Phosphorus uptake in emergent macrophytes: An evaluation of Vermont-native wetland plant suitability for floating treatment wetland applications in urban stormwater settings

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Phosphorus uptake in emergent macrophytes: An evaluation of Vermont-native wetland plant suitability for floating treatment wetland applications in urban stormwater settings

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Abstract

The USEPA’s revised total maximum daily load (TMDL) for Lake Champlain has Vermont scientists and legislators seeking effective means for curbing phosphorus loads in the Lake Champlain Basin. Developed lands are a critical nonpoint source for phosphorus loading, and green stormwater infrastructure (GSI) ecologically and effectively slow and/or capture nutrients and other pollutants characteristic of urban stormwater runoff. Floating treatment wetlands (FTWs), buoyant mats fitted with wetland plants, are an inexpensive and effective option for improving the water quality of runoff. In urban settings, FTWs are frequently applied to wet stormwater ponds as retrofits. While there are studies demonstrating the efficacy of this practice worldwide, there is currently no research on FTW performance for Vermont’s climate. The goal of this experiment is to evaluate some commonly used and untested plant species for phosphorus removal. A greenhouse microcosm study was performed using twelve Vermont-native emergent wetland plant species. The plants were grown hydroponically in simulated floating treatment wetlands for a period of twelve weeks. Species tested included common genera for this application, among other less commonly used macrophytes: Carex, Schoenoplectus, Pontederia, Sparganium, Scirpus, Sagittaria, Iris, Asclepias, Symphyotrichum, Lobelia, and Zizania. Plants were grown in high (control) and low (simulated stormwater) nutrient solutions of tap water and diluted 7-9-5 NPK fertilizer. After harvest, plants analyzed for total phosphorus concentration of whole-plant biomass using ICP-AES. In low nutrient conditions, Sparganium, Scirpus, Carex comosa, Asclepias, Schoenoplectus, and Pontederia, respectively, accumulated the most phosphorus in their tissues. The results of nutrient uptake analysis, when considered with qualitative root and shoot growth habit in this setting, will inform plant selection for a FTW to be launched in South Burlington, Vermont in May 2016.
Chapter 1. Introduction

Lake Champlain is one of Vermont’s most valuable natural resources. The Lake Champlain Basin is currently imperiled by excessive loading of phosphorus, nitrogen, and other pollutants, which are transported by stormwater runoff. While this is a topic of concern at interstate and international scales, practical solutions can and must be performed at the local watershed level in order to effectively curb pollutant loading into this water body.

Many residential, municipal, and commercial sites within Vermont’s portion of the Lake Champlain Basin combat the issue of stormwater runoff with EPA designated “Best Management Practices” (BMPs), such as retention (wet) ponds and constructed wetlands. However, the efficacy these practices have limitations for removing certain pollutants, such as total dissolved phosphorus (TDP), and have room for improvement (Brustlin et al., 2011). The floating restorer, a concept developed by Dr. John Todd in the 1970s, has become the object of recent innovation in bioremediation and ecologically-informed design, known formally in the literature as the “floating treatment wetland” (FTW). It has been demonstrated that the addition of FTWs to retention ponds can improve the quality of effluent exiting pond and entering the watershed (Borne, 2014; Headley & Tanner, 2008; Ladislas et al., 2013; Tanner & Headley, 2011; Wang & Sample, 2014).

Practically and scientifically conducted applications of FTWs have shown elevated removal rates for nitrogen, phosphorus, heavy metals, suspended solids, and other pollutants in wastewater and stormwater settings. However, many of these applications have utilized non-native plant species and/or been established in southern climates, where longer growing seasons and more regional plant biodiversity are of greater advantage when compared to New England. There have been little to no known applications of the FTW technology in northeastern climates like that of Vermont. In the literature, the northernmost applications have been in Montana and Pennsylvania (Floating Island International, 2011); both states have very different climates and native wetland plant species than New England.

To address this gap in the literature, a greenhouse microcosm study employing twelve different emergent wetland macrophytes native to Vermont will be conducted. By performing a scientifically rigorous study that utilizes native Vermont species in a simulated floating treatment
wetland, practical insights, applicability, and logistics of plant species selection for FTW use in northeastern climates can be better understood.

The goal of the experiment is to determine which of twelve species accumulate the most phosphorus in their tissues, while evaluating and considering root mass, fibrosity, and surface area for the development of microbial biofilm. Species tested include plants in genera *Symphyotrichum, Asclepias, Pontederia, Schoenoplectus, Iris, Scirpus, Carex, Sagittaria, Lobelia, Zizania, and Sparganium*, many of which have been applied in the literature on floating treatment wetlands. All but *Zizania* are perennial. Each of the tested species will be grown in experimentally established “high” and “low” nutrient conditions, where the “high” condition operated as a control, and the “low” condition simulated nutrient levels characteristic of nutrient-poor urban stormwater runoff. Inductively coupled plasma atomic emissions spectroscopy (ICP-AES) will be used to determine total phosphorus concentration (mg/kg) and accumulation (g) in each specimen. Qualitative observations, measurements, and ICP-AES results will inform which species would best perform and thrive in the low nutrient conditions characteristic of urban stormwater ponds.
Chapter 2. Literature Review

Human development is responsible for many of the environmental issues we face today. Developed and densely populated municipalities are covered with high proportions of impervious surfaces, such as concrete and asphalt. When it precipitates, these surfaces contribute to the deposition of polluted stormwater runoff into the watershed.

Stormwater runoff is the movement of precipitation over surfaces, and is accelerated by the impervious surfaces characteristic of developed lands, such as driveways, roofs, sidewalks, and roadways, which prevent the water from seeping into the ground (EPA, 2003). In urban settings, runoff often carries many different types of pollutants, which can range from debris and sediments to pathogens and hazardous chemicals (EPA, 2003). Even elevated temperatures of stormwater are considered to be a “pollutant” in the context of runoff inputs into cold, freshwater streams, where species like trout are highly sensitive to temperature fluxes (Hester & Bauman, 2012). The weather-dependent flux of polluted waters deposited by runoff in streams, lakes, ponds, wetlands, and other management infrastructure can have significant implications for water quality, the surrounding ecosystems, and the health of the watershed.

*Pollutants and Water Quality*

Pollutants carried by stormwater runoff, if discharged directly into surface waters, degrade water quality and put freshwater sources for both humans and entire ecosystems at risk. For example, sediments transported in stormwater runoff increase the turbidity of the water, which can inhibit plant growth and dramatically disturb or destroy aquatic habitats (EPA, 2003). Bacteria and pathogens, such as *E. coli*, can pose health hazards; household hazardous wastes, such as pesticides, solvents, and petroleum products (i.e., hydrocarbons) can be poisonous and even carcinogenic to fauna and flora; excess nutrients, primarily as nitrogen and phosphorus, can result in eutrophication and anaerobic aquatic environments (EPA, 2003).

Excessive loads of nitrogen and phosphorus are arguably the most prevalent and therefore most problematic pollutants in runoff. The presence of these nutrients in runoff is primarily derived from animal wastes and lawn fertilizers (EPA, 2003). Nitrogen (in the forms of ammonia, nitrite, and nitrate) and phosphorus are key limiting nutrients in aquatic ecosystems, with phosphorus being the limiting nutrient in freshwater systems and nitrogen in saline systems.
Excessive quantities of nutrients in water lead to boom-and-bust curve patterns for algae populations: as the unnaturally high population of algae dies, the decomposition process consumes oxygen because of the biological oxygen demand (BOD) exerted by the heterotrophic bacteria consuming the dead algae (EPA, 2003). This results in anoxic conditions, or dead zones, which, in the most extreme cases, kills everything in the ecosystem except anaerobic microbes. This process results from the eutrophication of the water body.

Elevated concentrations of nitrogen and phosphorus can also lead to toxicity in surface waters to both the biota living within it and the organisms (including humans) who consume it. Even low levels of ammonia-nitrogen in water have been noted to negatively impact the health and reproductive success of fish species (Chang et al., 2012). High levels of nitrites and nitrates in drinking water have been linked to various cancers and liver damage in humans (Chang et al., 2012). Excessive loading of these nutrients into water bodies through runoff not only threaten the health of aquatic ecosystems, but threaten the health of humans as well.

At present, there are many different forms of stormwater infrastructure in place to divert and treat stormwater runoff from crucial surface waters. This infrastructure alleviates some of the direct water quality impacts imposed by peak flows of urban stormwater runoff. Some of the most widely used of these practices include retention ponds and constructed wetlands.

Stormwater Management Infrastructure

Infrastructure: Stormwater Retention Ponds

Retention (wet) ponds are excavated basins that contain permanent pools of water, which are designed to treat stormwater runoff (EPA, 2014). They are designed to meet the treatment volume characteristic of 10 year or 100 year storms, which varies with local climate and state regulations (EPA, 2014). Wet ponds can even be used to treat runoff from stormwater “hotspots” (i.e., areas that generate highly contaminated runoff), if the pond remains separate from groundwater flow (EPA, 2014). Most wet ponds contain inflow and outflow pipes with a smaller sedimentation forebay that precedes the main “micropool” of water (EPA, 2014). Retention ponds facilitate water treatment through processes of sedimentation and algal, microbial, and to a limited degree, vegetation uptake (EPA, 2014).

Though retention ponds are designated as “best management practices” by the U.S. Environmental Protection Agency, they pose some significant challenges and impacts with
respect to the quality of their effluent: they require thorough and consistent maintenance. Poorly managed wet ponds can perform counteractively, resulting in nutrient (nitrogen and phosphorus) accumulations, reduced dissolved oxygen levels, foul odors and conditions, and algal blooms (CWP & EPA, 2009). Retention ponds also have the potential to accumulate excessive amounts of sediment. When the influent and effluent structures are not periodically dredged, sediment loading can clog the inlet and outlet pipes, drastically reducing the efficacy of the structure itself (CWP & EPA, 2009). Excessive sediment increases turbidity and smothers vegetation, which can disturb other biota within the pond and thus eliminate the biological functions necessary for the treatment of pollutants in stormwater (CWP & EPA, 2009). Without the necessary maintenance, retention ponds can have poor nutrient removal rates and even experience overflows, meaning the pond itself can be a source of pollution in nearby surface waters (CWP & EPA, 2009).

Another pressing issue of concern associated with stormwater runoff and retention ponds, especially in regions with cold, freshwater trout streams, is thermal disturbance, also called “thermal pollution.” Wet ponds have the potential to exacerbate or create thermal disturbances in stream ecosystems. As pond water stands for extended period of time before exiting the pond, water temperatures often increase by the time they enter the surrounding stream. It is important to note that peak stormwater flows over heated impervious surfaces during the summer can lead to large fluxes of warm water into wet ponds or directly into the surrounding stream ecosystems. These temperature fluxes can stress and kill trout, which can have broader ecological implications for the surrounding watershed (Hester & Bauman, 2012).

**Infrastructure: Constructed Wetlands**

Constructed treatment wetlands are systems that model the ecosystem services performed by natural wetlands for the purpose of water treatment, including stormwater runoff (Engelhardt & Ritchie, 2001). There are two forms: free water surface (FWS) constructed wetlands, which most closely resemble natural wetlands, and vegetated submerged bed (VSB) wetlands, which are comprised of gravel beds planted with submerged and emergent wetland plants (EPA, 2000). Both the FWS and VSB constructed wetlands contain berms, which structure the wetland area, as well as inlet and outlet pipes, which adjust the water levels and maintain stable water flow throughout the wetland (EPA, 2000). The system itself facilitates volatilization and adsorption of
pollutants to organic and inorganic surfaces, while creating an environment that supports plant uptake and microbial uptake and degradation (Stewart et al., 2008).

The ecology of constructed wetlands is biologically dependent on bacteria and microbes, algae, emergent herbaceous plants, and floating plants. Bacteria and other microorganisms on plant roots and sediments, also called biofilm, can take up pollutants like phosphorus, nitrogen, and others, and/or facilitate their transformation non- or less toxic forms (Stewart et al., 2008). Unfortunately, while the functions of biofilm can be critical in water phytoremediation, the efficacy of microbial uptake and transformations can be limited in colder climates (Stewart et al., 2008). The presence of algae is also critical ecological component of constructed wetland systems, which must be considered in the system’s design. However, poorly designed systems have the potential to over-facilitate the growth of algae and thus reduce the quality of effluent (EPA, 2000). Emergent herbaceous plants (also referred to here as emergent macrophytes) and floating plants take up nutrients and pollutants and store them in root and shoot tissues (or biomass), while root structures provide habitat for the microorganisms that comprise the biofilms (Hadad et al., 2006). Animal species also play a role in maintaining the ecological integrity of the system, although they do not directly facilitate pollutant removal or uptake (EPA, 2000).

Though constructed wetlands have their benefits in treating water, providing habitat for various species of fauna and flora, and creating a useful ecological system, they do have their drawbacks. Because of sedimentation, the gravel media in these systems are prone to clogging, which inhibits the functionality of these systems without routine maintenance. Additionally, the emergent vegetation is rooted in sediments, which prevents plants from accessing all of the nutrients and pollutants available for uptake that are suspended in the water column (Stewart et al., 2008). Also, these plants are relatively sensitive to water levels; if emergent plants become too inundated by excessively high water levels, die-off can occur (Headley & Tanner, 2008). Constructed wetlands also require vast areas of land filled with shallow water to be effective, as the microorganisms within the system require large surface areas to function (Stewart et al., 2008; Winston et al., 2012). Specific sizing can range from less than two to over two hundred acres of land per million gallons per day (or, 4 to 530 liters per meter squared per day), (EPA, 2000) which renders this strategy unfeasible in urbanized areas, where undeveloped land is limited, if it is available at all.
The Case for Floating Treatment Wetlands to Improve Water Quality

The floating treatment wetland (FTW) is an option for treating stormwater runoff that (1) uses existing infrastructure and (2) combines the benefits of both retention ponds and constructed wetlands while eliminating their shortcomings. The concept of the floating treatment wetland is born from the marriage of the water treatment mechanisms facilitated by retention ponds and constructed wetlands. A floating treatment wetland combines the sedimentation and sorption potential of retention ponds with the biological processes of constructed wetlands (Tanner & Headley, 2008).

A floating treatment wetland, as a system, can be most simply defined as a constructed community of wetland plants suspended by a buoyant mat on the surface of a water body designed to treat polluted waters (Tanner and Headley, 2008). Floating treatment wetlands have been applied to a vast array of impaired water systems, including streams (Stefani et al. 2011), industrial wastewaters (Hadad et al., 2006), sewage (Floating Island International, 2011), and more simply, detention (Ladislas et al., 2013) and retention ponds (Borne, 2014). These systems introduce emergent macrophytes to the pond, foster the growth of biofilm on both plant roots and substrate (Headley & Tanner, 2008), and can provide shade (Khan et al., 2012; Floating Island International, 2015) to mediate excessive algal growth (Headley & Tanner, 2008) and increased temperature fluxes imposed by both runoff over hot pavement and stagnant water in the pond itself (Hester & Bauman, 2012). Floating treatment wetlands also have the potential to increase biodiversity by providing habitat for birds and other fauna (Alden Research Laboratory, n.d.), some of which can minimize mosquito populations that would otherwise be problematic in traditional retention pond settings (Midwest Floating Island, 2014).

Noted Benefits

There are many recorded benefits of using floating treatment wetlands as opposed to retention ponds or constructed wetlands alone. Floating treatment wetlands have been described as cheaper and more effective in large scale wastewater applications than conventional, mechanical water treatment systems (Zeller, 2008), which are energy intensive and require expensive upgrades when loads exceed certain thresholds (Stewart et al., 2008). In stormwater pond or wastewater lagoon retrofits, FTWs do not require expensive, heavy earth-moving machinery, as the installation or expansion of a new pond or wetland might (Winston et al.,
Also, as FTWs are buoyant, they do not significantly detract from the existing water volume of stormwater ponds, so ponds can maintain the same volume from the peak flows they were designed to divert and treat (Winston et al., 2012).

The functioning of floating treatment wetlands is not affected by significant fluctuations in water level, unlike the vegetation in constructed wetlands. This is due to the fact that the plants in floating treatment wetlands are floating on the surface of the water; as water level decreases or increases, the FTW follows, maintaining a constant level of inundation for the plants (Stewart et al., 2008). This way, plants in the FTW are not subjected to stresses associated with excessive inundation.

Floating treatment wetlands also significantly increase the amount of surface area available for microbial biofilm in the smaller volume of retention ponds (Stewart et al., 2008). For the commercially available, BioHaven® matrix, the manufacturer states that 250 ft² of an FTW can treat an acre’s worth of natural or constructed wetland surface area, creating a “concentrated wetland effect” (Floating Island International, 2015). While the extension of roots into the water column also provides more surface area for biofilm, roots can also slow the flow of water through the pond, increasing sedimentation and therefore reducing the turbidity of effluent (Winston et al., 2012).

FTWs have been praised for their removal rates of total-, ammonia-, and nitrate-nitrogen, phosphorus (Floating Island International, 2011; Borne, 2014), metals (e.g., copper, zinc, nickel, and cadmium) (Tanner & Headley, 2008; Ladislas et al., 2013), total suspended solids, and dissolved organic carbon in surface waters (Floating Island International, 2015). Floating Island International, Inc. states that “independent laboratory tests” using their floating treatment wetland matrix reflect pollutant removal rates that far exceed those of traditional ponds and waterways (2015). It can be inferred that FTW applications using buoyant media (other than commercially available FTW substrates) can still facilitate the benefits of phytoremediation in retention ponds.

