FLOATING TREATMENT WETLANDS AS A STORMWATER BEST MANAGEMENT PRACTICE IN NORTH CENTRAL FLORIDA

By

NEAL BEERY

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To Wade, Pam, Maria, Kevin, and Megan. Each of you propped me up, gave me something to lean on, and pushed me forward.

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LIST OF ABBREVIATIONS

BMP	Best Management Practice, in the context of water treatment, these are used by resource managers to guide and aid in controlling changes in water quality and quantity
DO	Dissolved oxygen, the amount of oxygen found in water
FTW	Floating Treatment Wetland, an artificial floating island or mat, installed in stormwater systems, on which plants grow
MAPS	Managed Aquatic Plant Systems, a best management practice which utilizes growing plants for the use in stormwater treatment
TMDL	Total Maximum Daily Load, the allowable upper limit of a constituent found in waters of the State
TSS	Total Suspended Solids, the amount of solids found in water that can be filtered out using a filter of a determined pore size

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Neal Beery

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Chair: Mark Clark
Cochair: George Hocmuth
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Floating treatment wetlands (FTWs) are being considered to reduce pollutant loads associated with non-point sources. FTWs are artificial floating islands or mats, installed in stormwater systems, on which plants grow. The plants utilize nutrients found in stormwater and assimilate nutrients and other constituents within their tissues.

Three FTWs were deployed in stormwater systems in Gainesville, Florida over the course of one growing season. Plant biomass was harvested and analyzed for biomass, carbon, nitrogen, phosphorus, zinc, copper, cadmium and chromium content. The goal of the study was to determine the overall efficacy of FTWs and their various component parts to assimilate contaminants from within a stormwater basin.

The average (m^{-2} d^{-1}) mass assimilation of the FTWs were as follows: biomass 6.86±4.78g, carbon 2.52±1.75g, nitrogen 0.115±0.074g, phosphorus 15.3±8.8mg, metals ranging from a high of zinc (0.311±0.330mg), to a low of cadmium (0.0008±0.0009mg). Mass assimilation (m^{-2}) for the above-mat zone was highest with biomass of 856.2±649.1g, carbon 322.8±44.1g, nitrogen 9.5±6.2g, phosphorus 0.9±0.42g, metals ranging from a high for zinc (39.2±46.4mg), and cadmium with

unmeasurable amounts. The planted species with the highest biomass assimilation (m^{-2}) were *C. flaccida* (306.4±392.6g) and self-recruited species (296.2±174.4g).

It was concluded that FTWs can be an effective stormwater BMP, that *C. flaccida* and species that that self-recruited during the period of deployment were most effective in the study's conditions. It was also concluded that focusing on the FTW components above and below the plastic matrix allowed for the most constituents to be harvested.

CHAPTER 1
INTRODUCTION

Stormwater Management

Impairment of Natural Waterbodies

Surface water quality in many areas around the world is greatly affected by pollutants associated with human activity in both urban and agricultural settings. Pollutants are defined as natural or artificial substances that occur in concentrations harmful to the environment (United Nations, 1997). In the context of water systems, pollutants include nutrients in excess of a system's natural load, suspended particulate matter, heavy metals and other chemicals from human-manufactured materials (Mitsch et al., 2000). Water quality problems arise when these pollutants are physically transported from upland sources, or are directly released into water bodies through human activities (Lee and Bang, 2000).

Degradation of surface water quality through pollution is widespread, including in Florida, where an estimated 550 square miles of estuaries, 2,000 miles of rivers and streams, and more than 375,000 acres of lakes were found to have excessive nutrient concentrations, with other types of pollutants affecting still more of Florida's water bodies (FDEP, 2010a). Criteria that set the maximum threshold for pollutants found in waters of the state are part of the Federal Clean Water Act which seeks to protect water resources for continued human use and natural function by setting specific maximum values of pollutants that cannot legally be exceeded (FDEP, 2010a; Chapter 403, Florida Statutes, Section 304.067).

The most common pollutants affecting Florida waters include nitrate, nitrite, ammonia, phosphorus, *E. coli*, petroleum hydrocarbons, mercury, aluminum, lead, cadmium, chromium, copper, zinc, and suspended solids (Harper and Baker, 1997). The quality of water resources is important for the well-being of humans (drinking water, irrigation, recreation) and natural systems (biodiversity, ecological function) (Wanielista et al., 2012). Protection of these resources through pollution control is required to ensure their continued use (Hubbard, 2010; Fulcher, 1994; US EPA, 2009; Chapter 62-40.431, F.A.C.).

Management of Stormwater Runoff

Increases in human population and their subsequent activities have led to extensive conversion of land to more intensive management and an increase in impervious surfaces such as roadways, sidewalks, parking lots, and conventional roofs. This increase in impervious area, combined with the additional loading of previously mentioned pollutants has led to the detriment of natural water systems. As more surface area becomes impervious, the volume of precipitation that is able to percolate into the ground during and after a precipitation event decreases, thus exacerbating stormwater runoff issues of both quantity and quality (Staddon, 2011).

The United States Environmental Protection Agency (2009) has recognized urban stormwater runoff as one of the major contributing factors to the decline in surface water quality in the United States. In urban settings, pollutants in the form of excess fertilizers, organic debris, oil and grease from vehicles and equipment, or manmade substances (such as residue from the wearing of vehicle brake pads), can be carried by stormwater runoff, water that runs laterally over the landscape (US EPA, 2007).

Stormwater runoff is often collected in retention and detention systems either for temporary or long term storage, whereupon it can be released as surface water into natural water bodies or percolate into soil as groundwater. These systems were originally designed and built mainly for flood control and not for removal or control of pollutants (Wanielista et al., 2012). New designs, techniques and technologies are being considered and implemented in order to address the increased pollutant loads associated with non-point source pollution. These efforts have focused on incorporating treatment as a main goal of newly constructed stormwater basins, as well as the retrofitting of older basins to include a variety of best management practices (BMPs) that address pollution. These technologies may include entirely human-constructed mechanisms such as baffle boxes, or designs that incorporate natural organisms (such as algae and macrophytes) and systems such as constructed wetlands into the treatment process. Examples of wetland treatment technologies include shallow littoral zones that allow for the growth of emergent macrophytes in stormwater basins or systems that utilize floating macrophytes positioned in open water areas of a wet detention basin (FDEP, 2010a; Headley and Tanner, 2006).

Deficiencies in Stormwater Regulation

Stormwater management and regulation began with the goal of flood control (quantity of stormwater) but this focus is shifting focus to include management for pollutants that enter water bodies and groundwater (quality of stormwater). Florida regulations regarding stormwater have been updated over the past forty years to include goals for water quality as well as quantity. The “Water Resource Implementation Rule”, (Chapter 62-40 F.A.C.) states that “the discharge from … [stormwater management] systems will comply with the State water quality standards.” If the source of water pollutants cannot be reduced through management, education or regulation, then in order to comply with Florida regulation, efforts will be necessary to address the removal of pollutants from managed retention systems and possibly natural systems.

Stormwater regulation in the late 1970's permitted land development on a qualitative basis, such that the stormwater discharge of an applicant being determined "insignificant" or "significant" would require efforts to store stormwater runoff (Chapter 17-4.248, F.A.C.). This regulation was updated in 1982 with Chapter 17-25 of the F.A.C., which required stormwater permits for all new stormwater discharges and required retrofits for discharges that saw increases in flow or pollutant loading; this legislation did not include the use of BMPs for treatment of stormwater quality. The current criteria for stormwater treatment in Florida were set in 1995 by Chapter 62-40 of the F.A.C. This criteria states that a minimum of 80% of the average annual load of pollutants of concern must be removed by stormwater treatment systems; additionally, a stormwater system that discharges into an Outstanding Florida Water (water bodies that are "worthy of special protection because of their natural attributes") must remove 95% of the average annual pollutant load (FDEP, 2012). However, the state's stormwater rule does not currently include incentives to utilize newer technologies and techniques that would bring new stormwater treatment systems closer to meeting the new criteria (Livingston, 2009).

Harper and Baker (2007) state in their report to the Florida Department of Environmental Protection (FDEP) that several commonly used stormwater systems often do not meet set criteria for stormwater treatment (Table 1-1). Their study compiled mean performance efficiencies of ten stormwater management systems (all were wet detention systems that had close to 14-day residence times). Mean performance efficiencies were as follows: total nitrogen reduction was 37%, total phosphorus reduction was 69%, TSS reduction was 77%, and reductions of copper and zinc metals was 69% and 85%, respectively. This data suggests that the level of treatment efficiency in these systems is not adequate to meet the current or proposed requirements set forth by Florida's stormwater quality criteria. This failure of current stormwater treatment design to meet criteria is at least in part contributing to the number of the State's water bodies impaired by pollutants (US EPA, 2007; US EPA, 2009).

Proposed New Statewide Stormwater Rule

According to a 2009 presentation by Dr. Eric Livingston, Chief of FDEP's Bureau of Watershed Management, new regulation on the design and implementation of stormwater treatment systems was proposed and began development in order to update Florida's stormwater management and address the issue of current stormwater treatment failing to meet permit design criteria (Livingston, 2009). As of January 2013, the new regulation was still under development. This new regulation, generally referred to as the Statewide Stormwater Rule, will sometimes be referred to as the Rule in this thesis. Within the most recent draft of this new rule's Applicant's Handbook, provisions have been set for the design and implementation of particular BMPs (FDEP, 2010b). The new Rule also proposes that, for most discharge permits, the performance of new or retrofitted stormwater systems must meet the following requirements: either, reduction by 85% of pollutant loading that are attributable to development, or the pollutant loading must be less than or equal to the amount of pollutant loading prior to any development of the land, whichever is less (FDEP, 2010b).

One of the BMPs identified in Section 14 of the Draft Applicant's Handbook, sets design criteria for use of Managed Aquatic Plant Systems (MAPS), which includes the use of floating wetlands. Floating wetlands are described in the Handbook as islands or mats on which plants grow, utilizing nutrients found in stormwater and accumulating nutrients and other constituents of stormwater within their tissues. The Handbook recognizes that removal of biomass from the floating wetlands and transportation of this biomass away from the stormwater treatment system allows for nutrients and other constituents of concern to be removed from the stormwater system (FDEP, 2010b).

The Handbook indicates that when floating wetlands are applied as a BMP within a stormwater treatment system, the proposed nutrient reduction credit is 20%-40% for both total nitrogen and total phosphorous. This proposed range of nutrient removal is a significant portion of the proposed 85% removal criteria (as well as the existing 80% removal criteria), and implies that floating wetlands and other MAPS, when properly utilized, may be an effective tool for permit applicants seeking to boost the performance of their stormwater treatment system.

Section 14.4 of the Draft Applicants Handbook sets out criteria for the use of floating wetlands as BMPs. Figure 1-1 is an excerpt from the Handbook that describes these criteria (emphasis and notes are from the source) (FDEP, 2010b).

If the Statewide Stormwater Rule is adopted into Florida law with an Applicant's Handbook containing provisions for floating wetlands as MAPS, the amount of treatment credit awarded to floating wetlands could motivate many stormwater managers to install these systems. The environmental products firm that provided the floating wetland MAPS design for this research wished to construct and evaluate performance of their system so that they could determine treatment credit that would be allotted when marketing their systems in order to meet probable demand from stormwater managers seeking to boost stormwater treatment system performance.

Floating Treatment Wetlands

Naturally Occurring Floating Wetlands

In naturally occurring floating wetlands, the general components are the mat (substrate made of live and dead organic, mineral, trapped gases and vegetation roots and rhizomes), roots extending below the mat, leaf and shoot biomass extending above the mat, the free water within and below the wetland, and in some cases a layer of organic matter that rests below the wetland which has sloughed off the mat (Sasser et al., 1991; Clark, 2000). Figure 1-2 depicts these components in a constructed floating wetland.

In North America, floating wetlands are most prevalent in Louisiana where they occur in both freshwater and brackish coastal marshes of the Mississippi River Delta (Sasser, 1994). They are also found in Arkansas, Georgia and Florida, where they are found inland in freshwater systems (Sasser and Gosselink, 1984; Clark, 2000). Floating wetlands can be found in varying forms throughout the world, and are also known as flotant (Sasser, 1994), tussocks, floatons or sudds in their respective locales (Mallison et al., 2001).

Floating wetlands can exhibit great ecological differences from the rooted wetlands in adjacent littoral zones. They create conditions and behave in ways that make them ecologically important and distinct from rooted wetlands (Sasser, 1994). Their flotation allows them to escape the effects of hydropattern (depth, duration, frequency of flooding) that other rooted wetlands are subjected to, which in turn influences vegetation, biogeochemical processes, and wildlife. The hydrologic regime of the adjacent rooted wetland can exhibit fluctuations that causes vegetative succession to favor plants that can cope with changes or are best suited for the prominent flooded conditions, while floating wetlands hydrologic regime remains relatively stable unless their buoyancy is altered or the water body in which they float is no longer as deep as their mat (Sasser, 1994).

Floating wetlands in different regions have a variety of plant species that grow upon them. Even in the same region, such as Orange Lake in Florida, floating islands can be dominated by different plant species; Mallison et al., (2001) describe floating wetlands dominated by pickerelweed (*Pontederia cordata*) growing in close proximity to floating wetlands dominated by Cuban bulrush (*Scirpus* cubensis) and *Hydrocotyle* sp.. This is of interest not only for the apparent variety in species that colonize the wetlands, but also for the characteristics of the species themselves. Also in Orange Lake, Mallison et al. (2001) observed floating wetlands with wetland obligate species such as cattail (*Typha latifolia*), in addition to broom sedge (*Andropogon virginicus*) and dog fennel (*Eupatorium capillifolium*), both of which are facultative species, meaning they are able to live in both moist and non-flooded conditions, but not necessarily flooded conditions.

The presence of wetland and non-wetland plants is important to note because it shows that on a single floating wetland, the hydrologic conditions can be such that a plant which thrives in anaerobic conditions and a plant that cannot tolerate permanently flooded conditions can be supported (Mitsch and Gosselink, 1997). A wide variety of vegetation types can be found on floating wetlands, mostly wetland plants due to the stress of low oxygen in most of the mat. The plant species may determine the buoyancy or longevity of the floating wetland, as the plant litter can accumulate and provide substrate for other species to colonize. This is especially true when the floating wetland's mat was formed by free-floating plants (such as *Hydrocotyle* sp.) creating a nucleus and then accumulating enough substrate for plants that require some sort of support (Clark, 2000).

The biomass assimilation of floating wetland plants varies as widely as the plant species that are found on the wetlands. Sasser (1994) found *Hydrocotyle* sp. to have a biomass assimilation rate of 0.12 g m^{-2} yr^{-1}, whereas, in the same region of Louisiana, maidencane (*Panicum hemitomon*) had a rate of 636.17 g m^{-2} yr^{-1}. Assimilation of floating wetland biomass is linked to drivers similar to that of rooted wetlands, without the important characteristic of flooding depth (Clark, 2000). Water is constantly available to a floating wetland, and thus so long as the plant species on the wetland are supplied with ample nutrient resources for growth they are able to assimilate biomass. This is not true of rooted wetlands where a drop in water level can drive productivity down due to the lack of water.

The main driver for Assimilation in floating wetland plants is often nutrient availability, since the plants are not connected with the geological substrate they do not have the soil as a source of nutrients (Mallison et al., 2001). In this way, hydropattern can have an indirect effect on floating wetlands, such as when an influx of sediment brings new nutrients into a waterbody (Clark, 2000). In the same sense, the productivity of floating wetlands can increase in water bodies undergoing eutrophication due to human nutrient inputs. Floating wetlands can be thought to be growing 'hydroponically', and therefore, other than climactic influence (such as wind, solar irradiance, humidity), the principal driving force for their Assimilation is the physical and chemical constituents of the water they are growing in (Headley and Tanner, 2006).

Constructed Floating Treatment Wetlands (FTWs)

Floating treatment wetlands are an emerging technology which can be used for removing nutrients and pollutants from stormwater and agricultural runoff. They behave in much the same way that natural floating wetlands do (Figure 1-3), but are designed, deployed and maintained by humans, instead of occurring naturally. Certain considerations in their design and maintenance must be made since FTWs may be deployed in already functioning stormwater treatment systems, natural water bodies, and in close proximity to humans and wildlife (Hubbard, 2010).

Constructed FTWs are comprised of the same basic components as that of natural floating wetlands, that is, emergent macrophytes rooted in a floating mat, suspended over free water (Headley and Tanner, 2006). The macrophytes can either be rooted in growing media or affixed some other way to the mat (Headley and Tanner, 2011). The mat, which is typically the constructed portion of the FTW, can be made of plastic or organic materials such as coconut fiber or bamboo, and can be rigid or flexible. The mat gives support and buoyancy to the macrophytes on the floating wetland (Headley and Tanner, 2006).

In natural ecosystems, floating wetland plants die and senesce which allows nutrients and other components to leach into the water column (Sasser et al., 1991). Constructed floating treatment wetlands function in much the same manner as natural floating wetlands, including the return of nutrients to the water column through senescing vegetation. This makes a harvesting plan for floating treatment wetlands necessary if optimizing nutrient removal is the principal objective. Therefore, at least a portion of the vegetation biomass growing on FTWs deployed for pollution control must be harvested seasonally in order to remove the plant-bound nutrients or pollutants from the system (Headley and Tanner, 2006).

A unique opportunity is available for the utilization of floating treatment wetlands due to their sole source of nutrients being the water column in which they float. When compared with rooted wetlands, floating wetlands would be a better option for some water quality treatment purposes, such as the removal of nutrients and other pollutants in a basin with fluctuating water depth, since constructed floating treatment wetlands behave in the same way as natural floating wetlands with respect to hydropattern. For example, if a stormwater pond receives runoff in seasonally varying amounts, thus causing the water level to rise or fall, emergent vegetation on the littoral shelf may not be in contact with the pollutant-laden water during certain periods, and can even die or be displaced by species that thrive in the drier conditions. Utilizing floating wetlands to provide treatment of the water may be more reliable since the wetland will rise and fall with water levels, thus providing treatment at all stages of the hydropattern.

This approach to water treatment has been studied in Auckland, Australia as well as Germany, India and the United States (Headley and Tanner, 2008). Several studies have been done in the past five years (Chua et al., 2012; Wanielista et al., 2012; DeBusk et al., 2004; Stewart et al., 2008), at the laboratory, mesocosm, and pond-sized scales, though as recently as 2006 Headley and Tanner reported that “published data on the treatment performance of the various FTW applications are limited”. A brief summary of some of the performance data for floating treatment wetlands in stormwater applications can be found in Table 1-2.

Additionally, using a mesocosm scale study, Van de Moortel et al. (2010) found that FTWs have proven to be effective at removal of nitrogen, phosphorus, total organic carbon, and several heavy metals, when compared to a control group with no FTW. Average removal efficiencies of FTWs for TN, and TP were 42% and 22% respectively, compared to 15% and 6% for the control.

Objectives and Hypotheses

Objectives

The possible adoption of a unified Rule for Florida's stormwater managers served as impetus for this research. The new statewide Rule and its inclusion of Managed Aquatic Plant Systems (such as floating treatment wetlands) increases the possibility that these BMPs could be prevalent across the state. Their possible prevalence increases the importance of determining the actual performance of FTWs.

As stated earlier, impairment of the State's water bodies is closely linked to the quality of stormwater that enters waters of the state. Allotting more treatment credit to floating wetlands than is justified by their actual performance could allow for stormwater treatment systems to be permitted without meeting the legal 80% (or proposed 85%) nutrient reduction criteria. This failure to meet the reduction criteria could impact Florida's water bodies, causing more impairment to the State's water resources. Therefore, it is important to the natural resources of Florida that research is carried out which evaluates the efficacy of floating wetlands used as BMPs. Furthermore, the methods used to evaluate the efficacy of floating wetland MAPS permitted for use in stormwater treatment systems must become standardized and accurate. This is to ensure that new floating wetland designs are tested equally and so floating wetlands installed as MAPS are as effective as the treatment credit they are allotted.

This research project sought to deploy floating treatment wetlands in actual stormwater retention settings in order to determine the ability of floating wetlands to take up nutrients and heavy metals, as well as to determine possible issues pertaining to the maintenance efforts of FTWs for maximum benefits as stormwater BMPs.

Hypotheses

- H1: Floating treatment wetlands assimilate total carbon (TC), total nitrogen (TN), total phosphorous (TP), cadmium (Cd), chromium (Cr), copper (Cu), and zinc (Zn).
- H2: Within floating treatment wetlands there is an edge effect where more TC, TN, TP, Cd, Cr, Cu, and Zn are assimilated by the outer portions of the floating wetland than the inner portion.
- H3: Macrophyte species planted on floating treatment wetlands that have been shown in previous field studies to assimilate more TC, TN, TP, Cd, Cr, Cu, and Zn than other species will assimilate more nutrients or metals.
- H4: Partitioning of nutrients (TC, TN, TP) and metals (Cd, Cr, Cu and Zn) below the mat (roots) within the mat (rhizomes) and above the mat (petioles and leaves) will be different and follow similar distribution patterns to previous field studies.

Table 1-1. Treatment efficiencies for wet detention systems based on selected research studies in Florida; from Harper and Baker, 2007, pp. 5-8.

Location, Land Use	Reported Removal Efficiency (%)			
	TN	TP	Zn	Cu
Brevard County, FL, Commercial	--	69	--	--
Boca Raton, FL, Residential	12	55	--	--
Maitland, FL, Highway	35	81	92	56
EPCOT, FL, Highway	44	62	88	
Orlando, FL, Urban	--	38	--	--
Orlando, FL, Residential	--	91	96	90
DeBary, FL, Commercial & Residential	30	70	95	50
Tampa, FL, Light Commercial	--	65	51	--
Tampa, FL, Commercial	63	90	87	55
Melbourne, FL	36	65	--	92
Mean	37	69	85	69

Table 1-2. Summary of performance data for total phosphorus (TP), total nitrogen (TN) and biomass removal for a variety of floating treatment wetlands.

Study	Removal (g m^{-2} day^{-1})		
	Biomass	TN	TP
Debusk, Dierberg and Reddy (2001)	42		0.031 - 0.370
Hubbard, Gascho and Newton (2004)	33.9	0.046 - 1.096	.006 - 0.162
Chua et al. (2012)		0.002 - 0.0160	.0002 - .0016
Tanner et al. (2011)		0.16 - 0.24	.0023 - 0.0054
Wen and Recknagel (2002)			0.043 -0.086
White (2009)			0.001 - 0.002

Floating Wetland Design Criteria: (SUBJECT TO CHANGE AS MORE DATA BECOMES AVAILABLE)

(a) The area of floating wetland mats shall be at least five percent (5%) of the surface area of the wet detention pond. (What about load reduction if > 5%)

(b) The floating wetland island or mats shall use a variety of plants that have been documented to have high nutrient uptake in their plant tissues. Some proven plants include Canna flaccida, Juncus effuses, Spartina spp., Pontederia cordata, ADD TO LIST/EDIT

(c) Floating wetland mats or islands shall be installed and maintained in accordance with permitted design specifications and the manufacturer's instructions.

