter media consisting of a three-to-four-foot layer of pea stone (small stones approximately 1/8 in. (0.318 cm) to 3/8 in. (0.9525 cm) in size with rounded edges that have become smooth from natural weathering) was added to wetland two in year 2 to assist with nutrient removal (Figure 2).

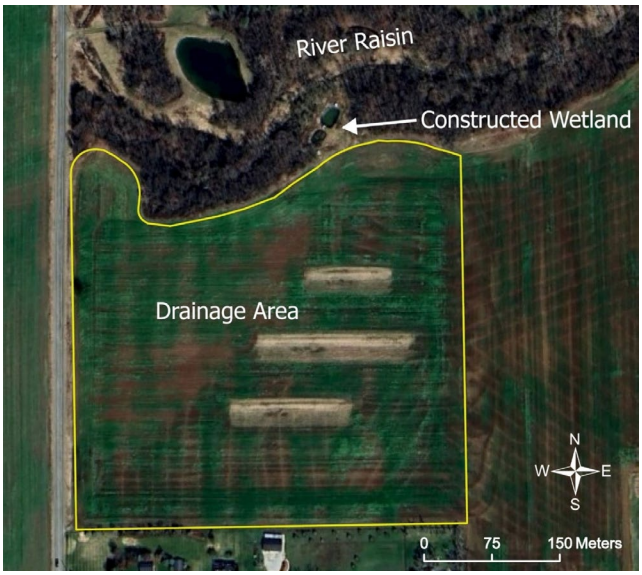


FIGURE 1 | Aerial view of field draining to the two-stage constructed floating wetland.

2.3 | Wetland Sizing

In many cases, a constructed wetland is scaled according to its treatment drainage area, with the standard being within the 0.5% to 2.0% range (Tyndall and Bowman 2016). Sizing is also dependent on nutrient loading to the wetland, nutrient removal goals, available land, and budget (Borne 2014).

For this project, the two-stage constructed wetland size and configuration were designed to minimize the use of productive farmlands for the site. Since the site was initially wooded, an area of approximately 0.3 acres was cleared of trees. Within the cleared area, the two wetlands and equipment required approximately 0.15 acres of space. After construction, the two wetlands had a combined surface area of approximately 214 m^2 (2300 sq. ft). The maximum holding capacity of the two wetlands was approximately 17,700 gal, and they treated a drainage area of 3.25 ha (7.5 acres). Therefore, a 0.7% ratio of wetland surface area to drainage area was utilized.

2.4 | Construction Costs and Maintenance

Installation of a constructed wetland system with the same specifications as the one installed for this project would cost approximately $22,000, equating to $102.90 per square meter of wetland. The cost estimate above includes all design efforts, the clearing of vegetation work needed at the end of each growing season, installation work, mats, plants, pots, and other materials necessary for a typical wetland installation. The value above does not include the pond liners and monitoring equipment. Pond liners were added to our system to limit outside influence from groundwater for research purposes but would be unnecessary in a typical installation; for this reason, they were not included in the total cost listed above. Site preparation is a major factor in determining installation costs. The site selected for our wetland had many large trees that needed to be removed in preparation for its installation, increasing the installation cost at this site.

2.5 | Implementation of Floating Mats and Plant Selection

The four plants originally selected were Dark Green Bulrush (*Scirpus atrovirens*), Fox Sedge (*Carex vulpinoidea*), Common Rush (*Juncus effusus*), and Hispid Buttercup (*Ranunculus*

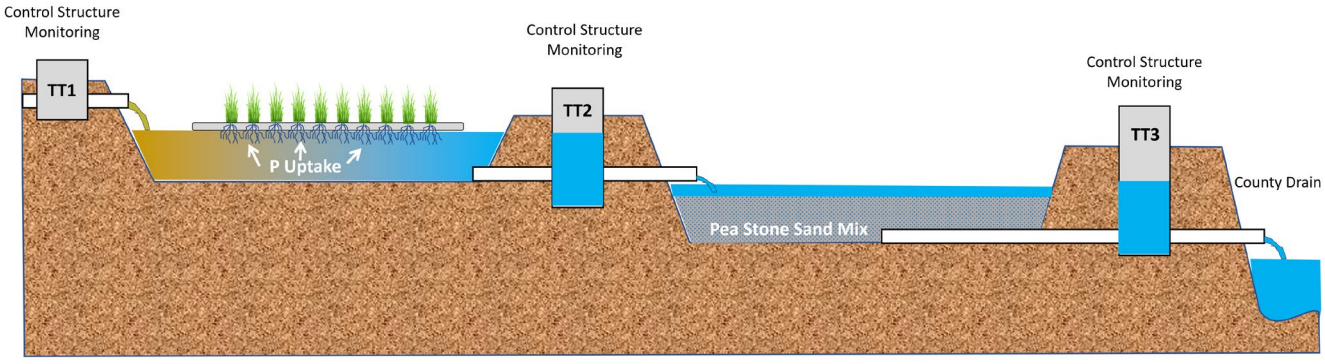


FIGURE 2 | Two-stage constructed floating wetland treatment design.

