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Mainstreaming Green Infrastructure: The Nexus of Infrastructure and Education

Using the Green Space Based Learning (GSBL) Approach for Bioretention Plant Selection

by

Ryan Charles Robert Locicero

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Civil and Environmental Engineering
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Date of Approval:
March 31, 2015

Keywords: Stormwater Management, Rain Gardens, K-12 STEM
Grand Engineering Challenges, Community Engagement

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DEDICATION

This dissertation is dedicated to my family, friends, fellow graduate students, and professors that guided and encouraged me to achieve this milestone in my life.

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ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. 1200682 and 1156905, the U.S. Department of Education (DoE) under Award Number P200A090162, the Tampa Bay Estuary Program, Southwest Florida Water Management District, and a Water Environment Federation (WEF) Canham Graduate Studies Scholarship. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation and other specified funding agencies.

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ABSTRACT

The Green Space Based Learning (GSBL) approach builds on a long-term partnership between a Research I university, surrounding community, and local school district, transforming underutilized community green space into an interactive educational tool to addresses national infrastructure and educational challenges. The GSBL approach is an educational platform for engaging K-12 and the local community in engineering design and construction of sustainable Green Infrastructure (GI) projects. GSBL was piloted as a part of a federally funded Research Experience for Teachers (RET) program in which teachers participated in two intensive 6-week summer research experiences and two consecutive academic year components. The summer experience focuses on the development of Science Technology Engineering and Mathematic (STEM) lessons and activities that meet Common Core and Next Generation Science Standards and the dissemination of the RET research experience. Approximately 400 K-12 students and teachers participated in both formal and informal educational activities that led to GSBL approach outputs throughout the academic year. These outputs included 4 Campus GI Challenge's for identifying areas of implementation and student driven GI design, the publication of 7 curricular products, the design and installation of 70 personal rain gardens and 8 bioretention cells (a type of GI), one of which was designed as a field scale research site within the Hillsborough County Public Schools (HCPS) district.

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The eight bioretention cells, seven of which are on three public school campuses and one located at a local community leader's house were designed and implemented as a result of university research, K-12 outreach, and community engagement. These sites were selected based on one or more hotspot factors (e.g. localized areas of flooding, access to site, presence of learning space, willingness to pay, property ownership, visibility of location) and designed to restore the hydrology and water quality to pre-development conditions. The bioretention cells were designed to capture a storm-event ranging from 1.27 cm to 2.54 cm and cost between $550 and $1,650 to construct depending on the design scope, scale, and installation methods. The installed bioretention systems route stormwater runoff to a ponding area sized approximately 2-5% of the total catchment area, are designed to capture between 31% and 67% of annual runoff (March 2010 – March 2015), and attenuate between 97,500 and 226,100 mg N annually.

The educational sites were used to provide insight into hydraulic performance, maintenance requirements, and nutrient management impacts associated with bioretention design. Three of the bioretention cells (BR 1, BR 2, and BR 3) were used as a field research site for collecting bioretention plant performance data on 12 Florida native plant species, *Coreopsis leavenworthii*, *Flaveria linearis*, *Salvia coccinea*, *Solidago fistulosa*, *Canna flaccida*, *Tradescantia ohiensis*, *Tripsacum dactyloides*, *Hymenocallis latifolia*, *Iris virginica*, *Sisyrinchium angustifolium*, *Spartina patens*, and *Equisetum hyemale*

Mean baseline accumulated nitrogen concentration for tested species was 18.24 ± 5.76 mg N/g biomass. This compared to a harvested mean concentration rate of 12.28 ± 2.23 mg N/g biomass, a reduction of uptake capacity of nearly 33% after two growing seasons. This study found a similarity in mean total nitrogen concentration between

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baseline and harvested plant species for *Flaveria linearis, Sisyrinchium angustifolium, Solidago fistulosa, Canna flaccida, Salvia coccinea, Spartina patens*, and *Coreopsis leavenworthii* and a significant difference in means for *Equisetum hyemale, Iris virginica, Salvia coccinea*, and *Tradescantia ohiensis*. These harvested data were used to calculate mean total nitrogen concentration per square meter with *Sisyrinchium angustifolium, Equisetum hyemale, Spartina patens, Solidago fistulosa, Salvia coccinea, Coreopsis leavenworthii, Iris virginica* ranging from 286 mg N/m^2 to 4,539 mg N/m^2, *and Canna flaccida, Flaveria linearis, Tradescantia ohiensis* ranging from 12,428 mg N/m^2 to 15,409 mg N/m^2. Seven of the twelve species (*Flaveria linearis, Equisetum hyemale, Iris virginica, Tripsacum dactyloides, Coreopsis leavenworthii, Salvia coccinea, Tradescantia ohiensis*) displayed highly desirable results, ranking ($>0.20\overline{x}$) when evaluated across 10 quantitative attributes and assessed for their applicability for the subtropical Tampa Bay area.

This research developed a plant selection utility index (PSI) that allows for individual plant scoring based on qualitative and quantitative plant selection criteria. The qualitative PSI was used to evaluate 26 native and regionally friendly plant species commonly found within the subtropical Tampa Bay climate to provide an example and act as a template for selecting plant species. The qualitative PSI scores categorized the identified plant species as highly desirable (n=4, PSI ≥ 80), *Flaveria linearis, Tripsacum dactyloides*, *Salvia coccinea, and Chamaecrista fasciculata*; moderately desirable (n=15, 80 > PSI ≥ 65), *Solidago fistulosa, Hymenocallis latifolia, Canna flaccida, Tradescantia ohiensis, Arachis glabrata, Mimosa strigillosa, Callicarpa Americana, Penta lanceolata, Monarda punctate, Muhlenbergia capillaris, Helianthus debilis, Glandularia tampensis, Silphium asteriscus, Stachytarpheta jamaicensis, and Coreopsis lanceolata*; and least desirable (n=7,

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PSI < 65) *Spartina patens, Equisetum hyemale, Sisyrinchium angustifolium, Iris virginica, Coreopsis leavenworthii, Myrcianthus fragrans, Zamia puila*. The quantitative PSI was used to evaluate attributes of 11 of the 26 species within a 32.5 m^2 field-scale bioretention system (BR 1, BR 2, and BR 3) ter two-growing seasons. The tested species scored as highly desirable (n=2, PSI ≥ 70) for *Salvia coccinea, Tradescantia ohiensis*; moderately desirable (n=5, 70 > PSI ≥ 50) for *Equisetum hyemale, Sisyrinchium angustifolium, Solidago fistulosa, Iris virginica, Coreopsis leavenworthii,* and least desirable (n=4, PSI < 50) for *Spartina patens, Flaveria linearis, Canna flaccida, Hymenocallis latifolia*. Both qualitative and quantitative scores were combined on a 0-200 scale to provide a list of recommended species based, ranking from high to low: Salvia coccinea (PSI=160), *Tradescantia ohiensis* (PSI = 148), *Sisyrinchium angustifolium* (PSI =127), *Flaveria linearis* (PSI = 125), *Solidago fistulosa* (PSI = 124), *Iris virginica* (PSI =121), *Coreopsis leavenworthii* (PSI = 117), *Equisetum hyemale* (PSI = 114), *Canna flaccida* (PSI = 104), *Spartina patens* (PSI = 103), *Hymenocallis latifolia* (PSI =90).

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CHAPTER 1: INTRODUCTION

The National Academy of Engineering (NAE) has identified 14 *Grand Engineering Challenges of the 21st Century*, two of which, restore and improve urban infrastructure, and manage the nitrogen cycle, are directly related to "rethinking" traditional infrastructure in urban environments (NAE, 2008).

Over the past several decades both economic and social drivers have accelerated urban coastal population growth, with Florida leading US states with 75 percent change in coastal population (NOAA, 2013). During this time period the average population density within the nation's coastal counties increased to 182 persons/square mile, which is more than double that of non-coastal areas. This increase in coastal population density coupled with changing land use patterns and *Grand Engineering Challenges* provides opportunities for communities to reinvent their ageing infrastructure (e.g. transportation, water, wastewater, stormwater, health, education) and implement more sustainable solutions.

"Grey" infrastructure for stormwater management is defined as any traditional engineering-based method for managing stormwater runoff, consisting of both storm sewer and combined sewer systems, detention/retention ponds, and curbs and gutter systems. The continued expansion and maintenance of "grey" infrastructure presents high construction, repair and maintenance costs, combined sewer overflow events, and the introduction of pollutants into receiving waters (EPA, 2013a). The American Society of Civil Engineers estimates that over the next twenty years "grey" infrastructure capital

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investment will exceed $298 Billion, with fixing and expanding of pipes accounting for 75% of the total need (ASCE, 2013). However, these high capital improvement projects are difficult for cash strapped cities that are now dealing with increasing populations and urban development, increasing energy costs, and changing weather patterns. Current research shows that a far more cost effective stormwater management approach is the use of green infrastructure (Kadlec, 2009). Green Infrastructure (GI) for stormwater management is a decentralized method for managing stormwater runoff at the source using natural elements that promote infiltration, provide water quality treatment, and promote vegetative growth (Holman-dodds et al., 2003; Davis, 2008).

Green infrastructure for stormwater management can be implemented at small private residences, community spaces, and within large public and private properties. There are many opportunities to implement green infrastructure in ways that meaningfully engage community stakeholders. Educating and engaging community stakeholders on green infrastructure projects plays a significant role in the successful implementation and long term maintenance of these systems. K-12 schools, churches, and other large institutions are a unique location to implement green infrastructure as they have the largest and most consistent reach within a community.

Vegetation within bioretention systems has been shown to significantly improve the water quality when compared to non-vegetated systems in both laboratory (Davis et al., 2006, Barrett et al., 2013) and field-scale research (Davis et al., 2006; Brown and Hunt, 2011a, 2011b; Welker et al., 2013). However, performance characteristics of individual plant species have not been previously directly quantified within these US based studies. Instead, the presence of vegetation contributed indirectly to an increase in overall system

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performance. The only comprehensive plant performance studies within the bioretention literature are for regions of Australia. These studies focus on the role that plant species play in promoting media permeability, improving nitrogen removal and uptake, extending nitrogen removal life expectancy, and increasing aerobic and anaerobic processes such as nitrification and denitrification. Gaps in research include regionally specific plant performance data and a set of qualitative and quantitative plant selection criteria for recommending plant species applicable to bioretention design.