(d) Where necessary, exclusion netting shall be used on floating islands or mats to prevent turtles, grass carp, or other animals from eating the plant roots or plants such that they adversely affect the successful growth of the aquatic plants. The applicant may propose alternative mechanisms to minimize eating of plant roots or plants based on an affirmative demonstration, based on manufacturer's recommendations, plans, test results, calculations or other information, that the alternative design is appropriate for the specific site conditions and will meet the above considerations.

(e) Within 6 months of installation, the floating wetland island or mat shall have at least 90 percent coverage with no more than 10% consisting of exotic or nuisance species.

(f) Plants on the mats or islands shall be removed and replaced at a minimum on an annual basis. The harvested plant and potting materials shall be removed and disposed of in such a manner that nutrients will not re-enter the stormwater treatment system.

Figure 1-1. Floating wetland design criteria, an excerpt from the draft rule handbook (FDEP, 2010b).

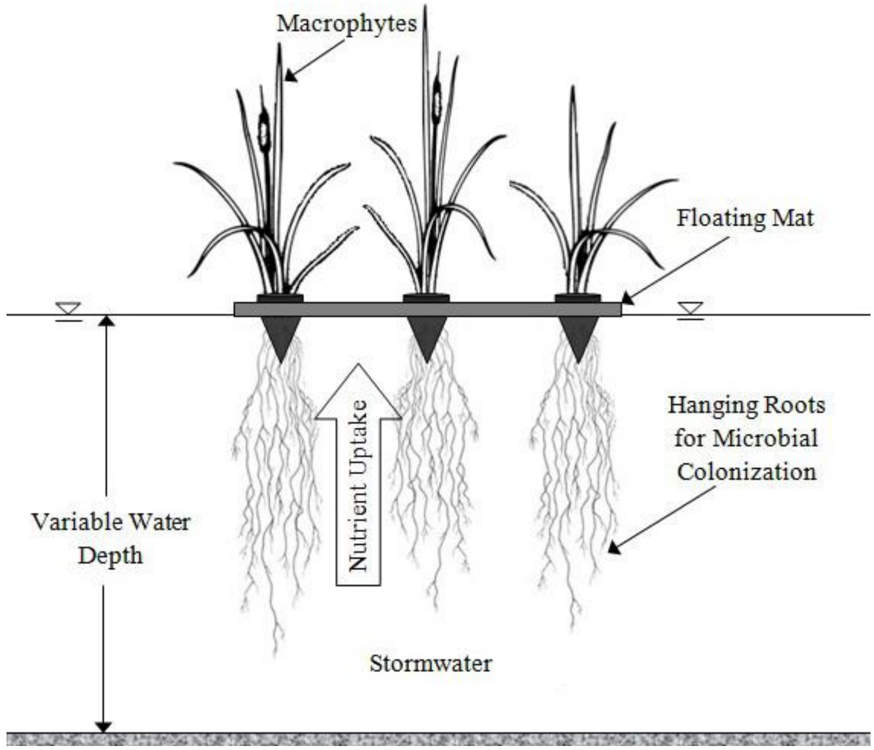


Figure 1-2. Components of a floating wetland; source: Wanielista et al., 2012.

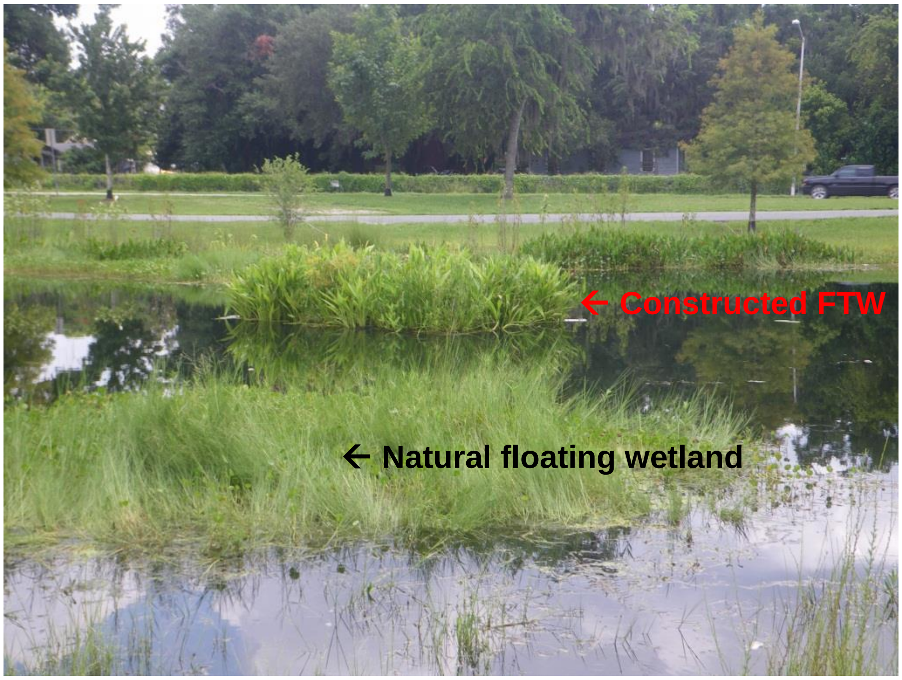


Figure 1-3. A natural floating wetland (foreground) and constructed floating wetland (background), photo courtesy of Neal Beery.

CHAPTER 2
MATERIALS AND METHODS

Floating Treatment Wetland Design

The FTWs for this research were constructed and maintained by following the instruction of ACF Environmental Inc., who provided the materials, design and on-site assistance in the construction and deployment of the FTWs. Each FTW consisted of three 1.22 m by 2.44 m positively buoyant plastic panels strung together with nylon rope to create a single mat 2.44 meters wide by 3.66 meters long with an area of 8.93 m^2 (Figure 2-1). Sealed 1 inch PVC pipes, running along the width of the each individual panel, were installed within the matrix to add buoyancy. Each panel consisted of a composite open cube matrix 5 x 5 cm square with 4 cm diameter circular holes throughout (Figure 2-2). Each 1.22 m by 2.44 m section will be referred to as a Panel, and all three attached Panels installed with macrophytes will be referred to as a Floating Treatment Wetland (FTW).

Three species of wetland plants were used to initially populate each floating treatment wetland: *Juncus effusus* (common rush), *Pontederia cordata* (pickerelweed), and *Canna flaccida* (canna). ACF Environmental was responsible for choosing and supplying the plant species used. The plants were supplied as bare root individuals washed clean of soil and substrate.

Each FTW was planted by placing the individual plants through the holes in the plastic matrix so the roots extended below the mat and the petioles extended above the surface in the manner of emergent macrophytes. Cable ties were used to secure the individual plants to the plastic matrix when the young plants were too small to remain fixed in place. Approximately thirty to fifty ‘clumps’ of each species were planted on each wetland in a generally random pattern with approximately three clumps per square foot. A ‘clump’ consisted of between one and three individuals of a species inserted into one hole of the plastic matrix. This planting pattern was overseen by employees of ACF Environmental. Exact numbers of clumps for each Site are found in Table 2-1.

An anchor was tied to a PVC pipe that was fixed to one corner of the FTW, with the PVC pipe secured to the platform (Figure 2-3). The anchor was installed in order to keep the FTWs from migrating toward the shore, thus keeping the conditions consistent over time. An anchor scope ranging from 3:1 to 5:1 was used to allow each FTW to pivot within the free water but prevent the FTW from running into the littoral zone. The PVC attachment was fixed to the platform in order to keep it from cropping plant material if the PVC attachment were to swivel around. At each site, the Panel affixed with the anchor attachment was referred to as Panel A, the middle Panel was referred to as Panel B, and the Panel furthest from the anchor attachment was Panel C (Figure 2-4).

Each FTW was towed by canoe to the area in which it would remain anchored for the duration of the study. Each area was determined to have adequate depth and clearance from any possible obstructions. Where possible, photographs were taken of the floating islands from each end of the three Panels making up the platforms in order to provide visual documentation of plant growth and condition over the period of the study.

Study Area

The City of Gainesville, located in north-central Florida (latitude 29°65’N, longitude 82°32’ W), has a humid subtropical climate, and receives an average annual rainfall of 122.8 cm. In the summer months, the minimum and maximum daily mean temperatures are 18°C and 35°C, respectively, and the daily mean relative humidity is 67%. In the winter months, minimum and maximum daily mean monthly temperatures are 4°C and 22°C, respectively and the daily mean relative humidity is 76% (Irmak et al., 2002; NOAA, 2012). The Gainesville area experiences its peak evapotranspiration rate in May, with the mean rate of 146 mm month^{-1}, and its minimum evapotranspiration rate in December, with the rate of 52 mm month^{-1} (Irmak et al., 2002).

Over the study period, which ran from March 9th, 2010 through December 12th, 2010, a weather station (approximately 10 miles north northwest of the study sites) received 75.3 cm of rainfall, and experienced an average daily minimum temperature of 16°C and an average daily maximum temperature of 29°C, an average relative humidity of 79%, an average windspeed of 7.06 km hr^{-1}, and an average evapotranspiration rate of 97 mm month^{-1} (FAWN, 2012). The climactic data for the study period seemed to fall within normal ranges for the region.

Site Descriptions

The study locations, which will be referred to as SS1, SS2, and SS3, consisted of three individual stormwater catchment basins in Gainesville, Florida (Figure 2-5).

All sites were located in areas of disturbed urban soils (UF CALM, 2012; USDA, 2012) and were in close proximity to roadways, parking lots, conventionally roofed buildings, and other developed surfaces from which they received stormwater runoff. These sites were chosen for their variety of possible characteristics, which were anticipated to be representative conditions of variation found in stormwater ponds. All sites were located in developed urban areas and so were expected to exhibit elevated nitrogen levels (Harper and Baker, 2007). One site, SS3, was also suspected to receive high levels of heavy metals due to its proximity to industrial runoff from a transit bus parking lot and maintenance area (Bringham et al., 2002).

Water quality data was taken at the three sites intermittently during the study period (Table 2-2). For TN and TP, water samples were taken from the ambient water near, but not under, each FTW by taking grab samples at approximately 35 cm deep. Samples were preserved with concentrated sulfuric acid, stored at 4°C until they were submitted for analysis. Analysis was performed by the UF/IFAS ANSERV Advanced Research Laboratory. TSS samples were analyzed according to EPA Method 160.2. A YSI multi-parameter probe was used to determine temperature, pH and DO (dissolved oxygen).

As a comparison with other stormwater runoff characteristics, Table 2-3 was recreated from a table from Harper and Baker (2007), which compiles data from stormwater runoff characterization studies performed in several parts of Florida. In comparison to the overall means, SS1 and SS3 had comparable TN and higher TP concentrations whileSS2 had lower TN and TP concentrations. It must be noted, however, that the Harper and Baker study was a compilation of data for the water quality of stormwater runoff itself, not for the water column of stormwater basins. TSS levels for SS1, SS2 and SS3 were similar to that of another study, performed in Tampa, Florida, which reported TSS levels for three stormwater ponds as ranging between 4 and 10 mg L^{-1}. These levels are considered normal to low for stormwater wet retention ponds (Rushton et al., 2004).

SS1 was located on Lake Alice, a small lake and stormwater catchment basin on the southwestern portion of the University of Florida campus (Figure 2-6, Figure 2-7). It is a eutrophic lake of approximately 81 acres that receives runoff from much of the University of Florida campus (Mitsch, 1976; UF CALM, 2012). During the period of this study, grass carp, turtles, alligators and a wide variety of water birds were seen at the site.

The area of land that drains to Lake Alice covers a surface area of 1,106 acres, of which an estimated 42% is impervious. The calculated pollutant removals originally permitted for the stormwater treatment system were as follows: TN removal of 15,874.6 kg yr^{-1},TP removal of 4,538.0 kg yr^{-1}, TSS removal of 507,209.5 kg yr^{-1}, Zn removal of 32.6 kg yr^{-1}, Cu removal of 14.9 kg yr^{-1}, Cr removal of 16.2 kg yr^{-1} (SJRWMD, 2010).

SS2 was located on a stormwater pond on SW 6th Street at Tumblin Creek Park (Figure 2-8, Figure 2-9). Tumblin Creek Park is a small recreational park located adjacent to Tumblin Creek and falls within the creek's watershed. According to the original permit, the stormwater pond covered an area of 1.08 acres, received the first flush of runoff from a developed area of 50.6 acres (approximately 70 percent of which is impervious), provided 3673 m^3 of water quality treatment volume, and discharges treated stormwater into Tumblin Creek. The calculated pollutant removals for the permitted stormwater treatment system were as follows: TN removal of 128.67 kg yr^{-1},TP removal of 19.10 kg yr^{-1}, TSS removal of 9,457.00 kg yr^{-1}, Zn removal of 15.42 kg yr^{-1} (SJRWMD, 2011; SJRWMD 2002).

The stormwater pond at SS2 was constructed with a littoral shelf, which is a stormwater BMP in which a shallow area with a low slope supports the growth of emergent macrophytes (NCDENR, 2005). The photograph in Figure 1-3, which depicts a natural floating wetland in the foreground, was taken at SS2 during the course of this study. The perimeter of this stormwater pond is populated with emergent macrophytes and natural floating wetland mats.

During the period of study it was noted that the Tumblin Creek Park stormwater retention system is maintained for aesthetic value with the use of a product similar to Aquashade®, a blue dye that absorbs solar radiation of the wavelength that is useful to photosynthetic plants. These types of dyes are often used to control algae and aquatic plant populations within water bodies, thus promoting water clarity. The shading provided by these blue dyes has been found to decrease the growth of aquatic plants due to shading of light (Manker and Martin, 1984). This decreased growth in aquatic plants may have had some effect on increased nutrient availability, and thus the growth of the FTW macrophytes, at this site.

SS3 was located on a stormwater pond adjacent to the Gainesville Rapid Transit System (RTS) Downtown Station on SE 10th Avenue (Figure 2-10, Figure 2-11). This approximately 1.5 acre stormwater pond is located in a stormwater park maintained for water storage, treatment and general aesthetic value. This pond was designed to receive runoff from the parking and maintenance lot for busses at the Gainesville RTS Main Street Station. A variety of wetland and upland species were found growing in a densely populated buffer zone and littoral zone surrounding the pond.

Early in the study period, *Hydrilla verticillata*, a non-native submersed aquatic macrophyte, was found growing thickly throughout the pond. Sometime during the study period the presence of *H. verticillata* severely declined. It was unknown whether this was due to management efforts (such as with the use of an aquatic herbicide, that may have affected the FTW located at this site) or natural factors. It was anecdotally mentioned by a stormwater manager for the site that treated wastewater effluent may have been discharged into the stormwater pond for a short period at the beginning of the study, but was cut off at some point. This could not be confirmed, but also may have played a role in the nutrient dynamics affecting the *Hydrilla* population as well as the FTW.

Methodology

Initial Macrophyte Sampling and Analysis

On March 31, 2010, after a 22 day period of acclimation post planting, each FTW site was visited for the purpose of taking initial macrophyte samples. Each species of originally installed macrophyte was sampled to determine the initial tissue concentration for the constituents of interest. Additionally, the initial biomass of each Panel was calculated using these samples by multiplying the mean mass of the six sampled clumps (two clumps of each species from each of the three FTWs) by the number of clumps installed on each Panel.

Two clumps of each species were taken from each FTW for initial sampling. One clump was taken from Panel A and a second clump was taken from Panel C near the anchor attachment edge. The clump sampled was the one occurring closest to a target point 45 cm from the edge in the center of each Panel as shown in Figure 2-12. Macrophyte samples were kept on ice and were sorted and processed for analysis off-site. Each clump was rinsed, the number of individual plants per clump was recorded, and each clump was separated with scissors into categories of petiole (live and dead), rhizome and root (Figure 2-13).

Plant tissue samples were dried at 45^{o}C for a minimum of ten days. The tissue was then ground using a ball mill. Tissue was ground into a homogenous powder that could pass through a 2 mm sieve and stored in opaque plastic scintillation vials until submittal for analysis. Plant tissue analysis was performed by the UF/IFAS ANSERV Advanced Research Laboratory in Gainesville, Florida. Samples were analyzed for concentrations of total nitrogen, total phosphorous, total carbon, cadmium, copper, chromium and zinc.

Final Harvest and Analysis

On December 2, 2010 macrophytes of SS3 and Panels A and B of SS2 were harvested. On December 17, 2010 macrophytes of Panel C of SS2 were harvested, and on December 22, 2010 macrophytes of SS1 were harvested. The protocol for harvesting the macrophytes of the respective FTWs follows.

While still floating in situ, the depth between the water surface and the plastic matrix was measured at the midpoint of the outer edge of each (see the red 'x' in Figure 2-14). Photographs of the macrophytes on each FTW were also taken. Each FTW was towed to shore by canoe. Each of the three Panels of the respective FTWs were separated and photographs of the top and bottom of each Panel were taken when possible.

Prior to harvesting, a survey for species richness was taken by visually looking over each Panel and clipping a small sample of each species found for later identification. After identification, these clippings were reincorporated into their appropriate species designation.

Each Panel was harvested separately. The harvest was separated into three vertical biomass zones relative to the plastic matrix that made up each mat. These zones were Above Mat, Mat, and Below Mat (Figure 2-15). Above Mat biomass was harvested by cutting macrophytes down to where their rhizomes began (live and senesced petioles and leaves were considered Above Mat biomass, but rhizome and root structures, even if they were physically above the plastic matrix were not). For the Above Mat Zone, biomass was sorted by the three initially installed Species (*P. cordata, C. flaccida, and J. effusus*) and a fourth group of ‘Other’ consisting of all other species of macrophytes.

The Below Mat Zone was harvested by shearing off all biomass (including any rhizome, root or any other plant structure) found below the plastic matrix; special care was taken to get as close to the plastic matrix as possible. No sorting by species was done for the Below Mat Zone, as physically identifying and separating clustered root structures was not possible.

For the Above Mat and Below Mat Zones, sub-samples were taken when the biomass exceeded an amount that would be practical for the tissue drying and grinding process. This estimation was conducted by a visual examination after each FTW was brought ashore; only site SS2 required sub-sampling. When sub-samples were taken, the wet mass of all harvested biomass was determined using a top-loading scale. Then, manageable amounts of biomass were separated into two to four sub-samples ranging from 2.25 kg to 5 kg then weighed when wet. After the sub-samples were dried, and the ratio of wet to dry mass for the sub-samples was found, this wet to dry ratio was then used to calculate the dry weight of the full harvest. The Mat Zone was harvested by including any biomass that was not harvested for the Above Mat or Below Mat divisions. No sorting by species was done for the Mat Zone, as physically identifying and separating clustered root structures was not practical.

Due to the physical difficulty of removing rhizome and other material from within the plastic matrix, biomass in the Mat Zone was sub-sampled using a stratified random subsampling. The construction design of each Panel divided the plastic matrix into five rows of five blocks. Figure 2-16 shows a representation of these divisions of a Panel. The rows run along the long edge of each Panel and the blocks run along the short edge. Thus, each Panel was divided into a five row by five block grid. A random number list was generated for numbers 1 through 5, and this list was used to select a single block out of each row in a stratified-random manner. The biomass from the five selected blocks (one block for each of the five rows) was harvested completely from the Mat Zone. This biomass was then combined to make the sub-sample of the Mat biomass from each Panel. As this biomass represented 1/5 of the biomass for the Mat Zone of each Panel, the dry mass for that Panel was calculated by multiplying the mass for its sub-sample by five.

All plant tissue samples from the Final Harvest were dried at $45^{o}C$ for a minimum of ten days. The tissue was then ground first using a Wiley Mill and then using a ball mill. Tissue was ground into a homogenous powder that could pass through a 2 mm sieve and stored in opaque plastic scintillation vials until submittal for analysis. Plant tissue analysis was performed by the UF/IFAS ANSERV Advanced Research Laboratory in Gainesville, Florida. Samples were analyzed for concentrations of total nitrogen, total phosphorous, total carbon, cadmium, copper, chromium and zinc.

After the total biomass for both the initial planting and final harvest was determined, biomass was multiplied by the concentration of TN, TP, TC, Cd, Cu, Cr, Zn to determine the total mass of each constituent for each Site, Panel, Zone and Species.

The initial mass for TN, TP, TC, Cd, Cu, Cr, and Zn was subtracted from the final mass for each constituent, which resulted in the net mass assimilation (removed from water column) by the FTW per Site, Panel, Zone and Species over the study period.

Data Analysis

The statistical package JMP 8.0 (SAS) was used to run statistical analysis on the data for this research. Data was compiled into sets depending on what result was being tested (for example, when testing for results between Zones, the per Site per Panel Zone data was compiled). Tests for normality were then run on each data set using JMP. When data sets were found to be normal, an ANOVA test was run to determine if significant differences existed between independent groups. If significant differences were found, Tukey's pairwise comparison test was used to determine which particular groups significantly differed from the others. When data was found to be non-normal, Wilcoxon tests were performed to determine if there were significant differences between the means of two samples (for example, between the initial mean biomass of a Species group and the final mean biomass of that Species group) and the Kruskal-Wallis test was used to determine if significant differences were present when the degrees of freedom was greater than 1 (for example, between the mean net biomass assimilation of all four Species groups). An alpha level (α) level of 0.05 was used for all statistical tests.

Table 2-1. Number of clumps of each species per site.

Site	Species	Clumps
SS1	*Juncus effusus*	52
	Pontederia cordata	41
	Canna flaccida	23
SS2	*Juncus effusus*	48
	Pontederia cordata	45
	Canna flaccida	28
SS3	*Juncus effusus*	37
	Pontederia cordata	32
	Canna flaccida	28

Table 2-2. Water quality data during the study period.

Site	Date	Parameter					
		TN (mg L^{-1})	TP (mg L^{-1})	TSS (mg L^{-1})	°C	pH	DO (mg L^{-1})
SS1	5/25/2010	1.08	0.69	-	-	-	-
	7/15/2010	0.36	0.49	-	-	-	-
	7/20/2010	0.12	0.50	1.66	-	-	-
	9/26/2010	1.97	0.54	-	-	-	-
	10/5/2010	2.14	0.55	6.57	24	9.1	14.8
	Mean	1.13	0.56	4.12	24	9.1	14.8
SS2	5/25/2010	0.58	0.05	-	-	-	-
	7/15/2010	0.16	0.05	-	-	-	-
	7/20/2010	0.03	0.03	1.10	-	-	-
	9/26/2010	0.64	0.04	-	-	-	-
	10/5/2010	0.72	0.04	1.50	24	7.0	4.8
	Mean	0.43	0.04	1.30	24	7.0	4.8
SS3	5/25/2010	1.03	0.06	-	-	-	-
	7/15/2010	0.23	0.13	-	-	-	-
	7/20/2010	0.12	0.10	3.14	-	-	-
	9/26/2010	1.20	0.10	-	-	-	-
	10/5/2010	1.33	0.09	5.99	23	7.2	7.5
	Mean	0.78	0.10	4.56	23	7.2	7.5

Table 2-3. Stormwater runoff characterization for low-intensity commercial areas in southern and central Florida; recreated from Harper and Baker (2007).