**Design: Substrate, Size, and Growth Media**

Principles of design for floating treatment wetlands in the literature vary among experiments. For stormwater applications, Tanner and Headley (2008) describe an overview for several variations on the design and structure for FTWs, which include: (1) a buoyant raft or
frame that supports a net containing growth media; (2) a buoyant, artificial matrix through which roots can penetrate; or (3) a self-buoyant mat comprised of weaved roots, rhizomes, shoots, litter, and organic matter that mimics the dynamics of naturally occurring floating wetlands. One of the more popular options is the commercially available buoyant, artificial matrix. The most common of the artificial matrices is the BioHaven® created by Floating Island International, Inc., which is a substrate comprised of post-consumer polyester mat injected with marine polystyrene (Tanner & Headley, 2008). The shape of the floating treatment wetland itself (i.e. geometric or free-form) does not appear to be a characteristic of concern for performance, although the free-form shapes that artificial, commercial substrates can be molded to appear more organic, “natural,” and aesthetically pleasing.

The optimal size and surface-area coverage of floating treatment wetlands is still unclear in the literature, ranging most commonly from 5-10% coverage (Chang et al., 2012; Dodkins & Mendzil, 2014), up to over 35% in aerobic systems (Headley & Tanner, 2008), and, in extreme cases, up to 100% in systems that are completely anaerobic and artificially aerated (i.e., wastewater lagoons) (Tanner & Headley, 2008). Since this percentage varies, for the purpose of stormwater applications the lower to moderate range of percent-cover should be considered as the limit for aerobic systems (10-20% cover). Excessive coverage by an FTW in an aerobic, unaerated system (e.g., a retention pond) can disrupt the chemical dynamics in the water. This can potentially result in an undesired, deoxygenized system, which is the opposite of the desired effect, and must be considered when designing an FTW for a specific site (Tanner & Headley, 2008). With respect to differing areas of coverage, different experiments have also looked into the efficacy of single large mats and multiple smaller mats. In their work, Khan and Shamseldin (2013) conclude that single, large floating treatment wetlands receive the greatest amount of hydraulic activity, and consequently have the potential to encounter and therefore possibly remove more pollutants. This result confirms that the basic design of a single floating mat is the ideal model for the application of a floating treatment wetland. However, this recommendation is tempered by the fact that it is much easier to construct, deploy, and retrieve smaller segments FTW structures than a large, individual mat, even in small retention ponds. For those not interested in purchasing commercially manufactured floating treatment wetlands, like BioHaven®, a single large mat may not be feasible.
Information regarding the thickness of the mat itself also varies among the literature. The clearest logistical data is available for the BioHaven® floating substrate. Using this substrate in their experiment, Tanner and Headley utilized an FTW that is 1.5cm (0.59in) thick along the edges with a 0.5cm (approximately 0.20in) thick depression in the center in their experiment (2008). Other experiments using BioHaven® substrate have had thicknesses between 7.2in (18.3cm) (Stewart et al., 2008) and 9.8in (25cm) (Winston et al., 2012). Thickness of floating substrate likely depends on the buoyancy of the matrix used, as well as the size and plant-holding capacity for the matrix, which Floating Island International, Inc. likely considers when manufacturing the FTW substrates. Data for other matrices are not described in the literature, but basic physical calculations could be conducted to determine the weight-holding capacity of the planned FTW material. Such calculations would be necessary when implementing a full-scale apparatus using a particular substrate and flotation material.

An element frequently considered in the establishment of an FTW is the media in which the plants should grow. Depending on the substrate, significant amounts of growth media may not be necessary. However, many of the different growth media utilized for the emergent macrophytes in the laboratory and field studies are still being experimented with and analyzed. Some of the different experimental media include coconut-peat (also called coconut coir, a common medium used in hydroponics), soil (Tanner & Headley, 2008), and mixtures of sand, peat, and compost (Headley & Tanner, 2008), although none have been qualified as being more effective than the other as of yet. Some scientists have even experimented with additions of activated charcoal (biochar) in growth media in the laboratory setting to improve nutrient removal rates before the selected macrophytes have been completely established (Dodkins & Mendzil, 2014). This addition is still questionable with regard to its efficacy and practical applications to field settings (Dodkins & Mendzil, 2014). The use of gravel and pozzolana (volcanic rock) as root-anchoring media has also been effectively applied in FTW experiments (Ladislas, 2013). The various options for growth media should be explored based on the conditions of one’s design, depending on the substrate, the chosen species and their needs, pollutant issues in the study area, and even the climate.
**Plant Selection**

Plant selection is perhaps the most critical component in the design of a floating treatment wetland: the plants are the operators and platforms for pollutant removal. Among the emergent macrophytes across numerous experiments, most tend to be native to the respective regions of the study area, although some have utilized non-native species selected for potential pollutant removal efficacy (Hunt et al., 2012). Common emergent macrophyte genera utilized in floating treatment wetland experiments include: *Typha* (cattails) (Hadad et al., 2006), *Juncus* (rushes), *Carex* (“true” sedges), (Ladislas et al., 2013), *Cyperus* (sedges), *Schoenoplectus* (sedges and bulrushes) (Headley & Tanner, 2008), *Phragmites* (reeds), *Sparganium* (bur-reeds) (Stefani et al., 2011), and *Pontederia* (pickerelweeds) (Wang et al., 2014). Many of these genera have species that can be found native in different climates all over the world. However, the data that supports the listed genera should not necessarily rule out other native emergent macrophytes in the experimentation process, though they do provide a data-supported recommendation for those planning to implement a floating treatment wetland, and prove useful especially in scenarios where there are time and budget constraints.

An important factor to consider in selecting plant species for use in floating treatment wetlands is the root growth pattern. Plants with long, fine, hairy roots are ideal for this application. This form of root growth and development creates more surface area for direct nutrient and pollutant uptake and for microbial biofilm colonization, that latter of which is the primary mechanism for remediation. In addition, long, fine roots extend deeper into the water column, which slows the flow of water and facilitates sedimentation.

Before employing any plant species, it is essential that they be evaluated for invasive potential, including natives. If any genus or species has a record for invasive potential in similar climates and ecosystems to the study area, they should not be employed in the floating treatment wetland apparatus.

Species richness (or diversity) is also a factor to consider when selecting plants to mimic the functions on natural wetland systems in a floating treatment wetland. Although specific species may be more responsible for pollutant removal and other ecosystem services than others, richness is essential for “functional redundancy” and mimicking essential ecosystem interactions that optimize pollutant removal and uptake (Engelhardt & Ritchie, 2001). Ecosystems are complex, diverse systems; modelling and applying these principles to ecologically designed
technologies, like floating treatment wetlands, improve their potential function in practical applications.

**Nutrient Removal Results: Nitrogen and Phosphorus**

Nutrient dynamics in aquatic systems are complicated and often site-specific; some sites have more trouble removing particular species of nutrients, such as ammonia (Borne et al., 2013). However, the application of floating treatment wetlands has proven to be an effective strategy in removing excessive levels of nitrogen (as nitrate and ammonia) and phosphorus, with 80% of removal attributable to the microbial biofilm on the substrate and plant roots and 20% of removal attributable to plant uptake (Floating Island International, 2011). Similar ratios of removal by biofilm and plant uptake have been reported in other studies (Borne, 2014).

Floating Island International (2015) reports that FTWs deployed with the BioHaven® substrate can demonstrate removal rates up to 20 times higher for nitrates, 11 times higher for ammonia, and 10 times more for phosphates than exhibited by ponds and waterways alone in previously published literature. This data is supported by several case studies conducted by the corporation (Floating Island International, 2011). Other studies have also experienced positive removal rates using FTWs, with BioHaven® and other floating substrates (Wang et al., 2014; Winston et al., 2012; Tanner & Headley, 2008; Tanner & Headley, 2011; Borne, 2014; Chang et al., 2012). Despite this promising potential of the removal rates, it is advised that those who implement FTWs for the purpose of nutrient removal in stormwater ponds should aim to reach a desired environmental concentration for nitrogen and phosphorus, rather than focus on the magnitude of removal rates alone (Winston et al., 2012). In the experimental application of floating treatment wetlands on retention ponds in North Carolina, Winston et al. (2012) note that some retention ponds alone function well at reducing pollutant levels, which can limit the conclusions drawn from the implementation of FTWs. They concluded that the addition of FTWs simply enables the existing infrastructure to function more efficiently and achieve a desired threshold of nutrient concentrations in effluent (Winston et al., 2012).

**Pollutant Removal Results: Suspended Solids, Metals, and Hydrocarbons**

In urban settings, eroded sediments, metals, and hydrocarbons have the potential to enter runoff. FTWs have shown to reduce fine suspended solids (particulates that remain after
preliminary settling in water) by 57%-67% after seven days, compared to a 23% reduction in a control setting (Tanner & Headley, 2008). Systems with FTWs have also shown 65-75% removal rates for copper, compared to no change in concentration for the control, and a 40% removal rate for zinc (Tanner & Headley, 2008). Carex, Juncus, and Typha are exemplary plant genera for metal removal (Englehardt & Ritchie, 2001; Hadad et al., 2006). At present, data on hydrocarbon removal by FTWs have not been reported in the literature. This is likely the case because the dynamics of removal are poorly understood, hydrocarbon testing is costly, and other pollutants may be of greater or more immediate concern to researchers.

**Long Term Maintenance of the Floating Treatment Wetland**

Floating treatment wetlands are a relatively new technology and can be made from a plethora of materials, all of which can have different longevities. A popular, commercially available substrate is Floating Island International’s BioHaven®, which is comprised of recycled plastics and has been used year-round for over a decade, withstanding extreme winter temperatures (Midwest Floating Island, 2014). According to the manufacturer, this particular substrate should persist indefinitely with limited UV exposure (i.e., shaded by the plants) (Midwest Floating Island, 2014). When planted with perennial plants, vegetation should grow yearly and regenerate within the substrate, perpetuating its function as a floating wetland within the pond ecosystem (Midwest Floating Island, 2014). The FTW should be anchored in the desired, optimal location in order to prevent unwanted movement around the pond (Midwest Floating Island, 2014).

Depending on the climate and circumstances, however, other structural strategies might be more favorable and/or affordable, and can still achieve optimal removal thresholds. Similarly functional apparati can be constructed with comparable materials to the BioHaven® design, but they can also be built out of extruded polystyrene with drilled holes (Ladislas et al., 2013), a floating raft supporting a net or mesh holding plant growth media, or even a self-buoyant mat of organic materials, like roots, rhizomes, plant litter, and organic matter (Headley & Tanner, 2008). There are many different variations on the floating treatment wetland that can be utilized effectively in the context of stormwater retention ponds. Since the broader application of this technology is still relatively new, how the substrates have been managed or maintained are not
uniform or explicitly stated in the literature. This is a matter that should be given serious consideration in the design process.

When targeting certain pollutants, like nutrients, harvesting biomass from the FTW is necessary in order to truly remove the pollutants from the stormwater system, as dying and dead plants release accumulated nutrients back into their environment. Essentially, the plants that accumulated nutrients from polluted stormwater over the course of the growing season would release them back into the water column at the end of the growing season. The few studies on the subject of FTW plant harvest state that aboveground (shoot) biomass harvest imposes less damage to the plant and floating treatment wetland system, as opposed to entire plant biomass (Wang & Sample, 2014). However, this does beg the question whether portions of root mass could also be harvested, removing with it colonies of biofilm. While this would be more slightly more challenging than harvesting shoots, and easier than harvesting entire plants, root mass harvest is a technique that would require further research. Shoot harvest should occur in September or October in temperate climates in order to prevent the return of nutrients back into the water (Wang & Sample, 2014). The optimal harvesting time and strategy still requires further research, although some studies recommend harvesting shoots at times of peak productivity (mid- to late summer) (Wang & Sample, 2014). The effects of multiple above-ground biomass harvests and plant sustainability in FTWs in temperate regions still require further research.

Applications to Vermont

Stormwater Retention Ponds in Vermont

The application of wet (retention) ponds is a common management practice for stormwater in Vermont. They are especially common in the more developed, urbanized areas like Burlington and the surrounding suburbs in Chittenden County.

An example of the performance of retention ponds in urbanized settings is demonstrated by the evaluation of the quality of effluent leaving the Farrell Street retention pond in South Burlington, Vermont. This pond was evaluated to be effective in significantly reducing total suspended solids (TSS), reducing concentrations from the northern and southern inlets from 191 mg/L and 12 mg/L (respectively) down to 7.2 mg/L in the outlet—a 96% removal rate (Brustlin et al., 2011). The pond’s effluent also exhibited a 60% removal of total nitrogen (TN), a 73% reduction of biological oxygen demand (BOD), and a 92% removal of total phosphorus (TP)
(Brustlin et al., 2011). This particular retention pond had high levels of E. coli and no means of treating it, so levels remained high in the effluent (Brustlin et al., 2011). Overall, this pond is determined to be an effective retention pond, although other pollutants such as metals and hydrocarbons were not evaluated. When applying such measures to the broader applications in Vermont, it must be considered that pollutant levels and removal are dependent on loads from the surrounding land uses (e.g. residences, parks, highways, etc.). The evaluation of the Farrell Street retention pond establishes a baseline for the study of the pollutant removal efficacy of retention ponds in Vermont, and inspires further study in other locales under different conditions.

The relatively poor removal rates of nitrogen and relatively effective removal rates of phosphorus by the Farrell Street retention pond challenge Vermonters to improve the quality of effluent entering the surrounding watershed. The application of floating treatment wetlands to wet ponds that are already effective has the potential to curb, and possibly even completely halt inputs of nitrogen and phosphorus into the Lake Champlain Basin. As Lake Champlain is confronted with nutrient loading and eutrophication, FTWs create an opportunity to aid in minimizing the effects of human-caused nutrient loading in the surrounding watershed, and ultimately the lake itself.

Native Wetland Plants

Vermont has many native wetland plant species that could be applied to floating treatment wetland systems. In the recommended genera Typha (cattails) (Hadad et al., 2006), Juncus (rushes), Carex (“true” sedges), (Ladislas et al., 2013), Cyperus (sedges), Schoenoplectus (sedges and bulrushes) (Headley & Tanner, 2008), Phragmites (reeds), Sagittaria (Sleeth, 2014; Wang et al., 2014), Sparganium (bur-reeds) (Stefani et al., 2011), Scirpus (bulrushes), Iris, Pontederia (pickerel weeds) (Wang et al., 2014), Vermont has a relatively broad selection of native analogs. Of these genera, Carex, Schoenoplectus, Sagittaria, Scirpus, Pontederia, Iris and Sparganium were employed in the experiment described below. Other genera examined in this evaluation include Symphyotrichum, Asclepias, Lobelia, and Zizania. Appendix I details the growth characteristics of the twelve tested plant species.
Chapter 3. Methodology

Twelve different Vermont-native wetland emergent macrophyte species were selected to test how well they would grow in a floating treatment wetland. The tested plants were grown hydroponically in greenhouse microcosms in order to simulate the growing conditions of a floating treatment wetland. Plants were grown in both high (control) and low (experimental) nutrient solutions to evaluate which plants would grow best and/or take up the most phosphorus in this setting.

3.1 Plant Selection

The plant species grown in this experiment include: *Symphyotrichum nova-angliae* (New England aster), *Asclepias incarnata* (swamp milkweed), *Schoenoplectus tabernaemontani* (softstem bulrush), *Pontederia cordata* (pickerelweed), *Carex lurida* (shallow sedge), *Iris versicolor* (harlequin blueflag iris), *Scirpus atrovirens* (green bulrush), *Sagittaria latifolia* (broadleaf arrowhead), *Zizania palustris* (wild rice), *Lobelia cardinalis* (cardinalflower), *Carex comosa* (long-haired sedge) and *Sparganium eurycarpum* (broadleaf bur-reed). All but *Zizania* are perennial species.

Some of the chosen species were selected based on the species or genus application in the literature on floating treatment wetlands (e.g., softstem bulrush, pickerelweed, broadleaf arrowhead, shallow and long-haired sedges). The other species selected based on local expert recommendation, wetland and native status, and potential for flowering/aesthetic value.

3.2 Growth Cell Materials & Installation

In this experiment, six 18-gallon polyethylene storage bins were used as hydroponic growth cells in a climate-controlled greenhouse in Vermont. The selected bins were opaque in color to inhibit algae growth. The growth cells were situated in the south side of the greenhouse for optimal sunlight exposure, as grow lights were not used.

Six miniature-scale “floating treatment wetlands” were constructed using 12-inch by 18-inch sheets of 1-inch polystyrene to fit the 15.9-inch by 23.9-inch surface dimensions of the
growth tanks. Each polystyrene board was drilled with four staggered 3.75-inch diameter holes to accommodate the polyethylene mesh pots in which the plants would grow.

![Simulated ‘floating treatment wetland” constructed using polyethylene mesh cups and 1-inch polystyrene boards (Westhelle, 2015)](image)

**Figure 3.1** Simulated ‘floating treatment wetland” constructed using polyethylene mesh cups and 1-inch polystyrene boards (Westhelle, 2015)

Growth media was not used in this experiment. Instead, rounded pea gravel was selected as an anchoring media for plant roots, as it is inexpensive and does not affect the chemistry of the water. It should be noted that the pea gravel was thoroughly rinsed prior to use in the experiment in order to prevent any potential contamination.

Each of the plant species were purchased as 2-inch seedling plugs from Vermont-based nurseries that specialize in wetland and rain garden plant cultivation. It should be noted that New England aster and cardinalflower lobelia were only available in 6-inch pots and were therefore slightly more mature than their 2-inch seedling plug counterparts, a consideration noted and understood throughout the course of the experiment. Four individuals of each of the chosen species were purchased for two reasons: (1) to pick the healthiest individuals for the experiment and (2) to have a back-up in the event an experimental specimen died early on in the experiment. The two remaining individuals were transplanted into polyethylene mesh pots, but remained in saturated soil media over the 12-week growth period as a precautionary measure.