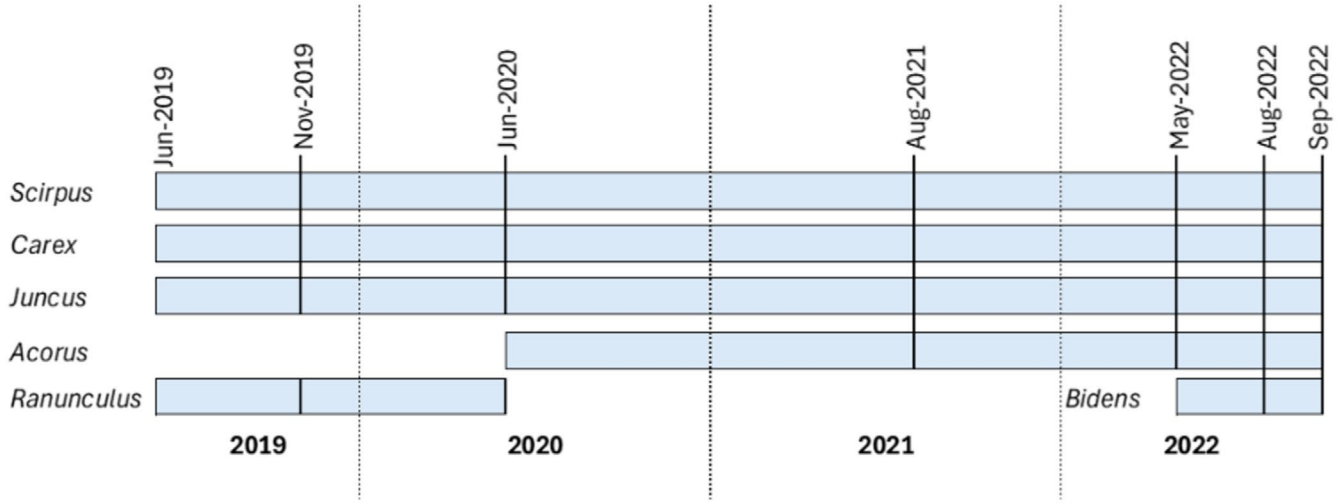


FIGURE 3 | Timeline of when species were planted on the floating mats, their length of residence (horizontal lines), and when selected species were harvested (solid vertical lines). Dotted vertical lines separate years.

hispidus). Due to poor performance and dying roots, *Ranunculus* was removed and replaced with *Acorus americanus* during the second year (2020). Additionally, during the last growing season in 2022, we experienced challenges with the invasion of the native plant (*Bidens connata*), which competed with some of our selected plant species on some of the mats.

Over the project duration, 12 mats were purchased from Beemats.com and installed in wetland one. Four mats were added in 2019, two in 2020, four in 2021, and two in 2022. These mats are 1/2 in. in thickness and comprise closed cell, cross-linked polyethylene foam, which helps to make them durable but also lightweight for floating. The plants selected for this project were all emergent plants and were chosen based on the literature, native plant retailers' suggestions, and the principal investigator's knowledge of wetland plant species (Fraser et al. 2004; Jinadasa et al. 2006; Maucieri et al. 2020; XiuLing et al. 2012). Plants were purchased in plugs, approximately 2 in. wide and 5 in. deep, with each plug containing one plant, or in quarts depending on availability. Initially, the plants were purchased from a local native plant producer, but due to low stock, plants purchased later in the project were ordered from Cardno (now known as Stantec Native Plant Nursery) since their selection was much larger, and plants were in stock when needed. Individual plugs ranged in price from $1.30 to $1.50 per plant.

Prior to introducing the plants to the constructed wetland, they were first rinsed to remove any soil from their root systems that would contribute nutrients into the wetlands. Once free of soil, the plants were placed into empty aerator pots. Zip ties were used to secure the plants to each pot so that the plants would not float and drift from their pots. Once the plants were secured in the aerator pots, the pots could then be snapped into place on the floating mat and placed in the wetland.

2.6 | Plant Harvesting and Processing

During the 2019 and 2021 growing seasons, an average of three to five individuals of each species was randomly selected and removed for analysis in early November and early August, respectively. During the 2022 growing season, two to seven plants of each species were harvested in May, August, and September. For each harvest, cups were removed from mats and plants were separated from the soil for analysis. Roots were separated from shoots, and each portion was air dried at room temperature for 2 weeks and then weighed. New plants were added to the vacant areas of the mats where a plant had died or had been removed for analysis, and its date of planting was recorded.

The separated roots and shoots were sent to A&L Great Lakes Laboratories Inc. for analysis of percent total phosphorus (TP). At the A&L lab, plant samples were dried overnight at 100°C–105°C. The dried roots and shoots were separately ground with a Wiley Mill Grinder and sieved through a 20 mesh screen. The plant tissue samples were digested using the Microwave Hot Acid Extraction Procedure (SW846-3051A). Total P was reported as a percentage and converted to grams of TP per gram of plant root or plant shoot. In 2020, root and shoot mass were not separately weighed. This inconsistent processing of data excluded them from our analyses (Figure 3). At the end of each growing season, all plant foliage above the mats was removed using hand shears, dried, weighed, and recycled back onto the field.

2.7 | Statistical Analysis

An analysis of variance (ANOVA) was performed using Jamovi software, version 2.3 (2022) to determine if significant differences existed with plant species biomass, time of harvest, percent P in plant tissue, and the combination of biomass multiplied by %TP (Jamovi 2022). The total number of plants analyzed for each species ranged from 4 to 23, with the 4 being species of *Ranunculus*, which were analyzed in 2019 but then removed from the mats in 2020. All other plants had at least 14 individuals analyzed. If the ANOVA showed significant differences, a Tukey post hoc multiple comparison test was used to identify specific differences among species and time. Where data did not meet the assumptions of normality, we ran a Kolmogorov-Smirnov

(KS) non-parametric test to confirm our conclusions concerning significance.

2.8 | Collection and Analysis of Water Samples

Drainage water control structures were installed between the field and wetland one (TT1), between wetland one and wetland two (TT2), and between wetland two and the River Raisin (TT3) (Figure 4). A one-way flap gate was installed at the outlet to the river to prevent backflow from the river into the constructed wetland. Drainage water control structures were installed to manage the flow of water passing through the system. A shed was placed around each of the water control structures to protect them and to house additional equipment. Discharge volume was determined at TT1, TT2, and TT3 by measuring water depth using 0 to 2-m submersible pressure sensors (Microsensor MPM4893W) installed on the upstream side of a 45-degree V-notch weir stoplog installed within a drainage control structure. Submersible pressure sensors were also installed in the tailwater section of each weir to monitor for submerged flow conditions. Cameras were installed to remotely monitor the condition in each wetland. All equipment, such as autosamplers, transducers, and cameras, were powered using batteries paired with solar panels.