Location	Mean Concentration (mg l^{-1})					
	TN	TP	Zn	Cu	Cd	Cr
Orlando, FL, Areawide Study	0.89	0.16	--	--	--	--
Ft. Lauderdale, FL, Coral Ridge Mall	1.10	0.10	0.128	0.015	--	
Tampa, FL, Norma Park	1.19	0.15	0.037	--	--	--
Orlando, FL, International Market Place	1.53	0.19	0.168	0.031	0.008	0.013
DeBary, FL	0.761	0.26	0.028	0.01	0.0005	0.003
Bradfordville, FL	2.14	0.16	--	--	--	--
Tallahassee, FL, Cross Creek Mall	0.925	0.15	0.045	0.008		
Sarasota County	0.88	0.31	--	--	--	--
Tampa, FL, Florida Aquarium	0.761	0.215	0.09	0.019	0.003	--
Overall Mean	1.18	0.179	0.094	0.018	0.006	0.013

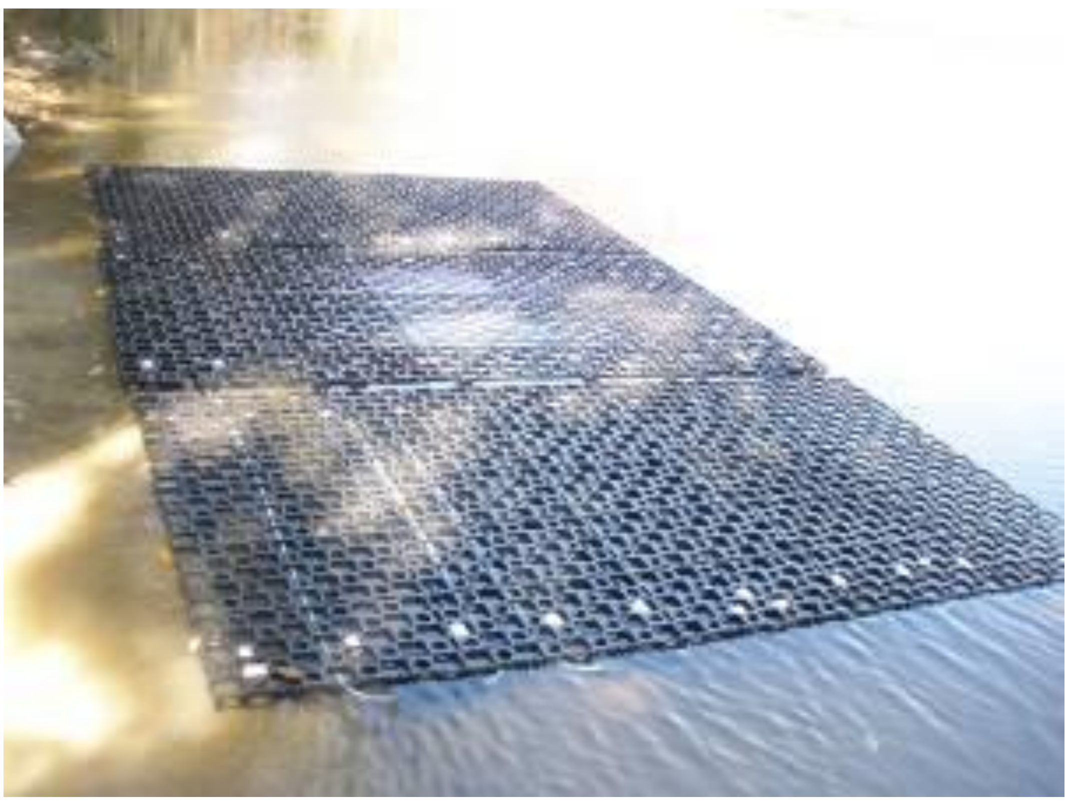


Figure 2-1. Unplanted plastic mat consisting of three 1.22 m by 2.44 m panels, photo courtesy of Neal Beery.

Figure 2-2. Close up view of the FTW mat plastic matrix viewed from below the mat looking up, photo courtesy of Neal Beery.

Figure 2-3. Floating wetland treatment panel with PVC anchor attachment located in the lower left hand corner, photo courtesy of Neal Beery.

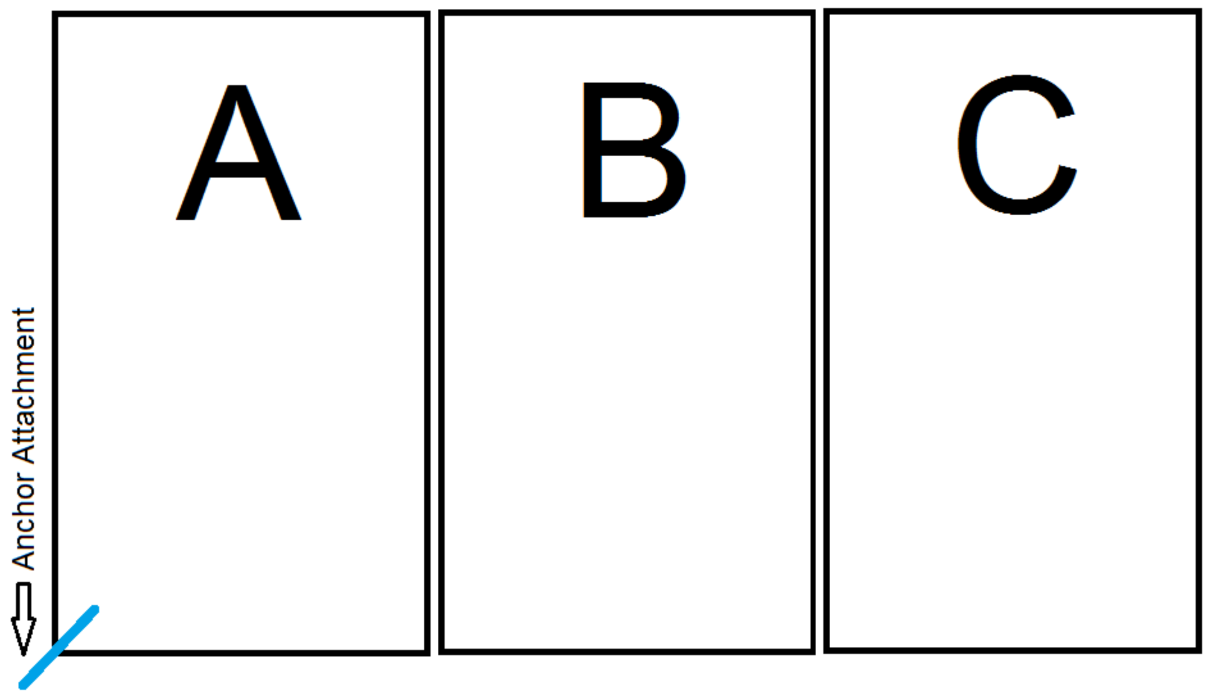


Figure 2-4. Location of anchor attachment and panels A, B and C.

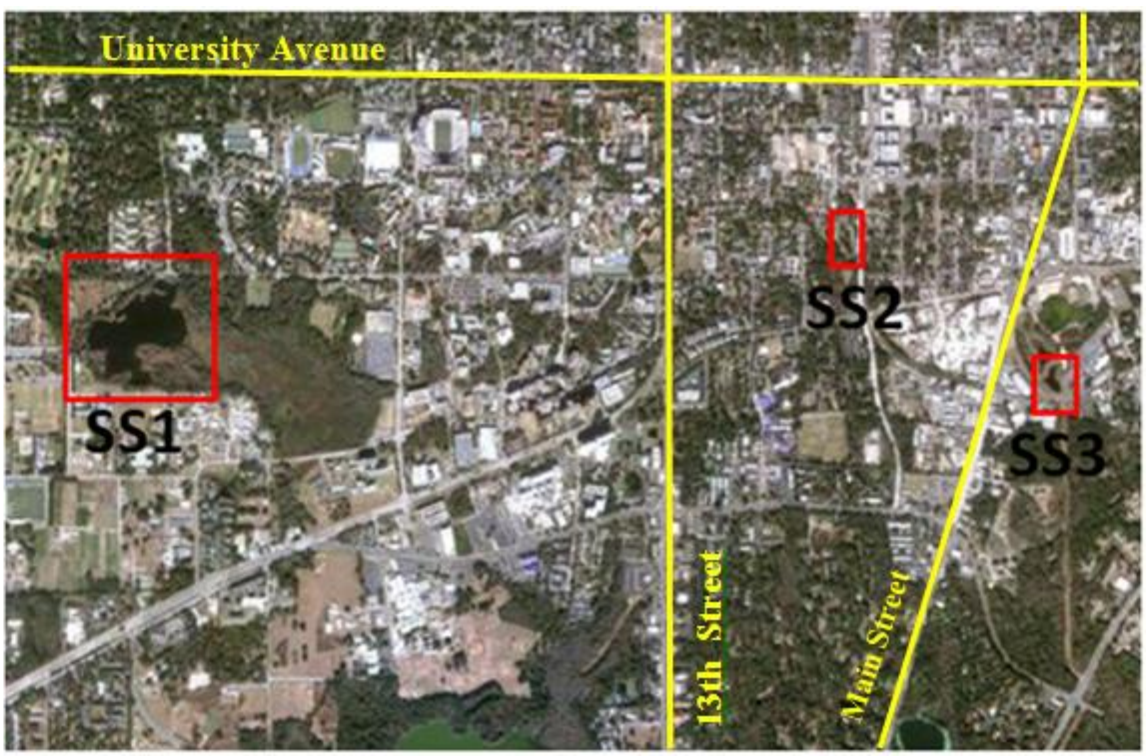


Figure 2-5. Aerial view of Gainesville, Florida with test locations outlined, photo courtesy of USGS, 2012.

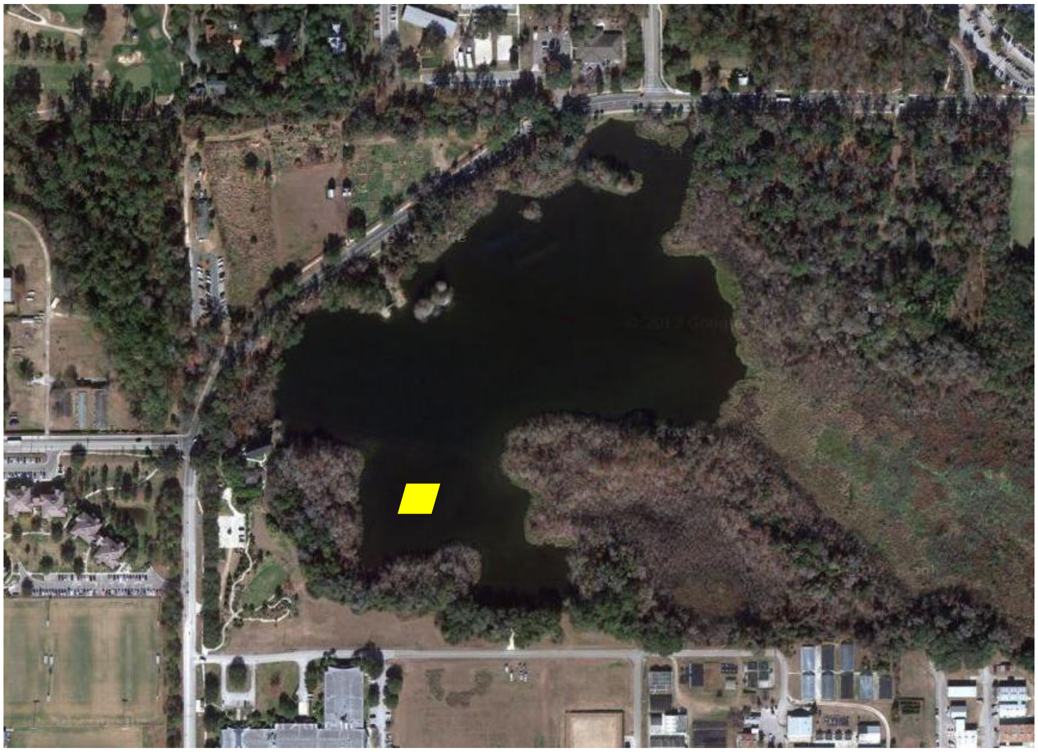


Figure 2-6. Aerial view of SS1 (Lake Alice), on the University of Florida campus, photo courtesy of USGS, 2012.

Figure 2-7. Ground level view of SS1 (Lake Alice).

Figure 2-8. Aerial view of SS2, Tumblin Creek stormwater pond, SW 6th St. to the right, photo courtesy of USGS, 2012.

Figure 2-9. Ground level view of SS2, Tumblin Creek stormwater pond, photo courtesy of Neal Beery.

Figure 2-10. Aerial view of SS3, RTS stormwater pond, with RTS parking lot to the right, photo courtesy of USGS, 2012.

Figure 2-11. Ground level view of SS3, RTS stormwater pond, photo courtesy of Neal Beery.

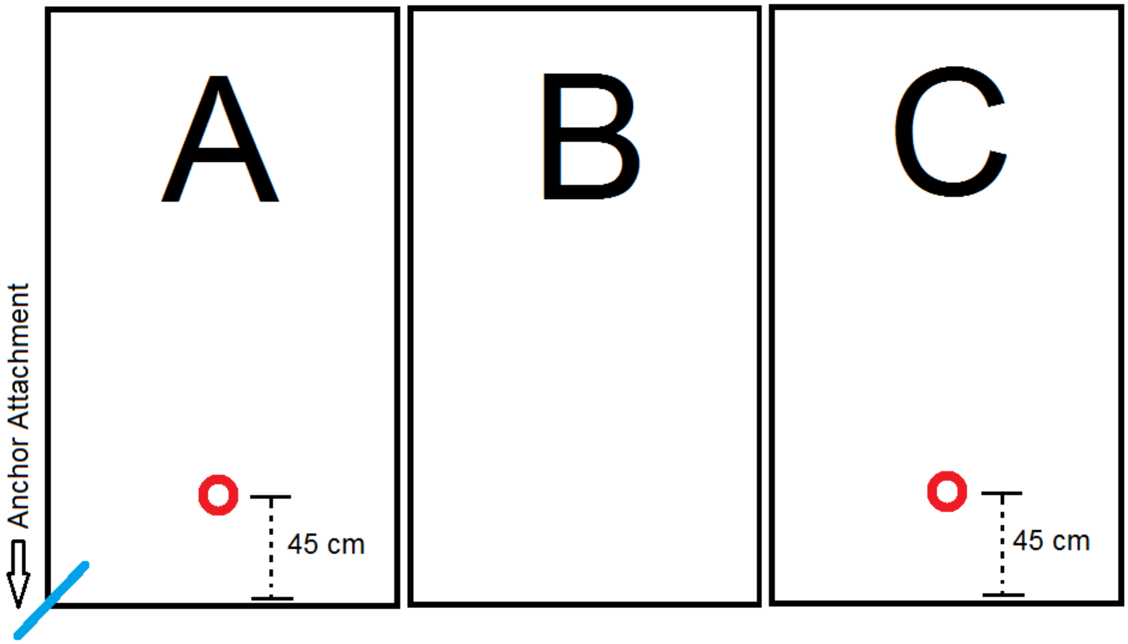


Figure 2-12. Position of target points for initial plant sampling.

Figure 2-13. Separated initial plant samples, photo courtesy of Neal Beery.

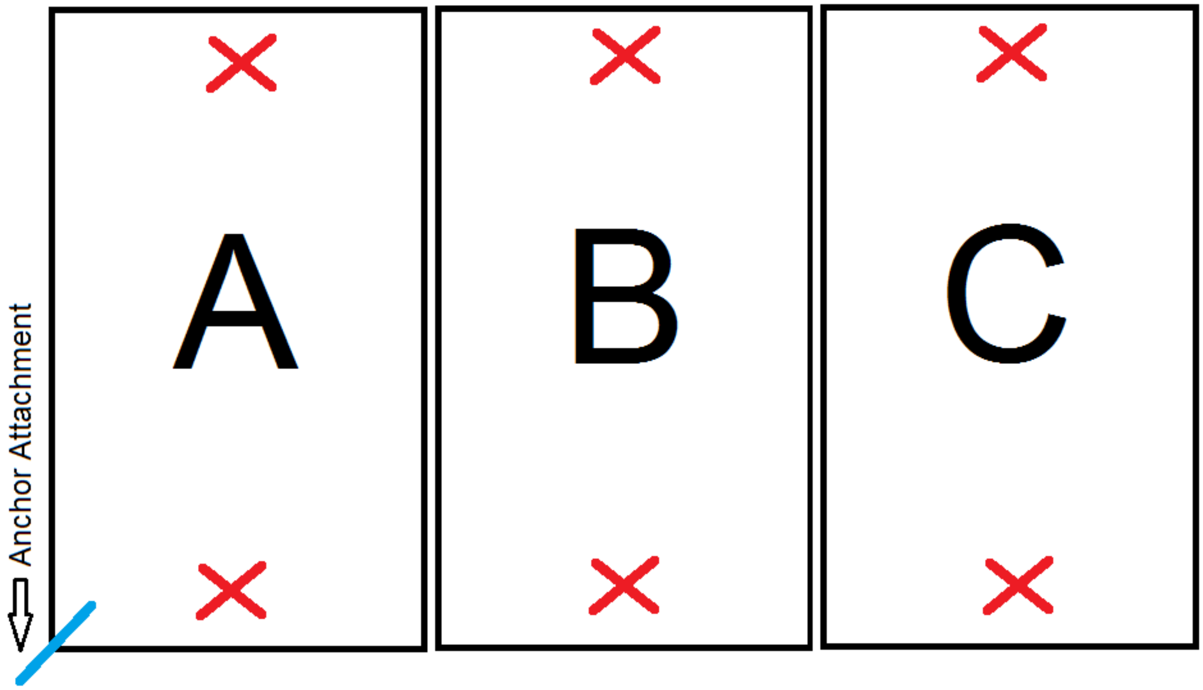


Figure 2-14. Locations of depth measurements prior to harvest.

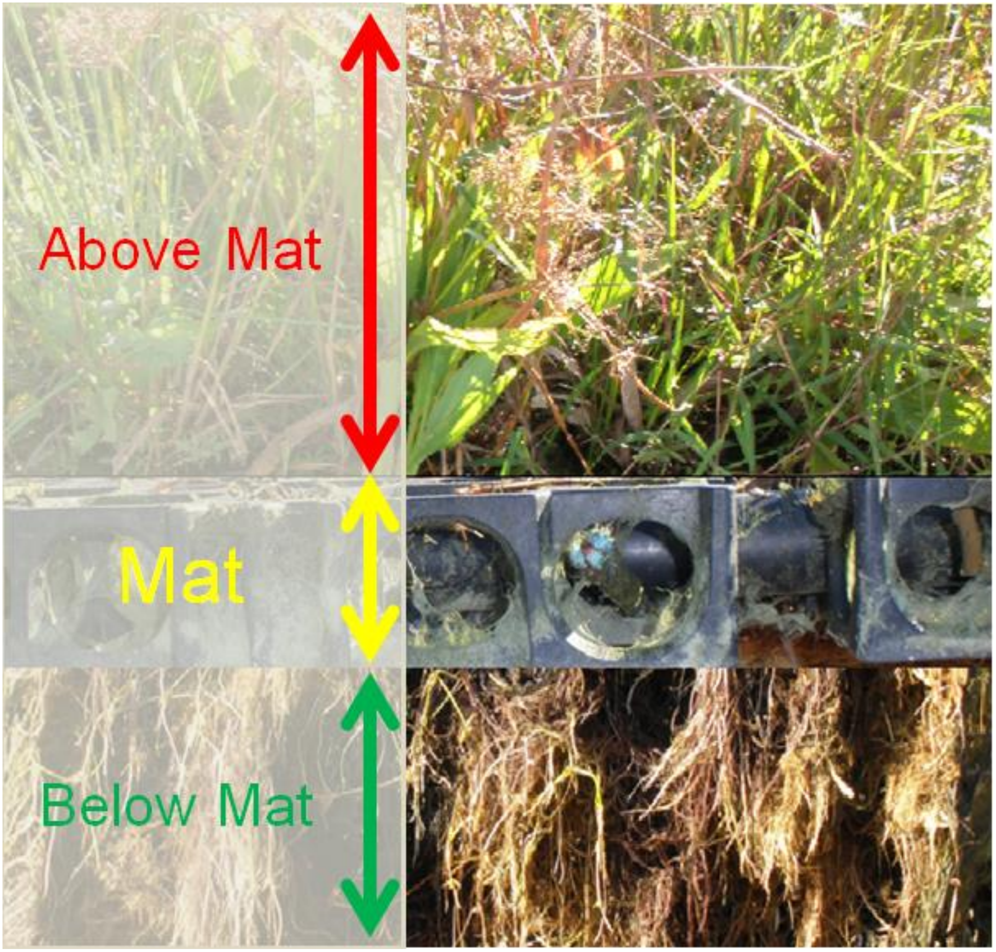


Figure 2-15. Above mat, mat, and below mat zones, photos courtesy of Neal Beery.

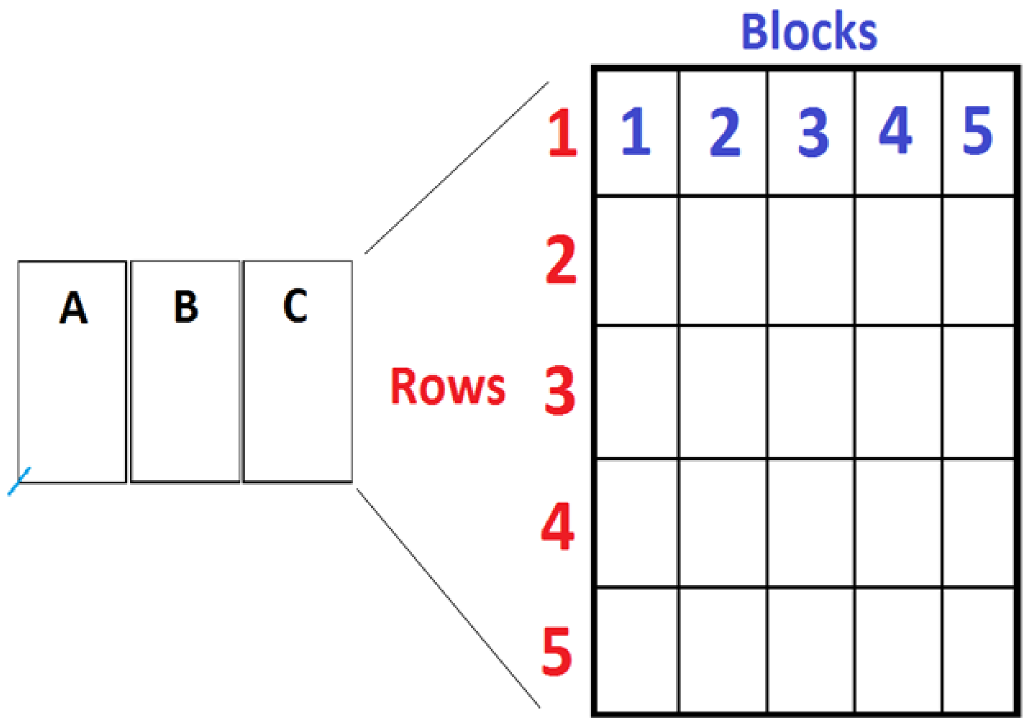


Figure 2-16. Division of panels into rows and blocks for mat zone stratified random sampling.