On June 29, 2015, all seedlings were removed from their plug trays (and in the case of cardinalflower lobelia and New England aster, pots). The soil was carefully and thoroughly removed from the roots of the plants, then rinsed until all roots were bare and free of any soil material. Each specimen was then added to a 3.75-inch polyethylene mesh pot and anchored with rounded pea gravel.
In each growth cell, plants were grouped randomly into three separate communities containing four different plant species. Though random in placement, each community contained at least one Vermont-native analog of plant species recommended in the literature on floating treatment wetlands. There was one replicate for each community: one grown in the high nutrient (control) solution and one grown in the low nutrient (experimental) solution. This makes a total of three different plant communities grown in two different treatments across six growth cells.

Cell 1 (high nutrients) and Cell 2 (low nutrients) contained New England aster (*Symphyotrichum nova-angliae*), swamp milkweed (*Asclepias incarnata*), softstem bulrush (*Schoenoplectus tabernaemontani*), and pickerelweed (*Pontederia cordata*).

Cell 3 (high nutrients) and Cell 4 (low nutrients) contained harlequin blueflag iris (*Iris versicolor*), green bulrush (*Scirpus atrovirens*), shallow sedge (*Carex lurida*), and broadleaf arrowhead (*Sagittaria latifolia*).

Cell 5 (high nutrients) and Cell 6 (low nutrients) contained cardinalflower lobelia (*Lobelia cardinalis*), wild rice (*Zizania palustris*), long-haired sedge (*Carex comosa*), and broad-fruited bur-reed (*Sparganium eurycarpum*).

Each specimen was coded according to its common name and treatment. **Table 3.1** is a key to each specimen’s cell, treatment, common and scientific names.

**Figure 3.2** The six experimental growth cells fitted with experimental floating treatment wetlands (Westhelle, 2015).
### Table 3.1. Plant Key, including configuration, treatment, scientific name, and common name

<table>
<thead>
<tr>
<th>Growth Cell</th>
<th>Plant Code</th>
<th>Treatment</th>
<th>Scientific Name</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NEA - H</td>
<td>High Nutrients</td>
<td><em>Symphyotrichum nova-angliae</em></td>
<td>New England aster</td>
</tr>
<tr>
<td></td>
<td>PW - H</td>
<td></td>
<td><em>Pontederia cordata</em></td>
<td>Pickerelweed</td>
</tr>
<tr>
<td></td>
<td>SMW - H</td>
<td></td>
<td><em>Asclepias incarnata</em></td>
<td>Swamp milkweed</td>
</tr>
<tr>
<td></td>
<td>SSB - H</td>
<td></td>
<td><em>Schoenoplectus tabernaemontani</em></td>
<td>Softstem bulrush</td>
</tr>
<tr>
<td>2</td>
<td>NEA - L</td>
<td>Low Nutrients</td>
<td><em>Symphyotrichum nova-angliae</em></td>
<td>New England aster</td>
</tr>
<tr>
<td></td>
<td>PW - L</td>
<td></td>
<td><em>Pontederia cordata</em></td>
<td>Pickerelweed</td>
</tr>
<tr>
<td></td>
<td>SMW - L</td>
<td></td>
<td><em>Asclepias incarnata</em></td>
<td>Swamp milkweed</td>
</tr>
<tr>
<td></td>
<td>SSB - L</td>
<td></td>
<td><em>Schoenoplectus tabernaemontani</em></td>
<td>Softstem bulrush</td>
</tr>
<tr>
<td>3</td>
<td>HBFI - H</td>
<td>High Nutrients</td>
<td><em>Iris versicolor</em></td>
<td>Harlequin blueflag</td>
</tr>
<tr>
<td></td>
<td>GRB - H</td>
<td></td>
<td><em>Scirpus atrovirens</em></td>
<td>Green bulrush</td>
</tr>
<tr>
<td></td>
<td>SS - H</td>
<td></td>
<td><em>Carex lurida</em></td>
<td>Shallow sedge</td>
</tr>
<tr>
<td></td>
<td>BLAR - H</td>
<td></td>
<td><em>Sagittaria latifolia</em></td>
<td>Broadleaf arrowhead</td>
</tr>
<tr>
<td>4</td>
<td>HBFI - L</td>
<td>Low Nutrients</td>
<td><em>Iris versicolor</em></td>
<td>Harlequin blueflag iris</td>
</tr>
<tr>
<td></td>
<td>GRB - L</td>
<td></td>
<td><em>Scirpus atrovirens</em></td>
<td>Green bulrush</td>
</tr>
<tr>
<td></td>
<td>SS - L</td>
<td></td>
<td><em>Carex lurida</em></td>
<td>Shallow sedge</td>
</tr>
<tr>
<td></td>
<td>BLAR - L</td>
<td></td>
<td><em>Sagittaria latifolia</em></td>
<td>Broadleaf arrowhead</td>
</tr>
<tr>
<td>5</td>
<td>CFL - H</td>
<td>High Nutrients</td>
<td><em>Lobelia cardinalis</em></td>
<td>Cardinalflower Lobelia</td>
</tr>
<tr>
<td></td>
<td>WR - H</td>
<td></td>
<td><em>Zizania palustris</em></td>
<td>Wild rice</td>
</tr>
<tr>
<td></td>
<td>LHS - H</td>
<td></td>
<td><em>Carex comosa</em></td>
<td>Longhaired sedge</td>
</tr>
<tr>
<td></td>
<td>BFBR - H</td>
<td></td>
<td><em>Sparganium eurycarpum</em></td>
<td>Broadfruited Bur-reed</td>
</tr>
<tr>
<td>6</td>
<td>CFL - L</td>
<td>Low Nutrients</td>
<td><em>Lobelia cardinalis</em></td>
<td>Cardinalflower Lobelia</td>
</tr>
<tr>
<td></td>
<td>WR - L</td>
<td></td>
<td><em>Zizania palustris</em></td>
<td>Wild rice</td>
</tr>
<tr>
<td></td>
<td>LHS - H</td>
<td></td>
<td><em>Carex comosa</em></td>
<td>Longhaired sedge</td>
</tr>
<tr>
<td></td>
<td>BFBR - L</td>
<td></td>
<td><em>Sparganium eurycarpum</em></td>
<td>Broadfruited Bur-reed</td>
</tr>
</tbody>
</table>

#### 3.3 Treatments

Nutrient solutions were drained and replenished every three weeks during the 12-week growth period. Each growth tank was filled with 17 gallons (64.4L) of tap water. The water was fertilized using Dyna-Gro Liquid Fertilizer, a 7-9-5 NPK fertilizer.

The high nutrient solution was prepared by adding 1tsp (4.93mL) per gallon of water, as prescribed by Dyna-Gro, for a total of 17tsp (84mL). This regimen resulted in an addition of 100.55g of “available phosphate” ($P_2O_5$) (Dyna-Gro, 2015) to the high nutrient growth cells.
every three weeks, meaning that about 43.72g of phosphorus was added with each dose. Therefore, the phosphorus concentration of the high nutrient solution was approximately 680mg/L. Over the 12-week growth period, an approximate total mass of 175.74g of phosphorus was exposed to the plants in each high nutrient cell.

The low nutrient solution was prepared by adding ¼ tsp (1.23mL) per gallon of water for a total of 4.25tsp (21mL). This regimen resulting in an addition of 25.14g of “available phosphate” to the low nutrient cells every three weeks, meaning that about 10.93g phosphorus was added to solution with each dose. Therefore, the phosphorus concentration of the low nutrient solution was approximately 170mg/L. Over the 12-week growth period, an approximate total mass of 100.55g of phosphate and 43.72g phosphorus was exposed to the plants in each low nutrient cell.

3.4 Monitoring & Harvest

Over the 12-week growth period, each plant was qualitatively observed weekly, taking special care in noting any changes in the growth and health of each individual. Each plant specimen was measured for changes in height and breadth weekly. Photographs were periodically taken of each growth cell at the time of observation.

Midway through the growth period, measurements for temperature (°C), conductivity (mS/cm), dissolved oxygen (mg/L) and pH were measured using a YSI 556 Handheld Multi-Parameter Instrument on three occasions: (1) prior to the first solution change; (2) three days post-solution change; (3) prior to the second solution change. These measurements were used to roughly gauge the conditions in each growth cell right before and after solution changes.

At the end of the 12-week growth period (September 21, 2015), the plants were harvested in their entirety from their respective growth cells. The final height and width of both roots and shoots were measured. After final measurements were taken, each specimen was set to dry in a paper bag until they could be properly prepared for analysis.

3.5 Plant Tissue Analysis for Total Phosphorus

The plants were dried in an oven at 50°C for a period of 48 hours. Each plant was then weighed for harvested dry biomass. After weighing, each plant was finely ground using a
Thomas ED-5 Wiley Mill fixed with a 16oz collection jar. Both the mill and sample jar were sanitized with compressed air and ethanol between samples.

**Figure 3.3** Softstem bulrush weighed for harvested dry biomass (g).

**Figure 3.4** Thomas Wiley Mill Model ED-5 used for grinding of plant tissue samples.
When completely ground, each sample was thoroughly mixed with a metal spatula sanitized with ethanol for a minimum of 30 seconds to ensure that the sample contained an even mixture of stem (for species like swamp milkweed and New England aster), foliage, and roots. From this mixture, a subsample for each plant species was collected and stored in sealed 20mL vials. Excess sample for each plant was stored in a separate paper bag.

From the collected subsample for each plant, 0.25g was weighed and mixed with nitric acid to perform a microwave-assisted strong acid digest. Plant tissues were then analyzed using an inductively coupled plasma atomic emission spectrometer (ICP-AES) for total phosphorus concentration.

3.6 Statistical Analysis: t-tests for Differences Among Treatments and Species

Five different t-tests were performed using the JMP platform to evaluate the differences between treatments and species. To test for differences in dissolved oxygen (mg/L), conductivity (mS/cm) and pH between the high and low treatments, independent Student’s t-tests and a nonparametric Kruskal-Wallis/Wilcoxon Signed Rank test were performed. To test for differences in total phosphorus tissue concentrations between the high and low treatments, an independent Student’s t-test was performed. To test for differences in total phosphorus tissue concentrations between species for the high and low treatments, a matched pairs dependent t-test was performed.
Chapter 4. Results

4.1 Plant Observations and Measurements

All but two of the tested plant species survived the 12-week duration of the experiment. All plant measurements are located in Appendix I, and observations and photographs are located in Appendix II. Refer to Table 3.1 for plant codes reported below.

In high and low nutrient conditions, New England aster did not reach full maturity by the time of harvest on September 21, 2015. Over the course of the growth period, NEA-H and NEA-L experienced a mild pest infestation and grew mold on basal leaves. At the time of harvest, NEA-H reached a height of 50cm, while NEA-L reached a height of 44cm. In both treatments, New England aster grew relatively poor root development, consisting mostly of short, thick, and smooth root systems. NEA-H’s root system reached a length of 16.1cm, and NEA-L’s root system reached a length of 27cm (Figure 4.11).

![Figure 4.1 NEA-L (Symphyotrichum novae-angliae) at harvest (Westhelle, 2015)](image)

In high and low nutrient conditions, swamp milkweed (Asclepias incarnata) reached full maturity and flowered by the time of harvest in both nutrient treatments. However, later in the growing season, SMW-H and SMW-L both experience severe pest infestations that degraded the
health of each specimen. At the time of harvest, SMW-H reached a height of 114cm, while SMW-L reached a height of 127cm. In both treatments, swamp milkweed developed a fibrous root system. SMW-H’s root system reached a length of 25cm, while SMW-L’s reached a length of 12.9cm (Figure 4.11).

Figure 4.1 SMW-H (Asclepias incarnata) at harvest. Roots appear shorter than reported (25cm), as root tips were very delicate and damaged during harvest (Westhelle, 2015).

In high and low nutrient conditions, pickerelweed (Pontederia cordata) reached full maturity and flowered by the time of harvest. Later in the growing season, PW-H and PW-L experienced very mild pest infestation, which did not appear to seriously affect the health of each specimen. At the time of harvest, PW-H reached a height of 60.5cm and a width of 93cm, while PW-L reached a height of 64.2cm and a width of 90cm. In both treatments, pickerelweed had a well developed fibrous root system with fine root hairs, which was notably purple and black in color. PW-H’s root system reached a length of 38cm, while PW-L’s root system reached a length of 47cm (Figure 4.11).
In both high and low nutrient conditions, softstem bulrush (*Schoenoplectus tabernaemontani*) reached full maturity but did not flower by the time of harvest. Both SSB-H and SSB-L were resilient against the pest infestation. At harvest, SSB-H reached a height of 155.3cm and a width of 17cm, while SSB-L reached a height of 115cm and a width of 20cm. In both treatments, softstem bulrush had a well developed fibrous and hairy root system. SSB-H’s root system reached a length of 50.2cm, and SSB-L’s reached a length of 42.5cm (*Figure 4.1, 4.2*).
In both high and low nutrient conditions, harlequin blueflag iris (*Iris versicolor*) remained at a state of immaturity and grew very slowly throughout the experiment. HBFI-H and HBFI-L appeared resilient against the pest infestation. At the time of harvest, HBFI-H reached a height of 29.9cm, while HBFI-L reached a height of 30.6cm. In both treatments, harlequin blueflag iris had very poorly developed, but fibrous root systems. HBFI-H’s root system had a length of 7.5cm, and HBFI-L’s had a length of 9.2cm (Figure 4.11).

**Figure 4.5** HBFI-H (*Iris versicolor*) at harvest (Westhelle, 2015)

In high nutrient conditions, green bulrush (*Scirpus atrovirens*) remained relatively immature. In low nutrient conditions, green bulrush reached maturity and flowered. Both GRB-H and GRB-L appeared resilient against the pest infestation. At the time of harvest, GRB-H reached a height of 62cm and a width of 63cm. GRB-L reached a height of 116cm and a width of 90cm at the time of harvest. The root system on GRB-H appeared somewhat poorly developed, but fibrous and hairy. The root system on GRB-L was extremely well developed, fibrous and hairy. GRB-H’s root system had a length of 13.3cm, and GRB-L’s root system had a length of 28cm (Figure 4.11).
In both high and low nutrient conditions, shallow sedge (*Carex lurida*) reached full maturity and flowered by the time of harvest. Both SS-H and SS-L appeared to be somewhat resilient against the pest infestation. At the time of harvest, SS-H reached a height of 108cm and SS-L reached a height of 93.3cm. The root system on both SS-H and SS-L were very well developed, fibrous and hairy. SS-H’s root system reached a length of 26.5cm, while SS-L’s root system reached a length of 19.6cm (*Figure 4.11*)
In high nutrient conditions, broad leaf arrowhead (*Sagittaria latifolia*) appeared stunted in growth, experiencing a slower rate of growth over the course of the growth period. It did appear to reach full maturity, but did not flower in this treatment. In low nutrient conditions, broadleaf arrowhead grew relatively quickly, reached full maturity, and flowered. Both BLAR-H and BLAR-L experienced severe pest infestations by the end of the growth period. At the time of harvest, BLAR-H reached a height of 48.8cm, and BLAR-L reached a height of 63cm. The root systems on both BLAR-H and BLAR-L were well developed, fibrous and hairy. BLAR-H’s root system reached a length of 25cm, and BLAR-L’s root system reached a length of 24cm (Figure 4.11).

![Figure 4.8](image)

**Figure 4.8** BLAR-H (*Sagittaria latifolia*) at harvest. Roots were delicate and damaged at harvest (Westhelle, 2015)

In both high and low nutrient conditions, long haired sedge (*Carex comosa*) appeared to reach full maturity but did not flower by the time of harvest. Both LHS-H and LHS-L experienced very mild pest infestations, but appeared to be relatively resilient in terms of health against it. At the time of harvest, LHS-H reached a height of 93cm and width of 30cm, and LHS-L reached a height of 91.5cm and a width of 44cm. The root systems on both LHS-H and LHS-L were well developed, fibrous and hairy. LHS-H’s root system reached a length of 31cm, and LHS-L’s root system reached a length of 33.3cm (Figure 4.11).
In both high and low nutrient conditions, broadfruited bur-reed (*Sparganium eurycarpum*) reached full maturity but did not flower by the time of harvest. Both BFBR-H and BFBR-L experienced severe pest infestations, and by the end of the growth period the health of both appeared to decline. At the time of harvest, BFBR-H reached a height of 136.5cm and a width of 62cm. and BFBR-L reached a height of 121.3cm and a width of 60cm. The root systems on both BFBR-H and BFBR-L were very well developed, fibrous, and hairy. BFBR-H tended to have more thick roots among the fibrous roots, while BFBR-L showed mostly thin, fibrous roots. BFBR-H’s root system reached a length of 21cm, and BFBR-L’s root system reached a length of 32cm (Figure 4.11).
Wild rice (*Zizania palustris*) and cardinalflower lobelia (*Lobelia cardinalis*) perished in both high and low nutrient conditions by week 10. At this stage, it was too late to replace them with their soil-grown alternates. It should be noted that all saturated soil-grown alternates did not grow much in size from their seedling form by the end of the growing season, despite having been repotted into 3.75-inch polyurethane mesh cups.