A flow-paced water sampler (WRMG LLC Custom Prototype) was installed inside a propane heated compartment inside each of the three sheds, which allowed for year-long sample collection. The samplers collected water from the top side of the water control structure and, using a peristaltic pump, pumped the sample into a 5-gal bucket inside the heated compartment. Inside each heated compartment, an ultrasonic sensor (SSI Technologies FT-AN2) was installed to monitor the water level in each sample bucket. The sampling frequency was flow-paced. Each time a sample collection was triggered, a 250 mL sample was collected. Individual samples were combined in the bucket to form one weekly composite sample for each drainage control structure. Buckets were lined with disposable waterproof bags that were replaced after each sample collection to prevent cross contamination between samples. A 1-l subsample of each composite sample was collected once per week, on average, starting in January 2020. To ensure sample preservation, samples were filtered using a 0.45 μm nylon membrane filter, stored in a refrigerator at 4°C, and analyzed within 72 h of collection. Additionally, Thermo Fisher standards (reference #984729) were used to complete all calibrations, while Hach standards (reference #256949) were used during sample analysis. Lastly, laboratory blanks consisting of de-ionized water and sample duplicates were used to measure instrument precision, accuracy, and sample consistency. Analysis of TP and SRP was done using EPA standard method 365.3 (Environmental Protection Agency 1978) (where all reagents and chemicals used for this study can be found) and a Gallery Discrete Analyzer by Thermo Fisher Scientific.



FIGURE 4 | Aerial view of drainage control structures (TT1, TT2, and TT3).

3 | Results and Discussion

3.1 | Plant Biomass

The average dry weight mass for roots and shoots was determined for all harvested plants in 2019, 2021, and 2022. An ANOVA test showed a significant difference in root dry mass among species, with Tukey's post hoc test indicating that *Scirpus* root mass averaged across all years was greater (22.5 g) and significantly different ($p < 0.001$) from the other plants, except for *Acorus* ($p > 0.1$) (Figure 5). There were no significant differences in root mass among the other plants. Shoot dry mass differed ($p < 0.001$) among species using ANOVA. Tukey's post hoc test showed that the average *Scirpus* shoot dry mass (17.1 g) was higher and significantly different from the other four species ($p < 0.005$). There were no significant differences in shoot dry mass among the other four plants (Figure 5).

Scirpus also had the greatest root dry mass in all but 1 year compared to the other species, ranging from an average of 13.4 g in May 2022 to 63.2 g in August 2021. The greatest average shoot dry mass for *Scirpus* occurred in August 2021 at 41 g. Only in September 2022, when an unexpected species, *Bidens*, colonized the mats, did *Acorus* have a slightly higher but not significant dry mass than *Scirpus* for roots and shoots (Figure 6).

3.2 | Comparison of Percent TP Between Initial and Post-Plant Harvests

After arriving from the plant nursery, subsamples of each plant species were taken back to the lab to determine an initial total phosphorus (TP) concentration. For all batches of plants, the concentration, reported as percent TP, was relatively high compared with plants that were grown in the wetland and later removed for analysis. This difference may have been due to the high amount of fertilizer used to initially grow the plants in greenhouse conditions. Additionally, Keizer-Vlek et al. (2014) found less TP at the end of their experiments in both roots and shoots compared with the beginning. The %TP in the roots of *Acorus* (0.65%) prior to planting in the wetland was significantly higher ($p < 0.001$) than the other species of *Carex* (0.21%), *Scirpus* (0.22%), and *Juncus* (0.26%) using an ANOVA followed by Tukey's post hoc multiple comparison test. There was no significant difference ($p \geq 0.05$) in %TP among the three other plants. For %TP in the shoots, *Acorus* (0.48%) was significantly