CHAPTER 3
RESULTS AND DISCUSSION

Measurements were made for assimilation of biomass, carbon, nitrogen, phosphorus, zinc, copper, cadmium and chromium. Measurements of each of these constituents were taken for the Above Mat portions of four species groups (*J. effusus*, *C. flaccida*, and *P. cordata* and self-recruited ‘other’ species). Measurements were also taken for all biomass of the Mat and Below Mat Zones with no separation of species. Measurements were taken for these separate groups on each of the three Panels (A, B, and C) of each of the three deployed FTWs (SS1, SS2, and SS3). These measurements were taken for the initially deployed FTWs and for the final growth of the FTWs at the end of the study.

General Growth Characteristics

‘Above Mat’ Biomass Observations

Visually, the size and extent of coverage of the FTWs increased from the initial planting over the course of the study (Figure 3-1). At the end of the period of study, the surface area of SS2 was almost entirely covered with macrophyte growth. Some surface area of SS3 was devoid of macrophytes, and large portions of the surface area of SS1, were devoid of macrophytes (Figure 3-2).

The loss of individual macrophytes may have occurred due to grazing or trampling by wildlife. The occurrence of grass carp, *Ctenopharyngodon idella*, was noted during the study period at SS1. During a high water period following heavy rain,grass carp were seen grazing on flooded grass banks, and it is speculated that they may have been grazing on the Below Mat portion of the SS1 macrophytes throughout the study. Common Moorhens, *Gallinula chloropus*, were seen on the SS3 FTW, and evidence of their grazing was observed on the Above Mat portion of that FTW. The killing or grazing of macrophytes by turtles may also have occurred, as turtles were seen at SS3 and SS1, resting on top of crushed or bent macrophytes.

'Mat' Biomass Observations

At the end of the study period, the Mat Zone (approximately 5 cm thick) of the FTWs contained rhizome, root and petiole sections of macrophytes as well as algal growth and organic detritus (Figure 3-3). When the FTWs were deployed into their respective stormwater retention ponds, the plastic matrix that made up the mat section was devoid of any material, except where macrophytes had been installed and passed through the mat. At the end of the study period, where macrophytes remained or had been recruited, the Mat Zone was filled with live and non-living biomass, mostly made up of rhizome sections of macrophytes.

When the mat section had little biomass or other materials, light and air could easily pass through (Part A of Figure 3-3) from above the mat. At the end of study, when the Mat Zone was filled with organic material, light and air would not have been able to pass easily through the mat section, possibly stressing algal, bacterial and macrophytic organisms due to lack of light and oxygen. Also, such dense material, especially living rhizomes, proved to be exceedingly difficult to remove from the mat Zone during the harvest of the FTWs. This has implications for the management of FTWs as BMPs, as stormwater managers may either design the plastic matrix so that materials could be more easily removed, or leave the materials in the mat Zone and redeploy the FTWs since this material is less prone to senescence and annual decomposition.

'Below Mat' Biomass Observations

Where macrophytes were present, the root growth of FTWs was extensive (Figure 3-4). Roots extended to depths (below the mat portion) of 10cm to 50cm in some cases. In some cases roots grew in very thickly matted clusters, and contained organic detritus, inorganic minerals and sometimes aquatic vertebrate and invertebrates such as tadpoles, fish and crustaceans (Figures 3-5).

FTWs were harvested carefully and manually in this study, and any animals that were found were not included in measurements. However, if applied as a stormwater BMP, harvesting of FTW roots may be done in a manner that any animal biomass within root clusters would be harvested along with macrophyte biomass. Additionally, root clusters may have been thick enough to support anaerobic conditions that may lead to the occurrence of denitrification processes, a method of nutrient removal that was not measured by this study.

Macrophyte Species Dominance and Recruitment

Each of the three Sites were initially planted with the macropyhte species *J. effusus*, *C. flaccida*, and *P. cordata*. These three species remained on all Panels of all Sites except for SS1, where at the end of the study *P. cordata* was not found on any Panel and *J. effusus* was not found on Panel A. During the study, FTWs were not managed through selective plant removal to retain only the originally installed species, thus allowing any new species to self-recruit. Many species not installed initially were found on the sites at the end of the study (Table 3-1).

A variety of self-recruited species were found at all three sites, and on all Panels at each of the Sites. At least twenty distinct species were identified at each Site, some of which were native to Florida and others were non-native species (IFAS, 2013). The mass assimilation (biomass and other constituents) of the “other” category rivaled or exceeded the final biomass of the three initially installed species. Quantitative descriptions of these results can be found in the ‘Biomass Assimilation by Species’ portion of this chapter.

Two of the self-recruited species, *Acer rubrum* and *Salix caroliniana*, are considered woody species and can become the size of shrubs or trees. If allowed to grow large enough, their mass and density would likely change the buoyancy characteristics of the mat and eventually cause the FTW to sink. Species such as these would need to be periodically removed in order to prevent possible damage to the FTW.

Nutrient and Metals Mass Assimilation

The principle of stormwater treatment by FTWs relies on healthy initially installed macrophytes and any self-recruited macrophytes to remove nutrients from the water column and to add this material to the FTW in amounts greater than what was installed (Kadlec and Wallace, 2009). The amount of initially installed mass is important to know in order to determine the net effect of the FTW once harvested. Table 3-2 lists the initial mean masses for the various constituents over the three study sites, along with standard deviations, minimum and maximum values for the Sites.

There were no significant differences found among sites nor were there significant differences found among Panels for total initial dry biomass (ANOVA, DF=2, N=3, α=0.05).

The removal of pollutants by FTWs was found by taking the difference of the final mass of the constituent from the initially installed mass of the constituent. The mass removals for this study were normalized on a per square meter basis. This normalization was done in order to allow managers to estimate the surface area coverage required to reach removal goals, as well as for other researchers to make comparisons to other FTWs, MAPS, or BMPs in general.

The mean site dry biomass assimilation over the course of the study was 1908 ± 1330 g m^{-2}, the minimum site mean assimilation was 655.8 g m^{-2} and the maximum site mean was 3749 g m^{-2} (Table 3-3). This range illustrates the potential of FTWs to remove biomass for a representation of stormwater treatment basins in similar climactic conditions.

Although not assimilated from the water column, carbon content of the biomass is also of interested to assess CO_2 assimilation as well as overall biomass characteristics. Over the course of the study, average mean carbon mass was 700.2 ± 488.2 g m^{-2}. The mean nitrogen and phosphorus assimilations over the course of the study were 32.0 ± 20.5 g m^{-2} and 4.25 ± 2.44 g m^{-2}, respectively. The average carbon, nitrogen and phosphorus content of the biomass were 34.5±1.9%, 1.81±0.04% and 0.281±0.058% respectively.

Among the metals evaluated, Zinc was assimilated in higher amounts than any of the other metals, with a mean mass of 86.5 ± 91.6 mg m^{-2} as compared to means of 9.43 ± 9.54 mg m^{-2}, 0.234 ± 0.263 mg m^{-2}, and 5.11 ± 4.82 mg m^{-2} for copper, cadmium and chromium respectively.

Significant differences were found between final and initial mass for each of the constituents (Wilcoxon Signed Rank, α=0.05). This result supports Hypothesis 1 in that FTWs had significantly more mass, of all measured constituents, per square meter at the end of the study than they did when macrophytes were initially installed. The FTWs were capable of removing some amount of all constituents over the period of the study, and therefore can be considered an effective method of stormwater treatment when compared to non-usage of FTWs.

The mass assimilations were converted to a rate (g m^{-2} day^{-1}) by dividing the mass per square meter results by the 278 day study period (Table 3-4). This rate applies to this FTW design with an installation date of mid-March and a harvest date of early to mid-December. Table 3-5 shows comparative mass assimilation rates for biomass, nitrogen and phosphorus across a variety of wetland systems, both natural and constructed.

Generally, the results of mass assimilation rates found by this study fell within the widely varying range reported by a variety of plant-based water treatment systems. This study's results for dry biomass assimilation of 6.9 g m^{-2} d^{-1} are similar to that of Headley and Tanner (2008) who found a range of 2.7-5.9 g m^{-2} d^{-1} for FTWs in mesocosm settings, and are low when compared to the high of 33.9 g m^{-2} d^{-1} found by Hubbard et al. (2004) using FTWs in swine waste lagoons. Hogg and Wein (1988) reported a value of 1939 g dry biomass m^{-2} for natural floating mats populated by *Typha latifolia*. This value is not a rate like the other values, but the mean dry biomass assimilated by FTWs in this study was comparable, with 1908 g dry biomass m^{-2}.

This study found a nitrogen assimilation rate of 0.115 g N m^{-2} day^{-1}, which was comparable to other FTWs in the literature, but lower than emergent treatment wetlands. For nitrogen assimilation, a low of .0017 g N m^{-2} d^{-1} was reported for FTWs in an urban stormwater setting (Chua et al., 2012), and a high of 2.2-2.6 g N m^{-2} d^{-1} was reported for emergent wetlands (Bachand and Horne, 2000). A high assimilation rate of

1.096 g N m^{-2} d^{-1} was found by Hubbard et al. (2004) for an FTW system, which was substantially greater than the results of this study, and was most likely due to the extremely high nutrient content of the swine waste lagoon site. While considering these values it is important to note that the referenced studies may have included losses of nitrogen due to transformations and volatilization of nitrogenous compounds. The current study only measured the nitrogen that was taken up by macrophytes, which may be reflected in lower values when compared to other studies.

Periphyton raceways studied by DeBusk et al. (2004) had low phosphorus assimilation rates, 0.88 mg P m^{-2} d^{-1}, when compared to the rate of 15.3 mg P m^{-2} d^{-1} for this study. However, the high rate of 0.162 g P m^{-2} d^{-1} reported by Hubbard et al. (2004) for FTWs in swine lagoons was higher than that of this study, again, most likely due to the extremely high nutrient content of the sites at which the Hubbard study was conducted.

The total mass of FTWs may have implications for the logistics and timing of the periodic assimilation of biomass. Three adults had difficulty manually removing a single 1.22 m by 2.44 m FTW Panel from most of the stormwater ponds. Also, the bulk biomass harvested from the FTW with the greatest growth (SS2) more than filled the bed of a conventional pickup truck. The harvesting plans for FTWs will need to include considerations for the wet weight and volume of biomass being harvested. The overall management of FTWs will need to take into consideration the transport, storage and disposal of the removed biomass.

At the end of the growing period, the FTWs were removed from the stormwater basin sites and the biomass was harvested and processed for evaluation. After having been harvested and prior to drying, the biomass contained the full weight of the water contained within the materials found on the FTW, and was referred to as the wet biomass. The mean final wet biomass of the FTWs was 14.7 kg m^{-2}, with close to half of that mass being from the matted, spongy roots in the Below Mat Zone (Table 3-6). Site SS2 had the greatest total wet biomass, with 28.8 kg m^{-2}, and SS1 had the least total wet biomass, with 4.74 kg m^{-2}.

For FTWs of the dimension used in this study (2.44 m by 3.66 m), the mean final wet biomass per FTW was 131 kg, and the maximum FTW wet biomass was 257 kg (Table 3-7). The FTW design used in this study easily allowed for panels to be removed separately; however, a mass of approximately 260 kg distributed evenly over three panels yielded a mass of around 86 kg per panel, which proved to be a difficult amount of biomass to maneuver and lift by hand. Additionally, the mass of the plastic FTW mat would add to the mass of the FTWs as a whole.

Assimilation Performance by Panel

Comparisons between Panels at each site were made in order to determine if an edge effect (where the middle Panel biomass and tissue characteristics differed from the Panels along the outer edge), possibly due to factors related to the FTW. These factors may have included light availability, air movement, temperature, dissolved oxygen levels, and or nutrient concentrations (Sasser, 1994). It was hypothesized that the outer portions of the FTWs in this study would have greater biomass and pollutant assimilation capacity due to their location on the FTW which may have experienced higher light intensity and duration, higher air velocity, and higher nutrient concentrations because water would not have to pass through other roots before reaching the inner portions.

Visual inspection among panels at the end of the study did not appear to have differences (Figure 3-6, Figure 3-7, and Figure 3-8). No noticeable patterns in petiole height, root length, leaf coloration, or general health were evident between Panels. Visually, growth on SS2 and SS3 seemed evenly distributed in biomass and species diversity across the FTW whereas growth was sparse overall on SS1 and some species were present on some Panels but not on others. This result on SS1 may have been due more to the mortality of specific individuals by trampling or grazing rather than patterns associated with an edge effect.

When quantitatively comparing the biomass and total mass of nutrients and metals average mass in Panel B was consistently lower than Panels A or C, however no significant differences were found among Panels (Table 3-8), thus Hypothesis 2 was rejected. It had been hypothesized that a buffering effect would exist, where the area of the FTWs closest to the edge of each panel would receive more nutrients and have a higher dissolved oxygen level, allowing for greater macrophyte growth and FTW performance. The amounts of dissolved nutrients, dissolved oxygen and nutrient-containing suspended particles have been found to decrease with respect to distance away from their source in emergent wetlands (Reddy and DeLaune, 2008). In this study, the source was the free water surrounding the FTWs, and so it was thought that the interior portions of the FTWs would receive less. If this buffering effect did occur to any degree it had no effect on FTW performance for any constituent. This was most likely due to the scale of the FTWs in this study, where there was never more than 1.22 meters between any point on the FTW and open water. However, if larger surface area was covered in contiguous FTW panels, an effect may have been observed. Also, the

B Panels may have received the same amount of constituents as A and C Panels from free water below the FTWs.

Additionally, no significant difference in overall tissue concentration between Panels were found for any parameter (Table 3-9). This indicates that nutrient and metal availability in the free water below the FTWs was not as affected by outer Panels or that water exchange with the roots is not unidirectional as originally expected. In addition, the lack of difference in tissue concentration between Panels suggested that growth of the macrophytes was not affected by other factors differing between Panels, or those factors did not differ among Panels.

Panels A and C were considered to be 'outer' portions of the FTWs and the B Panels were considered to be 'inner' portions. The lack of significant difference between any Panels, for both mass assimilation and tissue concentration, indicated the absence of an edge effect on FTWs with a surface area of 8.93 m^2.

The lack of edge effect at the 2.44 m by 3.66 m dimension implies that stormwater managers implementing FTWs as MAPS need not be concerned with edge effects affecting FTW performance at this scale. However, increasing the surface area of an FTW, or placing multiple FTWs adjacent to one another, may result in performance altering edge effects not seen in this study.

Assimilation Performance by Species

When designing and installing FTWs for treatment of stormwater, the species that are installed must be considered for their performance capabilities. Headley and Tanner (2006) offer this advice for choosing macrophyte species: "The choice of species often comes down to selecting locally occurring native species that exhibit vigorous growth within polluted waters under the local climatic conditions." The species used for this study were recommended by ACF Environmental as part of their FTW design. The Statewide Stormwater Rule Draft Applicant's Handbook lists the three initially installed species (as well as *Spartina spp.*) as part of its Floating Wetland Design Criteria, and describes them as having been documented as having high nutrient tissue concentrations, but does not offer references or values (FDEP, 2010b). The species used for this study were *J. effusus, C. flaccida, and P. cordata*, as well as additional self-recruited species. The self-recruited species were referred to as the Other group and consisted of any species not included in the three initially installed species groups.

No management of individual macrophyte species was performed over the period of study to select for any particular species, and no pruning or harvesting was conducted prior to the end of the study period. This allowed for comparisons to be made between the mass assimilation capabilities of the four Species groups at the end of the study. It is important to note that these among-Species comparisons were only made for the Above Mat portions of the macrophytes, as the Mat and Below Mat portions were not able to be separated by species in a practical or accurate manner. It is also important to note that upon harvesting the Above Mat biomass was not washed or cleaned of biofilms (such as algae, periphyton, and bacteria) or detritus; therefore, the per species concentration and mass data included these materials in addition to the tissue of the macrophytes.

Macrophytes were installed as seedlings or young plants purchased from a nursery, and contained nutrients within their tissue at the time of installation. This method of installing seedlings is seen as the most preferable method, as other studies have suggested that it would lead to higher success rates (Headley and Tanner, 2006). As the macrophyte seedlings matured and grew on the FTWs they absorbed nutrients and metals from the free water below the mat and carbon from the atmosphere. As no growth media, such as peat, potting soil or plant fibers, was used for the FTWs in this study, the macrophytes relied entirely on the free water as a source of nutrients.

Carbon, Nitrogen and Phosphorus Tissue Concentration by Species

It is important to note that there were multiple species groups growing on the FTWs in this study. When comparisons between species groups were made, it was a comparison of how different groups either thrived or declined on the same FTW Mat, not a comparison made between different FTWs installed with a single species group that did not compete with other species.

When reading the following descriptions of nitrogen, phosphorus and carbon concentrations in dry biomass of the three macrophyte species and Other species groups refer to Table 3-10, Table 3-11, and Table 3-12. The concentrations given in these tables are for dried, ground and homogenized macrophyte tissue. The columns labeled 'Min.' give the lowest mean concentration of the three sites for each species, and the 'Max.' column gives the highest mean concentration of the three sites for each species. The 'Sig. Diff.' column indicates significant differences between species groups for mean concentration (Wilcoxon signed rank test, N=3, $\alpha = 0.05$) where species that are not connected by the same letter are significantly different.

Headley and Tanner (2006) concluded that *Juncus* species were able to grow well in floating wetland systems in a relatively similar environment (Auckland, New Zealand), but another study found this species was not successful when used in swine lagoons or grown with one-quarter strength Hoaglund solution (Hubbard et al., 2004).

The current study found a mean carbon content of 411.5 ± 8.0 g C kg^{-1}, and Ho (1979) reported a comparable carbon content for dry *J. effusus* biomass (480 g C kg^{-1}). The current study found a *J. effusus* dry biomass nitrogen concentration ranging from 9.36 to 10.89 g N kg^{-1}. Professional Service Industries, Inc. (PSI) (2010), and McJannet et al. (1995) reported similar ranges of 8.9 to 12.6 g N kg^{-1} and 9.4 to 10.9 g N kg^{-1} for 'shoot' nitrogen concentration of *J. effusus* dry biomass in an FTW application and natural populations, respectively. The current study found a *J. effusus* phosphorus concentration of 0.85 to 1.47 g P kg^{-1}, which was similar to that of the 2010 PSI study reporting on FTW macrophytes (0.6 to 0.9 g P kg^{-1}), but lower than that reported by McJannet et al. (2.1 to 3.5 g P kg^{-1}) for emergent macrophytes. This may have been due to the fact that the McJannet et al. study was for emergent *J. effusus* that had access to phosphate in the soil porewater, while the 2010 PSI study was for floating *J. effusus* that only had access to the phosphate in the free water of the stormwater basins.

Canna flaccida has also been studied in FTW and emergent wetland applications. This study found a range for dry *C. flaccida* biomass carbon of 353.8 to 372.1 g C kg^{-1}; no similar research was found to make a comparison of carbon content for *Canna*. This study found the tissue nitrogen concentration for dry *C. flaccida* to range from 9.62 to 15.71 g N kg^{-1}, which is similar to that of the PSI (2010) study (12.1 to 18.4 g N kg^{-1}) and the Chang et al. (2012) study (9.6 g N kg^{-1} for 'shoot' nitrogen concentration). This study found the phosphorus concentration to range from 0.72 to 2.89 g P kg^{-1}, which is similar to the 2010 PSI study (0.9 to 1.3 g P kg^{-1}) (2010) and the Chang et al. study (2.5 g P kg^{-1} for dry shoot biomass).

This study found a carbon content ranging from 375.5 to 388.2 g C kg^{-1} for dry *P. cordata* biomass and master's research performed by Vogel (2012) found carbon content ranging from 403.3 to 430.1 g C kg^{-1}. This study found a nitrogen content for dry *P. cordata* biomass of 9.74 to 14.02 g N kg^{-1} which was somewhat lower than Vogel's study (16.4 to 32.3 g N kg^{-1}) and a study performed by Holt et al. (1999) (39 g N kg^{-1}). The Vogel thesis reported values for *P. cordata* growing on an FTW application in Florida that was more than double the value found at any site in the current study. This study found a phosphorus concentration range of 0.75 to 1.10 g P kg^{-1}, which was similar to that of *P. cordata* in an FTW setting as found in the PSI study (.37 to 0.60 g P kg^{-1}) but considerably lower than emergent *P. cordata*, as shown by the Holt et al. study (5.1 g P kg^{-1}). The high phosphorus content found by Holt et al. was most likely due to the emergent nature for that study, where higher phosphorus was available in the wetland soil at higher levels than that of the free water at SS1, SS2, or SS3. Also, iron plaque tends to accumulate on wetland soils due to oxidation of reduced soluble iron; this plaque often co-precipitates phosphorus, which may have led to higher phosphorus concentrations in the root zone for emergent wetlands.

The mean dry biomass carbon concentration found for the Other Species group at each site was 381.8 ± 10.2 g C kg^{-1}. Very little literature for the specific set of self-recruited species in this study was found, but typical carbon content for wetland species has been found to be 38%, or 380 g C kg^{-1}, a very similar value to that found in the current study (Radér, 2001). This study found the Other group to have a nitrogen concentration ranging from 11.6 to 13.0 g N kg^{-1}. In a synthesis study of 41 different wetland species growing in emergent wetland conditions, McJannet et al. (1995) found that the mean nitrogen concentration was similar, with a range from 10 to 14 g N kg^{-1} dry biomass. This study found a range of phosphorus content from 1.0 to 2.2 g P kg^{-1} for the Other species group, whereas the phosphorus content for the 41 species in the McJannet et al. study ranged from 0.29 to 0.35 g P kg^{-1} dry biomass. The reasons for the differing ranges are not fully understood, but could be due to the variety of species studied by McJannet et al. not being the same variety as studied in the current study.

McJannet et al. (1995) found lower P concentrations in facultative wetland species when compared to obligate wetland species. *J. effusus* is a facultative wetland species, *C. flaccida* and *P. cordata* are obligate wetland species, and the Other group contained both facultative and obligate wetlands species. *J. effusus* had a lower phosphorus concentration than *C. flaccida* and the Other species group, but higher than *P. cordata*. Facultative and obligate wetland species designations were not an accurate predictor of relative phosphorus tissue content in this study.

In the context of carbon fixation potential, Hypothesis 3 stated that the species group with higher concentrations reported in literature would have the highest concentration, and thus the highest potential to remove carbon. *J. effusus* was reported to have the highest carbon tissue concentration in the literature, and in the current study *J. effusus* was the species found to be significantly greater than any other species groups in this FTW study, therefore the hypothesis is confirmed for carbon.

When comparing among species groups' site mean carbon dry biomass concentration (Kruskal-Wallis Rank Sum, N=4, DF=3, α=0.05) of *P. cordata* and the Other group had no significant difference, but *J. effusus* and *C. flaccida* differed from each other and the two previously mentioned species groups, with *J. effusus* having a higher carbon concentration and *C. flaccida* having a significantly lower concentration.

No significant difference was found among species groups for nitrogen and phosphorus dry biomass concentrations (Kruskal-Wallis Rank Sum, N=4, DF=3, α=0.05). In the context of nitrogen assimilation potential, Hypothesis 3 stated that the species with higher concentrations reported in literature would also have the highest concentration in this study, and thus the highest potential to remove nitrogen. Though *P. cordata* was reported to have the highest nitrogen tissue concentration in the literature, no species was found to significantly differ from any other species in this FTW study, therefore the hypothesis is rejected for nitrogen.