![Root Length & Width of Plants at Harvest](image)

**Figure 4.11** Root length and width (cm) measurements for all plant species grown in high and low nutrient conditions. See **Table 3.1** for plant codes

4.2 Water Quality Metrics for Nutrient Solutions

On July 17, 2015, prior to the first solution change, the growth cell temperature (°C) ranged between 23.19°C and 23.85°C. The average temperature for all cells was 23.51°C. The average temperature for the high nutrient solution cells (Cells 1, 3, and 5 [see **Table 3.1** for plant species]) was 23.51°C (**Table 4.2**). The conductivity (mS/cm) ranged between 0.330mS/cm and 1.084mS/cm. The average conductivity for all cells was 0.700mS/cm. The average conductivity for the high nutrient solution cells was 1.062mS/cm, and the average conductivity for the low nutrient solution cells was 0.339mS/cm (**Table 4.2**). Dissolved oxygen ranged between 8.6% (0.72mg/L) and 41.7% (3.56mg/L) among the growth cells. The average dissolved
oxygen ratio for all cells was 25.3% (2.14mg/L). The average amount of dissolved oxygen for high nutrient cells was 29.0% (2.45mg/L), and the average dissolved oxygen for low nutrient cells was 21.7% (1.84mg/L). The pH among all of the cells ranged between 6.22 and 7.07. The average pH was 6.67. The average pH among high nutrient cells was 6.47 and the average pH among low nutrient cells was 6.86 (Table 4.2).

Table 4.2 Minimum, maximum, and average temperature, conductivity, Dissolved Oxygen, and pH of Nutrient Solutions

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<thead>
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<th>7/20/15</th>
<th>8/6/15</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Temp (°C)</td>
<td>Cond. (mS/cm)</td>
<td>DO (%)</td>
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<tr>
<td>Total Min.</td>
<td>23.19</td>
<td>0.330</td>
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<td>Total Max.</td>
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<tr>
<td>Total Avg.</td>
<td>23.51</td>
<td>0.700</td>
<td>25.3</td>
</tr>
<tr>
<td>High Avg.</td>
<td>23.51</td>
<td>1.062</td>
<td>29.0</td>
</tr>
<tr>
<td>Low Avg.</td>
<td>23.52</td>
<td>0.339</td>
<td>21.7</td>
</tr>
</tbody>
</table>

On July 20, 2015, three days after the first solution change, the growth cell temperature (°C) ranged between 27.43°C and 28.61°C. The average temperature for all cells was 27.77°C. The average temperature for the high nutrient solution cells was 27.87°C, and the average temperature for the low nutrient solution cells was 27.66°C. The conductivity (mS/cm) ranged between 0.439mS/cm and and 1.713mS/cm. The average conductivity for all cells was 0.819mS/cm. The average conductivity for the high nutrient solution cells was 1.183mS/cm, and the average conductivity for the low nutrient solution cells was 0.456mS/cm. Dissolved oxygen ranged between 63.5% (4.89mg/L) and 79.2% (6.24mg/L) among the growth cells. The average dissolved oxygen for all cells was 70.0% (5.46mg/L). The average amount of dissolved oxygen for high nutrient cells was 69.5% (5.40mg/L) and the average dissolved oxygen for low nutrient cells was 70.4% (5.52mg/L) The pH among all of the cells ranged between 6.00 and 7.01. The average pH was 6.69. The average pH among high nutrient cells was 6.41 and the average pH among low nutrient cells was 6.97 (Table 4.2).
On August 6, 2015, prior the second solution change, the growth cell temperature (°C) ranged between 23.62°C and 24.41°C. The average temperature for all cells was 23.97°C. The average temperature for the high nutrient solution cells was 24.08°C, and the average temperature for the low nutrient solution cells was 23.86°C. The conductivity (mS/cm) ranged between 0.366mS/cm and and 1.090mS/cm. The average conductivity for all cells was 0.716mS/cm. The average conductivity for the high nutrient solution cells was 1.053mS/cm, and the average conductivity for the low nutrient solution cells was 0.379mS/cm. Dissolved oxygen ranged between 11.7% (0.99mg/L) and 29.4% (2.48mg/L) among the growth cells. The average dissolved oxygen for all cells was 21.8% (1.83mg/L). The average amount of dissolved oxygen for high nutrient cells was 16.6% (1.38mg/L) and the average dissolved oxygen for low nutrient cells was 27.1% (2.28mg/L). The pH among all of the cells ranged between 5.57 and 6.55. The average pH was 6.14. The average pH among high nutrient cells was 5.76 and the average pH among low nutrient cells was 6.52 (Table 4.2).

For the water quality measurements of each individual growth cell during these observation periods, refer to Appendix III.

4.2.1 T-tests for Conductivity, Dissolved Oxygen and pH Between Treatments

To test for differences in water chemistry between the high and low treatments, independent Student’s t-tests were performed to see if there were significant differences conductivity (mS/cm), dissolved oxygen (mg/L) and pH.

The data for conductivity was not normally distributed (p<0.05). A nonparametric two-tailed Wilcoxon/Kruskal-Wallis Ranked Sums t-test indicated that Z=0.0004, which was below the significance threshold of Z<0.05. (Figure 4.11).

The data for dissolved oxygen (mg/L) was normally distributed (p>0.05). An independent Student’s t-test indicated that \( T_{(16)} = -0.150, p = 0.44 \). This exceeded the significant threshold of p<0.05 (Figure 4.3). An analysis of variance indicated that \( p=0.8828 \), confirming that there is no significant different in dissolved oxygen (mg/L) between the high and low nutrient treatments.

The data for pH was normally distributed (p>0.05). An independent Student’s t-test indicated that \( T_{(16)} = -3.062, p = 0.0048 \), which was below the significance threshold of p<0.05 (Figure 4.4). The Cohen’s effect size for this model was calculated to be 0.83, indicating that the results of this t-test were moderately meaningful. An analysis of variance indicated that
p=0.0074, confirming that there is a significant difference in pH between the high and low nutrient treatments.

**Figure 4.5** Nonparametric Wilcoxon/Kruskal-Wallis two-tailed t-test comparing treatment (high/low) with conductivity (mS/cm) using JMP

**Figures 4.3 and 4.4** Independent student’s t-tests and analysis of variance comparing treatment (high/low) with dissolved oxygen and pH (mg/L) using JMP

4.3. ICP-AES Results for Total Phosphorus Concentration in Plant Tissues
**Figure 4.5** reports all total phosphorus concentration (mg/kg) results analyzed through ICP-AES plant specimen. **Figure 4.6** reports the total mass (g) of phosphorus taken up by each specimen.

NEA-H (New England aster) had a total phosphorus concentration of 8,556mg/kg in its tissues and accumulated 0.119g phosphorus. NEA-L had a concentration of 5,893mg/kg and accumulated 0.086g phosphorus.

PW-H (pickerelweed) had a total phosphorus concentration of 7,357mg/kg in its tissues and accumulated 0.326g phosphorus. PW-L had a concentration of 7,140mg/kg and accumulated 0.172g phosphorus.

SMW-H (swamp milkweed) had a total phosphorus concentration of 6,916mg/kg in its tissues and accumulated 0.539g phosphorus. SMW-L had a concentration of 4,764mg/kg and accumulated 0.202g phosphorus.

SSB-H (softstem bulrush) had a total phosphorus concentration of 6,031mg/kg in its tissues and accumulated 0.180g phosphorus. SSB-L had a concentration of 8,187mg/kg and accumulated 0.179g phosphorus.

HBFI-H (harlequin blueflag iris) had a total phosphorus concentration of 7,311mg/kg in its tissues and accumulated 0.031g phosphorus. HBFI-L had a concentration of 4,084mg/kg and accumulated 0.010g phosphorus.

GRB-H (green bulrush) had a total phosphorus concentration of 6,236mg/kg in its tissues and accumulated 0.085g phosphorus. GRB-L had a concentration of 6,109mg/kg and accumulated 0.435g phosphorus.

SS-H (shallow sedge) had a total phosphorus concentration of 6,543mg/kg in its tissues and accumulated 0.220g phosphorus. SS-L had a concentration of 4,186mg/kg and accumulated 0.160g phosphorus.

BLAR-H (broadleaf arrowhead) had a total phosphorus concentration of 9,163mg/kg in its tissues and accumulated 0.087g phosphorus. BLAR-L had a concentration of 6,008mg/kg and accumulated 0.071g phosphorus.

LHS-H (long-haired sedge) had a total phosphorus concentration of 3,783mg/kg in its tissues and accumulated 0.135g phosphorus. LHS-L had a concentration of 3,849mg/kg and accumulated 0.235g phosphorus.
BFBR-H (broad fruited bur-reed) had a total phosphorus concentration of 10,421 mg/kg in its tissues and accumulated 1.094 g phosphorus. BFBR-L had a total phosphorus concentration of 8,008 mg/kg and accumulated 0.622 g phosphorus.

**Figure 4.5** Total phosphorus concentration in tissues of plants grown in high and low nutrient conditions. ++ indicates that a large amount (no greater than 5% of sample weight) of undigested solids (soil particles) were observed in the sample prior to ICP-AES analysis.

**Figure 4.6** Total phosphorus (g) accumulated in whole plant biomass.

### 4.3.1 T-tests for Total Phosphorus Concentration (mg/kg) Between Treatments and Species

The independent Student’s t-test performed for significant differences between total phosphorus concentrations (mg/kg) in the species grown in the high and low treatments (Figure
Data was normally distributed. For this comparison of treatments, $T_{(17.6)} = 1.855$, $p = 0.0402$. Reaching below the significance threshold of $p<0.05$, there was a significant difference in total phosphorus concentrations for the plants grown in high and low nutrient treatments. The Cohen’s effect size for this model was calculated to be 0.83, indicating that the results of this t-test were largely meaningful.

![Figure 4.7](image)

**Figure 4.7.** Independent student’s t-test comparing treatment (high/low) with total phosphorus concentration (mg/kg) using JMP

The matched pairs dependent t-test was performed to test for significance differences between phosphorus concentrations for each species grown in the high and low treatments (**Figure 4.8**). The difference column for this analysis was normally distributed. For the comparison of species grown in difference treatments, $T_{(9)} = -2.57$, $p = 0.0152$, which was below the significance threshold of $p<0.05$. The Cohen’s effect size for this model was calculated to be 0.83, indicating that the results of this t-test were largely meaningful.
**Figure 4.8** Matched pairs dependent t-test for total phosphorus concentration (mg/kg) between species
Chapter 5. Discussion

5.1 Treatments

5.1.1 Phosphorus

As stated, the liquid fertilizer is a 7-9-5 NPK solution, indicating that the solution contains 9% “available phosphate” (P$_2$O$_5$, diphosphorus pentoxide). It should be noted that “available phosphate” in fertilizers is derived from diphosphorus pentoxide (Fertilizer101.org). The phosphorus content of the fertilizer is specified the quantity of P$_2$O$_5$ because diphosphorus pentoxide is the anhydrous form of phosphoric acid, which is the phosphorus source added to the fertilizer solution (Shakhashiri, n.d.) As a result, phosphorus masses and concentrations were estimated according the molecular formula for P$_2$O$_5$, as indicated on the 7-9-5 NPK fertilizer label (Dyna-Gro, 2015).

The control, high nutrient solution adhered to the recommended fertilizer regime for non-recirculating hydroponic systems: 1 teaspoon (~5mL) per gallon for 17 gallons of water for a total of roughly 85mL per dose (Dyna-Gro, 2015). This treatment resulted in a phosphorus concentration calculated to be approximately 680mg/L (0.68g/L) in solution. Over four doses (initial dose and three solution changes) the plants in the high nutrient solution were exposed to 174.84g phosphorus in solution over the 12-week period. The experimental simulated stormwater solution was estimated and established to be one-fourth of the recommended fertilizer regime: ¼ teaspoon (~1.25mL) per gallon for 17 gallons of water, for a total of roughly 21mL per dose. As a result, this treatment contained a phosphorus concentration calculated to be approximately 170mg/L (0.170g/L) in solution. Over four doses, the plants in the low nutrient solution were exposed to roughly 43.72g phosphorus in solution over the 12-week period.

The aim of this experiment was to determine which native Vermont wetland plant species grow best and remove the most phosphorus in a low nutrient, floating treatment wetland setting, specifically to inform species selection for a project funded by the Lake Champlain Basin Program and carried out by the South Burlington Stormwater Utility and Lake Champlain Sea Grant. However, accurately establishing the dosage for the low stormwater solution proved challenging, and is likely flawed in many ways. The estimated dose for the low nutrient treatment was established before the water quality monitoring year for the Quarry Ridge stormwater pond was complete, and therefore there were no definable phosphorus concentrations
or loading masses for this pond. Even so, it should be noted that only influent and effluent samples for total phosphorus concentration were analyzed, not the actual total phosphorus concentration in the pond itself. Most studies on retention ponds focus solely on pond performance, based on the intention to evaluate whether what is going in is being treated before coming out (Brustlin et al., 2011). These values are usually very low, orders of magnitude lower than the concentration of the “simulated stormwater” solution. Regardless, there is little data to inform the levels of total phosphorus concentrations in ponds themselves. While influent and effluent measures are interesting to consider, they not very informative about the total phosphorus levels within the pond. Low total phosphorus concentrations entering and exiting the pond (e.g., 0.100mg/L TP influent, 0.016mg/L TP effluent) are likely to be vastly different of true phosphorus concentrations in the pond. This could be due to a variety of confounding factors, such as the presence of phosphorus in pond sediments and suspended in the water column as the result other ecological process and materials (Tharp & Westhelle, 2015). The complex nature of phosphorus cycling in pond systems makes this difficult to accurately imitate in a laboratory setting, especially when there is no solid data collected to suggest even approximate total phosphorus levels in pond bodies. Even without this data, it is very possible that the low nutrient treatment was more nutrient-rich in terms of total phosphorus concentration (peaking at 170mg/L) than stormwater ponds, especially since the growth cell volumes at 64.4L are miniscule when compared to the volume of a stormwater pond. This would make the concentration of the nutrient solutions appear high as the plants are exposed to similar “loading masses” of phosphorus stormwater pond might experience. It is also crucial to note that since there were no water quality analyses for the nutrient solutions over the course of the experiment, all phosphorus concentrations are merely rough estimates, and cannot be analytically confirmed. The dosing regime in this way, in addition to the growth cell set-up in a greenhouse setting, was flawed and increases the level of error as to how the tested plant species will actually perform in the field.

5.1.2 Interpreting Water Chemistry Results

A YSI 556 Handheld Multi-Parameter Probe was used on three separate occasions to measure temperature, conductivity, dissolved oxygen, and pH: on July 17, 2015, just before the
first solution change; on July 20, 2015, three days post-solution change; and on August 6, 2015, just before the second solution change. Overall, though this dataset is rather limited, it does function as a snapshot of the differences in the aforementioned water quality measures between the high and low nutrient treatments.

On July 20, the average conductivity for the high nutrient solution was 1.183mS/cm. On both July 17 and August 6, the average conductivity for the high nutrient solution is about 1.090mS/cm and 1.053mS/cm, respectively (Table 4.2). On July 20, the average conductivity for the low nutrient solution was 0.456mS/cm. On both July 17 and August 6, the average conductivity for the low nutrient solution is about 0.339mS/cm and 0.379mS/cm, respectively (Table 4.2). Based on these conductivity values for the high and low treatments measured pre- and post-solution change, it can loosely be concluded that conductivity is reduced over time, possibly due to plant uptake of nutrients. The nonparametric Wilcoxon/Kruskal-Wallis Ranked Sums t-test for conductivity (mS/cm) indicated that there was significant difference in conductivity between treatments (Z<0.0001): conductivity was significantly higher in the high treatment, and significantly lower in the low treatment (Figure 4.5). Based on the fertilizing regime, this makes sense. The high nutrient treatment received a dose of 1tsp (84mL) of 7-9-5 N-P-K fertilizer per gallon, while the low nutrient treatment received a dose of 1/4tsp (17mL) of 7-9-5 N-P-K fertilizer per gallon. The fertilizer contains a number of compounds, such as ammonium nitrate, potassium nitrate, ammonium phosphate, potassium phosphate, magnesium sulfate, and other compounds that dissociate in water (Dyna-Gro, 2015). The greater volume of fertilizer added to solution, the greater number of dissociated cations in solution, thus the greater the conductivity of the solution.

Dissolved oxygen (mg/L) was highly variable among all treatments on all three dates of measurement. An independent Student’s t-test indicated that there was no significant difference in dissolved oxygen (mg/L) (p=0.44) (Figure 4.6). Though it seems like the addition of plants and/or fertilizer could affect dissolved oxygen concentration, it did not appear that either of these factors did so in a significant way between the high and low nutrient treatments, though this conclusion is based on a limited water quality dataset. Since the growth cells were stagnant and non-recirculating, it makes sense that dissolved oxygen levels are higher post-solution change, as the replacement of the solution incorporates air and thus oxygen into the water.
pH ranged between 5.57 and 7.07 across the three measurement periods (Table 4.2). While an independent Student’s t-test indicated that there was a significant difference (p=0.0048) in pH between treatments, where the high nutrient solution had a significantly lower, more acidic pH while the low nutrient solution had a significantly higher, more neutral pH (Figure 4.7). While this relationship, like conductivity, could be related to the amount of fertilizer added to solution, it is less clearly defined; according to the material safety data sheet for the 7-9-5 N-P-K fertilizer used in this experiment, the pH is not determined, but liquid fertilizers are usually acidic (Dyna-Gro, 2015).

5.2 Overall Species Performance

5.2.1 *Symphyotrichum novae-angliae*

New England aster, a perennial facultative wetland and common rain garden species, was evaluated for this experiment for its tolerance for wet conditions, its importance for pollinators, its showy purple flowers, and its absence in the literature.