The overarching goal of this dissertation was to mainstream green infrastructure in an urban environment via educational approaches that increase community engagement with Science Technology Engineering and Mathematics (STEM). This research builds on a long-term partnership between researchers in the Civil and Environmental Engineering Department at the University of South Florida, the East Tampa community, and the Hillsborough County Public Schools, and develops the Green Space Based Learning (GSBL) approach for K-12 education using bioretention systems (also called rain gardens), a type of green infrastructure for stormwater management, and pilots the approach within the local community, including that outside of K-12 instruction. The specific research questions addressed in this dissertation are, (1) How does the Green Space Based Learning approach translate a university K-12 Science Technology Engineering and Mathematics (STEM) project into a K-12 educational approach that develops green infrastructure on school campuses, (2) How can educational activities developed through the GSBL mainstream green infrastructure in East Tampa, a highly urbanized community in the Tampa bay watershed, and (3) What are the plant recommendations for constructing a bioretention system within the Tampa Bay watershed?

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In this dissertation chapter 2 provides background information on bioretention systems, a green infrastructure for stormwater management, challenges facing K-12 STEM, and the history of the East Tampa community partnership and Green Space Based Learning (GSBL) approach. Chapter 3 describes the GSBL approach, provides background on the engineering design process and authentic scientific inquiry, and describes the GSBL outputs for evaluating the approach. Chapter 4 addresses the mainstreaming of green infrastructure via education and research pathways focusing on the East Tampa community, assessing the hydrology and water quality of the local watershed, community engagement, and opportunities for expansion of the approach. Chapter 5 focuses on quantifiable attributes of Florida native plant species and evaluates individual plant performance within a 32.5 m^2 field scale bioretention system. Chapter 6 identifies plant selection criteria (qualitative and quantitative) from literature, constructs a plant selection utility index, evaluates 26 native and regionally friendly plant species based on qualitative attributes and 11 native plant species based on quantitative field-scale performance data collected in Chapter 5 to recommend plant species applicable to bioretention design. Chapter 7 addresses conclusions and recommendations based on this work.

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CHAPTER 2: BACKGROUND

It is widely understood that stormwater runoff from urban environments contains high volumes of nutrients (EPA, 2011; NRC 2000a). As these nutrients accumulate and become mobilized they cascade through the urban infrastructure (Galloway et al., 2003). Left unchecked these nutrients slowly degrade surface water ecosystems, negatively impacting the local environment, human health, and local industry, as illustrated in Table 1. This anthropogenic increase in nutrient loading causes a series of direct and indirect impacts resulting in regional water quality concerns (Hsieh et al., 2007).

Table 1: Environmental, social, human health, and economic impacts of nutrient over-enrichment within coastal ecosystems (EPA 1993; NRC 2000a; Galloway et al., 2003; EPA, 2011, Wright-Wendel et al., 2011).

Environmental	Social and Human Health	Economic
Eutrophication	Loss of recreational use	Beach closings
Algal biomass (red and brown tide)	Sea lion deaths in California	Boating industry
Loss of habitat (seagrass beds) due to light reduction	Manatee deaths in Florida	Closure of important fisheries
Change in marine biodiversity and species distribution	Alteration of thyroid metabolism	Decrease in property value
Increased sedimentation of organic particles	Respiratory infection	
Depletion of dissolved oxygen (Hypoxia and Anoxia)	Photochemical smog	
Acidification of terrestrial and aquatic ecosystems	Methemoglobinemia	
Dead zones and fish kills		
Alteration of marine food webs		
Reduced buffering capacity		
Succession of wetland plant communities		
Loss of submerged vegetation, coral reefs, macroalgal beds		

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More than 70 cities are currently facing consent decree for regulators to improve the quality and reduce the volume of stormwater runoff entering into streams, lakes, rivers, wetlands and other waterways (EPA, 2013a). City official and water resource managers are now turning towards various green infrastructure applications (e.g. green roofs, vegetative walls, bioretention or rain gardens, bioswales, planter boxes, permeable pavement, porous asphalt, interlocking pavers, urban tree canopy, rainwater harvesting, downspout disconnection, green streets and alleys, and green parking) for managing both the water quality and water quantity of stormwater runoff. Table 2 summarizes the range of potential environmental, social, human health, and economic benefits of green infrastructure.

Table 2: Environmental, social, human health, and economic benefits of green infrastructure (Brix, 1997; Carmen and Crosman, 2001; Fraser et al., 2004; Davis et al., 2006; Hunt et al., 2012; EPA, 2013a; Kazemi et al., 2009; Welker et al., 2013).

Environmental	Social	Economic
Improved water quality	Improved aesthetics and beautification	Increased property value
Improved air quality	Increased urban greenways	Increased tourism
Groundwater recharge	Increased education/awareness	Reduced future cost of stormwater maintenance
Reduced energy usage	Reduced flash flooding	Reduced construction costs compared with grey infrastructure, or compared with upsizing grey infrastructure for increased runoff
Reduced greenhouse gas emissions	Green jobs	
Reduced heat-island effect	Increased economic development	
Reduced sewer overflow	Reduced crime	
Increased habitat	Increased recreational opportunity	
	Improved heath	
	Improved psychological well-being	

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2.1 Bioretention Systems: Overview

Over the past two decades bioretention has become an alternative and increasingly popular green infrastructure technology for managing urban stormwater runoff (PGC, 1993). Located in areas that either collect or intercept stormwater runoff during storm events, bioretention systems have 6 components (Table 3), including a ponding area for stormwater runoff, a bioretention cell (vegetative root and engineered media layers), and optional infrastructure used for bypass or overflow (underdrain, internal water storage) (Wang et al., 2013). These systems are typically designed to capture and store localized volumes of runoff from a catchment area less than one acre (PGC, 2000). Bioretention cells are traditionally constructed with high-permeability media, consisting of soil, sand, and organic matter, designed to maximize infiltration, improve water quality, and support vegetative growth (Roy-Poirier et al., 2010).

Table 3: Bioretention design components (PGC 2000; Davis et al., 2001; Kim et al., 2003; Davis et al., 2009; Roy Poirier, 2010; Hunt et al., 2012)

Bioretention Components	Description
Ponding Area	Visible surface area that collects runoff volume. Depth must be specified (15cm<30cm)
Mulch Layer	A layer of hardwood mulch to support vegetation, manage nutrients, and add aesthetic feature, (7.6 cm-10.2 cm).
Vegetative Root Layer	Upper media layer available to plant roots. Infiltrated stormwater in this zone is removed by evapotranspiration, and percolation (30.5 cm – 45.7 cm)
Engineered Media Layer	Lower media layer not easily available to roots. Infiltrated stormwater is removed by percolation and/or underdrains (30.5 cm – 45.7 cm).
Underdrain (optional)	Designed in areas that have poor draining soils and/or when impermeable liners are required. Stormwater is conveyed through (10.2 cm – 15 cm) PVC to traditional "grey" water infrastructure.
Internal Water Storage (IWS) (optional)	The IWS or saturated zone provides volume storage and increased contact time to facilitate nitrate transformation to gaseous nitrogen. The IWS is typically created with an upturned elbow.

Bioretention system guidelines recommend a ponding area between 2.0% to 5.0% of the total catchment area (Hunt et al., 2012). During construction this area is excavated

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to a depth of 61 cm to 122 cm (Davis et al., 2001; Roy-Poirier et al., 2010) and backfilled with an engineered media layer and a vegetative root layer. In general it is recommended that bioretention cells be planted with location appropriate species. Therefore these systems are traditionally designed with native and regionally friendly plants capable of mimicking the conditions found within the bioretention system that can withstand the extremes in weather and climate of the specified region. The vegetation can range from a low-maintenance groundcover to large trees depending on the size of the system. A top layer of hardwood mulch (5.1 cm – 10.2 cm) is typically specified to retain solids, moisture, and provide a carbon source for denitrifying bacteria (Hunt et al., 2012).

Kim et al. (2003) was the first to introduce a modification to the traditional bioretention design, incorporating a submerged anoxic zone or internal water storage (IWS) to increase the stormwater residence time, resulting in improved nitrate removal efficiency. An underdrain is connected to an upturned pipe and routed to an outflow dropbox or discharge area to hydraulically create the IWS. Figure 1 captures the IWS concept and main components of a bioretention system.

Numerous studies have examined impact of individual bioretention components on the water quality of stormwater runoff (Davis et al., 2001; Hsieh & Davis, 2005; Davis et al., 2006; Hsieh et al., 2007; Ergas et al., 2010; Brown & Hunt, 2011a; Cho, 2011; O'Reilly et al., 2012; Wu & Sansalone, 2013; Liu & Davis, 2014). Bioretention systems are effective at removing particulate matter and total suspended solids (54 % to 97 %) through both sedimentation and filtration processes within the ponding area and top 20 centimeters of fill media (Davis et al., 2003; Davis 2007, Li & Davis, 2008; Hunt et al. 2008; Hatt et al., 2009a, 2009b). The initial fill media contact area and thin overlaying mulch layer facilitates

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adsorption of heavy metals (Pb, Cu, Zn, Cd), oils, polycyclic aromatic hydrocarbons and other fuel based hydrocarbons (toluene, naphthalene) commonly present in stormwater runoff (Schwarzenbach et al., 2003; DiBlasi et al., 2009). Mechanisms for phosphorus removal include filtration of particulate-bound phosphorus and chemical sorption of dissolved phosphorus to hydrous oxide (LeFevre et al. 2015). Phosphorus and heavy metals accumulate within bioretention media layers and can be removed from the system by either excavating the media layer or harvesting of plant species.