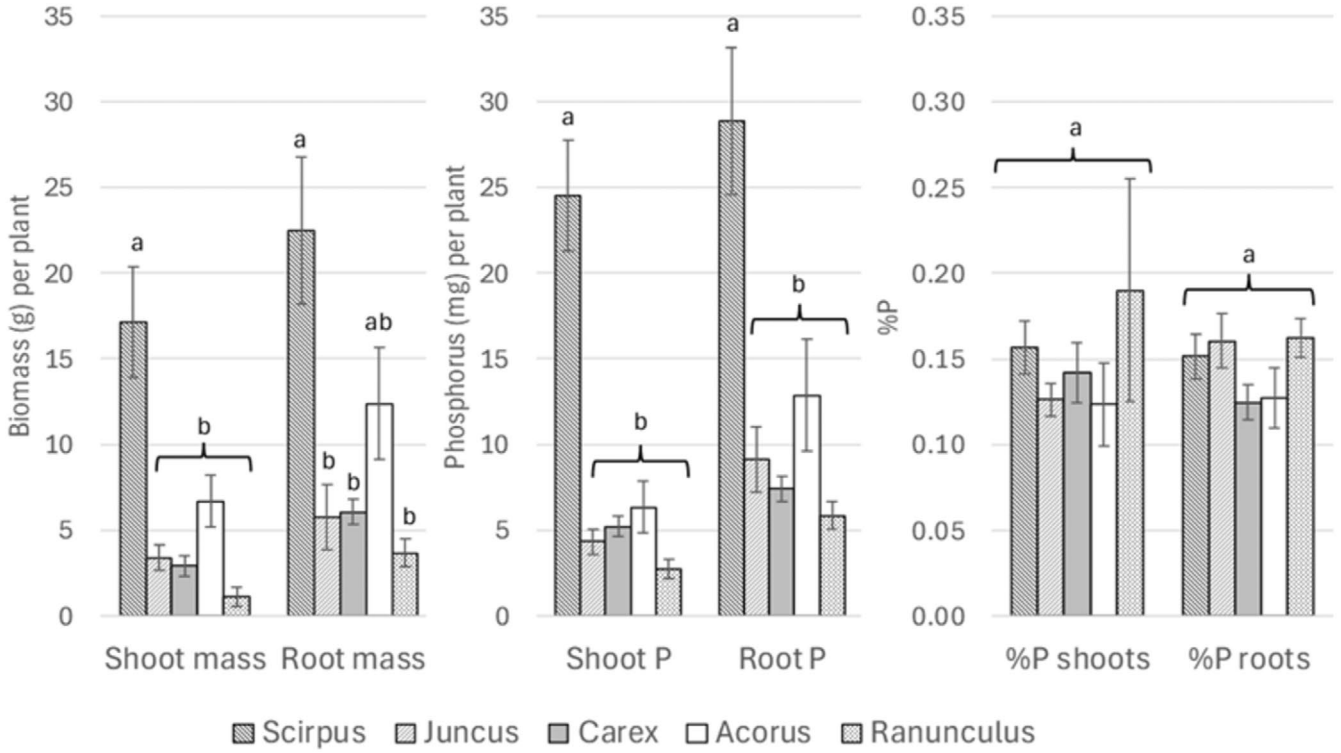


FIGURE 5 | Average shoot and root mass, shoot and root P, and %P in shoots and roots for each species from 2019 to 2022. Different letters (for each parameter) indicate significance at $p < 0.005$ for shoots and $p < 0.001$ for roots compared to other plants. *Acorus* root mass was not significant with any of the other plants. There were no significant differences observed for %P in shoots or roots. Values are presented as mean and standard error of the mean.

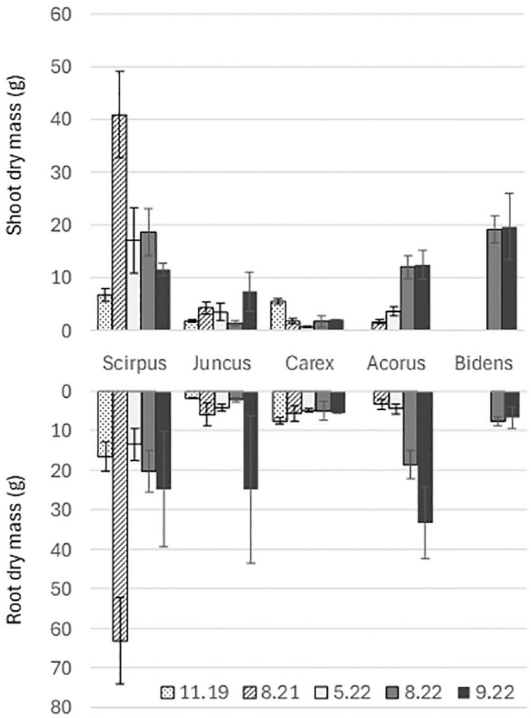


FIGURE 6 | Average shoot and root dry mass of plants based on harvest date (month/year). The unintended species, *Bidens*, colonized some of the mats during the summer of 2022. Error bars represent standard error.

higher ($p = 0.027$) than *Juncus* (0.35%), but not from the other plants. None of the other plants showed any significant differences at $p < 0.05$ in shoot %TP.

By the end of the first growing season, the %TP in the plant roots and shoots was not significantly different ($p \geq 0.05$) between or among species (Figure 5). In consequent seasons, no significant differences ($p > 0.1$) were found in the average %TP across all species in either the roots or the shoots for the species planted on the mats until an unintended species invaded the wetland mats.

There were, however, significant differences in the %TP present in the plant based on when it was harvested. The highest average %TP in the roots across all species occurred in late May 2022 (0.21%), followed by September 2022 (0.15%). The least %TP in plant roots occurred in August in both 2021 and 2022. May was the only month in which the %TP was significantly higher than that of the other months ($p < 0.001$) (Figure 7).

The highest average %TP in shoots across all species occurred in mid-November 2019 (0.19%) and late May 2022 (0.196%). These harvest dates were significantly different from August and September harvests ($p < 0.001$). Wang et al. (2015) suggested that shoots be harvested in either June for maximum P removal or in September to prevent P release due to senescing plants. Although we harvested all the shoots from the mats in mid-fall and prior to plant senescence, an additional harvest in late May could have increased overall P removal.

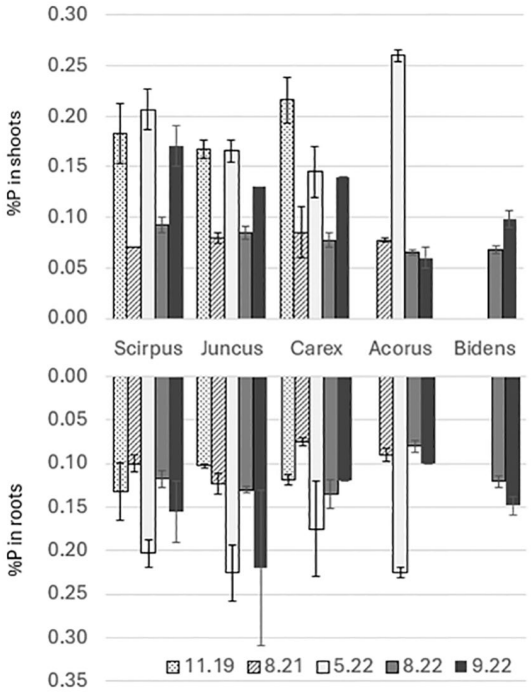


FIGURE 7 | Average %P in shoots and roots in each species at different harvest dates (month/year). The unintended species, *Bidens*, colonized some of the mats during the summer of 2022. Error bars represent standard error.

3.3 | Total Phosphorus in Roots and Shoots

To obtain the total P used by the plant as well as the amount currently in the tissues, root and shoot mass were each multiplied by the %TP (g of TP/100 g of plant). The total average across all years for both roots and shoots showed that *Scirpus* had a higher average total P mass (28 mg for roots, 24 mg for shoots) and was significantly different ($p < 0.01$) from the other plants (Figure 5). For individual harvest dates, of all the plants, *Scirpus* had the highest average P in roots in August 2021 (64 mg) and the highest average P in shoots (38 mg) in late May followed by August 2021 (28 mg).