NEA-H had a total phosphorus concentration of 8,556mg/kg of and accumulated 0.119g of phosphorus; NEA-L had a total phosphorus concentration of 5,893mg/kg and accumulated 0.086g of phosphorus. Overall, this species performed poorly at removing nutrients in both high and low nutrient settings, and stored little phosphorus in its tissues, although it did store more in the high nutrient setting.

At a height of 50cm for NEA-H and 44cm for NEA-L, this species did not reach its height at maturity, indicating that its growth was stunted in the experimental floating treatment wetland. Both NEA-H and NEA-L had relatively poor root development, consisting of short, thick, and smooth root systems, creating little surface area for microbial biofilm to grow upon.

This species’ limited growth, poor root development, susceptibility to pest infestation and rot, and limited phosphorus removal reflects that *Symphyotrichum novae-angliae* does not perform well in a floating treatment wetland setting, regardless of nutrient supply.

5.2.2 *Asclepias incarnata*

Swamp milkweed, a perennial obligate wetland plant, key pollinator, and common rain garden species, was evaluated for its ecological value, aesthetics, tolerance for moisture, and its absence in the literature on floating treatment wetlands.
This species performed surprisingly well in both high and low nutrient settings: SMW-H had a total phosphorus concentration of 6,916mg/kg in its tissues and accumulated 0.539g phosphorus; SMW-L had a concentration of 4,764mg/kg and accumulated 0.202g phosphorus. Overall, this species performed well at removing phosphorus, though it performed better in high nutrient conditions.

*Asclepias incarnata* reached full maturity, even flowering in both treatments by the end of the growth period. This indicates that this plant thrives enough in the floating treatment wetland setting to a point that it is reproductively viable, regardless of nutrient supply. However, *Asclepias* was arguably the most afflicted by the pest infestation, experiencing leaf and tissue yellowing, leaf drop, and mold, which could have affected the total phosphorus measures. However, the pest in question (greenhouse white fly) would not be likely to affect the species in the field, as it cannot overwinter in Vermont.

In both treatments, swamp milkweed demonstrated thin, well developed fibrous root systems, though they were slightly more well developed in the high nutrient solution (*Figure 4.11*). This root development would provide a moderate amount of surface area, though not as many as other tested plant species. However, despite the development of their root systems, the roots could not anchor the weight of the tall, thick stems and foliage, causing the plant to lean in the experimental floating treatment wetland.

Overall, *Asclepias* performed moderately well in this setting, reaching full maturity and flowering. However, its susceptibility to pests, heaviness, and relatively fragile root system indicate that this species would not be an ideal choice for applications in a floating treatment wetland.

5.2.3 *Pontederia cordata*

Pickerelweed, a perennial obligate wetland plant, was evaluated for is common application in the literature on floating treatment wetlands.

This species performed very well in both high and low nutrient settings: PW-H had a total phosphorus concentration of 7,357mg/kg and accumulated 0.326g phosphorus; PW-L had a concentration of 7,140mg/kg and accumulated 0.172g phosphorus. Overall this species was very effective at removing phosphorus, though, like other species, it performed better in high nutrient settings.
*Pontederia cordata* reached full maturity in both high and low nutrient conditions, flowering by the end of the growth period, indicating that this species would be reproductively viable in the floating treatment wetland setting. However, there was a distinction in growth habit between the high and low nutrient treatments: PW-H appeared to grow more laterally, while PW-L appeared to grow more upright. While this was directly related to the nutrient solution is unclear, but possible. For an urban stormwater field application, the latter (upright) would be the preferred growth form. It should also be noted that this species was resilient to pest infestation.

In both treatments, *Pontederia* had very well-developed fibrous and hairy root systems. PW-L’s root system reached a length of 47cm compared to PW-H’s 38cm. Longer roots in plants grown in low nutrient conditions was a trend for this and a few other species. It is possible that the roots grow longer to increase surface area and access to nutrients in the water column. While limited in nutrients, this increase in root surface area has greater potential to facilitate the growth of more microbial biofilm than its high nutrient counterpart, which in turn could result in even greater phosphorus and pollutant removals in the field setting.

Overall, *Pontederia* performs strongly in this setting, confirming recommendations existing in the literature. Its maturity, pest resiliency, and strong root development indicates that this species would perform well in both eutrophic and low nutrient settings, though symbiotic microbial pollutant removal is more probable in the low nutrient setting.

### 5.2.4 Schoenoplectus tabernaemontani

Softstem bulrush, a perennial obligate wetland plant species, was selected for its prevalence in the literature on floating treatment wetlands.

This species performed very well in this setting: SSB-H had a total phosphorus concentration of 6,031mg/kg and accumulated 0.180g phosphorus; SSB-L had a concentration of 8,187mg/kg and accumulated 0.179g phosphorus. This result was interesting; there was a pretty drastic difference in total phosphorus concentration between the two treatments, yet they were estimated to remove the same amount of phosphorus. This was likely due to the fact that the SSB-H grew slightly thicker stems and had more biomass, but whether this difference is attributable to individual variability or the nutrient treatment is unclear.

*Schoenoplectus* appeared to reach full maturity in both high and low nutrient conditions, but neither flowered by the end of the growth period. Regardless, this species’ overall vigor
demonstrates a strong tolerance for the floating treatment wetland setting, and its complete resilience against the pest infestation indicates that *Schoenoplectus* is a strong candidate.

In both treatments, *Schoenoplectus* had very well-developed fibrous and hairy root systems. Contrary to what was observed for *Pontederia*, SSB-H’s roots grew longer than SSB-L’s: SSB-H’s root system reached a length of 50.2cm, and SSB-L’s reached a length of 42.5cm. While this margin of difference could be the result of individual variability, it may not be. Regardless, the SSB-L’s roots would still provide sufficient surface area for microbial biofilm to grow upon in a low nutrient system, and would still be a highly effective plant species to use.

Overall, *Schoenoplectus* performed very well in the floating treatment wetland setting, and arguably better in the low nutrient setting. Its maturity, pest resiliency, and strong root development indicates that this species would perform well in both eutrophic and low nutrient settings, though enhanced symbiotic microbial pollutant removal would be more probable in the high nutrient setting based on these observations.

### 5.2.5 Iris versicolor

Harlequin blueflag iris, a perennial facultative wetland species, was selected for its frequent use in rain garden settings, its aesthetics, and the genus’ occasional used in the literature (Wang & Sample, 2015).

This species had considerable phosphorus concentrations, but minute accumulation: HBFI-H had a total phosphorus concentration of 7,311mg/kg and accumulated 0.031g phosphorus; HBFI-L had a concentration of 4,084mg/kg and accumulated 0.010g phosphorus. This was likely due to the fact that this species remained juvenile over the course of the 12-week growth period, never exceeding 29.9cm in height for HBFI-H and 30.6cm for HBFI-L. Though it is not certain whether a more mature *Iris* installed in this setting would perform better, based on these results it can be inferred that *Iris* is stressed by these conditions, and thus is not an effective species for FTW applications in Vermont.

In both treatments, *Iris* grew thin and fibrous root systems, but they were very poorly developed: HBFI-H’s roots reached a length of 7.5cm, and HBFI-L’s roots reached a length of 9.2cm, which is marginal when compared to other species (). This pattern follows the trend that plants in low nutrient solutions grow longer roots, but in this case it is likely due to individual variability.
Overall, *Iris* performed very poorly: it remained juvenile, accumulated little phosphorus, and created little surface area for microbial growth in both treatment settings, but it was resilient against pests. Thus, based on these observations *Iris* is not a suitable candidate for floating treatment wetlands in Vermont.

### 5.2.6 *Scirpus atrovirens*

Green bulrush, an obligate wetland plant species, was selected because bulrushes are frequently employed in the literature on floating treatment wetlands.

In both treatments, *Scirpus* demonstrated similar tissues concentrations of phosphorus, but drastically different accumulations: GRB-H had a total phosphorus concentration of 6,236mg/kg in its tissues and accumulated 0.085g phosphorus. GRB-L had a concentration of 6,109mg/kg and accumulated 0.435g phosphorus. In low nutrient conditions, *Scirpus* accumulated more phosphorus.

This species responded observably differently in each treatment: in the high nutrient setting, while vigorous in appearance, GRB-H was stunted compared to GRB-L. GRB-L reached full maturity and flowered, while GRB-H did not. GRB-H reached a height of 62cm and a width of 63cm, while GRB-L reached a height of 116cm and a width of 90cm. The difference in growth appears to be greater than what could be accounted for by individual variability.

In the high nutrient treatment, GRB-H appeared to show somewhat poor root development, reaching a length of 13.3cm, though it was fibrous and hairy, creating some potential of surface area for biofilm. In the low nutrient treatment, GRB-L showed extremely strong root development, reaching a length of 28cm, in which the roots were also fibrous and hairy, creating a great amount of potential surface area for microbial biofilm.

Overall, *Scirpus* performed observably better in low nutrient conditions. In terms of phosphorus concentration, accumulation, vigor, and root development, *Scirpus* would be a strong candidate for floating treatment wetlands in Vermont.

### 5.2.7 *Carex lurida*

Shallow sedge, an obligate wetland plant species, was selected for this experiment because the genus *Carex* is commonly used in floating treatment wetlands.

*Carex lurida* performed well in both treatments: SS-H had a total phosphorus concentration of 6,543mg/kg and accumulated 0.220g phosphorus. SS-L had a concentration of
4,186mg/kg and accumulated 0.160g phosphorus. In high nutrient conditions, Carex lurida accumulated more phosphorus.

Observably, Carex lurida reached full maturity and flowered in both high and low nutrient conditions. SS-H reached a height of 108cm while SS-L reached a height of 93.3cm, a relatively small difference in size. The root systems on both SS-H and SS-L were thin, fibrous, and hairy, creating a great amount of potential surface area for microbial biofilm. However, SS-H’s roots grew longer, to a length of 26.5cm, while SS-L’s roots reached only 19.6cm.

Overall, Carex lurida performed slightly better in high nutrient conditions, but was generally vigorous, developed a strong root system, was resilient to pests, and was hardy in the floating treatment wetland setting.

5.2.8 Sagittaria latifolia

Broadleaf arrowhead, a perennial obligate wetland plant species, was selected for its occasional application in the literature (Sleeth, 2014; Wang et al., 2014).

In both treatments, Sagittaria show distinct differences in tissues concentrations of phosphorus, similar accumulations: BLAR-H had a total phosphorus concentration of 9,163mg/kg in its tissues and accumulated 0.087g phosphorus. BLAR-L had a concentration of 6,008mg/kg and accumulated 0.071g phosphorus. In high nutrient conditions, Sagittaria accumulated more phosphorus. However, like Asclepias, Sagittaria was highly impacted by the infestation of greenhouse white flies, suffering from tissue yellowing, leaf drop, and mold, which could have slightly impacted the measures of phosphorus.

Contrary to what is suggested by the phosphorus uptake, this species responded observably differently in each treatment: in the high nutrient setting, BLAR-H was stunted for several weeks when compared to progressive growth of BLAR-L. In the first few weeks, BLAR-H showed slow growth for many small leaves and shoots, while BLAR-L showed hastened growth for fewer, but larger leaves. This pattern of growth was consistent throughout the growth period, although BLAR-H approached similar degree of maturity by the end of the experiment. BLAR-L reached full maturity and flowered, while BLAR-H approached full maturity but did not flower. BLAR-H reached a height of 48.8cm, while BLAR-L reached a height of 116cm and a width of 63cm. Based on the observed and distinct pattern of growth between the different treatments appears to be greater than what could be accounted for by individual variability.
In both treatments, *Sagittaria*’s roots appeared to be well developed, fibrous and hairy, and approximately the same length: BLAR-H’s root system reached a length of 25cm, while BLAR-L’s reached a length of 24cm. In both treatments, *Sagittaria*’s roots create a approximately the same amount of potential surface area for microbial biofilm.

Overall, *Sagittaria* grew observably better in low nutrient conditions, but performed slightly better in high nutrient conditions in terms of phosphorus tissue concentration. In terms of root development and vigor in this setting, *Sagittaria* would be an acceptable, though not ideal candidate for floating treatment wetlands in Vermont.

5.2.9 *Carex comosa*

Long-haired sedge, an obligate wetland plant species, was selected for this experiment because the genus *Carex* is commonly used in floating treatment wetlands.

*Carex comosa* performed well in both treatments: LHS-H had a total phosphorus concentration of 3,783mg/kg and accumulated 0.135g phosphorus. LHS-L had a concentration of 3,849mg/kg and accumulated 0.235g phosphorus. In low nutrient conditions, *Carex comosa* accumulated significantly more phosphorus, though tissue concentration could be the results of individual variability.

In both treatments, *Carex comosa* grew healthily and reached maturity, but did not flower. *Carex* also experienced a very mild pest infestation, but did not appear to be affected. LHS-H reached a height of 93cm and a width of 30cm, while LHS-L reached a height of 91.5cm and a width of 44cm. While relatively similar in height, LHS-L appeared to be much more full and accumulate more biomass than LHS-H. The root systems on both LHS-H and LHS-L were thin, fibrous, and hairy, creating a great amount of potential surface area for microbial biofilm. LHS-L’s roots grew slightly longer, to a length of 33.3cm, while LHS-L’s roots reached a length of 31cm.

Overall, *Carex comosa* performed observably and analytically better in low nutrient conditions, and was generally vigorous, developed a strong root system, resilient to pests, and hardy in the floating treatment wetland setting.
5.2.10 *Sparganium eurycarpum*

Broadfruited bur-reed, an obligate wetland plant species, was selected for this experiment based on professional recommendation, early sprouting time, and because genus *Sparganium* has been used in floating treatment wetlands (Stefani et al., 2011).

*Sparganium* performed exceptionally well in both treatments: BFBR-H had a total phosphorus concentration of 10,421mg/kg and accumulated 1.094g phosphorus. BFBR-L had a concentration of 8,008mg/kg and accumulated 0.622g phosphorus. In high nutrient conditions, *Sparganium* accumulated significantly more phosphorus. However, phosphorus uptake in both high and low nutrient conditions was greatest for *Sparganium*.

In both treatments, grew healthily and reached maturity, but did not flower. However, *Sparganium* also experienced a moderately severe pest infestation, and appeared to be suffering, especially in later weeks. Based on the amount of biomass and phosphorus this species accumulated, it appears unlikely that external sources of insects and mold impacted phosphorus results.

*Sparganium* was clearly the largest tested species. In high nutrient conditions, *Sparganium* grew slightly bigger: BFBR-H reached a height of 136.5cm and a width of 62cm, while BFBR-L reached a height of 121.3cm and a width of 60cm. However, these differences could be the result of individual variability. The root systems on both BFBR-H and BFBR-L were thin, fibrous, and hairy, creating a great amount of potential surface area for microbial biofilm, although BFBR-H’s root system appeared to contain more tuberous roots, while BFBR-L’s were primarily fibrous. BFBR-L’s roots grew observably longer, to a length of 32cm, while BFBR-H’s roots reached a length of 32cm.

Overall, *Sparganium* performed slightly better in high nutrient conditions, and was generally vigorous, developed a strong root system, hardy in the floating treatment wetland setting, but susceptible to pests.

5.2.11 Non-Survivors: *Lobelia Cardinalis* and *Zizania palustris*

As cardinalflower lobelia (*Lobelia cardinalis*) and wild rice (*Zizania palustris*) perished midway through the experiment. They were not replaced with soil-grown alternates due to the fact that both the high and low nutrient treated specimens perished around the same time, indicating that the hydroponic setting was too stressful for them to be viable. Based on the results
of this evaluation, *Lobelia cardinalis* and *Zizania palustris* are not viable species candidates for floating treatment wetlands.

*Lobelia cardinalis*, a facultative wetland plant with showy red flowers, was considered for its applications in Vermont rain garden settings (Andreoletti, n.d.) and for its ornamental value. While it grew relatively slow, but somewhat healthily in both high and low nutrient conditions in the first half of the growing season, it was prone to stress. The basal leaves, when wet, grew mold, and the high summer stress of heat and evaporation likely resulted in this species’ demise in both high and low nutrient conditions. The roots, which where thick and lacked any fibrous hairs, barely passed the base of the pot in both solutions. Evaluating this plant carried some inherent risk, given its tolerance for both moist and dry conditions, it had the potential serve both functional and aesthetic purposes, which could have increased popularity of the technology. Functional and aesthetic constructed wetlands (note: *not* FTWs) using ornamental plant species have been utilized in tropical climates (Calheiros et al., 2015), but it was worth testing to see if functional aesthetics applied in a New England climate with this particular species.

*Zizania palustris*, an annual obligate edible wetland plant species, was considered for its affinity for water and edibility. *Zizania* was stunted throughout the entire growth period, growing very slowly before gradually yellowing and dying in both high and low nutrient conditions halfway through the growth period. Depending on the level of contamination in the pond, this species afforded the possibility that FTWs could serve stacked functions: water remediation and providing a harvestable crop and/or a food source for wildlife. Unfortunately, *Zizania*’s sensitivity toward and rejection of the floating medium eliminated this interesting possibility.

### 5.3 Species Performance in Low Nutrient (Simulated Stormwater) Conditions

While it is useful to compare how species performed in both the control and in the experimental conditions, for field applications it is more important to consider how well each of the twelve species performed in the simulated stormwater conditions.

#### 5.3.1 Root development

Root development is a key consideration when selecting species to apply in floating treatment wetlands. Since 80% of pollutant removal is attributable to biofilm, it is important to
provide these microbial populations with sufficient surface area to optimize water remediation. The species that developed the greatest root mass (and potential surface area for biofilm) were *Pontederia* (PW), *Schoenoplectus* (SSB), *Carex comosa* (LHS), and *Sparganium* (BFBR), respectively (Figure 5.1). To maximize microbial biofilm development, these species should be applied in a low nutrient setting, like that of urban stormwater. The species that developed the least amount of root mass were *Iris* (HBFI), *Asclepias* (SMW), and *Carex lurida* (SS), respectively (Figure 5.1). Regardless of phosphorus uptake, the limited amount of potential surface area for biofilm severely limits remediation potential with these species.