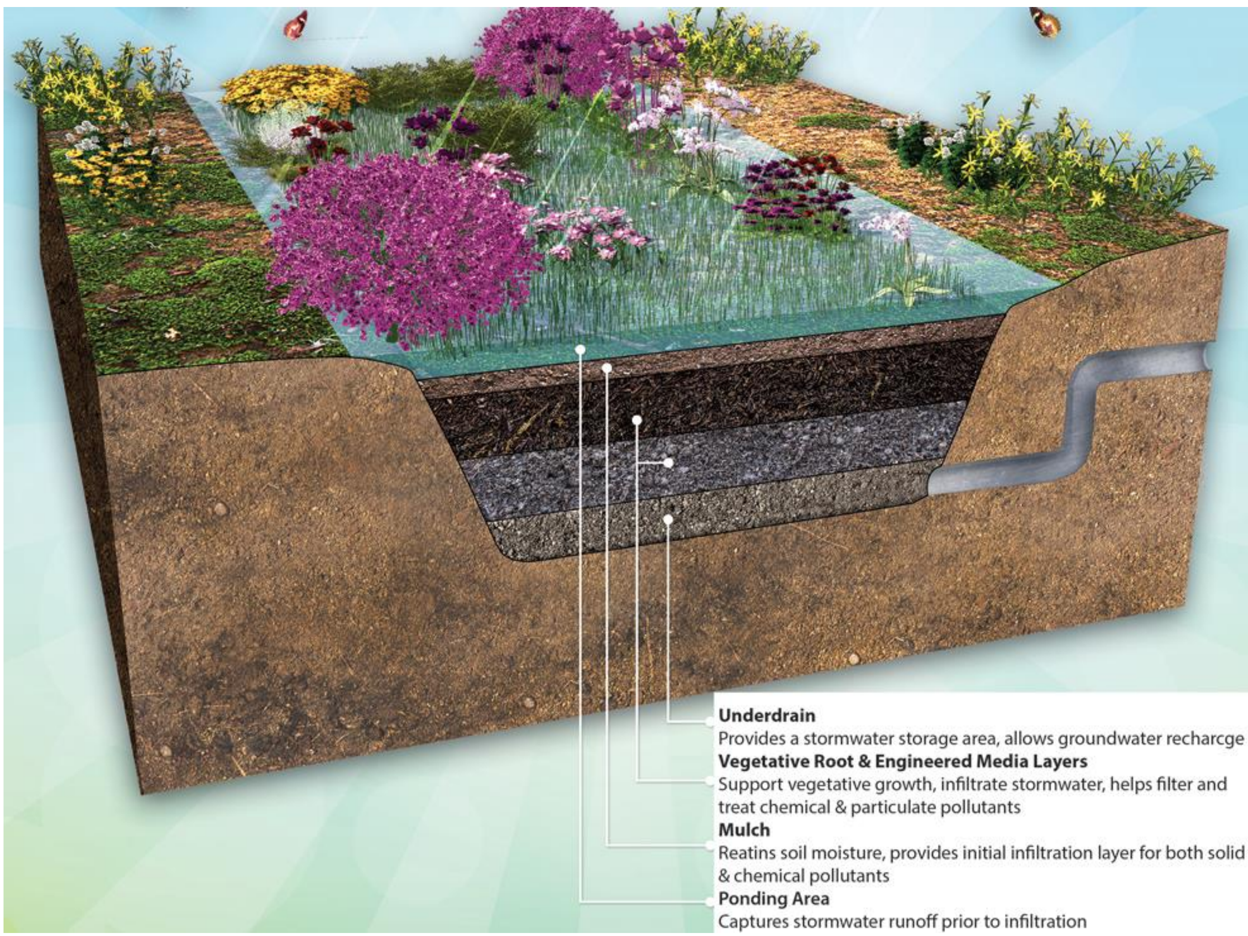

Figure 1: Bioretention system components

Within bioretention cells, organic nitrogen (org-N) is hydrolized to inorganic total ammonia nitrogen (TAN, NH_4^+ + NH_3) through the process of ammonification. Heterotrophic bacteria under aerobic or anaerobic conditions are responsible for carrying

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out ammonification, releasing TAN from both plant and animal tissue. Ammonium (NH_4^+) can sorb to negatively charged organic and inorganic substrates (Brady and Weil, 2002, Juang et al., 2001), volatilize to the atmosphere (pKa 9.3) as ammonia (NH_3), and transform to nitrate (NO_3^-) under a two-step microbial oxidation process, nitrification (Reddy & Patrick, 1984). Denitrification occurs within the IWS area and bioretention media layer through the dissimilatory reduction of nitrate (NO_3^-) to gaseous phase nitrogen. These reactions are summarized as:

Nitrification (First-Step):

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \tag{1}$$

Nitrification (Second-Step):

$$\mathbf{NO_2^- + 0.5O_2 \rightarrow NO_3^-} \tag{2}$$

Denitrification Reaction:

$$2NO_3^- \rightarrow 2NO_2^- \rightarrow 2NO \uparrow \rightarrow N_2O \uparrow \rightarrow N_2 \uparrow \tag{3}$$

This dissertation focuses on nitrogen removal from bioretention systems, as it is a limiting nutrient to coastal ecosystems and cause of surface water pollution within the research study area (EPA, 2013b). Bioretention studies usually record nitrogen species removal efficiency in the form of % concentration reduction of total nitrogen (TN), organic-N, ammonia (NH_3)[1], ammonium (NH_4^+)[1], nitrate (NO_3^-)[2], nitrite (NO_2^-)[2], and total Kjeldahl nitrogen (TKN = org-N + TAN). Table 4 provides the results from bioretention studies along with the main conditions under which they were performed (laboratory versus field, media type, and media depth). This research has provided a broad spectrum of laboratory and field scale efficiency data with values ranging from -630% to 99% for NH_X-N (Davis 2001,

[1] $NH_X = (NH_3 + NH_4^+)$
[2] $NO_X = (NO_2^- + NO_3^-)$

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2006; Hsieh and Davis, 2005; Smith and Hunt, 2006), -650% to 99% for NO_X-N (Davis et al., 2001; Dietz and Clausen, 2005; Hunt et al., 2006; Smith and Hunt, 2006; Blecken et al., 2007; Hsieh et al., 2007) -725% to 55% for TKN (Blecken et al., 2007; Davis, 2007), and -312% to 54% for TN (Bratieres et al., 2008; Lucas & Greenway, 2008).

Although most studies use percent removal on a concentration basis, Davis (2007) believes that mass removal is a more representative measure of overall system efficiency. Mass removal results from water quality treatment through the bioretention media layers and from attenuated flows. Flow management and treatment processes are equally important design parameters for the overall water quality improvement of bioretention systems (Davis, 2007).

2.2 Bioretention Systems: Media Depth and Media Composition

The relationship between depth of media and water quality improvement remains a critical design element associated with the implementation of bioretention systems (Davis et al., 2009). Despite the constraints associated with the many variables and conditions used for the studies in Table 4, there are some key findings on media depth selection.

In general the media depth should enhance pollutant filtration, adsorption, and biodegradation (Li et al., 2009), accommodate a vegetative root zone (PGC, 1993), and sustain selected vegetation. Carpenter et al. (2010) provided a review of 27 state, municipalities, and organization specific guidelines for bioretention design. This review identified 14 sources, specifically identifying vegetative root layer as a key component to overall media layer depth, ranging from 50 cm to 120 cm (Carpenter & Hallam, 2010). While the 120 cm media depth was required to accommodate for tree and shrub roots,

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vegetation with shallower root zones may be selected as a design alternative to reduce depth of media layer (PGC, 1993).

Media depth was also examined for its relationship to removal of nitrogen species. Increased contact time within the media layer, especially due to media depth, results in higher total nitrogen removal (Smith & Hunt, 2006; Davis, 2007; Li & Davis, 2008, 2009; Hunt et al., 2012). This does depend on the nitrogen speciation entering the bioretention cell. Researchers have found that the majority of nitrogen removal occurs in the top few centimeters due to organic nitrogen and TKN removal/transformation (Davis et al., 2006; Hatt et al., 2008, 2009a 2009b). This is supported by Bratieres (2008) 125-column optimization study, which concluded that filter depth did not influence the removal of ammonium or organic nitrogen (Bratieres et al., 2008). The potential leaching of nitrogen adsorbed in the top media layer was postulated after observing increased concentrations at depth as a function of detention time (Hatt et al., 2009a, 2009b). Others have found that ammonium (Davis, 2007; Cho, 2011) and TKN (Davis, 2007) removal increased with depth. Ten of the listed studies had conducted extensive research on the media for the removal of nitrogen from stormwater runoff and they are identified with data provided on media layer properties. The ten studies used various media compositions, design configurations, and varied from laboratory to field scale.

Hossain et al., (2010) conducted removal efficiency, isotherm, and kinetic experiments on a media mixture consisting of 50% sand, 20% limestone, 15% sawdust, and 15% tire crumb. Ammonium removal efficiency was observed to reach 100% at initial

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Table 4: Concentration based nitrogen removal efficiency of laboratory and field scale bioretention studies for various media layer types and vegetation conditions. Studies include bioretention, biofiltration, and infiltration basin systems.