The combination of highest biomass and highest %TP in the plant should determine when the harvesting of plants will provide maximum P removal for the system. With these data, no significant difference ($p > 0.05$) was seen in harvest date for total shoot P mass. In addition, the average %TP across all years was not significant among the four species. Therefore, maximum dry mass of the shoots could be used to determine when harvest should occur to provide maximum P removal from the system. This would not be the case for harvesting of roots, since the September harvest root P mass was significantly different ($p < 0.016$) from the other harvest dates except for August 2021 versus September 2022. However, harvesting the roots would not be economically advantageous since new plants would then need to be planted each year.

3.4 | Impact From Volunteer Native Species

Two conditions at the wetland differed in 2022 compared with previous years of the study. The overall precipitation and flow into the wetlands were greatly reduced, and a volunteer species, *Bidens*, became established on the floating mats. During the 2022 growing season, the native species, *Bidens connata*, invaded and colonized the mats and began growing in the aerator pots along with the planted species, although *Bidens* was not seen in May 2022. In some instances, *Bidens* crowded out the targeted species, particularly *Juncus* and *Carex*. While only one research plant was present in each cup, *Bidens* had as many as five plants within a cup. Its dry mass per cup was greater than that of the other plants and significantly different from that of the other species ($p < 0.005$), except for *Scirpus* (Figure 7).

In August and September of 2022, the average %TP in the roots was significantly different between *Acorus* and *Juncus* ($p = 0.001$) when *Bidens* was present but not between the other species or between the other species and *Bidens*. In other years where no *Bidens* was present, there was no significant difference among any of the species in %TP in roots. In %TP in shoots, *Acorus* was significantly different from all other species ($p < 0.05$) except Bidens; in other years there were no significant differences between Acorus and the other plants; however, there was a significant difference between *Bidens* shoot %TP and *Scirpus* ($p < 0.001$) in 2022 (Figure 7).

3.5 | Performance of Two-Stage Wetland in Reducing Phosphorus

3.5.1 | Annual Subsurface Drainage to Wetland One

A summary of the total inflow of subsurface drainage to wetland one across each year can be seen in Table 1. Drainage varied over the years, as it was highly dependent upon variables such as precipitation, water table levels, and soil moisture. While 2020 demonstrated near-average precipitation, high water table conditions were created as a result of above-average precipitation in multiple years prior. Additionally, periods of extreme wetness were seen in January and May of 2020, leading to flooding within southeastern Michigan during these time periods. In total, 13.1 million liters of subsurface drainage entered pond one from January 9th to December 30th, with 8.2 million liters (63% of the total annual flow) entering pond one during the spring thaw months.

In 2021, there was a major decrease in subsurface drainage to wetland one. Drought conditions were observed in the winter and worsened in the spring; but eventually gave way to unusually wet conditions in the summer and fall in southeastern Michigan. This led to very low flow volumes and even dry conditions during the typical spring thaw months (March–June), where subsurface flow would have been expected to be higher. In total, 8.6 million liters of subsurface drainage entered pond one from January 1st to December 30th, with only 1.2 million liters (14% of the total annual flow) entering pond one during the spring thaw months.

In 2022, southeastern Michigan recorded one of its hottest and driest summers on record, leading to low water table conditions and nearly a 3-month (July 25th to October 18th) period of the tile outlet draining to wetland one being completely dry. In total, 4.2 million liters entered pond one from January 6th to October 18th (project end date), with 3.1 million of those liters (76% of the total annual flow) occurring during the spring thaw months.

3.5.2 | Phosphorus Entering and Leaving the Two-Stage Treatment System

In 2020, analysis of weekly flow-paced composite samples for SRP and TP occurred from January 9th to December 30th; however, samples could only be collected from the TT1 and TT2 outlets. Therefore, only information regarding the performance of the first treatment pond (containing the floating mats) could be analyzed during this year. Samples could not be obtained from the TT3 outlet due to clogging caused by the initial treatment media utilized in pond two. Originally, a combination of sand and limestone was implemented, but was later dug out and replaced with pea stone to prevent future clogging issues in year two of the project. For this reason, the total nutrients exiting the TT3 outlet, along with the corresponding percent reductions, are unknown. It was determined that a combination of sedimentation and P uptake from the plants in pond one, however, led to a 66% and 55% reduction of TP and SRP, respectively (Table 2).

In 2021, drought conditions present throughout much of the year limited opportunities to collect weekly composite samples for SRP and TP analysis. For this reason, flow-paced composite samples could only be collected from July through December. Results from this time frame indicated that the pea stone substrate played a key role in increasing the P retention of the system, as the largest P reductions were not seen from TT1 to TT2 (pond 1 with floating mats), but from TT2 to TT3 (pond 2 with pea stone). Upon leaving the second treatment pond, the pea stone substrate contributed to an additional 28% decrease of TP and an additional 48% decrease of SRP, compared to 16% and 24% reductions of TP and SRP after leaving pond one (Table 2). Therefore, it is worth noting that the pea stone substrate played a major role in the P retention of the system. The total reduction of SRP and TP from the system as a whole (TT1 to TT3) was 61% and 41%, respectively.

In 2022, water analysis was conducted from January to July 25th. Due to dry conditions, samples could not be collected past this date; however, results from the January to July timeframe

TABLE 1 | Total subsurface drainage (or inflow) received by wetland one.

Year	Data collection period	Total inflow to wetland one (liters)	Total inflow (liters) during spring thaw (Mar–Jun)	Total precipitation (mm)
2020	January 9 to December 30	13.1 million	8.2 million	614.7
2021	January 1 to December 30	8.6 million	1.2 million	505.4
2022	January 6 to October 18	4.2 million	3.1 million	403.8

TABLE 2 | Percent reductions and nutrient loading (g and g/m^2) entering pond 1 (TT1), exiting pond 1 (TT2), and exiting pond 2 (TT3). Clogging within the filter substrate in pond two prevented data collection from TT3 in 2020 (see narrative for further information).