In the context of phosphorus assimilation potential, Hypothesis 3 stated that the species with higher concentrations reported in literature would have the highest concentration, and thus the highest potential to remove phosphorus. Though *J. effusus* was reported to have the highest phosphorus tissue concentration in the literature, no species was found to significantly differ from any other species in this FTW study, therefore the hypothesis is rejected for phosphorus.

Metal Tissue Concentration by Species

The mean dry biomass zinc concentration ranged from 28.3 ± 15.1 mg kg^{-1} for the Other group to 39.1 ± 19.9 mg kg^{-1} for *C. flaccida* (Table 3-13). The mean dry biomass copper concentration ranged from 2.17 ± 0.83 mg kg^{-1} for the Other group to 5.87 ± 1.68 mg kg^{-1} for *C. flaccida* (Table 3-14). For Above Mat biomass of the species groups at most of the sites, cadmium and chromium tissue concentrations were not found at levels high enough to exceed the minimum analytical detection limits, and so were not included in the results of this study. For zinc and copper, the results of all species groups in this study fell within the range, albeit the low end, reported in the literature. Fritioff (2005) reported concentrations of heavy metals in plant tissue grown in stormwater treatment areas; zinc ranged from 16 to 220 mg kg^{-1} dry biomass, copper ranged from 3 to 60 mg kg^{-1} dry biomass, and cadmium ranged from 0.04 to 35 mg kg^{-1} dry biomass.

There was no significant difference between species groups for dry biomass zinc concentration (Kruskal-Wallis, DF=3, α=0.05). For site mean copper dry biomass concentrations, *J. effusus*, *C. flaccida*, and *P. cordata* did not differ significantly, but *J. effusus* and *C. flaccida* did differ from the Other group's lower concentration; the Other group and *P. cordata* had no significant difference (Wilcoxon Signed Rank, DF=3, α=0.05). Chromium and cadmium concentrations were so low they oftentimes did not reach minimum detection levels, and so were not included.

In the context of heavy metal assimilation potential, Hypothesis 3 stated that the species with higher concentrations reported in literature would have the highest concentration, and thus the highest potential to remove metals. No species utilized in this study was reported in the literature to have specifically higher metals concentrations than others, therefore the hypothesis was neither confirmed nor rejected.

Biomass Assimilation by Species

Dry biomass assimilation (Table 3-15) for the Above Mat zone on a per square meter basis varied widely depending on the species, with a minimum of -8.6 g m^{-2} for *P. cordata* at SS1 and a maximum of 861.6 g m^{-2} for *C. flaccida* at SS2. The mean biomass assimilation ranged less widely among averaged across all sites (Figure 3-10), with *P. cordata* having the lowest assimilation (85.8 g m^{-2}) and *C. flaccida* having the highest assimilationt (306.4 g m^{-2}).

Significant differences were found between the Other group and *J. effusus* as well as between the Other group and *P. cordata*, with the Other group being greater than J. effusus and P. cordata (Wilcoxon Signed Rank, N=3, α=0.05). No significant difference was found between *J. effusus*, *C. flaccida* and *P. cordata*, although the mean biomass Assimilation for *C. flaccida* was 306.4 ± 392.6 g m^{-2} and the mean assimilations for *J. effusus* and *P. cordata* were 88.6 ± 101.9 g m^{-2} and 85.8 ± 69.3 g m^{-2}, respectively. This lack of significant difference among these Species groups was likely due to the large standard deviation for *C. flaccida*, possibly because of either the high mortality at SS1 or the dominance of *C. flaccida* growth at SS2 (Figure 3-9).

Carbon Assimilated by Species

The site mean carbon assimilation ranged from a low of 32.8 g C m^{-2} for *P. cordata* to a high of 114.2 g ± 68.0 C m^{-2} for the Other group (Table 3-16). There is little comparable literature for Above Mat carbon assimilation by FTWs. However, a thesis by Vogel (2012) that focused on FTWs in South Florida reported a range of 56 g C m^{-2} to 318 g C m^{-2} for all mat zones (which included what corresponds to the Above, Mat, and Below zones). The results from this study fall within the range in Vogel's study. The per square meter carbon assimilation from this study that came closest to Vogel's maximum was that of *C. flaccida* on SS2 at 309.1 g C m^{-2}, suggesting that this species can be utilized for maximized potential assimilation of biomass carbon in stormwater systems in Florida.

For all species groups, carbon assimilation was significantly greater than the per square meter initial mass of carbon (Wilcoxon Signed Rank, N=3, α=0.05), demonstrating that all species groups were effective at assimilating new carbon. Across all species groups for each panel at each site, carbon assimilation had a strong positive linear relationship with dry biomass assimilation, as shown in the following equation:

Carbon Mass Assimilation, kg =0.365(Biomass Assimilation, kg) + 0.834 R^2=0.9972

The significant differences between species groups were the same as for dry biomass assimilation but differed from that of the dry biomass tissue carbon concentration (Table 3-16), indicating that it was the ability of FTWs to incorporate biomass, not increase carbon tissue concentrations, that drove the net assimilation of carbon in this study.

When considering Hypothesis 3, *C. flaccida* and the Other group had approximately three times greater mean mass carbon assimilation than *J. effusus* and *P. cordata*. The site mean carbon assimilation for *C. flaccida* did not significantly differ from the means for *J. effusus* or *P. cordata*; however, the large standard deviation for *C. flaccida* probably influenced this lack of significant difference. When considering the maximum mass assimilation performance of the four Species groups, *C. flaccida* and the Other group had the greatest potential to assimilate carbon, and so should be considered over the other two species when designing FTW systems to assimilate carbon.

Nitrogen and Phosphorus Mass Assimilation by Species

The Other species group had the highest site mean Above Mat nitrogen assimilation with 3.70 ± 2.04 g N m^{-2}, and *J. effusus* had the lowest with 0.86 ± 0.92 g N m^{-2} (Table 3-17). This range was considerably lower than the nitrogen mass assimilation Vogel reported, 10.0 to 34.7 g N $m^{-2,}$ in an FTW application for species including *C. flaccida*, *J. effusus*, and *P. cordata*, as well as some of the same self-recruited species. This may have been due to the longer growing season experienced in Vogel's study which took place in South Florida. For the current study, across all species groups for each panel at each site, nitrogen assimilation had a strong positive linear relationship with dry biomass assimilation, as shown in the following equation:

Nitrogen Mass Assimilation, g =10.64(Biomass Assimilation, kg) + 0.330 R^2=0.952

The results of this study for site mean phosphorus mass assimilation ranged from 21.7 ± 41.2 mg P m^{-2} for *P. cordata* to 387.8 ± 152.3 mg P m^{-2} for the Other species group (Table 3-18). These results were comparable to the range of phosphorus assimilation found by White (2009) (47 to 184 mg P m^{-2}), but the high and low assimilation values differed for *C. flaccida* and *J. effusus*. White's result for *J. effusus* was higher, with a mean of 184 mg P m^{-2} assimilated, when compared to 67.6 ± 94.1 mg P m^{-2} for the current study. White's result for *C. flaccida* was lower, with a mean of 47 mg P m^{-2}, when compared to 234.6 mg P m^{-2} for the current study. It was hypothesized that the species with higher assimilations reported in the literature would have higher assimilations in the current study. This was rejected, as species reported to have high assimilations in the literature had low assimilations in this study and vice versa.

For the current study, across all species groups for each panel at each site, phosphorus assimilation had a positive linear relationship with dry biomass assimilation, however the correlation was not as strong as for carbon or nitrogen. The relationship is shown in the following equation:

Phosphorus Mass Assimilation, g =0.955(Biomass Assimilation, kg) + 0.062

R^2=0.664

For both nitrogen and phosphorus mass assimilation, species groups had significant differences similar to that found for biomass assimilation (Wilcoxon Signed

Rank, α=0.05), indicating that it was the growth of biomass that resulted in the mass assimilation characteristics across species, as opposed to varying concentration of nutrients. There were significant differences between the final and initial mean mass assimilations for all species groups, and therefore all species groups were capable at removing nitrogen and phosphorus, confirming Hypothesis 1 for each species.

Metal Mass Assimilation by Species

The mass assimilation of zinc per square meter was lowest for *P. cordata* (3.01 ± 4.06 mg Zn m^{-2}) and highest for *C. flaccida* (20.70 ± 28.56 mg Zn m^{-2}) (Table 3-19). The species groups significantly differed in the same pattern as for biomass assimilation (Wilcoxon Signed Rank, α=0.05), suggesting that the zinc assimilation was driven by biomass growth. The range of zinc assimilation was somewhat lower than that of the result by Fritioff (2005) for emergent macrophytes in a stormwater setting (48.8 mg Zn m^{-2}), though the Fritioff study was a measure of emergent macrophyte zinc in a stormwater setting. When considering Hypothesis 3 for metal mass assimilation, there were no consistently reported results in the literature so the hypothesis could be neither confirmed nor denied. For the current study, across all Species groups for each Panel at each Site, zinc assimilation had a relatively strong positive linear relationship with dry biomass assimilation, as shown in the following equation:

Zinc Mass Assimilation, mg = 67.89(Biomass Assimilation, kg) - 14.10 R^2=0.8848

The mass assimilation of copper was lowest for *P. cordata* (0.24 ± 0.36 mg Cu m^{-2}) and highest for *C. flaccida* (2.18 ± 2.86 mg Cu m^{-2}) (Table 3-20). The Species groups significantly differed in the same pattern as for biomass assimilation (Wilcoxon Signed Rank, α=0.05), suggesting that the copper assimilation was driven by biomass growth. The range of copper assimilation was comparable to that of the result by Fritioff (2005) for emergent macrophytes in a stormwater setting (1 mg Cu m^{-2}), though the Fritioff study was a measure of emergent macrophyte copper in a stormwater setting.

It is important to note that for the means of *J. effusus* and *P. cordata*, there was no significant difference (Wilcoxon Matched Pairs, α=0.05) between initial zinc or copper mass per square meter and final zinc or copper mass per square meter. This indicates that over the course of the study the FTWs, on a mean basis, were a source of zinc and copper to the sites in which they were installed, with the metals installed in the initial macrophytes' tissues accounting for the metal loading. A possible reason for this was the relatively high tissue concentration in the initially installed individuals of *J. effusus* and *P. cordata* coupled with the loss of most or all of the initial biomass (and therefore metals contained in the macrophyte tissue) over the course of the study.

Performance by Allocation of Biomass

The design of the FTW used in this study led to the FTW being harvested in three distinct sections, the Above Mat biomass, the Mat biomass and the Below Mat biomass. The entire FTW was removed from the water in order to facilitate the harvesting of the Below Mat and Mat biomass. The complete removal of the material that had grown within the Mat was difficult and time consuming due to the small openings of the plastic matrix that made up the floating platform. When FTWs are deployed in the field these same issues may be experienced by managers, and therefore a harvesting scheme that minimizes the difficulty and time of harvesting efforts is important.

Additionally, while addressing the issues of time and effort of harvesting, a harvesting scheme that efficiently and effectively removes the constituent(s) of interest is required. Examples of this would be a focus on the removal of zinc from a stormwater pond near a manufacturing site, or the removal of nitrogen from stormwater near a heavily fertilized area. Targeted harvesting certain portions of the FTWs (Above Mat, Mat or Below Mat) may be ineffective due to their relative harvest difficulty, as well as their being low mass of the constituent(s) of interest. However, greater amounts of the constituent(s) of interest in a particular portion of the FTW may make harvesting an individual portion an effective means of pollutant removal while maintaining a critical propagule for future plant establishment without having to replant the FTW. This part of the study sought to determine which, if any, portion of the FTW were more or less effective at removing the various constituents.

Carbon, Nitrogen and Phosphorus Concentration by Zone

For the current study, the Below Mat carbon biomass concentration was found to be similar to that of the Above Mat and Mat Zones, with a site mean of 331.5 ± 41.2 for Below Mat, 338.0 ± 49.1 for Above Mat and 367.0 ± 7.4 g kg^{-1} for the Mat (Table 3-21). The mean carbon biomass concentrations did not significantly differ between zones. A study by Xian et al. (2007) conducted in Scotland found that the carbon biomass concentration in the shoots of *J. effusus* (shoot concentrations are analogous to the Above Mat Zone in the current study, and root concentrations are analogous to Below Mat) were similar to that of the roots across three sites (479 g C kg^{-1}, 470 g C kg^{-1}, and 468 g C kg^{-1} for roots, 479 g C kg^{-1}, 477 g C kg^{-1}, and 481 g C kg^{-1} for shoots, respective of sites). Hypothesis 4 is supported by this data, as previous research has found carbon concentrations to be similar for Above Mat and Below Mat Zones.

For the current study, the Below Mat nitrogen biomass concentration was found to be greater than that of the Above Mat and Mat Zones, with a site mean of 24.1± 2.5 for Below Mat, 10.5 ± 1.0 g kg^{-1} for Above Mat, and 19.6 ± 0.3 g kg^{-1} for the Mat Zone

(Table 3-22). All three zones were found to be significantly different from each other. At the end of the study conducted by PSI (2010), it was found that the nitrogen biomass concentration in the shoots of *P. cordata* (shoot concentrations are analogous to the Above Mat Zone in the current study, and root concentrations are analogous to Below Mat) was higher than that of the roots (5.0 g N kg^{-1} for roots, 14.0 g N kg^{-1} for shoots). For two other species, *C. flaccida* and *J. effusus*, PSI (2010) found that root nitrogen biomass concentration was slightly higher than that of shoot nitrogen concentration (*C. flaccida* root was 22.0 g N kg^{-1}, shoot was 18.4 g N kg^{-1}; *J. effusus* root was 13.7 g N kg^{-1}, shoot was 10.7). These nitrogen concentrations were similar to those found in the current study, and the results of generally higher concentrations in the root (Below Mat) was similar as well, thus supporting Hypothesis 4 for nitrogen concentrations.

Below Mat phosphorus biomass concentration was found to be greater than that of the Above Mat and Mat Zones, with a site mean of 4.34 ± 0.92 g P kg^{-1} for Below Mat, 1.11 ± 0.29 g P kg^{-1} for Above Mat and 2.98 ± 0.84 g P kg^{-1} for the Mat Zone (Table 3-23). All three zones were found to be significantly different from each other. At the end of the study conducted by PSI (2010), it was found that the phosphorus biomass concentration in the shoots of *P. cordata* were similar (0.4 g P kg^{-1} for roots, 0.37 g P kg^{-1} for shoots). In the PSI study, for two species, *C. flaccida* and *J. effusus*, it was found that root phosphorus biomass concentration was similar, and considerably higher than that of shoot phosphorus concentration, respectively (*C. flaccida* root was 1.5 g P kg^{-1}, shoot was 1.3 g P kg^{-1}; *J. effusus* root was 1.2 g P kg^{-1}, shoot was 0.6 g P kg^{-1}). A ‘root’ concentration of around 1.8 g P kg^{-1} and a leaf/shoot concentration of around 2.0 g P kg^{-1} were found in a study by Hadad and Maine (2007). The phosphorus concentrations found in the two referenced studies were on the same order of magnitude as those found in the current study, though slightly lower overall, and the results of generally higher concentrations (*J. effusus* roots in the PSI study were found to have higher phosphorus concentrations than shoots) in the Below Mat for the current study was found to be at differ with the PSI study. Hypothesis 4 is not fully supported by this data for phosphorus concentrations by zone when considering all species reported in the referenced literature.

Metal Concentration by Zone

Although specific data was not given by Fritioff (2005), the general statement was made that across several emergent wetlands species; Zn, Cu, Cd and Cr were found to accumulate in greater concentration in roots than shoots for rooted wetland plants. This conclusion was explained by the bioavailability of heavy metals in the soils and sediments of the sites. Although this same study reports that free floating wetland species, such as *Lemna minor* and *Eichornia crassipes* have been found to accumulate higher levels of heavy metals than emergent species, no comparisons between roots and shoots was made.

The current study found that Below Mat metal concentrations were significantly greater than those of Above Mat Zones for the metals Cu, Cd, and Cr, but Zn concentrations did not significantly differ by zone. For Cu, Cd and Cr the Below Mat concentrations were higher than those of the Above Mat, and slightly higher than those of the Mat Zone (Table 3-24, Table 3-25, Table 3-26 and Table 3-27). Studies by Rai (2008) as well as Deng et al. (2004) found mean Zn biomass concentrations across several emergent wetland species to be slightly higher in the root zone when compared to the shoot zone (Rai: 56.4 mg Zn kg^{-1} for roots, 41.7 mg Zn kg^{-1} for shoots; Deng et al.: 78 mg Zn kg^{-1} for roots, 36 mg Zn kg^{-1} for shoots). For Cu, root biomass concentrations were found to be much greater than shoot concentration (Rai: 732 mg Zn kg^{-1} for roots, 73.6 mg Zn kg^{-1} for shoots; Deng et al.: 871 mg Zn kg^{-1} for roots, 67 mg Zn kg^{-1} for shoots).

It was hypothesized that the partitioning of constituents by zone would follow patterns found in previous field studies. This hypothesis was rejected for Zn, and supported for Cu. Zones did not significantly differ for Zn partitioning, and the Below Mat Zone was greater than (and significantly different from) the Above Mat portion, as was found by previous studies.

Biomass Assimilated by Zone

On an average sites basis, biomass harvested was the greatest in the Above Mat Zone (856 ± 649 g m^{-2}), and the Below Mat Zone had the lowest biomass harvested (486 ± 400 g m^{-2}) (Table 3-28). However there were no significant differences found between Zones.

The current study found that 44.9% of the biomass harvest was in the Above Mat Zone, and 55.1% was found in the Mat and Below Mat Zones, combined (29.7% from Mat, and 25.4% from Below Mat) (Figure 3-11). PSI (2010) divided their individual macrophytes into two positions, root and shoot, rather than three (Above Mat, Mat, and Below Mat, with Above Mat and Below Mat being analogous to shoot and root, respectively), however an approximate comparison between the current study and the PSI study can be made. Though, the exact sampling technique was not described in the PSI paper it is assumed that the rhizome section of the plant was included as the 'root' section and not the 'shoot' section. For a selection of four species (*Agrostis alba*, *P. cordata*, *C. flaccida*, and *J. effusus*) that made up the majority of the biomass in their study, PSI (2010) found 27.6% of the total biomass within the ‘shoots’ of their samples and 72.4% within the ‘roots’ of their samples. Though the PSI study had a larger difference between shoots and roots, the results of this study were similar in that the Below Mat (or ‘root’) Zone had a greater biomass harvest than the Above Mat Zone.

A study by Ladislas et al. (2013), which was a similar FTW study involving floating macrophytes, found that for *J. effusus* the shoots made up 47.1% of the total biomass, while roots made up 52.9%, and for *Carex riparia*, root biomass made up 47.7% and shoot biomass made up 52.3%. These results were similar to that of the current study. For a study by Hadad and Maine (2007), the results were basically similar to that of the current study, with approximately half of the biomass being found in the ‘submerged’ (akin to Mat and Below Mat Zones) position and half being found in the ‘aerial’ (akin to Above Mat Zone) position. Thus, Hypothesis 4 was supported for biomass harvest, in that the combined Mat and Below Mat Zones had greater biomass harvest; however, it is important to note that there were no statistically significant differences between any of the three groups.

Carbon Mass harvested by Zone

The harvest of carbon on a mean site basis mirrored the harvest of biomass, with the Above Mat Zone removing the most (323 ± 244 g m^{-2}) and the Below Mat Zone removing the least (168 ± 141 g m^{-2}) (Table 3-29). As with biomass, there were no significant differences between zones for carbon assimilation. Patterns evident in the harvest of biomass by zone were consistent with patterns for the assimilation of carbon by zone.

The percent of total carbon harvest within each zone was found to be very similar to that of the percent of total biomass harvested by zone, with 46.1% of the total carbon mass assimilation in the Above Mat Zone and 53.9% for the Mat and Below Mat Zone combined (Figure 3-12). As with the comparisons by species, it can be said that the biomass found in each zone was driving the mass of carbon found in each zone. As carbon is typically found to be directly related to the total biomass of wetland macrophytes (Hadad and Maine, 2007), the similarities between carbon and biomass are not surprising, both for the current study and the comparisons to other studies in the literature. Previous studies on partitioning of carbon assimilation by zone were not found on an area basis for floating macrophytes, therefore Hypothesis 4 could be neither supported nor rejected.

Nitrogen and Phosphorus Mass Harvest by Zone

The Below Mat Zone assimilated the greatest amount of nitrogen (11.4 ± 8.58 g m^{-2}), on a mean site basis, whereas the Above Mat Zone assimilated the least (9.55 ± 6.17 g m^{-2}) (Table 3-30). Again, there were no significant differences found between zones for nitrogen assimilations. This was expected, as the mean assimilations per zone were within 2 grams per square meter of one another. This overall even distribution of nitrogen throughout the Zones is important for the management of excess nitrogen in surface waters, as it shows that no one zone can be discounted when considering harvesting efforts or FTW design. This will be discussed further in the conclusions section.

In a study by Chen et al. (2009) an ornamental species of *Canna* lily had 86.9% of nitrogen assimilation performed by what is analogous to its Above Mat Zone, 5.4% by its Mat Zone, and 7.5% by its Below Mat Zone. The results of the current study do not reflect the results of Chen et al. (2009). For *P. cordata* in the same Chen et al. study the percent assimilation by position was as follows: 85.7% for Above Mat, 2.1% for Mat, and 12.1% for Below Mat. Again, these results were not similar to what was found in the Chen et al. study. As the Chen et al. study would have predicted that the Above Mat Zone would have assimilated a greater portion of the total nitrogen than the Mat and Below Mat Zones combined, Hypothesis 4 is rejected for nitrogen mass assimilation. This may have been due to the late-season harvest of the FTWs, which could have allowed time for the wetland macrophytes to begin shifting their nutrients to their roots and rhizomes for storage.

The Below Mat Zone assimilated the greatest amount of phosphorus (1.83 ± 1.35 g m^{-2}), on a mean site basis, whereas the Above Mat Zone assimilated the least (0.90 ± 0.42 g m^{-2}) (Table 3-31). Again, there were no significant differences found between Zones for phosphorus assimilations. However, the maximum phosphorus assimilation for the Below Mat Zone was nearly twice that of the maximum assimilation for the Above Mat Zone. The greater amounts of phosphorus assimilated by the Mat and Below Mat Zones could have implications for the design and maintenance of FTWs when the focus is on the removal of phosphorus.

The current study found that 21.2% of the phosphorus assimilation was in the Above Mat Zone, and 78.9% was found in the Mat and Below Mat Zones, combined (with 35.7% as Mat, and 43.2% as Below Mat) (Figure 3-14). In a study by Chen et al. (2009) an ornamental species of *Canna* lily had 93.5% of phosphorus assimilation performed by what is analogous to its Above Mat Zone, 2.4% by its Mat Zone, and 4.0% by its Below Mat Zone. The results of the current study do not reflect these results. For *P. cordata* in the same Chen et al. (2009) study the percent assimilation by Zone was as follows: 91.7% for Above Mat, 1.7% for Mat, and 6.6% for Below Mat. Again, these results were not similar to what was found in this study. As this other study would have predicted that the Above Mat Zone would have assimilated a greater portion of the total phosphorus than the Mat and Below Mat Zones combined, Hypothesis 4 is rejected for phosphorus mass assimilation. This result could have been due to adsorption of phosphorus to the detrital organic matter and mineral matter caught within the root mats (Sasser et al., 1991) that made up most of the Below Mat Zone of each FTW.