Study	Media*	Media Layer Properties	NH_X-N	NO_X-N	TKN	TN	Location Veg (V) No Veg (NV)
Davis (2001)	(T) (S) (L) (C)		(8) - 87	(89.2)	66	-	Laboratory (V)
Kim et al. (2003) (modified)	(T) (S) (L) (C) (N)		-	78.7 – 91.0	(725)	-	Laboratory
Hunt (2004)	(S) (M)		81 - 94	-	-	-	Laboratory and Field (NV)
Dietz (2005)	(T)		84.6	30.0	28.6	25.0	Field, CT (V)
Hsieh & Davis, 2005	(T) (S) (M) (L) (C)	Synthetic Media I = 1:2:2 Mass Ratio Mulch (d10 – 0.15 mm, d60 – 2.31 mm) : Soil 1 (d10 – 0.09 mm, d60 – 0.20 mm) : Sand I (d10 – 0.17 mm, d60 – 0.30 mm)	2 - 49	11	-	-	Field and Lab, Md.(NV)
Smith & Hunt (2006) (modified)	(A)		79.4	43.2	65.3	60.9	Laboratory
Hunt et al. (2006)	(S) (M) (L) (C)		13 - 75	40.0	(545)	(312)	Field, NC (V)
Davis (2006)	(T) (S) (L) (C)	Agricultural Topsoil: Sand (76%), Clay (8%), Silt (16%)	(8) - 79	(6) - 99	55.0	51.9	Field and Lab, MD (V)
Hsieh et al., (2007)	(T) (S) (L) (C)	Layered: Top: Synthetic Media = 1:1:2 Mass Ratio Mulch (d10 – 0.15 mm, d60 – 2.31 mm) : Soil IV (d10 – 0.10 mm, d60 – 0.32 mm) : Sand I (d10 – 0.30 mm, d60 – 0.84 mm), Middle: Sand II (d10 – 0.17 mm, d60 – 0.30 mm), Bottom: Soil IV (d10 – 0.10 mm, d60 – 0.32 mm)	51 - 92	(204) - 75	-	-	Laboratory (NV)
Davis (2007)	(T) (S) (M) (N)		-	84.6	-	-	Field, Maryland
Blecken (2007)	(T) (S)	Layered: Synthetic Media 1:4 Topsoil: Coarse Grain Sand, Medium Coarse Sand, Fine to Medium Coarse Sand, Coarse Sand, Fine Gravel	51.7 – 64.5	(650)	-	(72.7)	Laboratory (V)
Henderson et al., 2007	(S) (G)		72 - 96				Field (V) (NV)
Bratieres (2008)	(S) (P) (V) (P)		(630) - 96	(520)	-	(182)	Greenhouse (V)
Hunt et al. (2008)	(S) (L) (C)		73	(4.90)	44.4	32.1	Field NC (V)
Hatt (2008)	(S) (M) (C) (V) (P)		25 - 65	-	-	-	Field, Australia (V)
Hatt (2009b)	(T) (S) (L) (G) (P) (V)		40 - 96	(10.8)	-	0.1	Field, Australia (V)
Cho (2009)	(T) (S) (L) (C)		40 - 93	(144)	-	-	Laboratory (V)
Line & Hunt (2009)	(T) (S)		(39) - 87	28.0	(257)	42.0	Field, NC (V)
Passeport et al. (2009)	(S) (C) (A)	Expanded Slate Fines (80%), Sand (15%), Organic Matter (5%)	70 -88	8 - 33	54.1	54.0	Field, NC (V)
Carpenter (2010)		20% Compost, 50% Sand, 30% Topsoil	-	-	-	90.5	Review
#Hossain et al., 2010	(S) (T) (SD) (TC)	50% Sand, 20% Limestone, 15% Sawdust, and 15% Tire Crumb - Mass Basis	64 - 99	65 - 95			Field (V)
Brown & Hunt (2011a)	(S) (P) (L) (C)	87.5% sand, 10% silt and clay, and 2.5% certified compost	74 - 82	(142) – (81)	-	-	Field (V)
Cho (2011)	(T) (S) (L) (C)	Layered: Top: Mulch (d10 – 0.31 mm, d60 – 1.15 mm), Middle: Soil II (d10 – 0.30 mm, d60 – 1.42 mm), Bottom: Soil I (d10 – 0.15 mm, d60 – 0.68 mm)	88 - 98	(600) – (340)	-	-	Laboratory (NV)
Hunt (2011)	(S) (M) (L) (C) (G)		54.1 - 68	-	-	-	Field (V)
Zhang et al. (2007)	(T) (S) (G)		81 - 95	-	-	-	Laboratory (V)
Brown & Hunt (2011b)	(S) (L) (C)		70 - 78	-	-	-	Field (V)
#O'Reilly et al. (2012)	(S) (TC) (M) (L)	1.0:1.9:4.1 by volume mixture of tire crumb (~ 1mm diameter), silt and clay (<0.075 mm grain size), and sand (>0.075 mm grain size)	52 - 65	-	-	-	Laboratory (NV)
Maximum			99	99	55	54	
Minimum			(630)	(650)	(725)	(312)	

* Type of Media: Topsoil (T) Sand (S) Compost (P) Mulch (M) Silt (L) Clay (C) Slate (A) Gravel (G) Vermiculite(V) Perlite (P) Tire Crumb(TC) Sawdust (SD) Limestone (T) Newspaper (N). # Central Florida studies.

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concentrations of 0.50 mg/L and 2.5 mg/L after 1.0 h and 1.5 h hydraulic residence time (HRT), and 64% at an initial concentration of 5 mg/L after 1.5 h HRT. Removal efficiency was effective at removing nitrite and nitrate at initial concentrations of 0.50 mg/L and 2.5 mg/L after 5.0 h of HRT, performing less effectively under increased influent loading. The authors concluded that under appropriate HRT the majority of nutrient species would be effectively removed from a stormwater management system through both adsorption and absorption processes. The authors believe that higher surface area associated with clay/silt and of selected media will play an important role in the growth of microbes for nitrification and denitrification processes (Hossain et al., 2010).

Using two types of sand, three variations of soil, and one type of mulch as filter media, Hsieh & Davis (2005), evaluated infiltration rates and pollutant removal efficiency under various layering and homogeneous mixing configurations. Their experiment tested several media configurations, the first series of columns (C-1) consisted of three layers, an upper soil layer, middle sand, or synthetic media layer, and bottom sand layer. The second series of columns (C-2) consisted of an upper mulch layer, middle synthetic media layer, and bottom Sand I layer. The Synthetic Media I layer was comprised of a homogeneous mixture of mulch:soil:sand = 1:2:2 (mass ratio). Overall columns with a more-permeable synthetic media surface layer (C-2) provided better removal efficiency for nutrients than columns with less-permeable upper soil layer (C-1). Therefore it was concluded that a layered media configuration with a permeable sand/soil mixture layer would provide the best removal efficiency for bioretention systems (Davis et al., 2006). The experiment suggested that both soil and mulch media types provide the greatest nitrogen removal efficiency (Davis et al., 2006). However, the author found infiltration to play an important

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role in mass removal of nutrient species, and recommends a soil type with a d_{10} between 0.1 and 0.3 mm (Davis et al., 2006).

Cho (2011) investigated the effects of antecedent dry day (ADD) conditions (5, 10, and 20 days) on the ammonium and nitrate removal efficiencies of two (C1 and C2), three-layered bioretention columns. From top to bottom, each column consisted of a mulch layer, one of two coarse soil layers, a fine soil layer, and gravel drainage layer. Depending on the soil amendment, they found significant washout of nitrate in C1 after 10 days and C2 after 20 days ADD conditions (Cho, 2011).

Brown (2011a) carried out experiments on six bioretention cells located within a parking lot of a large commercial retail store in Nashville, NC. Three of the cells had a media depth of 0.6 m, and the other three cells had a media depth of 0.9 m. The fill media specifications were selected to have an infiltration rate of 1 in/h and consist of 87.5% sand, 10% silt and clay, and 2.5% certified compost. This is the typical media configuration recommended by NC State University and A&T State University Cooperative Extensions (Hunt et al., 2006). Results from this study showed excellent reduction of total ammonia nitrogen and a substantial export of nitrate during the first 7 months of the 20-month study likely due to release from the mulch-layer. Hsieh & Davis (2005) previously observed losses of 91% of the original nitrate from mulch.

Davis (2006) investigated the effects of runoff duration and intensity, pH, and nutrient concentration with respect to nitrogen removal and fate of transport in bioretention media. The media selected for this study was agricultural topsoil used for vegetable production and consisted of 76% sand, 8% clay, and 16% silt. Like Kadlec and

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Wallace (2009) they postulated that microbes within the first few cm of the surface mulch layer metabolized organic nitrogen into ammonium and then nitrate.

Passeport et al. (2009) experimented with expanded slate (80% expanded slate, 15% sand, and 5% organic matter) as a media amendment for capturing and removing nutrients from two grassed modified bioretention cells. They found that the soil condition (loamy clay) with the larger hydraulic residence time resulted in greater nitrate production.

Hsieh et al. (2007) constructed two layered bioretention columns with different three-layer media configurations to evaluate the fate of nitrogen species in bioretention media. Two types of soil media, two types of sand, and compost mulch were selected for this experiment. The authors observed patterns of increased removal efficiency followed by decreased efficiency and associated that with the relatively slow chemical and/or biological processes occurring in the water held within the media between experimental repetitions (Hsieh et al., 2007).

O'Reilly (2012) amended the soil layer beneath a stormwater infiltration basin to evaluate the potential for reducing nutrient loading to the surrounding groundwater table. The amendment media, named BAM for biosorption-activated media was characterized as 1.0:1.9:4.1 by volume mixture of tire crumb (~ 1 mm diameter), silt and clay (<0.075 mm grain size), and sand (>0.075 mm grain size) (O'Reilly, 2012). O'Reilly's results from the monitoring period (June 2007 – August 2010) show that the organic nitrogen to be the dominant species in stormwater influent. Effluent data collected from soil water and shallow groundwater beneath the basin was almost exclusively in the form of nitrate. The authors believe that nutrient retention was obtained from the tire crumbs and clay content

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whereas biological nutrient removal was aided by soil texture and large surface area per volume of soil allowing for biofilm development. Rivett et al. (2008) demonstrated that limited pore size as a result of fines in media restricted biofilm development, and Seiler and Vomberg (2005) determined that a pore size of approximately 50 μm was sufficient to support biofilm formation.

Blecken (2007) performed a biofilter mesocosm study to evaluate the effect of temperature on nutrient removal by biofilters. The filter media for each of the 15-biofilter columns was comprised of five layers: media mixture of 20% topsoil and 80% medium coarse sand, medium coarse sand, fine to medium coarse sand, coarse sand and fine gravel. For 2°C, 8°C, and 20°C, they observed a reduction in ammonium concentrations of 64.5%, 56.2%, and 51.7% respectively and nitrate export of (198%), (265%), and (1,461%) respectively. Higher temperatures increase nitrification and leaching behaviors of soils.

In reviewing 27 bioretention mix designs including state, municipalities, and organization specific specifications Carpenter (2010) found that the majority of states require a specific range of sand (30%-60%), compost (20%-40%), and topsoil (20%-30%) with a wide range of silt and clay contents from less than 5% to between 10% and 25%. Their preliminary investigation of overall mass removal of total nitrogen was determined for two media configurations (20 compost/50 sand/30 topsoil and 80 compost/20 sand) and they found mean removal efficiencies of 90.8% and 19.9% respectively. The authors suggest that total nitrogen removal was due to considerable plant growth observed during the summer months.