![Root Zone Length and Width for Plants Grown in Low Nutrient (Simulated Stormwater) Conditions](image)

**Figure 5.1** Root zone length and width for the twelve species grown in the experimental, simulated stormwater condition.

5.3.2 Phosphorus Concentration and Storage

In watersheds where eutrophication is a serious issue, like Lake Champlain’s, phosphorus uptake and storage is crucial. Of the twelve tested species, *Schoenoplectus* (SSB), *Sparganium* (BFBR), *Pontederia* (PW), and *Scirpus* (GRB) had the greatest concentration of phosphorus in their tissues, respectively (Figure 5.2). However, *Sparganium* (BFBR), *Scirpus* (GRB), *Carex comosa* (LHS), and *Asclepias* (SMW) accumulated the greatest mass of phosphorus, respectively.
(Figure 5.3). Although Carex comosa had the lowest tissue concentration of phosphorus (3,849mg/kg), its removal indicates that it does store a significant amount of phosphorus in its tissues, which could easily be removed by harvest due to its graminoid growth habit. Harvest of Asclepias, based on growth habit, would be more challenging because of its woody stem. Because Asclepias would be difficult to harvest and demonstrated poor root development when compared with the other tested species, the subsequent species that accumulated the most phosphorus was Schoenoplectus, followed closely by Pontederia (Figure 5.3).

**Figure 5.2** Total phosphorus concentration in plant tissues grown in low nutrient, simulated stormwater conditions.

**Figure 5.3** Total phosphorus accumulation in plant tissues grown in low nutrient, simulated stormwater conditions.
5.4 Flaws in the Experimental Design and Sources of Error

There were several limiting aspects to the design of this experiment that should be considered if similar plant evaluations for floating treatment wetlands are to be conducted.

This experiment was extremely simple: six open, non-circulating microcosms in a greenhouse. The nutrient solutions were simply tap water enriched with different doses of liquid plant fertilizer, which was a highly simplified model for how these plant species may perform in stormwater ponds. Other, more sophisticated approaches have employed test media, more accurately simulated stormwater, and circulating water systems (Floating Island International, 2011; Tanner & Headley, 2011). The simplicity of this experiment makes it easy to replicate, and provides some rough results, but evokes deeper questions as to how the “top performing” plant species determine in this experiment will respond when grown outdoors and in an actual urban stormwater pond.

One unintended and unexpected flaw of this experiment was the timing of plant establishment: the plants were not installed until the last week of June 2015, which limited the growth period of this experiment. Ideally, plants would have been installed in mid-May. However, the availability of specific wetland plant species from Vermont native plant nurseries were a constraint; most varieties were not available for purchase until mid-June. Contact and arrangements with Vermont growers established earlier in the season could have circumvented this roadblock; another option could have been to contact growers in warmer climates that carry common wetland plant species native also to Vermont. Overall, planning early with plant growers is the best way to extend the experimental or applied field growing season.

In hindsight, it would have been valuable to test the nutrient solutions for nutrient concentrations between solution changes in addition to testing the plant tissues. Analyzing the solutions after three weeks would have provided insight into how much phosphorus the “communities” in each growth cell were removing from the microcosm’s “water column.”

The effect of randomly assigned “communities” each plant was assigned was also not ideal. While species richness in FTWs has shown to be a positive characteristic in terms of functional redundancy of plant species (Engelhardt & Ritchie, 2001), it is possible these random configurations could have resulted in competition between species, especially in the low nutrient solution. For example, in Growth Cells 5 and 6, *Sparganium*, a very large and vigorous species, could have potentially competed with *Lobelia* and *Zizania*, playing a role in their demise midway
through the experiment. This could be a side-effect that could not be measured or confirmed with such a small sample size and limited scale. Also, given the small scale yet widespread evaluation of this experimental design, individual plant variability was not taken into consideration; the sample size for each species in each treatment is just one. This limits any more robust or complex statistical analyses that could have been performed. If a similar experiment should be performed, water quality testing, increased sample size, and control measures for potential plant competition should be addressed and considered in the experimental design.

Additionally, while this experiment was performed in a controlled greenhouse setting, pest control should have been but was not considered in the design of this experiment. However, it was an interesting turn in the experiment that demonstrated overall resilience of plants exposed to this impromptu stressor. The pest insects, later identified to be greenhouse whiteflies (*Trialeurodes vaporariorum*), proliferated during the last few weeks of the growth period. The infestation of these species inflicted significant damage, particularly in swamp milkweed (*Asclepias incarnata*), New England aster (*Symphyotrichum novae-angliae*), broadfruited bur-reed (*Sparganium eurycarpum*), and broadleaf arrowhead (*Sagittaria latifolia*) in both the high and low nutrient treatments. Greenhouse whiteflies puncture the surface of plant tissue, ingesting sap from the phloem that can cause yellowing and premature leaf drop on afflicted plants (Cranshaw, n.d.). While feeding, this pest (in nymph and adult forms) excretes honeydew, a substance that facilitates the growth of mold fungi that is sooty in appearance and is an additional source of damage for the weakened plant (UCIPM, 2014). All of the aforementioned plant species exhibited these symptoms, with *Asclepias* and *Sagittaria* demonstrated the most damage. Fortunately, this pest cannot overwinter in cold climates (Cranshaw, n.d.), so the potential that this organism would affect these species in a field FTW application is unlikely. However, the presence of residual white fly eggs, pupae, and mold on plant tissues could have implications for the phosphorus uptake results. Since these biological materials come from an uncontrolled, external source (i.e. insect infestation and mold), measures of total phosphorus for the tissues of these species are likely skewed, since insect eggs, pupae, residuals, and mold all contain phosphorus. How much of these materials made it into the samples ran through ICP-AES, and by how much the amount of these materials could have skewed the results is unclear, but likely marginal.
Figure 5.4 Greenhouse whitefly (*Trialeurodes vaporariorum*) on *Scirpus atrovirens* (GRB-L) flowers. Overall vigor in GRB was not observably affected by this pest (Westhelle, 2015)

As in any experiment where measurements and procedures are carried out by a human being, especially one completed in a non-sterile setting, there are many pathways for error. Measurements taken for shoot height, shoot width, root length, and root width all have room for error, especially since it is difficult to measure different plant species, each with its own growth habit, the same way as a plant develops over a 12-week period. It is also possible that there were valid margins for inaccuracy in the harvesting, weighing, and grinding methods; through these steps, it was very possible to lose portions of biomass, record inaccurate weights, and unintentionally introduce foreign materials into the sample. For example, if a weight is misreported as higher or lower than it truly is, the can calculated nutrient uptake masses are consequently and accordingly impacted. Also, the Wiley mill used to grind the plants was located in a former woodshop. While the mill itself was properly sanitized between samples, dust and dirt particles suspended in air or settled on surfaces then disturbed could have potentially entered some of the samples. Additionally, since the entirety of the plant biomass (root and
shoot) was ground, it is possible that, in spite of thorough mixing, the subsample stored into the 20mL vials were not proportionately representative of the plant. This source of error is further elevated considering that an additional subsample (0.25g) was taken from each of the vials for ICP-AES. It is possible that any and all of these pathways for error influenced total phosphorus results reported in this experiment; however, all of these procedures were approached meticulously and carefully, which limited all possible sources of error to the best of my ability.

The final sources of error can be connected to ICP-AES analysis for total phosphorus concentration. QA/QC measures indicated that all blanks were within 5% of the QC solution, suggesting a small margin of error. However, it was reported by the laboratory analyst who performed the ICP-AES of the twenty plant samples that in some of the strong acid digests of samples, there were undigested solids, possibly soil. These particles could have potentially introduced additional phosphorus to the sample. However, this result was peculiar, considering that the plants were all grown without soil and hydroponically, and roots were thoroughly rinsed before installation. It is possible that this “contaminant” could have entered the sample during grinding, or have been a remnant from the seedling plugs that was missed (possibly attached to the root ball) during the initial root rinsing and plant installation. An additional, though less certain possibility is that these particles were residual silicon from the plant shoots, which does not readily digest (Sivanesan & Park, 2014). Fortunately, even in the samples with the greatest amount of undigested particles, these particles were reported to likely make up no more than 5% of the present sample weight. Samples were rated with three symbols: “++” indicates the greatest amount of undigested particles, which was no more than 5% of sample weight: “+” indicates that there was a qualitatively observable amount of soil particles, but not much; and “-” indicates that there were little to no observable undigested particles. Table 5.1 below indicates which samples contained what ranking of undigested particles.
There were no two samples of the same species that had the highest observed amount of undigested solids. Examining these values while considering the ranking of undigested solids, it appears unlikely that the presence of these solids significantly affected these results. However, the possibility that these solids could have impacted these results in any way should be kept in mind when evaluating the total phosphorus concentration in the tissues of the tested species.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Total P, mg/kg</th>
<th>Undigested solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEA-H</td>
<td>8,556</td>
<td>+</td>
</tr>
<tr>
<td>NEA-L</td>
<td>5,893</td>
<td>+</td>
</tr>
<tr>
<td>SMW-H</td>
<td>6,916</td>
<td>-</td>
</tr>
<tr>
<td>SMW-L</td>
<td>4,764</td>
<td>+</td>
</tr>
<tr>
<td>PW-H</td>
<td>7,557</td>
<td>+</td>
</tr>
<tr>
<td>PW-L</td>
<td>7,140</td>
<td>++</td>
</tr>
<tr>
<td>SSB-H</td>
<td>6,031</td>
<td>+</td>
</tr>
<tr>
<td>SSB-L</td>
<td>8,187</td>
<td>+</td>
</tr>
<tr>
<td>GRB-H</td>
<td>6,236</td>
<td>+</td>
</tr>
<tr>
<td>GRB-L</td>
<td>6,109</td>
<td>-</td>
</tr>
<tr>
<td>SS-H</td>
<td>6,543</td>
<td>++</td>
</tr>
<tr>
<td>SS-L</td>
<td>4,186</td>
<td>-</td>
</tr>
<tr>
<td>BLAR-H</td>
<td>9,163</td>
<td>-</td>
</tr>
<tr>
<td>BLAR-L</td>
<td>6,008</td>
<td>+</td>
</tr>
<tr>
<td>HBFI-H</td>
<td>7,311</td>
<td>+</td>
</tr>
<tr>
<td>HBFI-L</td>
<td>4,044</td>
<td>+</td>
</tr>
<tr>
<td>LHS-H</td>
<td>3,783</td>
<td>++</td>
</tr>
<tr>
<td>LHS-L</td>
<td>3,849</td>
<td>+</td>
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<tr>
<td>BFBR-H</td>
<td>10,421</td>
<td>-</td>
</tr>
<tr>
<td>BFBR-L</td>
<td>8,004</td>
<td>-</td>
</tr>
</tbody>
</table>
Chapter 6. Conclusions and Recommendations

Overall, in both treatments genera commonly utilized in the literature (Schoenoplectus, Pontederia, Carex, and Sparganium) performed the best in the simulated floating treatment wetlands in terms of phosphorus uptake, root zone development, and overall vigor. Other genera utilized occasionally in the literature, like Iris, and Sagittaria did not perform well enough to compete with the other tested species. As one might expect, the genera not employed in the literature, like Symphyotrichum, Asclepias, Lobelia and Zizania did not perform or grow well (for the latter two, perished in this setting), and can be eliminated as viable candidates for floating treatment wetland applications.

For applications in nutrient-poor settings, like that of urban stormwater ponds, broadfruited bur-reed (Sparganium eurycarpum), green bulrush (Scirpus atrovirens), softstem bulrush (Schoenoplectus tabernaemontani), pickerelweed (Pontederia cordata), and long-haired sedge (Carex comosa) are top performers in terms of phosphorus uptake and root zone development and observable surface area. Among these, though, if Sparganium is to be utilized, its overall size and great mass should be considered and carefully planned, especially when using several different species on the same mat. In this setting, the listed species store the greatest amount of harvestable phosphorus, and provide the greatest amount of root surface area that would support the growth of microbial biofilm. The results of this experiment indicate that these species of the twelve tested Vermont-native species would be the best candidates to curb the greatest amount of phosphorus in an urban stormwater pond.
References

Andreletti, J. (n.d.). The Vermont Rain Garden Manual. In Winooski Natural Resources Conservation District; UVM Extension; Lake Champlain Sea Grant (Ed.).


Dyna-Gro. (2015). Safety Data Sheet (SDS): Dyna-Gro Liquid Nutrients; Grow, Bloom, All-Pro, Foliage-Pro, Orchid-Pro, Bonsai-Pro, Hi-N-Pro, Mag-Pro, CFR1910.1200(g) and GHS Rev 03. C.F.R.


Appendix I

Plant Species & Characteristics
New England Aster  
(*Symphyotrichum novae-angliae*)

- **Perennial or Annual?**: Perennial  
- **Vermont Native?**: Yes  
- **Growth Habit**: Forb/herb  
- **Growth Form**: Single Stem  
- **Growth Rate**: Slow  
  - **Regrowth after harvest**: n/a  
- **Active Growth Period**: Spring  
- **Height at maturity**: 4ft  
- **Minimum root depth**: 18in  
- **Shade tolerance**: Part shade  
- **Drought tolerance**: Low  
- **Salinity tolerance**: n/a  
- **Soil Preference**: moist, wet  
- **Wetland Indicator Status**: Facultative  
- **Bloom time**: July, August, September  
- **Vegetative Spread Rate**: none  
- **pH range**: 5.1-6.5  
- **Anaerobic tolerance**: n/a  
- **Known allelopath?**: No  
- **Literature**: n/a

Swamp Milkweed  
(*Asclepias incarnata*)

- **Perennial or Annual?**: Perennial  
- **Vermont Native?**: Yes  
- **Growth Habit**: Forb/herb (vascular w/o woody tissue)  
- **Growth Form**: Rhizomatous  
- **Growth Rate**: Moderate  
  - **Regrowth after harvest**: Slow  
- **Active Growth Period**: Spring  
- **Height at maturity**: 4.9ft  
- **Spread**: 2.5ft  
- **Minimum root depth**: 18in  
- **Shade tolerance**: Intolerant  
- **Drought tolerance**: None  
- **Salinity tolerance**: None  
- **Soil Preference**: Moist, Wet  
- **Wetland Indicator Status**: Obligate  
- **Bloom time**:  
- **Vegetative Spread Rate**: Slow  
- **pH range**: 5.0-8.0  
- **Anaerobic tolerance**: High  
- **Known allelopath?**: No  
- **Literature**: n/a
Pickerelweed
*(Pontederia cordata)*

http://plants.usda.gov/java/charProfile?symbol=POC014

**Perennial or Annual?**: Perennial
**Vermont Native?**: Yes
**Growth Habit**: Forb/herb (vascular w/o woody tissue)
**Growth Form**: Bunch
**Growth Rate**: Moderate
  **Regrowth after harvest**: Slow
**Active Growth Period**: Spring
**Height at maturity**: 3.2 ft
**Spread**: 2.5 ft
**Minimum root depth**: 10 in
**Shade tolerance**: Intolerant
**Drought tolerance**: None
**Salinity tolerance**: Low
**Soil Preference**: Moist, Wet
**Wetland Indicator Status**: Obligate
**Bloom time**: June, July, August, September
**Vegetative Spread Rate**: None
**pH range**: 4.9-8.7
**Anaerobic tolerance**: High
**Known allelopath?**: No
**Literature**: Wang and Sample (2014, 2015) – performs well (better than bulrush in water temps higher than 15 degrees C.