Metal Mass Assimilation by Zone

In general, it has been concluded in the available literature that metals are found in greater amounts in the lower portions of wetland plants, namely the roots and rhizomes. This is due to the adsorption and absorption of the roots that are in close proximity to metals bound to the soils in which they grow. As FTWs' roots are found in free water, this may not necessarily be the case (Fritioff, 2005). However, the matted root systems of FTWs also provide surface area in which mineral and organic materials are caught and held; these materials provide binding sites for metals, or may contain metals themselves (Headley and Tanner, 2008).

The assimilation of Zn on a mean site basis mirrored the assimilation of biomass, with the Above Mat Zone removing the most (39.2 ± 46.4 mg m^{-2}) and the Below Mat portion removing the least (20.2 ± 20.3 mg m^{-2}) (Table 3-23). As with biomass, there were no significant differences between zones for zinc assimilation. It is also interesting that while the site minimum assimilations for Zn are very close for the Above Mat and Below Mat Zones, the maximum Above Mat Zn assimilation for a single site is more than twice that of the maximum Below Mat Zn assimilation for a single site. This indicates that the potential for the Above Mat Zone to remove Zn is possibly greater than the potential for the Below Mat Zone to remove Zn.

The percent of total Zn mass assimilated was found to be similar to that of the percent assimilations by zone for biomass (and carbon). The current study found that 45.3% of the biomass assimilation was in the Above Mat Zone, and 54.7% was found in the combined Mat and Below Mat Zones, combined (with 31.3% as Mat, and 23.4% as Below Mat) (Figure 3-15). Studies by Deng et al. (2009), as well Fritioff and Greger (2003), measured the mass of various heavy metals within the tissues of a suite of wetland species and concluded that, with few exceptions, heavy metals are mostly found in the roots of these plants. This is partly supported by the study by Ladislas et al. (2013) which found that for *J. effusus* the shoots made up 58.4% of the total zinc, while roots made up 41.6%, and for *Carex riparia* shoot biomass made up 35.5% and root biomass made up 64.5%. So, for *Carex riparia*, the Ladislas et al. study agrees with the other studies, but for *J. effusus* the study does not agree. The current study found that when roots and rhizomes were combined (as Below Mat and Mat), they assimilated greater amounts of Zn than the shoot portion (Above Mat Zone). Though some literature is unclear as to whether upper or lower portions of wetland plants should be expected to be able to remove Zn in higher amounts, most of the literature found seems to agree with the results of the current study, thus Hypothesis 4 is supported for Zn mass assimilation.

The assimilation of Cu was around one tenth that of the assimilation of Zn, however, the highest and lowest assimilations by zone were not consistent between the two metals. Although no zone significantly differed from the rest, the Above Mat Zone had the highest assimilation (3.5 ± 3.8 mg m^{-2}) and the Mat Zone (not the Below Mat Zone as it was with Zn) had the lowest assimilation of Cu (2.5 ± 2.0 mg m^{-2}) (Table 3-

33). Another way that Zn and Cur assimilation patterns differed between zones is that the minimum assimilations as well as the maximum assimilations were similar for the Above Mat and Below Mat Zones.

These similar assimilation patterns, paired with the fact that the Above Mat and Below Mat Zones outperformed the Mat Zone resulted in the combined Above Mat and Below Mat Zones removing 73.2% of the Cu (37.3% for Above Mat, 35.9% for Below Mat), with the Mat Zone only removing 26.8 % (Figure 3-16). From a management perspective, the majority of Cu being found in the Above Mat and Below Mat Zones allows for managers concerned with the metal to make an informed decision on their design and maintenance of an FTW. Previous studies on partitioning of heavy metal assimilation by zone found the Below Mat portions to be higher, whereas this study found no significant difference among zones for Cu assimilation, therefore Hypothesis 4 was rejected.

Cadmium assimilation did not occur at an appreciable level (by concentration or mass), and will not be discussed. The assimilation of Cr was less than one tenth that of the assimilation of Zn, but close to the assimilation of Cu by zone in order of magnitude. However, a distinctly different pattern of assimilation by zone was found for Cr. The Mat and Below Mat portions were greater than that of the Above Mat Zone, and were significantly different (both the Mat and Below Mat Zones were significantly different from the Mat Zone). The Above Mat Zone had the lowest assimilation (0.462 ± 0.403 mg m^{-2}) and the Below Mat Zone had the highest assimilation of Cr (2.63 ± 2.59 mg m^{-2}) (Table 3-34). The maximum site assimilation for the Above Mat Zone did not even reach the average assimilations for Mat and Below Mat.

The low performance of the Above Mat Zone for Cr assimilation is pronounced when considering the percentage of Cr assimilation by zone, with the Above Mat Zone only representing 9.0% of the total, and the combined Mat and Below Mat Zones removing 91.0 % (39.6% for the Mat Zone, and 51.4% for the Below Mat Zone) (Figure 3-17). From a management perspective, almost all of the assimilated Cr being found in the Mat and Below Mat Zones allows for managers concerned with the metal to make an informed decision on their design and maintenance. Leaving the Mat Zone (which is more difficult and possibly costly to harvest) in place on the FTW after harvest would leave nearly forty percent of the Cr behind. Previous studies on partitioning of heavy metal assimilation by Zone found the Below Mat portions to be higher. This study found the Below Mat Zone to be significantly greater than the Above Zone for Cr assimilation, therefore Hypothesis 4 was supported.

Table 3-1. Self-recruited macrophyte species per site.

Species	Common Name	SS1	SS2	SS3
Acer rubrum	red maple	X		
Alternanthera philoxeroides	alligator weed	X		
Aster elliottii	Elliott's aster		X	
Aster lateriflorus	calico aster		X	
Bidens laevis	bur marigold		X	X
Carex unk.	sedge		X	
Cyperus odoratus	fragrant flatsedge	X	X	X
Cyperus polystachyos	flat sedge	X	X	
Cyperus sp.	spikerush	X		
Cyperus surinamensis	tropical flatsedge			X
Diodia virginiana	Virginia buttonweed	X		
Eclipta alba	yerba de tajo		X	X
Eleocharis sp	spikerush		X	X
Erigeron vernus	early whitetop fleabane			X
Eupatorium capillifolium	dog fennel	X	X	X
Galium tinctorum	stiff marsh bedstraw			X
Hydrocotyle umbulata	pennywort	X	X	X
Juncus sp.	rush		X	
Limnobium spongia	American spongeplant			X
Ludwigia leptocarpa	angelstem primrose-willow	X	X	
Ludwigia peruviana	water primrose	X		X
Ludwigia repens	red ludwigia	X	X	X
Mikania scandens	climbing hempvine			X
Phyla nodiflora	matchstick	X		X
Pistia stratiotes	bristlegrass	X		
Pluchea odorata	sweetscent	X		X
Pluchea rosea	rosy camphorweed	X	X	X
Poaceae sp.	grass, unknown	XX	XX	XX
Polygonum hydropiperoides	wild water pepper		X	X
Polygonum sp.	knotweed	X		
Rhynchospora caduca	beak rush			X
Rhynchospora odorata	fragrant beak rush			X
Sacciolepis striata	American cupscale grass		X	X
Salix caroliniana	coastal plain willow	X	X	X
Salvinia minima	water spangle			X
Setaria geniculata	Knotroot foxtail	X		
Setaria viridis	green bristlegrass	X		X
Typha latifolia	common cattail		X	
Wolffia sp.	watermeal	X		

Note: XX indicates multiple species of a genus were present.

Table 3-2. Initial mean constituent mass loading from planted macrophytes.

Parameter	Unit	Mean	Std. Dev.	Minimum	Maximum
Dry Biomass	(g m^{-2})	253.9	26.9	216.2	277.1
Carbon	(g m^{-2})	97.0	10.7	81.9	106
Nitrogen	(g m^{-2})	3.77	0.40	3.21	4.14
Phosphorus	(g m^{-2})	0.828	0.086	0.710	0.912
Zinc	(mg m^{-2})	13.1	1.40	11.2	14.3
Copper	(mg m^{-2})	2.07	0.22	1.76	2.25
Cadmium	(mg m^{-2})	0.026	0.002	0.022	0.028
Chromium	(mg m^{-2})	0.564	0.057	0.484	0.615

Table 3-3. Overall mean per square meter mass assimilation.

Parameter	Unit	Mean	Std. Dev.	Min	Max	W	p-value
Biomass	(g m^{-2})	1908	1330	655.8	3750	6.67	<0.0001
Carbon	(g m^{-2})	700.2	488.2	227.3	1372	6.78	<0.0001
Nitrogen	(g m^{-2})	32.0	20.5	10.8	59.7	5.83	<0.0001
Phosphorus	(g m^{-2})	4.25	2.44	2.25	7.68	5.12	<0.0001
Zinc	(mg m^{-2})	86.5	91.6	18.3	216	4.55	<0.0001
Copper	(mg m^{-2})	9.43	9.54	2.11	22.9	4.35	<0.0001
Cadmium	(mg m^{-2})	0.234	0.263	0.047	0.606	2.59	0.0225
Chromium	(mg m^{-2})	5.11	4.82	1.64	11.92	3.40	<0.0001

Means, standard deviations, minimums and maximums are on a mass assimilation per Site basis. The W and p-values were found using the Wilcoxon Signed Rank test for the significant differences between Final and Initial mass.

Table 3-4. Biomass assimilation rate per square meter per day for all parameters studied.

Parameter	Unit	Mean	Std. Dev.	Min.	Max.
Dry Biomass	(g m^{-2} d^{-1})	6.86	4.78	2.36	13.5
Carbon	(g m^{-2} d^{-1})	2.52	1.76	0.818	4.94
Nitrogen	(g m^{-2} d^{-1})	0.115	0.074	0.039	0.215
Phosphorus	(mg m^{-2} d^{-1})	15.3	8.8	8.09	27.6
Zinc	(mg m^{-2} d^{-1})	0.311	0.330	0.066	0.777
Copper	(mg m^{-2} d^{-1})	0.034	0.034	0.008	0.082
Cadmium	(mg m^{-2} d^{-1})	0.0008	0.0009	0.0002	0.0022
Chromium	(mg m^{-2} d^{-1})	0.018	0.017	0.006	0.043

Table 3-5. Comparison of nutrient assimilation rates in this study with other stormwater treatment systems.

Reference	Description	Mass Assimilation		
		Biomass ($g\ m^{-2}\ d^{-1}$)	Nitrogen ($g\ m^{-2}\ d^{-1}$)	Phosphorus ($mg\ m^{-2}\ d^{-1}$)
This study	stormwater FTW, Florida	6.86	0.115	15.3
	FTW, urban runoff, *Vetiver*		0.0017	0.16
	FTW, urban runoff, *Polygonum*		0.0028	0.4
Hubbard et al. (2004)	FTW, swine waste, *Typha latifolia*	33.9	1.097	162.4
	FTW, swine waste, *Juncus effusus*	1.3	0.046	6.57
	FTW, swine waste, *Panicum hematomon*	20.0	0.663	98.56
	FTW, 1/4 strength Hoaglund solution, *Typha latifolia*	22.7	0.718	126.89
	FTW, 1/4 strength Hoaglund solution, *Juncus eff.*	11.2	0.263	38.6
	FTW, 1/4 strength Hoaglund solution, *Panicum hem.*	18.3	0.410	55.64
Tanner et al. (2011)	FTW, batch-fed mescosm	-	0.64 - 0.76	54 - 58
	FTW, flow-through mesocosm, low-high loading	-	0.16 - 0.24	2.3 - 5.4
Tanner and Headley (2008)	FTW mesocosm (**rhizome mass not included)	2.7- 5.9**	-	-
Wen and Recknagel (2002)	FTW, *Myriophyllum, Paspalum* and *Ranunculus*	-		43 - 86
Jangrel-Bratli (2011)	stormwater FTW, unfertilized	-	0.17	8.5
	stormwater FTW, fertilized	-	0.16	3220
Hogg and Wein (1988)	Natural floating *Typha* mats (*g m^{-2}, found in situ)	1939*	-	-
Chang et al. (2002)	emergent mesocosm, *Scirpus* and *Pontederia*	-	0.036	1.5
Durham	emergent treatment wetland, swine waste, *Typha*	-	1.35	200
Bachande and Horne (2000)	emergent treatment wetland	-	2.2 - 2.6	-
Spieles and Mitsch (2000)	emergent treatment wetland, Ohio	-	-	18 - 20
US EPA (1999)	emergent treatment wetlands		0.20	60
DeBusk at al. (2004)	periphyton raceways, Florida Everglades	-	-	0.88

Table 3-6. Final wet biomass averaged among all three deployment locations.

	Final Wet Biomass (kg m^{-2})		
	Mean	Minimum	Maximum
Above Mat	4.20	1.72	8.63
Mat	4.10	1.57	6.76
Below Mat	6.39	1.45	13.4
All	14.7	4.74	28.8

Table 3-7. Overall final wet mass per FTW.

	Final Wet Biomass (kg per FTW)		
	Mean	Minimum	Maximum
Above Mat	37.5	15.3	77.0
Mat	36.6	14.0	60.3
Below Mat	57.1	13.0	120.0
All	131	42.3	257

Note: FTW dimensions were 2.44 m by 3.66 m.

Table 3-8. Mean net mass accumulation by panel.

Parameter	Unit	A	B	C
Biomass	(g m^{-2})	689 ± 473	590 ± 320	630 ± 549
Carbon	(g m^{-2})	252 ± 172	219 ± 121	229 ± 200
Nitrogen	(g m^{-2})	11.7 ± 7.9	10.3 ± 4.8	10.3 ± 8.1
Phosphorus	(g m^{-2})	1.63 ± 1.07	1.33 ± 0.49	1.29 ± 0.91
Zinc	(mg m^{-2})	25.2 ± 24	23.1 ± 21.7	38.1 ± 45.9
Copper	(mg m^{-2})	3.76 ± 4.07	2.59 ± 2.00	3.07 ± 3.48
Cadmium	(mg m^{-2})	0.145 ± 0.189	0.0473 ± 0.0391	0.0416 ± 0.0357
Chromium	(mg m^{-2})	2.324 ± 2.499	1.32 ± 0.919	1.468 ± 1.398

*Note: There were no statistical differences found between Panels at $\alpha < 0.05$ using the Kruskal-Wallis test, blocked by Site. Degrees of freedom for all tests was 2, and number of samples per Panel was 3.

Table 3-9. Mean tissue concentration by panel.

Parameter	Unit	A	B	C
Carbon	(g m^{-2})	347 ± 25	360 ± 15	349 ± 26
Nitrogen	(g m^{-2})	15.9 ± 1.2	16.8 ± 1.1	17.4 ± 0.7
Phosphorus	(g m^{-2})	2.31 ± 0.24	2.41 ± 0.25	2.57 ± 0.49
Zinc	(mg m^{-2})	29.7 ± 7.5	43.3 ± 13.8	37.7 ± 10.6
Copper	(mg m^{-2})	5.00 ± 2.53	4.67 ± 2.21	4.40 ± 1.60
Cadmium	(mg m^{-2})	0.123 ± 0.102	0.0775 ± 0.0256	0.0789 ± 0.0365
Chromium	(mg m^{-2})	2.38 ± 1.27	2.36 ± 0.68	2.30 ± 0.67

*Note: There were no statistical differences found between Panels at $\alpha < 0.05$ using the Kruskal-Wallis test, blocked by Site. Degrees of freedom for all tests was 2, and number of samples per Panel was 3.

Table 3-10. Carbon biomass concentration (g kg^{-1}) by species.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Juncus effusus	411.5	8.0	400.3	418.4	A
Canna flaccida	361.7	7.7	353.8	372.1	B
Pontederia cordata	381.9	6.3	375.5	388.2	C
Other	381.8	10.2	367.6	390.8	C

Note: Species with similar letters were found to have no significant difference for their Site means using the Wilcoxon Signed Rank test for significant difference (α= 0.05, DF=3, n=3), blocked by Site.

Table 3-11. Nitrogen biomass concentration (g kg^{-1}) by species.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Juncus effusus	10.23	0.64	9.36	10.89	A
Canna flaccida	12.13	2.60	9.62	15.71	A
Pontederia cordata	11.88	2.14	9.74	14.02	A
Other	12.51	0.62	11.64	12.98	A

Note: Species with similar letters were found to have no significant difference for their Site means using the Wilcoxon Signed Rank test for significant difference (α= 0.05, DF=3, n=3), blocked by Site.

Table 3-12. Phosphorus biomass concentration (g kg^{-1}) by species.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Juncus effusus	1.09	0.27	0.85	1.47	A
Canna flaccida	1.72	0.89	0.72	2.89	A
Pontederia cordata	0.93	0.17	0.75	1.10	A
Other	1.51	0.52	1.06	2.23	A

Note: Species with similar letters were found to have no significant difference for their Site means using the Wilcoxon Signed Rank test for significant difference (α= 0.05, DF=3, n=3), blocked by Site.

Table 3-13. Site mean zinc (mg kg^{-1}) concentrations by species.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Juncus effusus	31.2	8.90	19.2	40.6	A
Canna flaccida	39.1	19.9	19.1	66.3	A
Pontederia cordata	34.6	20.9	13.7	55.5	A
Other	28.3	15.1	15.6	49.6	A

Note: Species with similar letters were found to have no significant difference for their Site means using the Wilcoxon Signed Rank test for significant difference (α= 0.05, DF=3, n=3), blocked by Site.

Table 3-14. Site mean copper (mg kg^{-1}) concentrations by species.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Juncus effusus	5.48	1.75	3.36	7.66	A
Canna flaccida	5.87	1.68	3.62	7.65	A
Pontederia cordata	3.07	2.05	1.03	5.12	A B
Other	2.17	0.83	1.14	3.17	B

Note: Species with similar letters were found to have no significant difference for their Site means using the Wilcoxon Signed Rank test for significant difference (α= 0.05, DF=3, n=3), blocked by Site.

Table 3-15. Above mat net dry biomass assimilation (g m^{-2}) by species.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.	F > I
Juncus effusus	88.6	102	-6.21	228	B	*
Canna flaccida	306	393	21.9	862	A B	*
Pontederia cordata	85.8	69.3	-8.63	156	B	*
Other	296	174	105	527	A	*

Note: In Sig. Diff. column, Species not connected by the same letter are significantly different. Statistical tests were performed using the Wilcoxon Signed Rank test (α=0.05, DF=3, n=3), blocked by Site. In F>I column, an asterisk (*) indicates there was significantly more Final mass for that Species than Initial mass, and NS indicates there was no significant difference between Final mass and Initial mass (Wilcoxon Signed Rank, α=0.05).

Table 3-16. Above mat carbon (g m^{-2}) assimilation by species.

	Mean	St. Dev.	Min	Max	Sig. Diff.	F> I
Juncus effusus	36.9	42.4	-2.42	95.8	B	*
Canna flaccida	110	141	7.73	309	A B	*
Pontederia cordata	32.8	26.2	-3.21	58.4	B	*
Other	114	68.0	38.7	204	A	*

Note: In Sig. Diff. column, Species not connected by the same letter are significantly different. Statistical tests were performed using the Wilcoxon Signed Rank test (α=0.05, DF=3, n=3), blocked by Site. In F>I column, an asterisk (*) indicates there was significantly more Final mass for that Species than Initial mass, and NS indicates there was no significant difference between Final mass and Initial mass (Wilcoxon Signed Rank, α=0.05).

Table 3-17. Above mat nitrogen (g m^{-2}) assimilation per species.

	Mean	St. Dev.	Min	Max	Sig. Diff.	F> I
Juncus effusus	0.862	0.923	-0.032	2.13	B	*
Canna flaccida	3.03	3.75	0.223	8.33	A B	*
Pontederia cordata	0.940	0.753	-0.122	1.55	B	*
Other	3.70	2.04	1.43	6.39	A	*

Note: In Sig. Diff. column, Species not connected by the same letter are significantly different. Statistical tests were performed using the Wilcoxon Signed Rank test (α=0.05, DF=3, n=3), blocked by Site. In F>I column, an asterisk (*) indicates there was significantly more Final mass for that Species than Initial mass, and NS indicates there was no significant difference between Final mass and Initial mass (Wilcoxon Signed Rank, α=0.05).

Table 3-18. Above mat phosphorus (mg m^{-2}) assimilation per species.

	Mean	St. Dev.	Min	Max	Sig. Diff.	F> I
Juncus effusus	67.6	94.1	-14.5	199	B	*
Canna flaccida	235	266	29.4	610	A B	*
Pontederia cordata	21.7	41.2	-32.7	66.9	B	NS
Other	388	152	252	601	A	*

Note: In Sig. Diff. column, Species not connected by the same letter are significantly different. Statistical tests were performed using the Wilcoxon Signed Rank test (α=0.05, DF=3, n=3), blocked by Site. In F>I column, an asterisk (*) indicates there was significantly more Final mass for that Species than Initial mass, and NS indicates there was no significant difference between Final mass and Initial mass (Wilcoxon Signed Rank, α=0.05).

Table 3-19. Above mat zinc (mg m^{-2}) assimilation, per species.

	Mean	St. Dev.	Min	Max	Sig. Diff.	F> I
Juncus effusus	3.24	4.26	-0.64	9.17	B	NS
Canna flaccida	20.7	28.6	0.388	61.1	A B	*
Pontederia cordata	3.01	4.06	-0.440	8.71	B	NS
Other	10.9	10.6	1.83	25.8	A	*

Note: In Sig. Diff. column, Species not connected by the same letter are significantly different. Statistical tests were performed using the Wilcoxon Signed Rank test (α=0.05, DF=3, n=3), blocked by Site. In F>I column, an asterisk (*) indicates there was significantly more Final mass for that Species than Initial mass, and NS indicates there was no significant difference between Final mass and Initial mass (Wilcoxon Signed Rank, α=0.05).

Table 3-20. Above mat copper (mg m^{-2}) assimilation, per species.

	Mean	St. Dev.	Min	Max	Sig. Diff.	F> I
Juncus effusus	0.370	0.572	-0.0723	1.18	B	NS
Canna flaccida	2.18	2.86	0.0771	6.23	A B	*
Pontederia cordata	0.237	0.358	-0.0494	0.741	B	NS
Other	0.492	0.257	0.294	0.854	A	*

Note: In Sig. Diff. column, Species not connected by the same letter are significantly different. Statistical tests were performed using the Wilcoxon Signed Rank test (α=0.05, DF=3, n=3), blocked by Site. In F>I column, an asterisk (*) indicates there was significantly more Final mass for that Species than Initial mass, and NS indicates there was no significant difference between Final mass and Initial mass (Wilcoxon Signed Rank, α=0.05).