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2.3 Bioretention Media Recommendations

Given the range of conditions in the media studies reviewed, combined with the fact that only two were conducted in central Florida, selecting optimum media type and media depth is precarious. Needless, some key findings (Table 5) to consider are a more permeable vegetative media layer and a less permeable engineered media layer (Hsieh & Davis, 2005). This allows for infiltration and storage of stormwater runoff and increases contact time within the engineered media layer. The top layer should consist of sand and/or mulch in a layered or mixed combination. Sand and mulch provide adsorption sites for organic and ammonium species and support vegetative growth. Florida's soils consist primarily of sand and bioretention systems are designed to intercept nutrient rich stormwater runoff. Therefore, traditional vegetative media (i.e. topsoil) with its organic nutrient components are not recommended as leaching is commonly encountered. Davis (2006) found that microbes within the first few centimeters of the mulch layer were capable of metabolizing organic N and ammonium to nitrate, highlighting the importance of a properly designed engineered media for managing nitrate concentrations. Engineered media layer are recommended to include a porosity of $20 < \eta < 50$ (i.e. FDOT # 57 stone) to increase the volume of influent runoff treated. Nitrate is managed primarily within this layer and therefore biofilm formation, contact time, and carbon source for heterotrophic bacteria are important parameters to consider. An internal water storage (IWS) zone has been shown to improve nitrate performance (Kim et al., 2003). The IWS created by impermeable clay or synthetic liner and upturn pipe outfall allows for an anoxic and/or anaerobic environment to be maintained within the engineered media layer. Sand and tire crumb have been shown to provide a surface for biofilm formation (Davis et al., 2006;

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Hossain et al., 2010). Likewise, clay and silt have high surface area, providing additional sites for microbial growth, increase the overall contact time as a result of reduced infiltration rates, and are suggested to increase growth rate of microbes (Hossain et al., 2010). An organic carbon source may be sufficiently obtained from sawdust, mulch, newspaper or equivalent as has been demonstrated within the literature (Kim et al., 2003; Hsieh et al., 2007; Hossain et al., 2010). Specific design applications and cost benefit analysis should be carefully considered when selecting materials, as tire crumb has a significantly greater cost than other, naturally sourced materials (i.e. sand, granite).

Table 5: Media recommendations for southwest Florida bioretention systems based on reviewed literature.

Media Layer	Design Depths	Media Composition (combination of one or more type of media)	Rational
Vegetative	30.5 cm to 45 cm	Sand, mulch	Adsorption, absorption, support nitrifying microorganisms
Engineered	15 cm to 61 cm	FDOT #57 stone, sand, mulch, sawdust, newspaper, tire crumb, clay, silt	Storage area, contact time, carbon source, biofilm formation, support denitrifying microorganisms

2.4 Bioretention Systems: Plant Performance

A review of bioretention and wetland studies was conducted to identify specific characteristics where plant implementation contributed to nitrogen removal efficiency. Vegetation was determined to be a critical factor for the overall removal of nitrogen species (Hatt et al., 2007; Bratieres et al., 2008; Blecken et al., 2009; Cho et al., 2009; Davis et al., 2009). Nitrogen removal efficiency increases significantly under vegetative versus non-vegetative conditions and often exceeded expected plant uptake rates (Lucas 2008; Read et al., 2008). It is assumed that this is due to increased microbial populations and activity

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within the rhizosphere of plant species resulting in an increase in transformation of nutrients (Henderson et al., 2007).

Research has shown that a difference in concentration efficiency between the same plant species occurs as a result of plant size and maturity, plant species competition, and plant species monocultures (Tanner, 1996; Read et al., 2009; Liang et al., 2011). Monocultures are less resilient than mixed plant systems (Zhang et al., 2007), however natural selection and competition affect species dominance (Liang et al., 2011; Kadlec, Personal Communication 2012).

Studies show benefits from higher plant diversity (Engelhardt and Ritchie, 2001; Tews et al., 2004). Mixed plant species were more effective in root distribution, less susceptible to seasonal variations, and supported more diverse microbial populations than monoculture systems (Karathanasis et al., 2003; Amon et al., 2007). Research has also shown a high correlation between plant growth and ammonium removal (Kyambadde et al., 2004; Cheng et al., 2009), and that faster growing plants with dense root structure were favorable for facilitating nitrification by nitrifying bacteria (Liang et al., 2011; Fuchs et al., 2012).

Appropriately designed vegetation is indeed regionally specific and must take into consideration site-specific environmental factors as well as the desired functional and aesthetic uses of the system. In particular, the role that plants play has been overlooked by researchers studying bioretention performance in the United States, with limited amount of research on plant selection, plant growth, community structure, and nutrient removal capacity of plant species has been documented in the bioretention literature and no method for plant selection criteria significantly documented within the literature.

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However, performance characteristics of individual plant species were not directly quantified within these US based studies. Instead, the presence of vegetation was determined as indirectly contributing to an increase in overall system performance. The only comprehensive plant performance studies within the bioretention literature are for regions of Australia with plant performance and selection being poorly documented in the United States (Read et al., 2009).

Plant uptake into above and below ground biomass is facilitated by microbial immobilization and rhizosphere interactions, and can be a substantial component of nitrogen species sequestration. Plant roots promote aerobic conditions as well as improve the hydrology of vegetative media layers by increasing oxygen in soils and keeping pathways open for water to infiltrate into the media layers (Gerhardt et al. 2009) Above ground biomass uptake traditionally begins in spring, peaks in midsummer, and very minimal in the fall and winter months (Kadlec & Wallace, 2009). Gottschall et al. (2007) found that harvesting of above ground biomass and frequency of harvesting is a critical component to increasing the overall nitrogen removal efficiency.

The rhizosphere zone is an area extending approximately a few millimeters radially from the root surface. The rhizosphere zone is comprised of rhizosphere soil that forms a boundary layer between roots and the surrounding bulk soil. The rhizosphere soil within the boundary layer is responsible for mediating large fluxes of solution and gas phase nutrient compounds (Belnap et al., 2003). The bulk soil consists of a vast array of native soil bacterial and fungal communities that interact symbiotically with plant species to form the structure of the rhizosphere community (Stephan et al., 2000).

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2.5 Science Technology Engineering and Mathematics (STEM) Education

There is a push for increasing STEM literacy in the U.S. since these fields are seen as critical for a competitive 21st century workforce. Student preparation from K-12 is weak and enrollment in graduate degrees in these fields is abysmally low, posing a national security concern to the U.S. (NAE, 2007, 2008; NSB, 2010). Introducing K-12 students to engineering design concepts through problem- or place-based learning provides students the opportunity to connect hands-on with science content knowledge (Kolodner et al., 2003; Apedoe et al., 2008; Mehalik et al., 2008; Talley et al., 2013; Hiller & Kitsantas, 2014). Massachusetts mandated the use of engineering K-12 curriculum, with a focus on the engineering design process (EDP) as a framework to solve open-ended problems (MDE, 2011, MDESE, 2012; Zeid et al., 2013). The engineering design process is a decision-making process consisting of distinct steps, often iterative and cyclical in nature, in which basic science, math, and engineering concepts are applied to develop defendable solutions to meet an established objective (Kendall & Portsmore, 2013; Mangold & Robinson, 2013, Peritz & Hynes, 2013; Wilson et al., 2013). In their study, Mangold & Robinson (2013) found many teachers to have a limited engineering knowledge or lack the pedagogical theory to effectively engage students in engineering concepts. There exists a need for K-12 STEM education with an emphasis on engineering to facilitate the subjects of science, mathematics, and technology in a way that can improve students understanding of the subject area (NRC, 2000b; Zeid et al., 2013). At the same time engineers are beginning to fully integrate K-12 and community education into their solutions instead of simply adding education as an outreach activity after their research has been completed (Feldman, 2012; Mihelcic & Trotz, 2010).

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2.6 History of the East Tampa Community Partnership and the Green Space Based Learning Approach

The foundation for the GSBL approach began in 2008 under an EPA P3: People, Planet and Prosperity student design competition for sustainability, "Water Awareness, Research and Education (WARE)." The WARE program was initiated to raise environmental awareness around non-point source pollution within a large metropolitan area in the southeastern United States, using stormwater ponds as an initial focal point. Stormwater ponds are part of an aging infrastructure, typically disconnected and inaccessible from this community, and in many cases the only sizeable green space within the urban landscape. The university partnered with community groups to transform a community stormwater pond from an unusable and dilapidated space to a community resource with an exercise trail, workout area, gazebos for holding events, and an educational kiosk (Thomas et al., 2009). This transformative community project established the GSBL project criteria of repurposing underutilized green space into multi-use environments (e.g. formal, informal) and a nexus for sustainable healthy communities.

The stormwater pond project is located within a short distance of a local magnet middle school, providing the author of this dissertation the opportunity to partner with and create 7th and 8th grade math and science curriculum around traditional stormwater infrastructure, stormwater runoff, and water quality. A University professor and dissertation author implemented the curriculum, drawing on real world applications to National Academy of Engineering Grand Engineering Challenges (NAE-GEC). Multiple Outcome Interdisciplinary Research and Learning (MOIRL) is an approach that has been used to describe this research and education model in which K-12 teachers' and pupils'

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engage in authentic science experiences as participants in a scientific research project (Feldman, 2012).

In 2012, the National Science Foundation funded a Research Experience for Teachers in Engineering and Computer Science site, Water Awareness Research and Education (RET-WARE), at the University of South Florida (NSF, 2012). The goal of RET-WARE is to provide a proactive and well-structured research, education, and professional development experience for middle and high school science and mathematics teachers. The research was framed around three of the NAE-GECs: (1) manage the nitrogen cycle, (2) provide access to clean water, and (3) restore and improve urban infrastructure. As a part of RET-WARE the dissertation author served as a graduate mentor to nine in-service middle school teachers (grades 6-8), four in-service high school teachers (grades 9-12), three pre-service teachers, and a LEAD teacher from five different schools. It is through this mechanism that the GSBL approach was developed and applied.