Softstem Bulrush
*(Schoenoplectus tabernaemontani)*


**Perennial or Annual?**: Perennial
**Vermont Native?**: Yes
**Growth Habit**: Graminoid (Grass-like)
**Growth Form**: Rhizomatous
**Growth Rate**: Rapid
  **Regrowth after harvest**: Slow
**Active Growth Period**: Spring, Summer, Fall
**Height at maturity**: 9 ft
**Spread**: 4-5 ft
**Minimum root depth**: 16 in
**Shade tolerance**: Intolerant
**Drought tolerance**: None
**Salinity tolerance**: Low
**Soil Preference**: Wet to standing water
**Wetland Indicator Status**: Obligate
**Bloom time**: April, May
**Vegetative Spread Rate**: High
**pH range**: 5.4 – 7.5
**Anaerobic tolerance**: High
**Known allelopath?**: n/a
Green Bulrush
(*Scirpus atrovirens*)

**Perennial or Annual?:** Perennial  
**Vermont Native?:** Yes  
**Growth Habit:** Graminoid (Grass-like)  
**Growth Form:** Rhizomatous  
**Growth Rate:** Rapid  
  **Regrowth after harvest:** Slow  
**Active Growth Period:** Spring, Summer, Fall  
**Height at maturity:** 9ft  
**Spread:** 4-5ft  
**Minimum root depth:** 16in  
**Shade tolerance:** Intolerant  
**Drought tolerance:** None  
**Salinity tolerance:** Low  
**Soil Preference:** Wet to standing water  
**Wetland Indicator Status:** Obligate  
**Bloom time:** April, May  
**Vegetative Spread Rate:** High  
**pH range:** 5.4 – 7.5  
**Anaerobic tolerance:** High  
**Known allelopath?:** n/a

Shallow Sedge
(*Carex lurida*)

**Perennial or Annual?:** Perennial  
**Vermont Native?:** Yes  
**Growth Habit:** Graminoid (Grass-like)  
**Growth Form:** Rhizomatous  
**Growth Rate:** Slow  
  **Regrowth after harvest:** Slow  
**Active Growth Period:** Spring, Summer, Fall  
**Height at maturity:** 5ft  
**Spread:** 2.5ft  
**Minimum root depth:** 8in  
**Shade tolerance:** Moderate  
**Drought tolerance:** Low  
**Salinity tolerance:** Low  
**Soil Preference:** Moist, Wet  
**Wetland Indicator Status:** Obligate  
**Bloom time:** May, June, July  
**Vegetative Spread Rate:** Moderate  
**pH range:** 4.6-7.5  
**Anaerobic tolerance:** High  
**Known allelopath?:** No
**Broadleaf Arrowhead**  
*(Sagittaria latifolia)*

- **Perennial or Annual?**: Perennial  
- **Vermont Native?**: Yes  
- **Growth Habit**: Forb/herb  
- **Growth Form**: Bunch  
- **Growth Rate**: Moderate  
- **Regrowth after harvest**: Slow  
- **Active Growth Period**: Spring  
- **Height at maturity**: 4.9ft  
- **Minimum root depth**: 18in  
- **Shade tolerance**: Intolerant  
- **Drought tolerance**: None  
- **Salinity tolerance**: None  
- **Soil Preference**: Moist, Wet  
- **Wetland Indicator Status**: Obligate  
- **Bloom time**: July, August, September  
- **Vegetative Spread Rate**: None  
- **pH range**: 4.7-8.9  
- **Anaerobic tolerance**: High  
- **Known allelopath?**: No

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**Harlequin Blueflag Iris**  
*(Iris versicolor)*

- **Perennial or Annual?**: Perennial  
- **Vermont Native?**: Yes  
- **Growth Habit**: Forb/herb  
- **Growth Form**: Tuber  
- **Growth Rate**: Slow  
- **Regrowth after harvest**: None  
- **Active Growth Period**: Spring  
- **Height at maturity**: 3ft  
- **Minimum root depth**: 8in  
- **Shade tolerance**: Part shade  
- **Drought tolerance**: None  
- **Salinity tolerance**: n/a  
- **Soil Preference**: Moist, Wet  
- **Wetland Indicator Status**: Obligate  
- **Bloom time**: May, June, July  
- **Vegetative Spread Rate**: Slow  
- **pH range**: <6.0  
- **Anaerobic tolerance**: n/a  
- **Known allelopath?**: n/a
Long Haired Sedge  
(*Carex comosa*)

- **Perennial or Annual?**: Perennial
- **Vermont Native?**: Yes
- **Growth Habit**: Graminoid (Grass-like)
- **Growth Form**: Rhizomatous
- **Growth Rate**: Slow
  - **Regrowth after harvest**: Slow
- **Active Growth Period**: Spring, Summer, Fall
- **Height at maturity**: 5ft
- **Spread**: 2.5ft
- **Minimum root depth**: 8in
- **Shade tolerance**: Moderate
- **Drought tolerance**: Low
- **Salinity tolerance**: Low
- **Soil Preference**: Moist, Wet
- **Wetland Indicator Status**: Obligate
- **Bloom time**: Indeterminate
- **Vegetative Spread Rate**: Moderate
- **pH range**: 4.6-7.5
- **Anaerobic tolerance**: High
- **Known allelopath?**: No

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Broadfruited Bur-reed  
(*Sparganium eurycarpum*)

- **Perennial or Annual?**: Perennial
- **Vermont Native?**: Yes
- **Growth Habit**: Graminoid (Grass-like)
- **Growth Form**: Colonizing
- **Growth Rate**: Moderate
  - **Regrowth after harvest**: Slow
- **Active Growth Period**: Spring, Summer, Fall
- **Height at maturity**: 4.9ft
- **Spread**: 2.5ft
- **Minimum root depth**: 12in
- **Shade tolerance**: Moderate
- **Drought tolerance**: None
- **Salinity tolerance**: None
- **Soil Preference**: Moist, Wet
- **Wetland Indicator Status**: Obligate
- **Bloom time**: Indeterminate
- **Vegetative Spread Rate**: Moderate
- **pH range**: 5.0-8.5
- **Anaerobic tolerance**: High
- **Known allelopath?**: No
Wild Rice
(Zizia palustris)

Perennial or Annual?: Annual
Vermont Native?: Yes
Growth Habit: Graminoid
Growth Form: Rhizomatous
Growth Rate: Slow
   Regrowth after harvest: n/a
Active Growth Period: Summer
Height at maturity: 8ft
Shade tolerance: Intolerant
Minimum root depth: 8in
Soil Preference: Moist, Wet
Wetland Indicator Status: Obligate
Bloom time: Summer, Fall
Vegetative Spread Rate: None
pH range: 6.0-8.0
Anaerobic tolerance: High
Known allelopath?: No
Drought tolerance: None
Salinity tolerance: None
Cardinalflower Lobelia

*(Lobelia cardinalis)*

http://www.easywildflowers.com/quality/lob.ca1.jpg

Perennial or Annual?: Perennial  
Vermont Native?: Yes  
Growth Habit: Forb/herb  
Growth Form: Single Stem  
Growth Rate: Moderate  
Regrowth after harvest: n/a  
Active Growth Period: Spring  
Height at maturity: 5.9ft  
Minimum root depth: 18in  
Shade tolerance: Intolerant  
Drought tolerance: Medium  
Salinity tolerance: None  
Soil Preference: Moist, Wet  
Wetland Indicator Status: Facultative  
Bloom time: July, August, September  
Vegetative Spread Rate: None  
**pH** range: 5.8-7.8  
Anaerobic tolerance: High  
Known allelopath?: No

*All plant information was extracted from the USDA Plant Database (http://plants.usda.gov) and Ladybird Johnson Wildflower Center Native Plant Database (https://www.wildflower.org/plants/).*
Appendix II

Plant Observations, Measurements, and Photographs
**Table IIA. Plant observations by growth cell and species (See Table 3.1 for plant codes)**

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<thead>
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<th>DATE</th>
<th>OBSERVATIONS</th>
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<tr>
<td>6/29/15</td>
<td><strong>CELL 1 (HIGH)</strong> Immature 6&quot; pot plant. Very green and healthy. Tiny 2&quot; plug seedling</td>
</tr>
<tr>
<td></td>
<td><strong>CELL 2 (LOW)</strong> Immature 6&quot; pot plant. Very green and healthy. Tiny 2&quot; plug seedling</td>
</tr>
<tr>
<td></td>
<td><strong>CELL 3 (HIGH)</strong> HBFI-H GRB-H SS-H BLAR-H</td>
</tr>
<tr>
<td></td>
<td><strong>CELL 4 (LOW)</strong> HBFI-L GRB-L SS-L BLAR-L</td>
</tr>
<tr>
<td></td>
<td><strong>CELL 5 (HIGH)</strong> CFL-H WR-H LHS-H BFBR-H</td>
</tr>
<tr>
<td></td>
<td><strong>CELL 6 (LOW)</strong> CFL-L WR-L LHS-L BFBR-L</td>
</tr>
<tr>
<td></td>
<td>Establishment period. Height = from base of stem to tip of tallest leaf; width = leaf to leave. In the more narrow varieties, this is measured closer to the base of the stem. In some species, like the sedges, width is measured as breadth across the approximate widest part of the plant.</td>
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</tbody>
</table>

6/29/15: The high nutrient (control) solution concentration was selected by merely following the dose of 7-9-5 NPK hydroponic fertilizer at a concentration of 1 tsp per gallon for 17 gallons of water. Approximately 7.56g of phosphorus was added with each dose. The low nutrient (experimental) solution concentration is 1/4 of the control solution.
### CELL 1 (HIGH) vs. CELL 2 (LOW)

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<tbody>
<tr>
<td>Acclimating</td>
<td>Growing very tall and wide. Some basal leaf die-off.</td>
<td>Growing taller, wider, and more green.</td>
<td>Very green. Grown a lot since last week.</td>
<td>Lighter green than NEA-H. Growing slowly.</td>
<td>Much smaller than SMW-H. Some basal leaf dieback, some dead spots on foliage.</td>
<td>Growing tall, wide, and more green, similar to PW-H</td>
<td>Appears green and healthy, although slightly shorter than SSB-H</td>
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### CELL 3 (HIGH) vs. CELL 4 (LOW)

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<tbody>
<tr>
<td>Showing very slow progress. Exhibiting some die-back on leaf tips, but has turned a darker green.</td>
<td>Appears to be growing healthy, turning more green.</td>
<td>Very small still, some pale yellow spots appearing on leaves.</td>
<td>Showing slow progress and leaf tip dieback like HBFI-H, but slightly paler green in color.</td>
<td>Growing bigger and healthier than GRB-H</td>
<td>Growing healthy.</td>
<td>Growing healthy.</td>
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### CELL 5 (HIGH) vs. CELL 6 (LOW)

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<tbody>
<tr>
<td>Showing a lot of new growth.</td>
<td>Showing a lot of new growth.</td>
<td>Some yellowing leaves, but generally healthy.</td>
<td>Growing very big and tall very quickly.</td>
<td>Appears slightly smaller, though just as healthy as CFL-H</td>
<td>Appears healthier than WR-H</td>
<td>Appears healthy and is showing signs of new growth.</td>
<td>Growing just as big, healthy, and fast as BFBR-H</td>
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### 7/13/15

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### 7/17/15

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<tr>
<td>Roots appear established.</td>
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<tr>
<td>7/20/15</td>
<td>NEA-H</td>
<td>SMW-H</td>
<td>PW-H</td>
<td>SSB-H</td>
<td>NEA-L</td>
<td>SMW-L</td>
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<td></td>
<td>HBFI-H</td>
<td>GRB-H</td>
<td>SS-H</td>
<td>BLAR-H</td>
<td>HBFI-L</td>
<td>GRB-L</td>
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<td></td>
<td>Appears to be doing</td>
<td>Has grown a lot,</td>
<td>Observably wider,</td>
<td>Growing very tall and</td>
<td>Significantly smaller</td>
<td>Growing slightly</td>
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<tr>
<td></td>
<td>much better than in</td>
<td>even in the past</td>
<td>taller, and larger</td>
<td>very fast. Lots of</td>
<td>than high nutrient</td>
<td>slower, but just</td>
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<td></td>
<td>the first few weeks.</td>
<td>three days. Tall and</td>
<td>than PW-L. Has a lot</td>
<td>new growth. Doing</td>
<td>counterpart, but</td>
<td>as healthy as</td>
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<td></td>
<td>Very green, and taller.</td>
<td>green. Much</td>
<td>of new growth.</td>
<td>very well under high</td>
<td>growing healthy.</td>
<td>SSB-H. Has</td>
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<td></td>
<td>Leaves near the base</td>
<td>much larger than</td>
<td></td>
<td>nutrient conditions.</td>
<td>Interesting</td>
<td>more small,</td>
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<td></td>
<td>of the stem have</td>
<td>SMW-L</td>
<td></td>
<td>Stems are taller and</td>
<td>candidate at this</td>
<td>skinny stems.</td>
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<td></td>
<td>speckles.</td>
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<td>wider, but fewer</td>
<td>stage.</td>
<td>Showing new</td>
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<td>stems.</td>
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<td></td>
<td>Showing some leaf-tip</td>
<td>Growing healthy.</td>
<td>Still very small (tiny),</td>
<td>Growing very slowly,</td>
<td>Growing bigger and</td>
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<tr>
<td></td>
<td>dieback, but new</td>
<td>Showing new growth</td>
<td>but showing signs of</td>
<td>, but healthily. Some</td>
<td>healthier and</td>
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<td></td>
<td>growth appear to be</td>
<td>and broadening of</td>
<td>new growth. Some</td>
<td>leaf-tip dieback, but</td>
<td>than BLAR-H; leaves</td>
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<td></td>
<td>doing well.</td>
<td>leaflets.</td>
<td>leaves are yellowing.</td>
<td>leaves look</td>
<td>are much broader, stem</td>
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<td>Slow-growing thus far.</td>
<td>arbitrarily healthier</td>
<td>height is taller.</td>
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<td>than HBFI-H. No signs</td>
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<td>NEA-H</td>
<td>SMW-H</td>
<td>PW-H</td>
<td>SSB-H</td>
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<td>Appears to be doing</td>
<td>Has not grown</td>
<td>Observably different</td>
<td>Growing very healthy.</td>
<td>Growing bigger</td>
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<td></td>
<td>much better than in</td>
<td>taller at tallest</td>
<td>than weeks prior.</td>
<td>Growth habit appears</td>
<td>and healthier</td>
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<td></td>
<td>the first few weeks.</td>
<td>point on plant, but</td>
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<td>wider than tall at</td>
<td>than BLAR-H</td>
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<td></td>
<td>Very green, and taller.</td>
<td>is showing many new,</td>
<td></td>
<td>this point.</td>
<td>A lot of new</td>
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<td></td>
<td>Leaves near the base</td>
<td>long, healthy</td>
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<td>growth and leaf</td>
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<td></td>
<td>of the stem have</td>
<td>shoots.</td>
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<td>Vastly different</td>
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<td>than BLAR-H; leaves</td>
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<td>are much broader, stem</td>
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<td>height is taller.</td>
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<tr>
<td>7/23/15</td>
<td>&quot;</td>
<td>Growing healthy.</td>
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<tr>
<td>7/23/15</td>
<td>Appears to be doing</td>
<td>Has not grown taller</td>
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<td>Growing very healthy.</td>
<td>Appears to be</td>
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<td></td>
<td>well before, but is</td>
<td>at tallest point on</td>
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<td>Growth habit appears</td>
<td>growing fuller and</td>
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<td></td>
<td>showing a lot of</td>
<td>plant, but is showing</td>
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<td>wider than tall at</td>
<td>healthier than</td>
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<td></td>
<td>dieback.</td>
<td>many new, long,</td>
<td></td>
<td>this point.</td>
<td>LHS-H</td>
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<td></td>
<td>healthy shoots.</td>
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</table>
A film has appeared on the water’s surface of most of the growth cells. Some algae growth has also been observed. Tiny white flies have been observed on some of the plants. Considering a method of pest management.

<table>
<thead>
<tr>
<th>CELL 1 (HIGH)</th>
<th>CELL 2 (LOW)</th>
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<tbody>
<tr>
<td>NEA-H</td>
<td>SMW-H</td>
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<tr>
<td>PW-H</td>
<td>SSB-H</td>
</tr>
<tr>
<td>NEA-L</td>
<td>SMW-L</td>
</tr>
<tr>
<td>PW-L</td>
<td>SSB-L</td>
</tr>
<tr>
<td>Has grown significantly taller, with new stems growing at the bottom. Some lower leaves are splotchy or moldy, likely due to proximity to standing water.</td>
<td>Showing similar signs of development as PW-H, though no signs of flowering. New unfurling leaves have appeared on the main stem. Appears almost very slightly healthier than high nutrient.</td>
</tr>
<tr>
<td>Has grown significantly since last measurement, though still quite small. Leaves are growing up and out.</td>
<td>Is also showing signs of tremendous growth, though still shorter than SMW-H. Two stems. No signs of flowering yet.</td>
</tr>
<tr>
<td>Showing signs of a lot of new growth. Very tall and wide. Many broad leaves. Beginning to flower.</td>
<td>Growing taller, but no new growth. Also exhibiting struggling basal leaves.</td>
</tr>
<tr>
<td>Individual stems are becoming more girthy. Showing signs of new growth. Very healthy. One thick stem is growing underneath the mat.</td>
<td>Growing well, but bottom leaves appear to be getting moldy, likely due to proximity to water.</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>CELL 3 (HIGH)</th>
<th>CELL 4 (LOW)</th>
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</thead>
<tbody>
<tr>
<td>HBFI-H</td>
<td>GRB-H</td>
</tr>
<tr>
<td>SS-H</td>
<td>BLAR-H</td>
</tr>
<tr>
<td>HBFI-L</td>
<td>GRB-L</td>
</tr>
<tr>
<td>SS-L</td>
<td>BLAR-L</td>
</tr>
<tr>
<td>Growing very slowly, but there is new growth.</td>
<td>Tremendous growth! Leaves are large and growing up and out. Based on the vast difference, it could be inferred that this species prefers lower nutrient settings.</td>
</tr>
<tr>
<td>Growing pretty well. Much smaller than GRB-L</td>
<td>Growing at approximately the same rate as SS- H. Beginning to flower.</td>
</tr>
<tr>
<td>Has grown significantly since last measurement. Beginning to flower.</td>
<td>Slow growing, but showing new growth.</td>
</tr>
<tr>
<td>Showing a lot of growth since last measurement, though still quite small. Leaves are growing up and out.</td>
<td>Tremendous growth. Significantly larger than GRB-H</td>
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<table>
<thead>
<tr>
<th>CELL 5 (HIGH)</th>
<th>CELL 6 (LOW)</th>
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</thead>
<tbody>
<tr>
<td>CFL-H</td>
<td>WR-H</td>
</tr>
<tr>
<td>LHS-H</td>
<td>BFBR-H</td>
</tr>
<tr>
<td>CFL-L</td>
<td>WR-L</td>
</tr>
<tr>
<td>LHS-L</td>
<td>BFBR-L</td>
</tr>
<tr>
<td>Growing well, but bottom leaves appear to be getting moldy, likely due to proximity to water.</td>
<td>Drastic growth. Appears to be growing similar to BFBR-H, though slightly more full. Growing very well.</td>
</tr>
<tr>
<td>Not doing well. Showing lots of yellowing of stem and leaves, although there is some new growth.</td>
<td>Not doing well. Only one living leaf remains.</td>
</tr>
<tr>
<td>Growing tall and very green. Some outer leaflet dieback, though others are very very green and healthy.</td>
<td>Tremendous growth. Very green, appears to be much more full than LHS-H</td>
</tr>
<tr>
<td>Drastic growth. Signs of new growth at the base of the plant, as well as lengthening and broadening of existing leaflets. Growing very healthy.</td>
<td>Growing well, but bottom leaves appear to be getting moldy, likely due to proximity to water.</td>
</tr>
<tr>
<td>Growing well, but bottom leaves appear to be getting moldy, likely due to proximity to water.</td>
<td>Not doing well. Only one living leaf remains.</td>
</tr>
</tbody>
</table>

8/3/15
### Algae Proliferation

- **9/4/15**
  - Showing a lot of dieback on lower leaves, but a lot of new growth at apical meristem.
  - Basal stem looks wood.
  - Grown tall and laterally. Flowering.
  - Consistent with growth.
  - A lot of dieback on lower leaves.
  - Growing big, like SMW-H. Both stems have flowered.
  - Grown more tall (less laterally) than PW-H. Looks healthy.
  - Demonstrating consistent, healthy growth.