Table 3-21. Carbon biomass concentration (g kg^{-1}) by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Above Mat	338	49.1	275	395	A
Mat	367	7.39	359	377	A
Below Mat	332	41.2	274	371	A

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-22. Nitrogen biomass concentration (g kg^{-1}) by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Above Mat	10.5	1.05	9.02	11.5	A
Mat	19.6	0.335	19.1	19.9	B
Below Mat	24.1	2.55	22.1	27.7	C

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-23. Phosphorus biomass concentration (g kg^{-1}) by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Above Mat	1.11	0.290	0.779	1.48	A
Mat	2.98	0.841	2.15	4.14	B
Below Mat	4.34	0.918	3.60	5.63	C

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-24. Zinc biomass concentration (mg kg^{-1}) by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Above Mat	32.7	8.29	22.8	43.1	A
Mat	42.3	18.9	24.3	68.4	A
Below Mat	43.2	19.0	18.0	64.0	A

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-25. Copper biomass concentration (mg kg^{-1}) by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Above Mat	3.76	1.55	1.64	5.31	A
Mat	4.77	1.95	2.04	6.49	A B
Below Mat	6.80	3.47	2.04	10.2	B

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-26. Cadmium biomass concentration (mg kg^{-1}) by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.
Above Mat	0.00768	0.00983	0.000592	0.0216	A
Mat	0.130	0.109	0.0227	0.280	A B
Below Mat	0.219	0.0738	0.122	0.300	B

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-27. Chromium biomass concentration (mg kg^{-1}) by zone.

	Mean	St. Dev.	Min	Max	Sig. Diff.
Above Mat	0.370	0.123	0.274	0.544	A
Mat	3.27	1.37	1.49	4.81	B
Below Mat	5.29	1.82	2.79	7.10	C

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-28. Biomass (g m^{-2}) assimilation by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.*
Above Mat	856	649	349	1770	A
Mat	566	300	207	941	A
Below Mat	486	400	99.1	1040	A

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-29. Carbon (g m^{-2}) mass assimilation by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.*
Above Mat	323	244	127	667	A
Mat	209	111	74.7	345	A
Below Mat	168	141	25.4	360	A

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-30. Nitrogen (g m^{-2}) mass assimilation by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.*
Above Mat	9.55	6.17	4.57	18.2	A
Mat	11.1	5.96	3.98	18.6	A
Below Mat	11.4	8.58	2.23	22.8	A

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-31. Phosphorus harvest (g m^{-2}) by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.*
Above Mat	0.901	0.417	0.425	1.44	A
Mat	1.52	0.733	0.836	2.53	A
Below Mat	1.83	1.35	0.575	3.71	A

Note: Zones with similar letters were found to have no sig. diff. for their Site means using the Kruskal-Wallis test for sig. difference (α= 0.05, DF=2, n=3), blocked by Site.

Table 3-32. Zinc (mg m^{-2}) mass assimilation by zone.

	Mean	St. Dev.	Min.	Max.	Sig. Diff.*
Above Mat	39.2	46.4	5.38	105	A
Mat	27.1	25.1	6.38	62.3	A
Below Mat	20.2	20.3	5.22	48.9	A

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference ($\alpha = 0.05$, DF=2, n=3), blocked by Site.

Table 3-33. Copper (mg m-2) mass assimilation by zone.

	Mean	St. Dev.	Min	Max	Sig. Diff.*
Above Mat	3.51	3.88	0.556	9.00	A
Mat	2.53	2.01	0.966	5.37	A
Below Mat	3.38	3.65	0.590	8.54	A

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference ($\alpha = 0.05$, DF=2, n=3), blocked by Site.

Table 3-34. Chromium (mg m^{-2}) mass assimilation by zone.

	Mean	St. Dev.	Min	Max	Sig. Diff.
Above Mat	0.462	0.403	0.142	1.03	A
Mat	2.02	1.83	0.702	4.60	B
Below Mat	2.63	2.59	0.724	6.29	B

Note: Zones with similar letters were found to have no significant difference for their Site means using the Kruskal-Wallis test for significant difference ($\alpha = 0.05$, DF=2, n=3), blocked by Site.

A

B

C

Figure 3-1. Initial (left) and final (right) above mat FTW macrophytes. A) SS1, B) SS2, C) SS3; photos courtesy of Neal Beery.

A  B

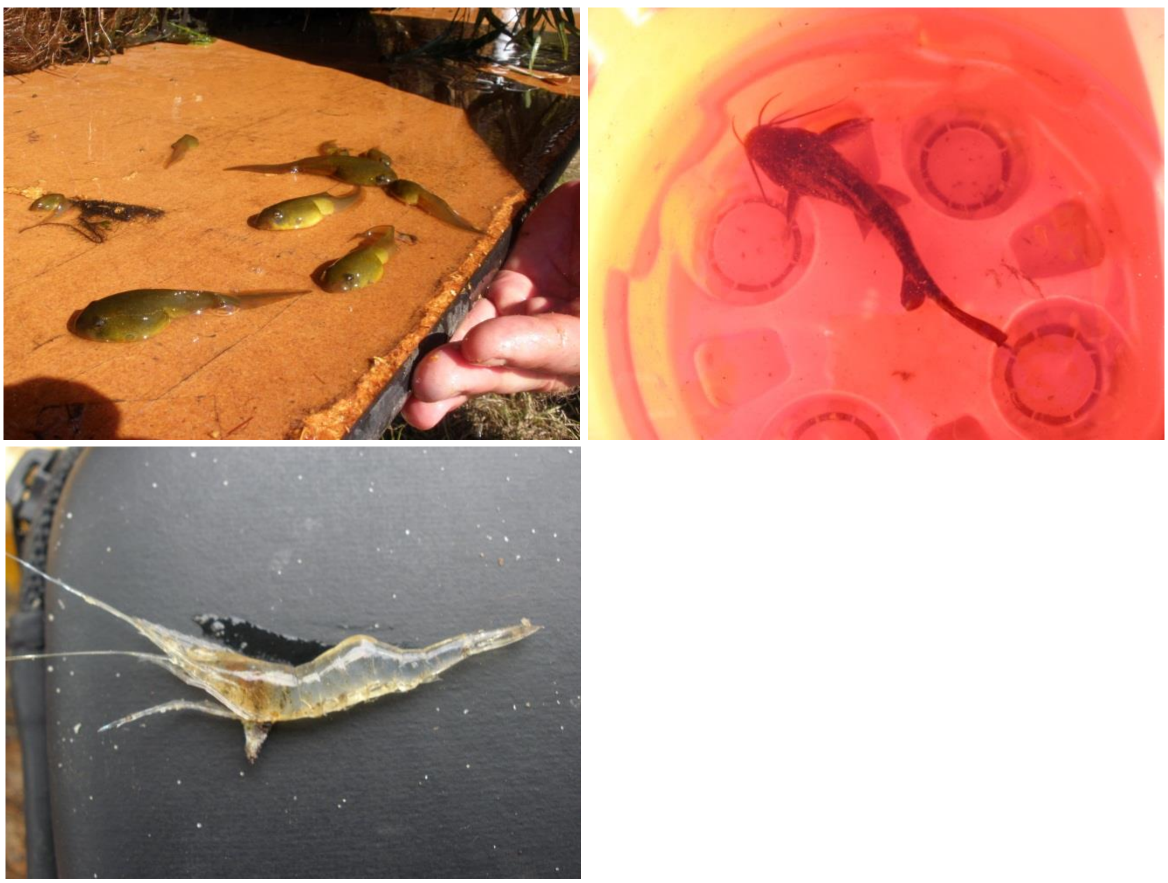
Figure 3-2. Surface area of SS3 and SS1. A) SS3 with oncomplete cover, B) SS1 with incomplete cover of macrophyte growth; photos courtesy of Neal Beery.

A  B

Figure 3-3. Mat zone of FTWs. A) Mat at the beginning of the study period, B) Mat during the harvest at the end of the study period; photos courtesy of Neal Beery.

A B

Figure 3-4. Examples of extensive root growth on FTWs. A) Surface area coverage by macrophyte roots on a panel from SS3, B) Roots hanging below the mat of SS3; photos courtesy of Neal Beery.



A B

C

Figure 3-5. Aquatic vertebrates and invertebrates found in FTW below mat zone. A) Tadpoles (possibly *Rana catesbeiana*), B) catfish (possibly of the Ictaluridae family), C) freshwater shrimp (possibly *Palaemonetes paludosus*); photos courtesy of Neal Beery.

Figure 3-6. SS1 panel growth, panel A, B, and C (left to right); photos courtesy of Neal Beery.

Figure 3-7. SS2 panel growth, panel A, B, and C (left to right); photos courtesy of Neal Beery.

Figure 3-8. SS3 panel growth, panel A, B, and C (left to right); photos courtesy of Neal Beery.

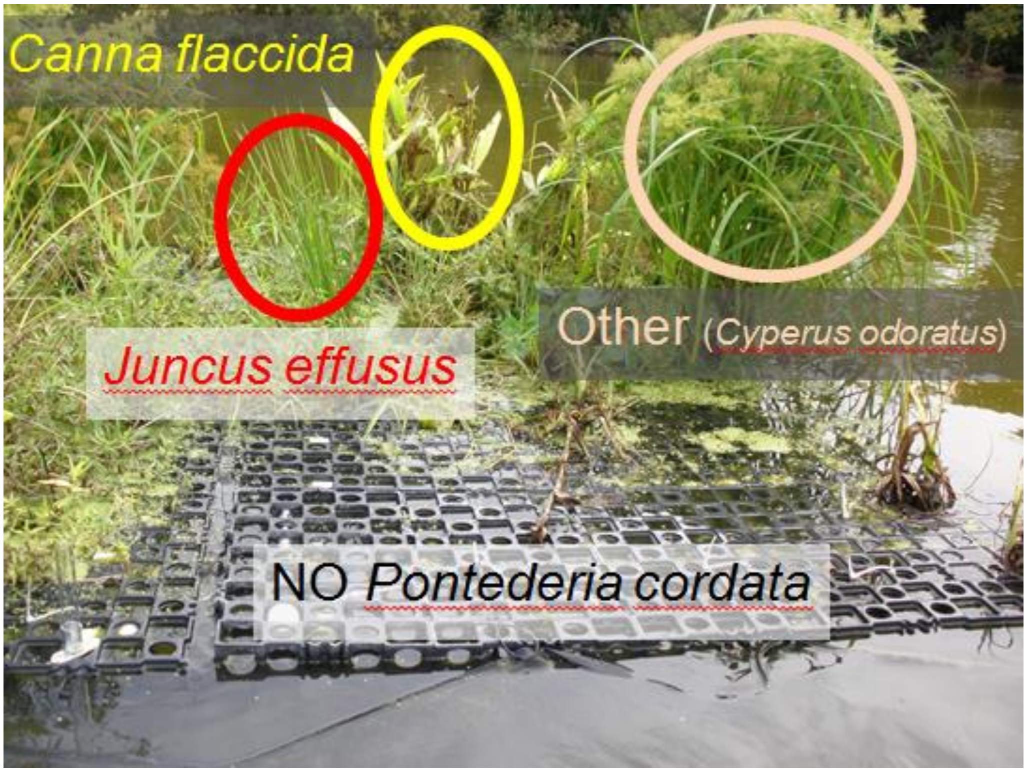


Figure 3-9. Example of lack of *Pontederia cordata* on SS1, panel C; photo courtesy of Neal Beery.

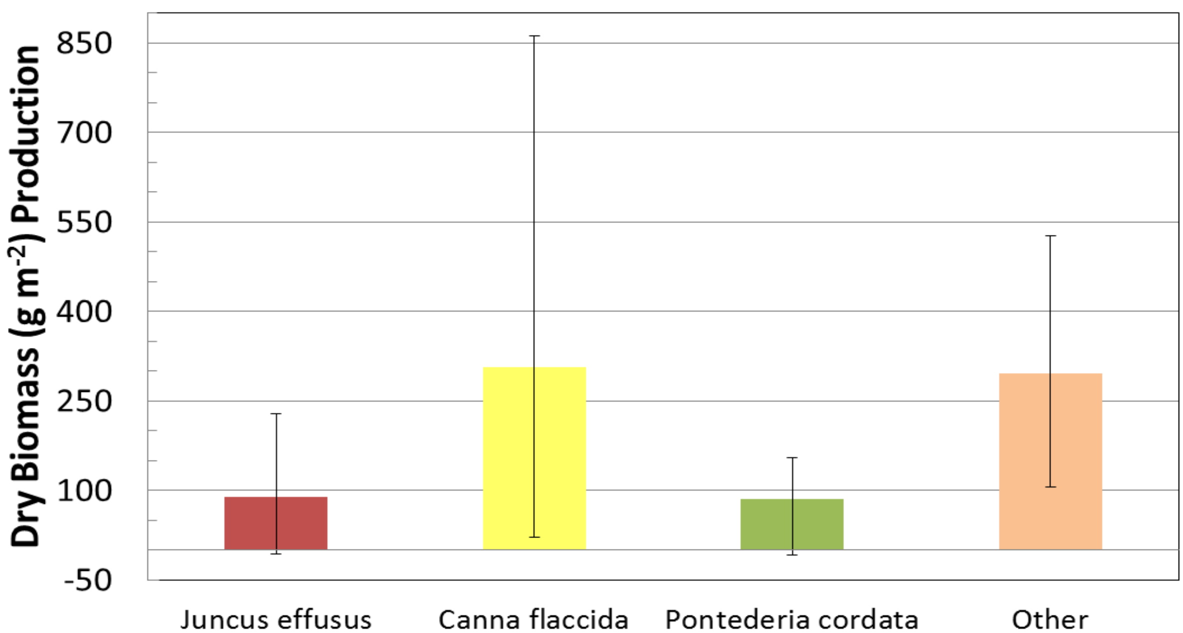


Figure 3-10. Mean, maximum and minimum of biomass assimilation among species groups on FTWs in this study.

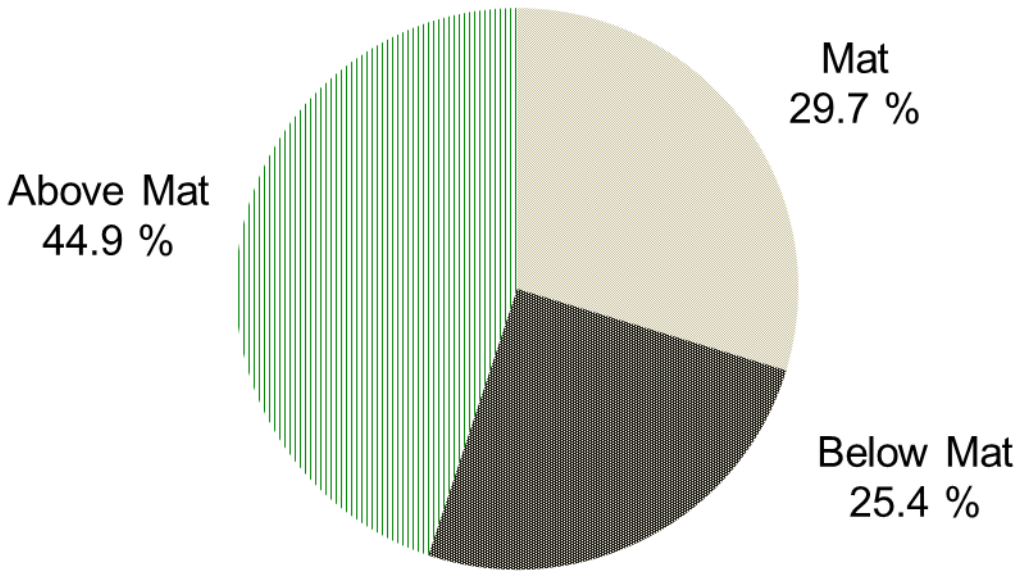


Figure 3-11. Percent of biomass harvested by each zone.

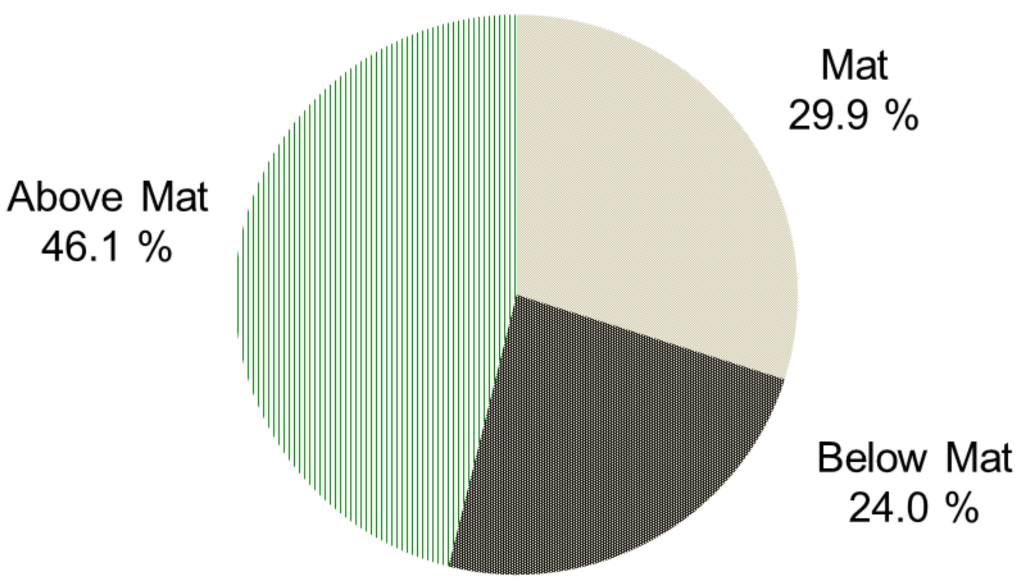


Figure 3-12. Percent of carbon assimilated by each zone.

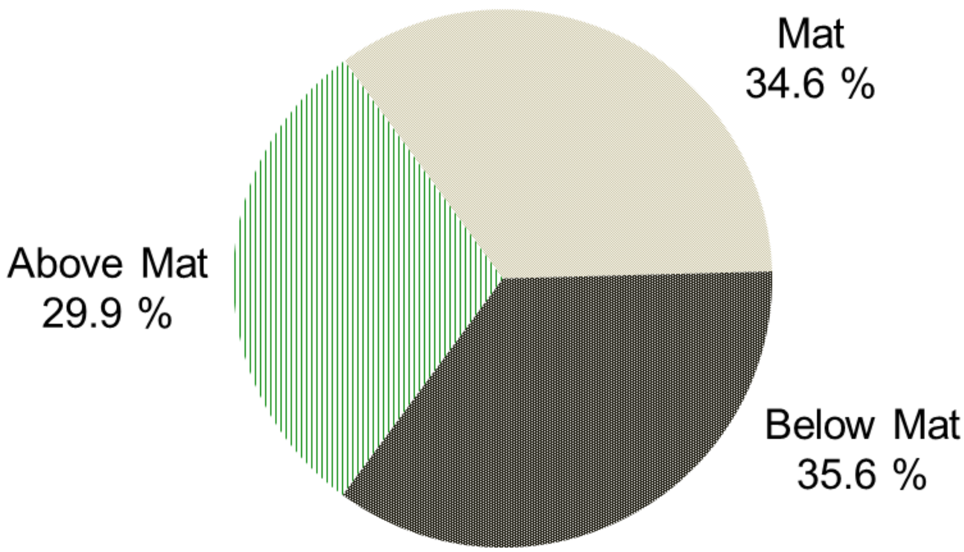


Figure 3-13. Percent of nitrogen assimilated by each zone.

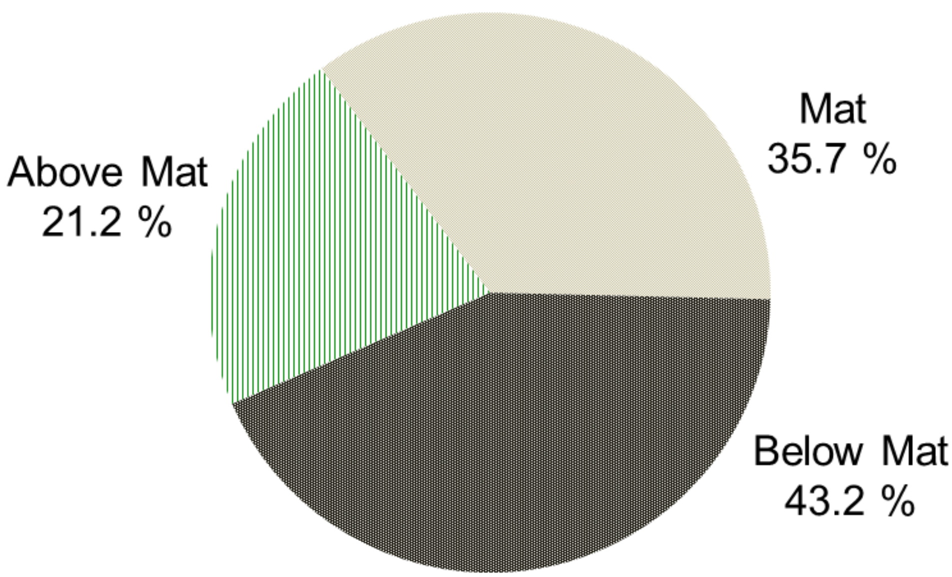


Figure 3-14. Percent of phosphorus assimilated by each zone.

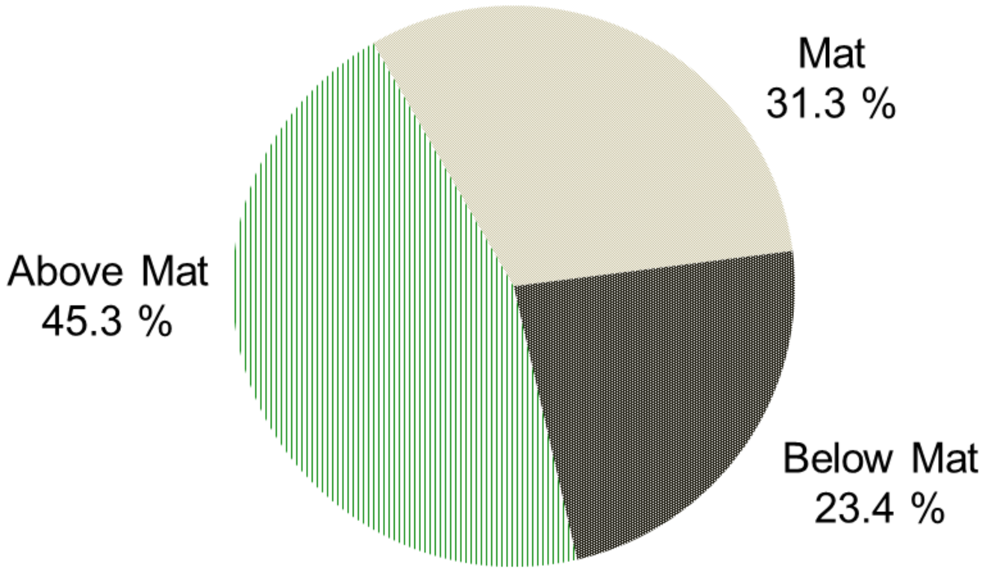


Figure 3-15. Percent of zinc assimilated by each zone.