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CHAPTER 3: GREEN SPACE BASED LEARNING APPROACH FOR REPURPOSING UNDERUTILIZED GREEN SPACES WITHIN SCHOOL CAMPUSES

3.1 Introduction

Economic studies have shown that over half of the growth in Gross Domestic Product is indirectly related to job growth created by advancements in science and technology (Boskin & Lau, 1992). While U.S. economic advantage within the global market is directly related to innovation, problem solving skills, and technical literacy (Jordan et al., 1999; Ondracek & Leslie-Pelecky, 1999), the U.S. currently ranks 48th in quality of mathematics and science education (World Economic Forum, 2012), 27th in mathematics, and 20th in science in Program for International Student Assessment (PISA) scores among Organization for Economic Cooperation and Development nations (OECD, 2012). There is currently great emphasis in boosting the US based STEM workforce and the National Research Council's (NRC) *Framework for K-12 Science Education* and *Next Generation Science Standards* underlines the need for exposing K-12 students to engineering practices and methodologies that use content appropriate material (NRC, 2011).

All this when US urban infrastructure is in dire need of improvement without adequate funding to meet the minimum system upgrades (ASCE, 2013). The American Society of Civil Engineers (ASCE) estimates that over the next twenty years capital investment for "grey" infrastructure for stormwater, any traditional engineering-based method for managing stormwater runoff, consisting of both storm sewer and combined

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sewer systems, detention/retention ponds, pumps, and curbs with gutters will exceed $298 billion, with fixing and expanding of pipes accounting for 75% of the total need. Current research shows that a far more cost effective stormwater management approach is the use of green infrastructure (GI) (Kadlec & Wallace, 2009), a decentralized method for restoring the hydrology and water quality to that of predevelopment conditions. GI reduces the peak flow rate and volume of runoff discharging to traditional stormsewer systems, reducing the demand for system upgrade and capital costs. There are many opportunities to implement green infrastructure in such a way that it meaningfully engages community stakeholders. Likewise, there are numerous publications that support social, environmental, educational, and human health benefits associated with vibrant, interactive green spaces within a community (Taylor et al., 1998, Taylor et al., 2001; VanWoert et al., 2005; Maas et al., 2006; Aldous, 2007; Verheij et al., 2008; Arbogast et al., 2009; Seymour et al., 2010; Van den Berg andCusters, 2011; Keniger et al., 2013).

This chapter focuses on Green Space Based Learning (GSBL), an educational approach to mainstream green infrastructure within urban environments that builds on a long-term partnership between a Research I university, surrounding community, and local school district. The GSBL approach was developed and a portion of it piloted as a part of this dissertation through a federally funded Research Experience for Teachers (RET) program in which teachers participated in two intensive 6-week summer research experiences and academic year components to transform underutilized green spaces on their school campuses into multi-use educational environments. Chapter 2 section 5 presented the history of community engagement that led to the development of the Water Awareness Research and Education (WARE) Research Experience for Teacher program

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through which GSBL emerged. This chapter specifically addresses the development, components, and outcomes of the GSBL approach by: (1) defining the relationship between the engineering design process, authentic scientific inquiry, and GSBL components (2) outlining the GSBL approach Primary and Secondary Phases, and (3) discussing the results after using the approach with in-service teachers.

3.2 Engineering Design Process

The application of engineering is a critical component for integrating STEM content within K-12 schools, and the Engineering Design Process (EDP) is viewed as one of the fundamental components of K-12 science education (NRC, 2011; NAE, 2010). Engineering provides real world context to both science and math subjects and is a central focus of successful technological based education (Hill, 2006, Lewis, 2004). This integrated understanding has prompted the *Next Generation Science Standards* (NGSS) to incorporate engineering with sciences, and as a result required engineering to be taught in the K-12 classroom (NAE, 2010, Roehrig et al., 2012, Carr et al., 2012, Hsu & Cardella, 2013). The EDP is an iterative, creative and non-linear decision-making process, in which science, math, and engineering concepts are applied to develop optimal solutions to a given problem or objective (Mangold & Robinson, 2013, Burghardt, 2013). Optimal solutions are iterative and can change, leading to modified or different solutions all together. This is very different and in significant contrast to traditional scientific and mathematical instruction where questions typically structured around getting the "right" answer.

K-12 teachers' educational background often provides them with limited exposure and familiarity with engineering pedagogy and content (Yasar et al., 2006; Hsu, 2011; Burghardt, 2013). Teacher misconceptions about engineering often include building and

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constructing, leading to traditional assembly type classroom activities (Jarvis & Rennie, 1996; Cunningham et al., 2006, Capobianco et al., 2011). Therefore, it is important to provide teacher professional development that emphasizes the EDP and the tools to design appropriate lesson content and activities (Mangold & Robinson, 2013).

3.3 Scientific Inquiry, Inquiry Learning, and Inquiry Teaching

The use of inquiry within the literature refers to scientific inquiry, inquiry learning, and inquiry teaching. The National Research Council views inquiry as a cornerstone for students' comprehensive understanding of authentic scientific investigation and the nature of science (NRC, 2000b). It is the Council's recommendation that students learn scientific concepts and principles, learn to develop methods for scientific investigation, and understand the nature of science.

To inquire is to learn and scientific inquiry refers to the way in which scientist pose questions about the natural world and explain observed phenomena based on evidence derived from their research (Crawford, 2007). Scientific inquiry is viewed as research that "real" scientist do when they do science (Anderson, 2002; OECD, 2003; Feldman et al., 2009). Inquiry teaching is open-ended and is dependent on a teacher's subject matter content knowledge, experience with inquiry based pedagogy, and support from other teaching professionals (Anderson, 2002). The National Science Education Standards (NSES) defines differing degrees of inquiry teaching, from "open inquiry" to "structured inquiry" (NRC, 1996). The former allows students to generate authentic questions from their experiences, design an experiment, recording and interpreting data, develop a approach that supports their investigation, and disseminate finding; in the later the instructor defines the question or problem and specific set of procedures for the investigation.

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3.4 Methods

3.4.1 The Green Space Based Learning Approach Primary Phase

The author used the EDP and experience with K-12 outreach from spring 2011 to summer 2012, to develop the GSBL approach for mentoring teachers between summer 2012 and spring 2015 in a formal RET program. The formal RET program provides two years of teacher support, the majority of which occurs during a six-week summer session each year. The National Science Foundation (NSF) RET program started in 2001 with teacher follow up during the school year being a major challenge (Russel & Hancock, 2007) that was subsequently addressed by the NSF with new site proposal criteria stressing engagement beyond the summer program (Klein-Gardner et al., 2012; NSF, 2012). The WARE RET program began in summer 2012 and the GSBL approach has been used to date with the 2013 and 2014 cohort of teachers working in one of the co-major professors of the dissertation author's research group. Prior to summer 2012, the author worked with teachers at a particular middle school on curriculum development, some of which was integrated with the GSBL approach. During that time period the author was building his own field research site and had selected that middle school as its location to continue the partnership developed there since the WARE P3 grant discussed in Chapter 2.

Various engineering design approaches developed and used with professional engineers, college-level engineering students, and K-12 students (Ertas & Jones, 1996; Yasar et al., 2006; Cunningham et al., 2006; Atman et al., 2007; Hynes et al., 2011; Capobianco et al., 2011; Lammi & Denson, 2013; Wilson et al., 2013) were combined to define the engineering design process, (Figure 2) for the Green Space Based Learning Primary Phase. This process was translated into a GSBL primary phase for first year RET

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participants that is presented in Figure 3. Each step of the outlined EDP provides RET participants with the data and materials required to produce an effective and defendable poster written in the context of the scientific method.

3.4.1.1 Step 1: Identify and Define the Problem and Objective

The "problem" is presented to the teachers as one of the two identified grand engineering challenge, (1) restore and improve urban infrastructure, and (2) manage the nitrogen cycle, and is placed in a global and then local scale. This is similar to research in Texas where an evolving curriculum process with K-12 schools was developed to incorporate Grand Challenges as the framework for design and pedagogical theory (Talley, 2013). Unlike Talley's approach, GSBL is locally focused with tangible GI implementation. The "objective" is to visit the RETs school and identify a current campus design issue, campus sustainability initiatives, and/or campus need that relate to one of the two grand engineering challenges. The school visit is usually done by the teacher and university researchers and includes meetings with other school officials like the principal and science coach.

3.4.1.2 Step 2: Perform Due-Diligence

RET participants review literature on green infrastructure, grand engineering challenges, and traditional stormwater infrastructure. In addition, teacher participants perform due-diligence at their school campus to account for existing infrastructure, existing permits, and permit requirements for modifying existing infrastructure. In the case of bioretention installation, the school district gave the USF researchers permission to submit permit applications to the Southwest Florida Water Management District on their

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behalf. These applications were completed and submitted by the USF researchers, with designs based on spaces identified by teachers, school facilities, and principal.

3.4.1.3 Step 3: Develop Specific Requirements/Criteria and Possible Solutions

A list of site constraints, objectives, and assumptions are generated from Step 1 and Step 2 to create a list of specific requirements and possible design solutions for selecting and sizing an appropriate green infrastructure type. This step identifies several components (e.g. evapotranspiration, hydrology, materials) of the green infrastructure design solution that the curriculum content will focus on.

3.4.1.4 Step 4: Select a "Best" Solution

Several constraints to consider in selecting a "best" solution are the overall scale of the green infrastructure project, capital cost of construction, runoff characteristics, and how well the curriculum fits into the existing NGSS and/or Common Core Standards. Each solution should be normalized and evaluated to determine an optimum solution. One method for determining the optimum solution is to use a decision matrix. A decision matrix is a chart with specific requirements/criteria on one axis and the possible solutions on the other. A numeric evaluation scale can be used to compare which design solution is "best" (e.g. 2 = meets requirements/criteria, 1 = somewhat meets requirements/criteria, 0 = does not meet requirements/criteria).