Year	Analyte	*N*	TT1—Nutrients entering Wetland 1	TT2—Nutrients exiting Wetland 1	TT3—Nutrients exiting Wetland 2	Percent reduction (%) from TT1 to TT2	Percent reduction (%) from TT2 to TT3	Percent reduction (%) from TT1 to TT3
2020	TP	26	3020 (g) 14.1 (g/m^2)	1020 (g) 4.76 (g/m^2)	Could not be measured	66	N/A	N/A
	SRP	27	1067 (g) 4.98 (g/m^2)	478 (g) 2.23 (g/m^2)	Could not be measured	55	N/A	N/A
2021	TP	20	1297 (g) 6.06 (g/m^2)	1084 (g) 5.06 (g/m^2)	771 (g) 3.60 (g/m^2)	16	28	41
	SRP	20	1157 (g) 5.41 (g/m^2)	875 (g) 4.08 (g/m^2)	456 (g) 2.13 (g/m^2)	24	48	61
2022	TP	25	132.9 (g) 0.62 (g/m^2)	308.4 (g) 1.44 (g/m^2)	91.2 (g) 0.43 (g/m^2)	−132	71	31
	SRP	25	65.7 (g) 0.31 (g/m^2)	146.5 (g) 0.68 (g/m^2)	20.4 (g) 0.10 (g/m^2)	−119	86	69

indicated that pond one may have reached a point of saturation, as TP increased by 132% and SRP by 119% (Table 2). Another explanation could be related to evaporation in the first pond further concentrating the nutrients present before the next storm event could move additional water through the system. Varying temperature and precipitation can significantly change evaporation rates from year to year; however, evaporation rates were not calculated for this study. Therefore, this study cannot explain how seasonal or weather variation impacted phosphorus concentrations within the ponds, but can highlight the added value of having a pea stone substrate present for additional P retention. Despite the increases observed in pond one, an overall reduction in P was still seen upon leaving TT3. Total phosphorus was reduced by 71% after leaving the second pond with the pea stone substrate, and SRP was reduced by 86%. Overall reductions (TT1 to TT3) equated to a 31% decrease of TP and a 69% decrease of SRP.

3.5.3 | Phosphorus Concentration Results

As recommended by the US Environmental Protection Agency (US EPA) to control eutrophication, TP in streams that enter lakes should remain at or below 0.05 mg/L, while TP in flowing waters should remain at or below 0.1 mg/L (Litke 1999). There are no official guidelines for phosphorus concentrations in subsurface drainage; therefore, the EPA recommendations mentioned previously were used to determine if the average concentrations leaving the wetland system were contributing to further eutrophication in this region. As shown in Table 3, the average concentration (across all 3 years) of TP leaving TT1 during the non-growing season (NGS) and growing season (GS) was 0.111 mg/L and 0.168 mg/L, respectively; however, these concentrations were reduced to 0.025 mg/L and 0.068 mg/L upon exiting TT3. These results suggest that this system may have benefited from additional pea stone substrate in the second wetland to further reduce total phosphates during the growing season to keep concentrations below both the 0.1 mg/L and 0.05 mg/L recommendations. Further research is needed to determine the optimal substrate to wetland ratio.

3.5.4 | Seasonal Variability

While it is known that variables such as rainfall, water temperature, and air temperature can influence the P retention of floating wetland systems, it was not the intention of this study to examine these seasonal variabilities closely. Daily rainfall and air temperature were monitored using a nearby weather station; however, this data was not used to conclude the impact these variables may have had on P retention. Additionally, water temperature was not collected on a regular basis. During summer visits when it was measured, temperatures were similar from the water surface to the bottom, indicating that no stratification was occurring. Also, it has been found that the presence of vegetation can result in more stable water temperatures (Hill and Payton 2000), and with Michigan having a mild summer climate, we did not anticipate water temperature to have a significant impact on the system overall.

As this study was an on-farm trial, our focus remained on the performance of the selected plants and the P removal of the system, despite the variability of the changing seasons, as these variables could not be controlled by farmers in real-life scenarios. While this limits our understanding of when this system may have been at its peak or worst performance, it does not negate what was learned about its ability to retain P on an annual basis over the time period of this study.

TABLE 3 | Comparison of average phosphorus concentrations at each treatment stage during the growing season (GS) and non-growing season (NGS).

Average concentrations (mg/L) from January 2020 to July 2022		Avg. conc. across all years during NGS months[b]	Avg. conc. across all years during GS months[c]
TT1	SRP avg. conc. (mg/L) and SEM[a]	0.024 ± 0.013 (n = 21)	0.087 ± 0.027 (n = 51)
	TP avg. conc. (mg/L) and SEM	0.111 ± 0.056 (n = 21)	0.168 ± 0.046 (n = 50)
TT2	SRP avg. conc. (mg/L) and SEM	0.031 ± 0.016 (n = 21)	0.055 ± 0.014 (n = 50)
	TP avg. conc. (mg/L) and SEM	0.056 ± 0.014 (n = 20)	0.114 ± 0.020 (n = 50)
TT3	SRP avg. conc. (mg/L) and SEM	0.012 ± 0.004 (n = 21)	0.029 ± 0.011 (n = 31)
	TP avg. conc. (mg/L) and SEM	0.025 ± 0.006 (n = 14)	0.068 ± 0.016 (n = 27)

[a]Standard error of the mean (SEM).
[b]Non-growing season (NGS) is defined as mid-November to mid-March.
[c]Growing season (GS) is defined as mid-March to mid-November.

3.6 | Recycling Plant Material to Reduce Phosphorus Release Over Winter

To avoid the potential for P release from plants after the growing season (mid-March to mid-November) ended, the shoots of the plants growing on the mats were harvested from the mats. This process assists in removing P from the wetland and prevents any P release from plants during winter senescence or during winterkill (Dekle et al. 2024). After harvest, plants were bagged, dried, and weighed. Plant shoot dry mass was greatest in 2022, the last year plants were harvested. While there were more overall mats than originally added to the wetland, the average plant mass per mat in 2022 was greater than in the two previous growing seasons. Mats with *Scirpus* as the dominant plant generally had higher plant mass than those mats with other plant combinations. Following the analysis, plants were then spread on the nearby farmland to recycle the nutrients taken up during the growing season. The overall process is intended to reduce nutrient release within the wetland and likely extend the length of time that the wetland can continue to remove nutrients from the incoming tile drainage and avoid nutrient saturation in the wetland. Richardson (1985) noted that unless biomass was harvested, wetlands would only be short-term sinks for P. A direct correlation was found between harvest frequency and P removal (Reed et al. 1995).