- **8/7/15**
  - Nutrient cells (1, 3, and 5).
  - Algae proliferation seems to be more apparent in high nutrient cells (1, 3, and 5).
  - Appears to be growing healthy; becoming more green.
  - New growth is getting bigger.

### Cell 1 (High)

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<tbody>
<tr>
<td>Showing short, thick roots. Growing pretty well. White flies appear to be attracted to this species.</td>
<td>Showing well developed, fibrous (but not hairy), but short root system. Many new stems branching. Flowers are developing.</td>
<td>Showing short, thick roots and many signs of new foliage growth.</td>
<td>Showing long, hairy roots. Showing signs of new growth, widening of stems. 123.2cm is likely a maximum height for this plant.</td>
<td>Poorly developed roots, barely pass through mesh pot. Showing signs of new branching off main stem.</td>
<td>Showing well developed roots, but not nearly as long as SMW-H. Growing healthy. Two stems growing apart. Preparing to flower. Some lower leaves dieback.</td>
<td>Long and hairy root systems, better than PW-H. Growing very healthy, tall. No signs of flowering yet.</td>
<td>Showing longer and hairier roots than SSB-H. Measurements do not include stems growing beneath the mat.</td>
</tr>
</tbody>
</table>

### Cell 2 (Low)

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</thead>
<tbody>
<tr>
<td>Very poorly developed root system that does not extend past base of the pot. Appears to be growing healthy; becoming more green.</td>
<td>Showing a somewhat poorly developed root system, but roots present are hairy. Much better than HBFI. Still growing healthy, but nowhere as large as GRB-L</td>
<td>Roots are long and hairy. Appears to be flourishing, and flowering. Looks to be growing at the same rate as SS-L.</td>
<td>Roots appear to be relatively long and hairy. Growing bigger, but not anywhere close to BLAR-L. May have more individual leaves, but are tiny in comparison.</td>
<td>Very poor root development. Appears to be growing better than in previous weeks, taller and greener, but still very small.</td>
<td>Great root development—long, fibrous, and hairy. Much larger than GRB-H.</td>
<td>Great, long, fibrous, and hairy root system. Growing healthy. Arguably more upright than than SS-H.</td>
<td>Surprisingly strong root development; long, fibrous, and hairy. Growing very big and tall. New smaller leaves are growing from base of the stem.</td>
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### Cell 3 (High)

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</thead>
<tbody>
<tr>
<td>Appears to be growing well, but has a pest problem, as well as some mildew on basal leaves.</td>
<td>Appears to be rebounding, but still yellowing leaves and is not doing well.</td>
<td>Growing great. Shows a tiny bit of dieback, but not much compared to the overall biomass of the plant.</td>
<td>Growing well, similar to CFL-H. Leaves are more upright and spread out. Demonstrating similar pest and mildew issues.</td>
<td>Down to its last living leaf. Not doing well.</td>
<td>Growing healthy. Appears to be more full than LHS-H.</td>
<td>Growing great, perhaps better than BFBR-H, but very close.</td>
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### Cell 4 (Low)

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<tr>
<td>CELL 1 (HIGH)</td>
<td>CELL 2 (LOW)</td>
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<tr>
<td>NEA-H</td>
<td>SMW-H</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PW-H</td>
<td>SSB-H</td>
<td></td>
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</tr>
<tr>
<td>NEA-L</td>
<td>SMW-L</td>
<td></td>
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</tr>
<tr>
<td>PW-L</td>
<td>SSB-L</td>
<td></td>
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</tr>
<tr>
<td>Still growing, but shows a lot of leaf dieback around the base of the plant. New leaves are much smaller than older ones. Somewhat infested.</td>
<td>Growing very tall and heavy for the apparatus. Floppy. Badly infested.</td>
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<tr>
<td>Growing well, growing out more than up. Leaves are large. Somewhat infested.</td>
<td>Still flowering, infested.</td>
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<tr>
<td>Consistent with growth.</td>
<td>Some dieback, like NEA-H. Somewhat infested.</td>
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</tr>
<tr>
<td>Flopping over a lot, getting heavy. Really bad infestation; leaves look very unhealthy.</td>
<td>Still growing well. Grows more vertically than laterally.</td>
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<tr>
<td>Consistently healthy, growth.</td>
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<table>
<thead>
<tr>
<th>CELL 3 (HIGH)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>HBFI-H</td>
<td>GRB-H</td>
</tr>
<tr>
<td>SS-H</td>
<td>BLAR-H</td>
</tr>
<tr>
<td>HBFI-L</td>
<td>GRB-L</td>
</tr>
<tr>
<td>SS-L</td>
<td>BLAR-L</td>
</tr>
<tr>
<td>New leaves, very slowly growing taller. Consistent in growth.</td>
<td>Many new flowers and lengthening leaves. Has grown significantly taller, has flowered. Catching up but still slightly smaller than low nutrient counterpart.</td>
</tr>
<tr>
<td>Has grown significantly taller, has flowered.</td>
<td>Very slow growing.</td>
</tr>
<tr>
<td>Consistently in growth.</td>
<td>Significantly larger than GRB-H. flowered and significantly greater amount of visible biomass.</td>
</tr>
<tr>
<td>Leaves are bigger, more flowers than BLAR-H.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CELL 5 (HIGH)</th>
<th>CELL 6 (LOW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFL-H</td>
<td>WR-H</td>
</tr>
<tr>
<td>LHS-H</td>
<td>BFBR-H</td>
</tr>
<tr>
<td>CFL-L</td>
<td>WR-L</td>
</tr>
<tr>
<td>LHS-L</td>
<td>BFBR-L</td>
</tr>
<tr>
<td>Died.</td>
<td>Died.</td>
</tr>
<tr>
<td>Massive. Healthy, though some leaves show signs of dieback.</td>
<td>Has grown a lot taller, but has not flowered.</td>
</tr>
<tr>
<td>Generally good.</td>
<td>Died.</td>
</tr>
<tr>
<td>Growing healthy. Appears to have far more biomass than LHS-H.</td>
<td>Died.</td>
</tr>
<tr>
<td>About the same as BFBR-H. Maybe slightly healthier.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CELL 1 (HIGH)</th>
<th>CELL 2 (LOW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBFI-H</td>
<td>GRB-H</td>
</tr>
<tr>
<td>SS-H</td>
<td>BLAR-H</td>
</tr>
<tr>
<td>HBFI-L</td>
<td>GRB-L</td>
</tr>
<tr>
<td>SS-L</td>
<td>BLAR-L</td>
</tr>
<tr>
<td>Very slow growing. Some Tip dieback.</td>
<td>Small, but healthy, flowering.</td>
</tr>
<tr>
<td>Growing well, but infested.</td>
<td>Growing well, flowering.</td>
</tr>
<tr>
<td>Very slow growing, little tip dieback.</td>
<td>Growing big and tall, flowering.</td>
</tr>
<tr>
<td>Consistently healthy, flowering.</td>
<td>A lot of dieback. Still bigger than BLAR-H, though infestation is taking a toll; showing dieback.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CELL 5 (HIGH)</th>
<th>CELL 6 (LOW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFL-H</td>
<td>WR-H</td>
</tr>
<tr>
<td>LHS-H</td>
<td>BFBR-H</td>
</tr>
<tr>
<td>CFL-L</td>
<td>WR-L</td>
</tr>
<tr>
<td>LHS-L</td>
<td>BFBR-L</td>
</tr>
<tr>
<td>-</td>
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</tr>
<tr>
<td>Large, but infested. Some dieback, a lot of fibrous and tuberous roots.</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>Large, but infested. Some dieback. More fibrous roots than BFBR-H.</td>
</tr>
</tbody>
</table>

9/11/15 Final solution change. Pest situation is getting out of hand, possibly due to season, or plant stress.
Table IIB. Weekly plant height and width measurements

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Cell 1 - High Nutrients</strong></td>
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<td></td>
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</tr>
<tr>
<td>NEA - H</td>
<td>8.1</td>
<td>14</td>
<td>10</td>
<td>15</td>
<td>12.8</td>
<td>19.3</td>
<td>15</td>
<td>20.4</td>
<td>16</td>
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<td>18.2</td>
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<tr>
<td>PW - H</td>
<td>11.2</td>
<td>10</td>
<td>14</td>
<td>13</td>
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<td>22.5</td>
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<tr>
<td>SMW - H</td>
<td>24.2</td>
<td>12.5</td>
<td>28.1</td>
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<td>24.1</td>
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<td>29.7</td>
<td>51.6</td>
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<td>SSB - H</td>
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<td>120.8</td>
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<tr>
<td><strong>Cell 2 - Low Nutrients</strong></td>
<td></td>
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<tr>
<td>NEA - L</td>
<td>7.6</td>
<td>15</td>
<td>8.1</td>
<td>16.4</td>
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<td>12.3</td>
<td>18.4</td>
<td>14.2</td>
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<tr>
<td>PW - L</td>
<td>11.4</td>
<td>13</td>
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<td>13.4</td>
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<tr>
<td>SMW - L</td>
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<td>19.1</td>
<td>8.9</td>
<td>24.4</td>
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<tr>
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<td><strong>Cell 4 - Low Nutrients</strong></td>
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<tr>
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<td>33.5</td>
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<td>CF - H</td>
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</tr>
<tr>
<td>CF - L</td>
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<td>35.8</td>
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<tr>
<td>LHS - L</td>
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<td>4</td>
<td>30.1</td>
<td>4.1</td>
<td>32.4</td>
<td>6.4</td>
<td>39.9</td>
<td>9.5</td>
<td>46</td>
<td>10</td>
<td>52.6</td>
</tr>
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<td>BFBR - L</td>
<td>11.6</td>
<td>1.3</td>
<td>14.2</td>
<td>2.5</td>
<td>31.2</td>
<td>3.7</td>
<td>45.9</td>
<td>5.4</td>
<td>52</td>
<td>6</td>
<td>56.5</td>
</tr>
</tbody>
</table>
IIC. Photographic Log (Westhelle, 2015)
Week 1: June 29, 2015 – Installation Day

Cells 1 (High) and 2 (Low). **Clockwise**: New England Aster (NEA), Swamp Milkweed (SMW), Softstem Bulrush (SSB), and Pickerelweed (PW) (Westhelle, 2015)

Cells 3 (High) and 4 (Low). **Clockwise**: Shallow Sedge (SS), Broadleaf Arrowhead (BLAR), Harlequin Blueflag Iris (HBFI), and Green Bulrush (GRB) (Westhelle, 2015)

Cells 5 (High) and 6 (Low). **Clockwise**: Broadfruited Bur-reed (BFBR), Longhaired Sedge (LHS), Cardinalflower Lobelia (CFL), and Wild Rice (WR) (Westhelle, 2015)
Week 2: July 6, 2015

Cell 1 (High) aerial and profile. Note significant growth in stem height in both SSB-H and SMW-H (Westhelle, 2015)

Cell 2 (Low), aerial and profile (Westhelle, 2015)
Cell 3 (High) aerial and profile

Cell 4 (Low) aerial and profile (Westhelle, 2015)
Cell 5 (High). Note dieback on WR-H.

Cell 6 (Low). Some dieback on WR-L, though not as severe as WR-H (Westhelle, 2015)

Cell 2 (low). SSB-L and SMW-L have grown, though slower than high nutrient counterparts (Westelle, 2015).
Cell 3 (High). BLAR-H has not grown much. Some tip dieback on HBFI-H (Westhelle, 2015)

Cell 5 (High) More dieback in WR-H. Gradual growth in other species (Westhelle, 2015)

Cell 6 (Low). WR-L appears healthier than high nutrient counterpart. Quicker rate of growth in this cell (Westhelle, 2015)
Week 3: July 17, 2015

Experimental set up, pre- and post- first solution change Note the increases in height in PW, SSB, and SMW in both treatments (Westhelle, 2015)
Experimental set-up, pre-final solution change. Note the massive growth in SMW, SSB, PW, and BFBR. Suffering health in NEA-H is apparent (Westhelle, 2015)
Cells 1 (High) and 2 (Low), respectively. SMW has flowered by this point. SMW-H and NEA-H are leaning (Westelle, 2015)
Cell 3 (High) and 4 (Low), respectively. Note that GRB-L and BLAR-L are significantly larger than high nutrient counterparts. HBFI appears stunted in both settings. SS is growing about the same in both treatments (Westhelle, 2015)
Cell 5 (High) and 6 (Low), respectively. WR and CFL has perished in both treatments. BFBR and LHS have grown tremendously in both treatments (Westelle, 2015)
Left: CFL-L perished, possibly due to stress or competition in both treatments. Right: PW-H flowering (Westhelle, 2015)
Left: GRB-L flowering. GRB demonstrates a preference for the low nutrient treatment, as GRB-H did not flower. Right: BLAR-L flowering; BLAR grew much larger and flowered faster in the low nutrient treatment (Westhelle, 2015)
LHS-L demonstrating strong root development beneath the mat (Westhelle, 2015)
Cells 1 (High) and 2 (Low), respectively. Overall vigor is winding down. Greenhouse white fly infestation is affecting some species, like SMW (Westhelle, 2015)
Cells 3 (High) and 4 (Low), respectively. GRB-L has flowered, and overall biomass is more prevalent in Cell 4 (Low). BLAR I both settings is experiencing dieback, likely due to the pest infestation (Westelle, 2015)
Cells 5 (High) and 6 (Low). Leaf dieback on BFBR in both treatments is apparent, likely due to pest infestation. LHS-L is more upright and full than LHS-H (Westhelle, 2015)
Cells 1 (High) and 2 (Low), respectively. Both treatments are experiencing a lot of dieback. SMW-L has yellowed more due to pest infestation. PW-H has grown more laterally than upright. NEA in both treatments shows a lot of basal leaf dieback and mold (Westhelle, 2015)

Week 12: September 17, 2015
Cells 3 (High) and 4 (Low), respectively. BLAR-H now appears to be healthier than BLAR-L, which has yellowed and experienced dieback. GRB-L is still much more full than GRB-H. HBFI is still stunted in both treatments, indicating it does not thrive in these conditions (Westhelle, 2015)
Cells 5 (High) and 6 (Low), respectively. BFBR-L appears to have experienced more leaf dieback than BFBR-H, while LHS-L appears to be more full than LHS-H (Westhelle, 2015)
Close up view of greenhouse whitefly infestation (webs, larvae, individuals, and pupae) (Westhelle, 2015)
Right: PW-H; Left: PW-L

Left: SSB-H; Right: SSB-L
Pictured: HBFI-H; Documentation for HBFI-L was lost, though it was comparable in appearance and root length.

Left: GRB-H; Right: GRB-L
Left: SS-H; Right: SS-L

Left: BLAR-H; Right: BLAR-L
Left: BFBR-H; Right: BFBR-L

Left: LHS-H; Right: LHS-L
Appendix III

Water Quality Measurements
Table IIIA. Temperature, conductivity, dissolved oxygen, and pH reported by YSI 556

<table>
<thead>
<tr>
<th></th>
<th>YSI Probe Readings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7/17/2015 (Before solution change)</td>
</tr>
<tr>
<td></td>
<td>Temp (°C)</td>
</tr>
<tr>
<td>Cell 1 - High Nutrients</td>
<td>NEA-H</td>
</tr>
<tr>
<td>Cell 1 - High Nutrients</td>
<td>SMW-H</td>
</tr>
<tr>
<td>Cell 2 - Low Nutrients</td>
<td>NEA-L</td>
</tr>
<tr>
<td>Cell 2 - Low Nutrients</td>
<td>SMW-L</td>
</tr>
<tr>
<td>Cell 3 - High Nutrients</td>
<td>HBFI-H</td>
</tr>
<tr>
<td>Cell 3 - High Nutrients</td>
<td>GRB-H</td>
</tr>
<tr>
<td>Cell 4 - Low Nutrients</td>
<td>HBFI-L</td>
</tr>
<tr>
<td>Cell 5 - High Nutrients</td>
<td>CFL-H</td>
</tr>
<tr>
<td>Cell 5 - High Nutrients</td>
<td>WL-H</td>
</tr>
<tr>
<td>Cell 6 - Low Nutrients</td>
<td>CFL-L</td>
</tr>
<tr>
<td>Total Average</td>
<td>23.51</td>
</tr>
<tr>
<td>Total Minimum</td>
<td>23.19</td>
</tr>
<tr>
<td>Total Maximum</td>
<td>23.85</td>
</tr>
<tr>
<td>High Average</td>
<td>23.51</td>
</tr>
<tr>
<td>Low Average</td>
<td>23.52</td>
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</table>