3.4.1.5 Step 5: Construct a Model

A physical approach is a visual representative and sometimes operational version of the optimal solution. GSBL participants create a physical approach that represents the content they plan to cover and use this approach to guide them in the development of their curriculum. This physical approach allows the GSBL participant to gain valuable feedback

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from university professors, graduate mentors and peers within the program. Teachers develop a prototypical lesson based on the physical approach, guiding students through the EDP. Each lesson is accompanied by a minimum of one hands-on activity that relays current engineering principles and practices covered in the lesson. Curriculum must meet NGSS, Common Core, and apply to green spaces within their school campus. A computer simulation is an abstract approach used to simulate a system. The graduate assistant and/or consultant may be requested to utilize the data collected in Steps 1 through Steps 4 to run a hydrologic and/or water quality model of the proposed green infrastructure improvement project.

3.4.1.6 Step 6: Test and Evaluate Optimal Solutions

Testing and evaluating optimal solutions gives teachers the opportunity to instruct their students through the developed curriculum. Teachers are given the opportunity to modify their curriculum based on student feedback, time constraints, and what worked and didn't work in the classroom. This step occurs during the fall or spring semester of the following school year.

The graduate assistant and/or consultant may be requested to use the model to run simulations, testing and evaluating different scenarios to obtain an optimal design solution. A budget for the construction of the optimal design may then be calculated and provided to the teacher. It is the responsibility of the teacher to schedule a construction date post curriculum implementation and secure funding through external sources.

3.4.1.7 Step 7: Disseminate Findings

Dissemination of findings is the most critical component of the design process if true social change is to be realized. Teacher participants present a poster presentation during

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the last week of their 1st year summer program. The poster session highlights the EDP steps for developing a green infrastructure improvement project on their school campus. Teachers submit their curriculum to teacher training resource, teachengineering.org after testing and evaluating with their class the following year. Optimal design solutions will be presented during research group meetings or a lunch and learn for graduate student mentors and consultants respectively.

3.4.1.8 Step 8: Redesign if Necessary

The curriculum and green infrastructure designs may require minor tweaking and potentially a complete redesign based on evaluated testing and dissemination feedback. In the case of a redesign, refer back to step 3, Figure 2.

With practice and professional development, teachers are made aware of how to recognize the elements of engineering design without the prescription that they happen in a specific order every time (Kendall, 2013). Kendall (2013) found that their students already seem to know this, as they make use of planning, testing, and revision instinctively while they build.

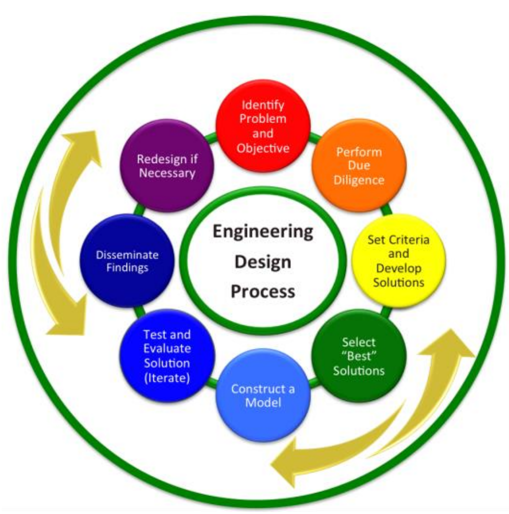

Figure 2: Green Space Based Learning Engineering Design Process

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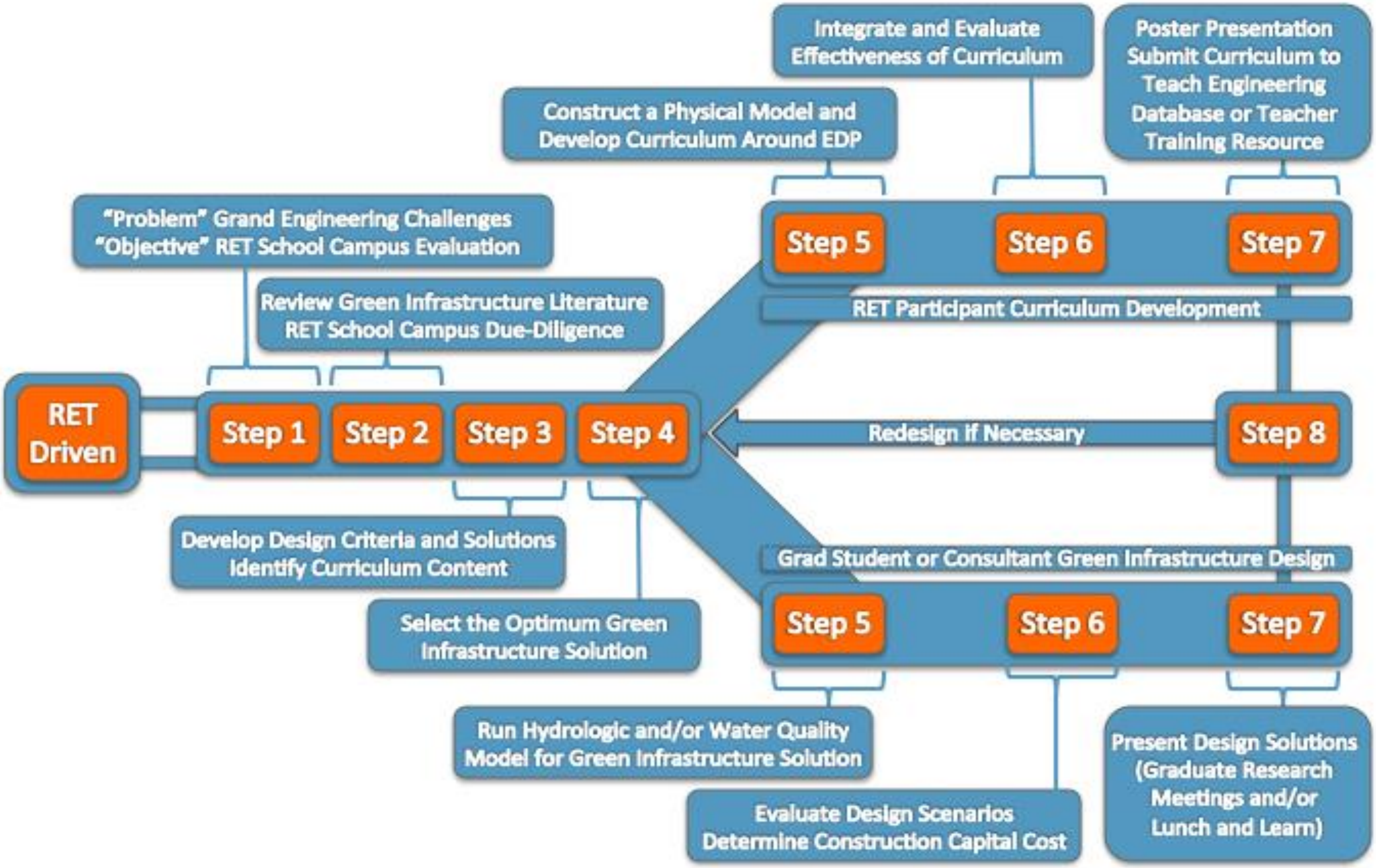

Figure 3: Green Space Based Learning 6-week RET Primary Phase

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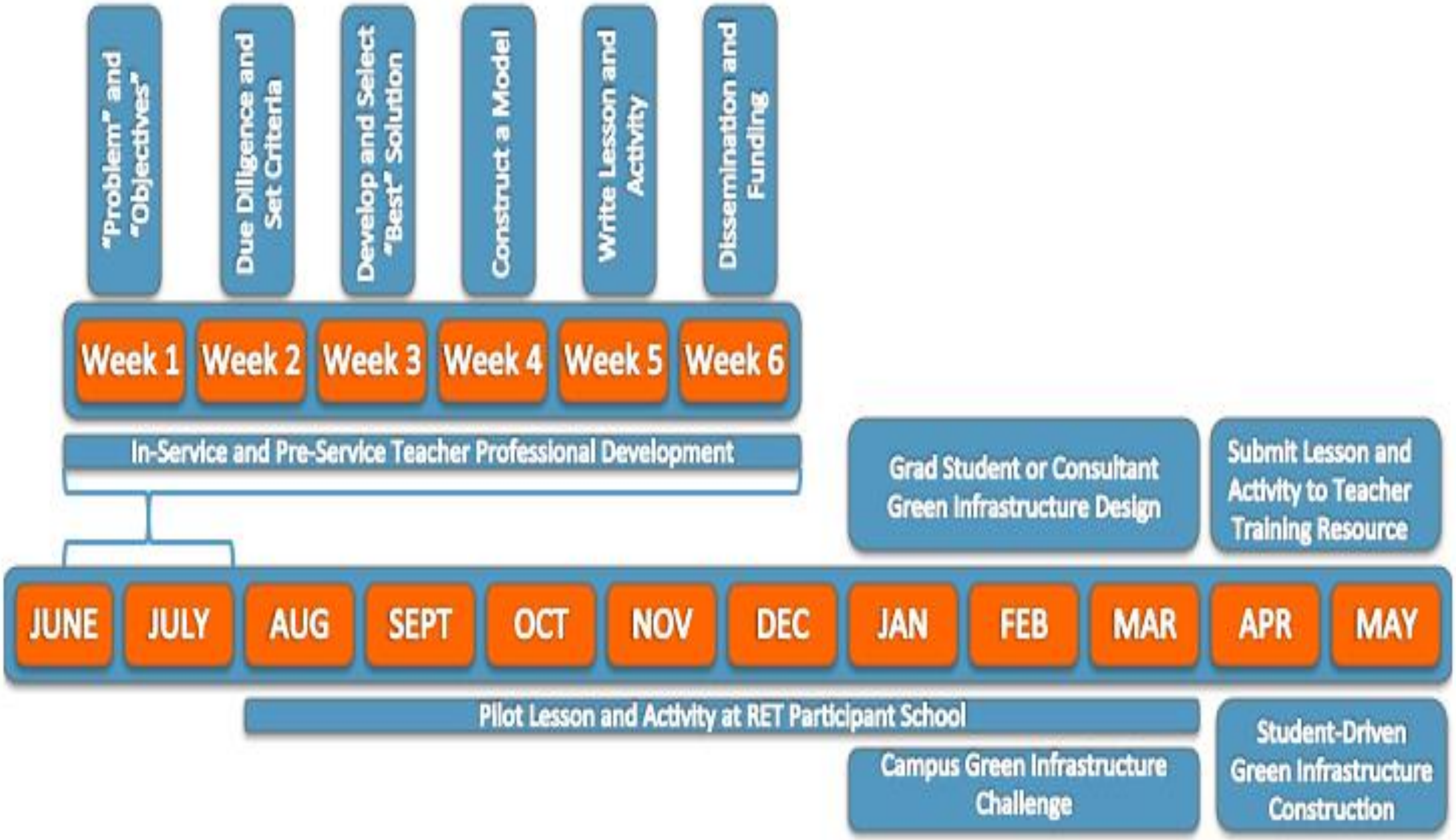

Figure 4: Green Space Based Learning Primary Phase timeline

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Figure 4 shows the GSBL Primary Phase timeline which covers one calendar year, beginning with the first six-week summer RET program. The primary phase outputs includes professional teacher development that results in: teacher driven lessons and curriculum writing, a poster presentation, graduate assistant (GA) or consultant green infrastructure design, application for external funding, Campus Green Infrastructure Challenge funding, curriculum piloting at teacher's school, student-driven construction of green infrastructure design, and submission of lessons and curriculum for publication to teacher training resource, teachenginering.org.