3.7 | Plant Ability for Phosphorus Removal Through Uptake and Harvesting

When comparing similar dates of harvest within and across years, the %TP in roots or shoots did not differ significantly among or between species except when *Bidens* was present. The average total P in plant roots and shoots was usually highest in May, when highest flow volumes occurred; however, there was no significant difference among the plants for all years combined. The root and shoot biomass of plants did differ; therefore, the differences in any of the plants' ability to remove P from agricultural drainage water were a function of the plants' accumulated biomass. Jiang et al. (2011) reported that plants with high biomass could uptake and store more nutrients in their tissue and suggested that selection of plant species for constructed wetlands should be based on plant biomass but also on root surface area; however, in this study, root surface area was not determined.

Scirpus had a higher average biomass during all harvests except for September 2022 when *Acorus*' dry root mass slightly surpassed *Scirpus'* dry root mass. However, there was not a significant difference between the two. This change may have been due to the unintended colonization of *Bidens* and its ability to compete with or outcompete the planted species, although no significant difference between these two species was found. It might also be due to the small sample size harvested in September. Only two plants of each species were harvested as opposed to the typical 4–5 plants per species at other times. In this study, the best harvest date to obtain maximum P removal from the agricultural drainage occurred when the plant reached its maximum biomass. For these plants, that time was late August or late September. Verhofstad et al. (2017) suggested that harvesting more than once per season may increase the overall nutrient removal from the system; but Kim and Geary (2001) found that less than 10% of TP was stored in plants in bucket experiments and that harvesting just the above-ground biomass would account for less than 5% of the TP within the system. Keizer-Vlek et al. (2014) indicated that whole-plant harvest was not needed in their study on *Iris* sp. and *Typha* sp. for removal of P since total P uptake by the roots was negative. Although that was not the case in this study, root harvest would result in a need to replant the following season and would not be a recommended option for a long-term wetland treatment system.

3.8 | Factors Affecting Growth and Biomass

One factor affecting shoot biomass was plant height and growth characteristics. The ability of *Scirpus* and *Carex* to grow taller and shade out *Ranunculus* was likely one of the factors that resulted in *Ranunculus*' poor growth and ultimate death. Another factor potentially affecting growth was the position of plants on the mat and the position of the mat in the wetland. Although the mats were tied to the outlet structure in the middle of the wetland, the wetland itself was not that large, and strong winds resulted in the mats drifting toward the edge. Plants growing along the outer edge of the mats were more prone to float closer to shore, and during drought conditions, they were sometimes deprived of sufficient water, which, in some instances, resulted in decreased growth or death.

The total P coming into the first wetland from the tile drain during the growing season averaged 0.168 mg/L. Based on these concentrations, it is unlikely that the plants were limited in their growth by TP even when other species infiltrated and grew in the wetland (Daniel et al. 1994; Correll 1998; Chambers et al. 2008). These concentrations are indicative of a eutrophic system (Wetzel 2001), however, no experiments were done to determine if the plants were limited by TP.

Volunteer growing vegetation included the filamentous green algae (*Cladophora* and *Spirogyra*) and a macrophytic algae (*Chara*). The filamentous algae formed floating masses throughout the wetland's surface and were prevalent from early spring through summer. *Chara* grew mainly in summer, attached to sediment that had accumulated in the wetland. Samples were taken, dried, and sent to the lab for analysis. Similar to the larger vascular plants, the %TP in the filamentous algae was measured at 0.1% and for *Chara*, 0.09%. Since these algae were left in the wetland and not harvested, any nutrients taken up were eventually returned to the system when the algae died. However, the addition of colonizing plants to a wetland could enhance P uptake and removal if those plants were also harvested during or at the end of the growing season.

3.9 | Estimated Accumulation of TP in Plants and %P Removal From the Wetland

Based on the total number of plants that were added to the 12 mats overall, the average TP mass in the shoots of each plant and a total mat area of 37.15 m^2, an estimate of the grams of TP that had been taken up by all plant shoots over a growing season was calculated at approximately 12.7 g or 0.34 g/m^2. For the roots, 16.74 g or 0.45 g/m^2 of total P could be taken up. However, only the shoots were harvested at the end of the season, while the roots remained in the wetland throughout the study.

The plant with the greatest biomass was *Scirpus*. If it had been planted in all aerator pots on all 12 mats, the total P removal from the harvested shoots in one growing season would have averaged 24.4 g or 0.66 g dry wt/m^2, nearly twice as much as the amount removed using multiple species. Harvesting the roots would not be recommended since replanting the following season would be required.

For 2021 and 2022, where both flow data and plant data were available for the entire growing season, the total mass of phosphorus estimated to be in the shoot tissues was 10.3 g and 12.7 g, respectively (Table 4). This increase in phosphorus mass in 2022 was attributed to an increase in wetland mat area, as two wetland mats were added that spring. While the total mass of P removed by the shoots was similar in both years, the influent phosphorus loading in 2022 was much lower than in 2021 (Table 2). Therefore, the estimated %P removed from wetland one by the floating plants was between 0.89% and 19.3% based on 1157 g of SRP entering the wetland in 2021 and 65.7 g entering in 2022, respectively (Tables 2 and 4). SRP was used since it is the portion of TP biologically available to plants.

The difference in the %P removed from the system was dependent on the P load, which considers both concentration and flow.

TABLE 4 | Estimated total P that plants could remove from wetland one in 2021 vs. 2022 based on SRP entering the system.