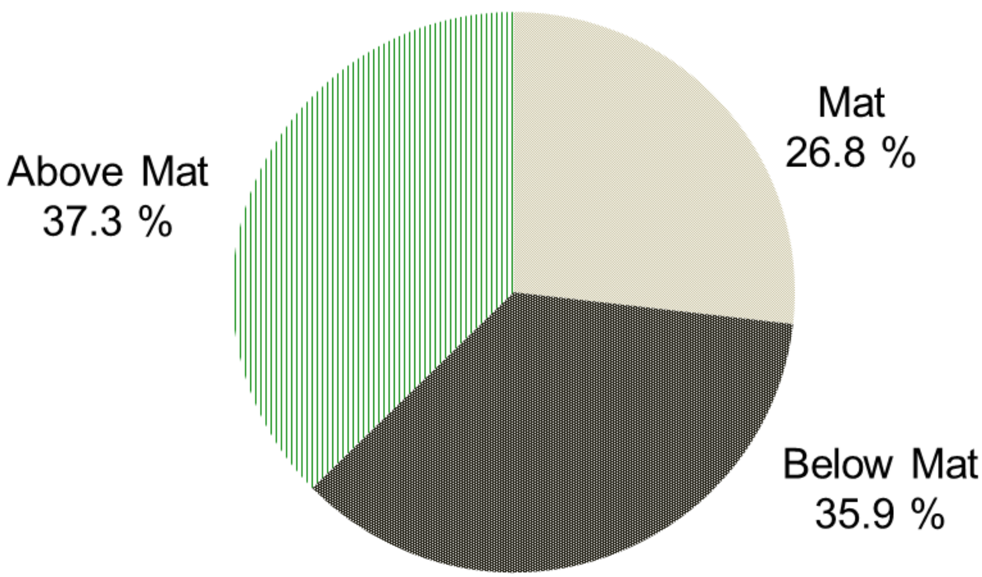


Figure 3-16. Percent of copper assimilated by each zone.

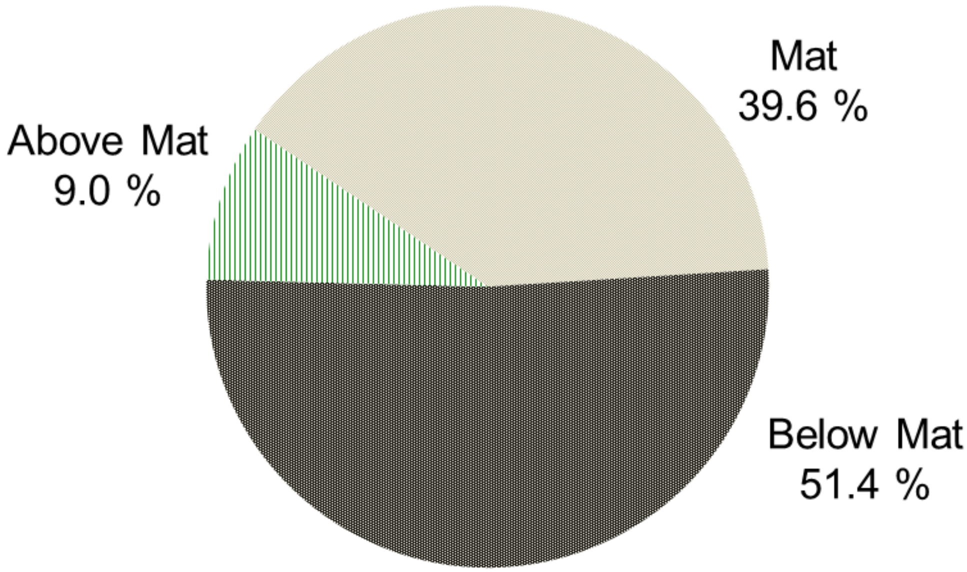


Figure 3-17. Percent of chromium assimilated by each zone.

CHAPTER 4
CONCLUSIONS

The goal of this study was to measure the efficacy of FTWs deployed in several stormwater treatment systems representative of wet retention ponds in a humid sub-tropical climate. With evolving stormwater regulation in Florida, stormwater managers could receive treatment credit for the use of BMPs including FTWs, making a known performance standard for FTWs important in the proper allocation of these credits. If FTWs are to be used as BMPs the design and management for optimal, consistent, and predictable treatment performance are also important for proper treatment credit allocation.

For this study, the installed FTWs were allowed to function throughout a growing season, and then were harvested, and their various constituents were analyzed. Analysis was performed in order to determine the FTW design's effectiveness at removing various contaminants from the stormwater at the study sites. This study sought to measure various features of FTWs that may have an impact on BMP design or management. Effectiveness was evaluated by categories reflected by the FTW design, including the FTW as a whole, by separate panels that make up the FTW, by each species group originally installed (and a conglomerate group of self-recruited macrophyte species), and by the three vegetative zones relative to the constructed Mat (Above Mat, Below Mat, and the Mat itself).

Overall Performance of FTWs

The hypothesis that the FTW design would remove constituents of interest was supported. Over the period of the study the installed macrophytes as well as macrophytes that self-recruited added biomass to the FTWs at each of the three sites.

The macrophytes' biomass contained the constituents of interest (carbon, nitrogen, phosphorus, zinc, copper, cadmium and chromium) and increased throughout the study, thus increasing the mass of the harvested FTWs to an amount greater (and significantly different) than that of the mass found in the initially installed FTWs. This conclusion may seem obvious, or not in need of testing. However, determining that this FTW design in this application is actually effective in removing the constituents of interest allows for purposeful further study of FTWs of this design.

The performance of the FTWs could be gauged by their visual appearance. The FTWs with greater assimilation of biomass and other constituents were evident through a higher density of plant growth. The originally installed species remained present on the FTWs that performed well, as opposed to those that performed less well, where they were more absent and replaced by self-recruiting species. These visual cues could be useful to managers as they make decisions about when to harvest, when to continue to use FTWs as a BMP, and various other changes in design that may arise.

The FTWs were installed at three separate sites for this study, and the biomass Assimilation varied. For example, for biomass Assimilation ranged from 655.8 g m^{-2} to 3750 g m^{-2} (mean of 1908 ± 1330 g m^{-2}). The maximum mass assimilation of all other constituents occurred at the site which showed the maximum biomass Assimilation. Also, the site with the minimum biomass Assimilation showed the lowest mass assimilation for most other constituents; the exceptions were copper and chromium, whose per site minimum mass assimilations were found at the site with the second highest biomass assimilation, which was likely the influence of higher metal concentrations in the water column.

The biomass that FTW macrophytes produced during the study was made up of material assimilated from the sites and the surrounding atmosphere. Carbon was taken from the surrounding atmosphere, and all other constituents were removed from the free water of the stormwater systems. The biomass to carbon assimilation ratio was consistently around 3:1, and the site mean nitrogen assimilation was 700.2 ± 488.2 g m^{-2} (2.52 ± 1.76 g m^{-2} on a per day basis over the period of the study). The biomass to nitrogen assimilation ratio was consistently around 60:1, and the site mean nitrogen assimilation was 32.0 ± 20.5 g m^{-2} (0.115 ± 0.074 g m^{-2} on a per day basis over the period of the study). The biomass to phosphorus assimilation ratio was consistently around 450:1, and the Site mean phosphorus assimilation was 4.25 ± 2.44 g m^{-2} (15.3 ± 8.8 mg m^{-2} on a per day basis). The metal with the highest assimilation was zinc with a assimilation of 86.5 ± 91.6 mg m^{-2} (0.311 ± 0.330 mg m^{-2} d^{-1}), and the lowest metal assimilation was cadmium with a assimilation of 0.233 ± 0.263 mg m^{-2}. Thus, FTWs are capable of removing metals that are of interest to stormwater managers.

Positive relationships were found between the Assimilation of FTW dry biomass and Assimilation of carbon, nitrogen, phosphorus and zinc. The relationship for phosphorus to biomass was the least strong, with an r^2 value of 0.664, and the other relationships had r^2 values of 0.885 (zinc), 0.952 (nitrogen), and 0.997 (carbon). If further research finds similar relationships for these constituents, a general model can be generated in order to determine the mass of constituents produced by FTWs across sites by only measuring biomass. This would help stormwater managers by providing a convenient method to gauge their BMPs' performance. Research would need to be done across the state to account for varying growth conditions, such as length of growing season as well as variations in water quality, but would help ensure that such a model is an appropriate tool to help ensure FTWs perform to expectations set out by permitted treatment credit.

As can be determined from the high standard deviations on many of the means for FTW performance in this study, there was widely variable performance among SS1, SS2 and SS3. As this study sought to determine FTW effectiveness in general, the disparate minimum and maximums of the three sites show that there is the potential for FTW performance to be high or low, although it is not yet known what factors specifically determined performance, further investigation of these factors would be beneficial to optimize treatment potential and limit overestimation performance of FTWs in some areas. It will be the task of stormwater managers to determine if an FTW design is appropriate at certain sites and to plan and maintain the FTWs in a manner that achieves the desired results. It is important to note that all sites in this study were relatively large and deep wet detention ponds with nutrient levels that seemed adequate. Possible problems may have arisen due to wildlife and water chemistry, such a pH levels, but overall, the FTWs in this study were successful in assimilating the constituents of interest in a range of conditions.

Panels and Edge Effects

There were no issues with edge effects among panels. It was thought that the outer panels may have taken up or physically blocked nutrients, moving air, dissolved oxygen or sunlight before reaching the inner portions of the FTWs, reducing the growth and overall performance of the inner panels. This was not found to be the case. However, the FTWs in this study were single 8.93 m^2 installations that did not take up a considerable percentage of any site's surface area. For FTWs of the size used in this study, the hypothesis that an edge effect would exist (H2) was not supported.

Had the FTWs been installed in larger contiguous patterns there could have been issues with buffering inner portions or not protecting outer portions, thus affecting performance. This design issue may be important to stormwater managers seeking to maximize FTW performance. Also, issues such as the FTWs shading the free water and modifying water column dissolved oxygen levels may affect the performance of the overall stormwater system. Anecdotally, this study had a separate portion that was not reported on in this thesis which found possible issues with the reduction of dissolved oxygen when FTWs were placed in isolated chambers. This reduction of oxygen levels in the water column is hypothesized to be the result of a large percentage of the surface area being covered by the FTW and a high biological oxygen demand associated with the Mat and Below Mat portions of the FTW. More information on these and similar issues will be needed in the future to determine the appropriate maximum surface area coverage and surface area density of FTWs in stormwater systems.

Macrophyte Species Selection

The macrophytes installed on an FTW are the active part of the design; they assimilate the constituents of interest and are then harvested. In order to maximize the performance of FTWs, the species that are installed or allowed to self-recruit are important. As it was found that the biomass Assimilation was the principal factor determining the amount of potential pollutants harvested, it is important to choose and maintain the species that grow successfully and attain a high level of Assimilation. Nitrogen, phosphorus and zinc biomass concentrations had no significant differences among species. For constituents such as carbon, *J. effusus* significantly differed in concentration from the other species and had the highest concentration of carbon; however, this species did not have the highest mass assimilation of the four species groups. This indicated that it was not the constituent biomass concentration of particular species that made them perform better or worse for mass assimilation, rather, it was the general biomass that was grown by that species that lead to greater performance.

C. flaccida and the Other Species groups assimilated the most biomass, with their site means being 306 ± 390 g m^{-2} and 296 ± 174 g m^{-2} respectively, as opposed to 88.6 ± 102 g m^{-2} and 85.8 ± 69.3 g m^{-2} for *J. effusus* and *P. cordata*, respectively. The success of these two species groups for the biomass constituent indicated that utilization of *C. flaccida* would be appropriate for FTW design, and that space can be left between initially installed individuals in order to allow for self-recruitment. Self-recruitment may also be useful because these individuals will most likely be currently present in the sites in which FTWs are installed and therefore may be well suited to the conditions at particular sites.

If stormwater managers are using FTWs to fix carbon from the atmosphere, *C. flaccida* and self-recruited species would be the most effective, according to the results of this study. A mean assimilation of 110 ± 141 g m^{-2} for *C. flaccida* and 114 ± 68.0 g m^{-2} for the Other Species group were found, and were nearly three times greater than the other two species. The FTW design that gave greater potential to harvest carbon was found to utilize the same species groups as for the maximization of biomass harvest.

The pattern for biomass and carbon harvest maximization applied to the assimilation of nitrogen and phosphorus as well. *C. flaccida* and the Other Species group had the greatest mass assimilations of these two constituents with 3.03 ± 3.75 g m^{-2} and 3.70 ± 2.04 g m^{-2} respectively for nitrogen assimilation, 235 ± 266 g m^{-2} and 388 ± 152 g m^{-2} for phosphorus assimilation, respectively. These mass assimilations were three to four times greater than the other two species groups. It was found that *C. flaccida* and self-recruited species should be utilized for nutrient removal by stormwater managers working in similar conditions to those of this study.

When considering the assimilation of zinc and copper, the pattern for the previously mentioned constituents applied once again. *C. flaccida* and the Other Species group assimilated the greatest metal mass of the species groups: zinc assimilation was 20.7 ± 28.6 mg m^{-2} and 10.9 ± 10.6 mg m^{-2}, respectively, and copper assimilation was 2.18 ± 2.86 mg m^{-2} and 0.492 ± 0.257 mg m^{-2}, respectively. For zinc assimilations, *C. flaccida* and the Other group assimilated three to seven times more than the other two groups. For copper assimilations, *C. flaccida* and the Other group assimilated two to six times more than the other two groups. Also, for both zinc and copper, *J. effusus* and *P. cordata* did not have significantly more metal mass at the final harvest than they did when initially installed. It was thus concluded that *C. flaccida* and the Other group were the only two species groups effective at removing zinc and copper from stormwater systems. As with the other constituents, it was the amount of biomass that was grown by these two species groups that lead to their efficacy, not the concentrations at which the metals were found in the biomass of particular species groups. Chromium and cadmium were not found in appreciable amounts at the end of the study, and thus it was concluded that the species utilized in this study's FTW design were not effective in removing those two metals or that concentrations in the water column were not at high enough levels for these plants to accumulate .

Harvesting by Zone

The hypothesis that the zone found by other studies to have greater potential for assimilating the constituents of interest would have similar potentials in this study was supported in some instances, but not in others. This depended mostly on which constituent was being considered.

For biomass, 44.9% of the total biomass was harvested from the Above Mat Zone, compared to 29.7% and 25.4% for the Mat and Below Mat Zones, respectively. However, due to the large standard deviation, there was no significant difference among Zones for the mass of biomass harvested. When the easily harvested zones, Above Mat and Below Mat, are combined, 70.3% of the biomass would be assimilated by only harvesting these two zones and leaving the Mat Zone as propagule for the next growing season. Carbon harvesting results closely mirrored those for biomass, and the same conclusion was drawn, especially since there was no significant difference among zones for carbon biomass concentration.

Nitrogen biomass concentration significantly differed among all zones, with the Below Mat Zone having the highest concentration (24.1 ± 2.5 g kg^{-1}), and the Mat and Above Mat having lower concentrations (19.6 ± 0.3 g kg^{-1} and 10.5 ± 1.0 g kg^{-1}, respectively). However, the mass of nitrogen assimilation did not significantly differ among zones. Each of the zones' mass assimilation ranged from 29.9% to 35.6% of the total, and the combined Above Mat and Below Mat Zones assimilation was 65.5% of the total. When combined, these two zones contained the majority of the nitrogen mass.

Phosphorus biomass concentration significantly differed among all zones, with the Below Mat Zone having the highest concentration (4.34 ± 0.92 g kg^{-1}), and the Mat and Above Mat having lower concentrations (2.98 ± 0.84 g kg^{-1} and 1.11 ± 0.29 g kg^{-1}, respectively). However, the mass of phosphorus assimilation did not significantly differ among zones, due to the high standard deviations associated with the means. The Below Mat Zone was responsible for 43.2% of the phosphorus that was assimilated, and the Above Mat Zone only assimilated 21.2% of the total. The Mat Zone was closer to that of the Below Mat Zone with 35.7% of the total. Still, 64.4% of the assimilated phosphorus would be assimilated if only the easily harvested Above and Below Mat Zones were removed.

It was hypothesized that metals would be assimilated in greater amounts by the Below Mat Zone. This was found to be true for chromium, but not for zinc, copper (or cadmium, which was not found in appreciable levels in any zone). Zinc had no significant differences among zones for concentrations and mass assimilations, but the Above Mat zinc mass assimilation was 45.3% of the total (68.7% of the total zinc assimilated was found in the Above Mat and Below Mat Zones combined, leaving 31.3% in the Mat Zone). If managers are focused on zinc removal, harvesting only the Above Mat and Below mat Zones would remove more than the majority of the total. Copper had no significant differences among zones for mass assimilation and the percentages of the total assimilated copper for each zone were similar, however, harvesting only the Above Mat and Below Mat Zones assimilated 73.2% of the total. For chromium, the Above Mat Zone was less than and significantly different from the other two zones, and only made up 9.0% of the total amount of chromium assimilated.

Leaving the Mat Zone on the FTW would have left 39.6% of the total behind; the Below Mat Zone made up 51.4% of the total chromium assimilated. The majority of the chromium assimilated could be harvested by removing the Below Mat and Above Mat Zones.

It was concluded that managers could harvest only the Above Mat and Below Mat Zones and still remove 60 to 70% of assimilated nutrients, and 60 to 80% of assimilated metals. This would allow managers to expend fewer resources reinstalling macrophytes, while leaving the Mat Zone to reestablish biomass on the FTWs to be harvested later. Most of the Mat Zone is made up of biomass that had taken nutrients and metals from the stormwater system; only 14.1 g m^{-2} of biomass was made up of the rhizome portions of the installed macrophytes, whereas 580.4 g m^{-2} of biomass was found in the Mat Zone at the end of the study. There would be little risk of loading the stormwater system with nutrients or metals from the initial installation after a harvest, as the Mat Zone mass that is left over came from the system, not from outside of the system. In addition, much of the mass associated with the Mat Zone is living tissue that will not senesce at the end of the growing season, as would be the case for Above and Below Mat Zones.

Recommendations for Further Research

This study sought to determine whether FTWs were an effective method for stormwater management across a number of constituents commonly focused on by stormwater BMPs. It was generally concluded that FTWs can be an effective stormwater BMP, that this size of FTW installed in large enough stormwater systems pose no negative impact on FTW performance, that *C. flaccida* and self-recruited species were most effective in the study’s conditions, and that focusing on the easily harvested FTW zones allows for most of the assimilated constituents to be harvested. There were other more particular issues and questions that were brought forth by this general study.

Some issues arose with the previous maintenance (unrelated to this study) of the stormwater system sites. Possible grazing by grass carp, which were installed at SS1 as aquatic weed control, may have led to decreased FTW performance at that site. The presence of grazers of any sort must be considered or mitigated through exclusionary devices. It was not directly confirmed, but herbicides may have been used at SS3 on submerged aquatic vegetation during the study; this may not have had an effect on the FTW macrophyte growth, but herbicides and other chemicals, such as the dye used at SS2, need to be considered before installing FTWs.

The physical design of stormwater systems may also cause potential limitations for the functioning of both FTWs and the stormwater systems themselves. In addition to the previously described issues with surface area coverage, the depth of a stormwater system could affect FTW performance. The root depth approached a meter below the Mat Zone for FTWs in this study. If the depth of the stormwater system were to be less than the length of the FTW roots, the roots could interact with the bottom of the stormwater system, thus allowing nutrient uptake from sediments and restricting uptake from the water column. Alternatively, if the depth of the water column were significantly greater than the root length, then the treatment potential facilitated by contact between roots and water column would be limited.

Along with issues arising from the design and maintenance of stormwater systems in which FTWs would be installed is the issue of water chemistry at all stormwater sites that may affect FTWs' efficacy as a BMP. Stormwater systems range widely in their levels of available nutrients, pH, oxygen, turbidity, and other factors, and the performance of FTWs may vary due to the effects of these site conditions. Research needs to address possible effects of these conditions on FTW performance in order for stormwater managers to properly utilize FTWs as BMPs. The nutrient levels in the sites in this study were all sufficient for FTW growth, but this may not be the case in every stormwater system.

Harvesting schemes were another aspect of FTW design and maintenance that further research should address. This study had one harvest in a calendar year, allowing for FTW macrophytes to grow essentially one entire growing season. As the Mat Zone could be left unharvested and regrow quickly in the middle of a growing season, multiple harvests per growing season could increase the efficacy of FTWs to remove certain constituents. Research could address this, as well as determining if performance is increased by harvesting only the Above Mat Zone, or both the Above Mat and Below Mat Zones. Additionally, the amount of effort required to remove the bulk mass may need to be addressed, as some mechanical device may make harvesting FTWs significantly more efficient and therefore less costly.

The FTWs in this study were left with 80% (the portion that was not taken as part of the sub-sampling of this Zone) of the Mat Zone biomass after harvesting and were allowed to grow throughout another season. At the end of a second growing season, the FTWs at SS2 and SS3 were found to have visually similar amounts of growth as compared to the first growing season of this study (SS1 had very little growth). Further study is necessary to determine the efficacy of this approach, and whether maximization of performance requires FTW plants to be entirely reinstalled after a certain number of growing seasons.

Issues may arise due to the nature of removing what may be unwanted constituents from stormwater systems by utilizing FTWs. In order for FTWs to effectively remove constituents from stormwater systems and ultimately keep them from reaching natural surface water bodies, the biomass (and the constituents of interest) must be harvested and taken off-site. The disposal of this biomass must be addressed in order for FTWs to be an effective BMP. Possible disposal methods would be conventional landfills, composting of the biomass, and use as fuel in biomass combusting energy Assimilation. The constituents may leave the watershed of the stormwater system from which they were removed and placed in another. An example of an issue arising from the disposal of FTW biomass is composting. Composting of the biomass may be a beneficial method, as the end result could be used for soil amendments and cut down on the amount of fertilizer brought in from outside sources, however the biomass may be high in heavy metals or leach nutrients into surface waters or ground water. The nature of the problems being addressed by the utilization of FTWs may dictate the appropriate method of disposal, but this issue will need to be considered by stormwater managers who install and maintain FTWs.

This study found general values for FTW performance across three representative stormwater systems in north central Florida. If utilized as a stormwater BMP, the credit allotted to FTWs for treatment must correspond to quantifiable and appropriate indicators of performance. The assimilation of constituents on a mass per square meter per day basis was used in this study, and may prove to be a useful unit of measure for further studies as well as governmental agencies overseeing the implementation of FTWs. The guidelines for approving, installing, maintaining and assessing FTWs must be consistent in order for this BMP to be utilized in a manner that ensures the performance that it is credited while remaining a viable option for stormwater managers.

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BIOGRAPHICAL SKETCH

Neal Beery was born in Jacksonville, Florida. His playgrounds have been tracts of Florida upland and lowlands, rivers, creeks and coastline. His wish is to work towards the conservation of natural resources, especially water. Neal attended the Paxon School for Advanced Studies in high school, where he took a course in Environmental Science and realized that a career in natural resource conservation was possible. His time as an undergraduate at the University of Florida narrowed his interests to the science and policy of water and wetlands. Neal completed an internship with the Estuaries Policy Division of the Conservancy of Southwest Florida and gained an appreciation of the efforts that many people around the state put towards protecting the resources we utilize and enjoy every day. A short stint working with the development of the stormwater section of the Town of Marineland's Land Use Code put Neal in further contact with his Wetlands professor, Dr. Mark Clark. Neal somehow convinced Mark Clark to take him on as a student in the Wetlands Biogeochemistry Laboratory within the UF Soil and Water Science Department, where he conducted and reported on this research. Now, Neal is beginning his career working towards protecting and conserving his former and current playground, the outdoors of Florida.