	Scirpus		*Juncus*		*Carex*		*Acorus*		Totals	
	2021	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**
Number of plants on all mats	325	366	151	170	112	128	157	174	745	838
Average total P shoot mass removal (g)	9.3	10.25	0.6	0.85	0.22	0.19	0.16	1.4	**10.3 (ns)**	**12.7**
Average total P root mass removal (g)	20.8	9.52	0.6	2	0.11	0.82	0.2	2.2	**21.7 (ns)**	**14.5**
Average total P removal (g)	30.1	19.76	1.2	2.9	0.34	1	0.36	3.6	**32 (ns)**	**27.2**
SRP load entering TT1 (g)									**1157 ($p < 0.01$)**	**65.7**
Estimated P removed from wetland by floating plants (%)									**0.89 ($p < 0.01$)**	**19.3**
Average shoot total P (g/m^2/growing season)									**0.35**[a]	**0.34**[b]

[a]Size based on 10 mats (29.72 m^2).
[b]Size based on 12 mats (37.15 m^2).

When loading was high (2021), plants accounted for a lower percent of SRP removed from the wetland compared to 2022 when the load was much lower. However, when normalized to wetland mat area, the average phosphorus in the shoots was similar in both years at approximately 0.35 g/m^2 (Table 4), despite the difference in influent TP loading, influent flows, and total mat area.

In general, the %P removal attributed to the harvest of shoot biomass in this study was consistent with previous studies which show variable removal of TP by shoot biomass. Kim and Geary (2001) determined that less than 5% of total P in a wetland system was removed by harvesting shoot plant biomass. Similarly, Tanner and Headley (2011) found that only a small fraction of total P was removed through P uptake by plants, and that this method would not be the dominant mechanism for P removed from the wetland. We observed a similar performance in 2021, which was a wet year resulting in a high P load to the wetland. However, in another study, Li et al. (2015) estimated that plants could remove 25% to 33% of P through assimilation. This observation was more consistent with the wetland performance during the 2022 dry year where low TP loading occurred.

In the wet year 2021 where %P removal was less than 1%, the TP and SRP percent reductions after exiting the first wetland were 16% and 24%, respectively (Table 2). Thus, other factors played a role in P removal and/or sequestration, including the sediment, algae, and other plants that colonized the wetland. Although this study did not monitor TP accumulation in the sediment or within the floc trapped around the plant roots, other studies have reported that biofilm formation within the root zone to trap particles and soil accretion may also influence removal of P (Skinner 2022; Shen et al. 2022).

The floating plant mats can also provide other benefits in addition to the P they remove. Unlike the plants growing and rooted in a wetland substrate, the floating plants can be easier to remove at the end of the season. This harvest decreases P in the wetland and may increase the wetland's longevity for holding P. The unharvested roots remain intact in the wetland and provide substrate for microbial processes and habitat for aquatic life.

4 | Conclusion

This study investigated the effectiveness of a two-stage treatment wetland consisting of floating mats populated with northern native plant species in pond one and a pea stone filter media in pond two. The results of this study were beneficial in understanding how these systems will perform under real-world and varying conditions. Of the native, northern plant taxa selected, *Scirpus* had the highest dry mass and average TP shoot mass and was significantly greater than the other species examined.

Overall, the percentage TP removal attributed to the harvest of shoot biomass in this study was consistent with previous studies which show variable removal of TP by shoot biomass. Total P removal by plant shoots ranged between 0.89% and 19.3% of the SRP entering the wetland, depending on the year. Therefore, *Scirpus atrovirens* would be an ideal plant species to utilize in future treatment systems residing in northern climates.

Over the 3-year period, the average annual SRP and TP reductions from discharge entering and exiting the system equated to 65% and 36%, respectively. Additionally, the average SRP concentration across all 3 years during the growing season was reduced from 0.087 mg/L to 0.029 mg/L and TP was reduced from 0.168 mg/L to 0.068 mg/L, keeping both SRP and TP effluent concentrations below maximum concentrations recommended for flowing waters to minimize eutrophication and harmful algal blooms.

Further, the wetlands consistently reduced SRP and TP in all 3 years, despite an increase in SRP and TP within the first pond in 2022. It is possible that the first pond reached a point of saturation in year three of the study; however, further exploration would be needed to confirm that this was the cause of the

increase. This drew attention to the importance of the pea stone filter media used in the second pond, which played a critical role in reducing TP and SRP to maintain an overall reduction across both treatment ponds each year.

In summary, a two-stage constructed floating wetland with a 0.7% size ratio of wetland to drainage area, containing a combination of *Scirpus atrovirens* and a pea stone filter media, can be expected to provide up to 65% and 36% reductions of SRP and TP, respectively. Plant shoots should be harvested annually and recycled onto the field, while roots should remain in place to avoid re-planting the following year.

Finally, in the context of increasing BMP adoption within the WLEB, offering low-maintenance options for permanent or semi-permanent practices will be vital to helping meet phosphorus reduction goals. Floating treatment wetlands, or a hybrid system as described in this study, would not require expensive equipment upgrades, would have limited to no impact on potential opportunity costs, and would not require further maintenance once installed (unless the farmer chooses to harvest and recycle the plants each season). Additional research, however, would be beneficial regarding optimal sizing and the length of time these types of wetlands will remain effective at removing phosphorus, as well as a cost–benefit analysis that explores the potential increased reductions of P relative to added pea stone substrate.

Author Contributions

Alaina Nunn: writing – original draft, writing – review and editing, formal analysis, supervision, data curation, project administration, investigation, validation, visualization, methodology. **Lois Wolfson:** writing – review and editing, data curation, formal analysis, methodology, software, investigation, visualization, writing – original draft, supervision, conceptualization, project administration, resources. **Dawn Dechand:** conceptualization, methodology, writing – review and editing, formal analysis, data curation, software, writing – original draft, supervision, project administration, investigation, resources, visualization. **Cole Kelley:** writing – review and editing, writing – original draft. **Quinton Merrill:** writing – review and editing, writing – original draft. **John Day:** writing – review and editing, writing – original draft. **Kasey A. Matusik:** writing – review and editing, writing – original draft. **Jeremiah Asher:** funding acquisition, methodology, conceptualization, writing – review and editing, project administration, supervision, resources.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data that supports the results and analysis of this work is not publicly available; however, it may be accessed upon request from the submitting author, Alaina Nunn, who can be contacted at nunnalai@msu.edu.

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