3.4.2 Green Space Based Learning Approach Secondary Phase

GSBL Primary phase teacher participants are eligible for a second summer of participation in the RET program and the GSBL secondary phase takes advantage of this teacher-university partnership. During the second 6-week summer RET program, teachers, with direction from a graduate mentor, develop strategies for implementing an open-inquiry or structured-inquiry project that encompasses one academic year. The on-campus green infrastructure project allows students to participate in authentic scientific inquiry. This experience provides students with practice that are congruent with what actual scientists do, which can be further broken down to student-directed tasks and open-ended inquiry (Braund and Reiss, 2006). The initial student project is considered structured because the subject area and constraints (i.e. green infrastructure improvement, project category) has been pre-selected for them. However, students have the unique opportunity to work alongside their local university to gather valuable research data and being acknowledged in scientific papers and discourse.

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The one-year GI project includes two lessons (Figure 5), the first lesson is designed to engage student participants in collecting system function, monitoring, and performance data and the second lesson is structured around student driven campus and community dissemination. The selected GI project and dissemination lesson allows teachers to introduce new content that aligns with NGSS and/or Common Core standards. The lessons are designed to use inquiry-based pedagogy and current theories on how people learn in alignment with the learning cycle.

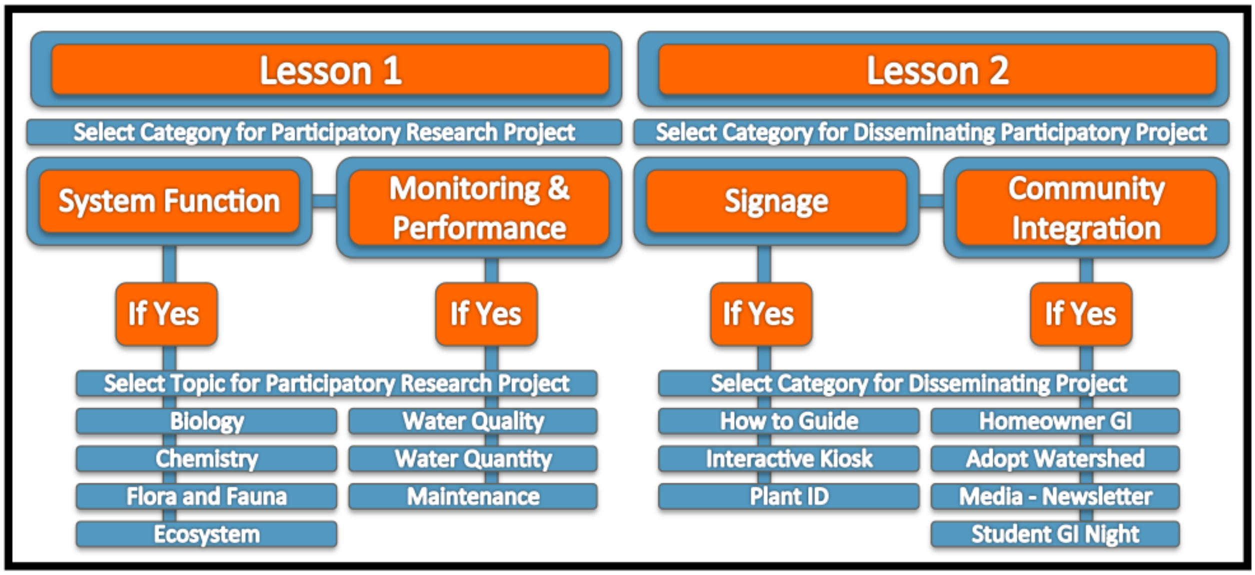

Figure 5: Green Space Based Learning 6-week RET Secondary Phase

The GSBL framework is designed to be self-sustaining and it is the goal of the Secondary Phase is to strengthen the GSBL participants' ability to perform and instruct engaging scientific lessons and facilitate "open" and "structured" inquiry-based practices beyond the limits of the established program. Similar to the Primary phase, the Secondary phase covers one calendar year (Figure, 5). Within this timeframe, teacher participants introduce students to the GI project and develop a class schedule for collecting data. Teachers collect this data from their students and provide quarterly data reports to their

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graduate mentor. The graduate mentors' role is to assist each teacher in submitting a scientific research manuscript to the National Science Teacher Association (NSTA) peer-reviewed journal, *Science Scope* (grades 6-8) or *Science Teacher* (grades 9-12). The teacher participant is also required to submit lessons for publication to teacher training resource, teachenginering.org, and participate in dissemination (e.g. poster presentation).

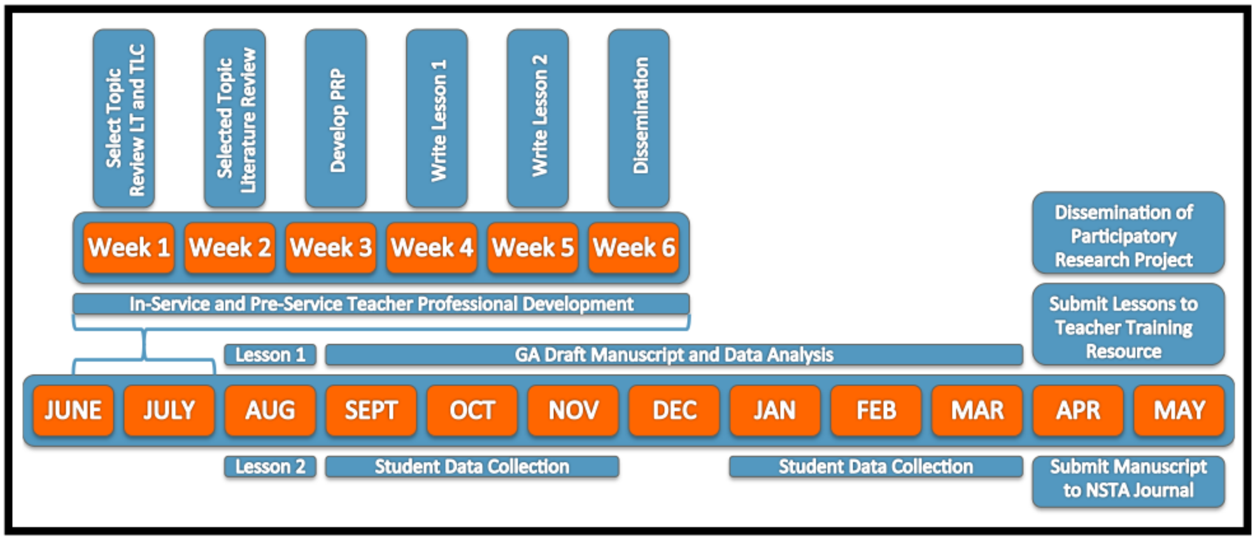

Figure 6: Green Space Based Learning Secondary Phase timeline

3.5 Results & Discussion

Table 6 summarizes the GSBL outputs from each of the twelve teacher participants from spring 2011 to spring 2015. During this time period, seven bioretention cells were constructed at three public school campuses. Eight of the twelve GSBL participants were part of the RET cohort and took part in the GSBL primary phase (2013/2014). The four non-RET participants either piloted portions of the GSBL approach or instructed informal Green Infrastructure Science Summer Camps (Summer 2013, 2014). The Science Summer Camps were used as a recruitment tool to attract incoming 6th grade students and engage returning 7th grade students to STEM fields. All RET participants developed a lesson plan or activity and presented a poster as part of the GSBL 6-week summer primary phase.

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Table 6: Green Space Based Learning participant Primary Phase outputs. [#]Teachers participated in either the initial piloting of the program or informal summer program and were not apart of the RET cohort. * Funding was by outside sources prior to applicationGSBL participant received funding through the RET program to construct their green infrastructure improvement projects.**

GSBL Participant	Year	K-12 Environment	(C) Curriculum, (L) Lesson Plan, (A) Activity Implementation	Dissemination: (P) Poster, (I) Informal, (F) Formal	Pilot Lesson	Campus Green Infrastructure Challenge	Apply for Funding	Receive Funding	Green Infrastructure Construction	Personal Rain Garden (#PRG)	Submit Lesson to Teacher Training Resource
B[#] (LEAD)	2011-2015	Middle (grades 6-8)	(C) Urban Stormwater Management Curricular Unit	(I) Green Infrastructure Science Summer Camp	Yes	Yes (Pilot)	N/A*	Yes ($6,300)	Host: BR1, BR2, BR3, BR4, BR5	Yes	N/A
P[#]	2011-2013	Middle (grades 6-8)	(C) Urban Stormwater Management Curricular Unit	(F) Piloted Urban Stormwater Management Curricular Unit	Yes	Yes (Pilot)	N/A*	Yes ($4,300)	Host: BR1, BR2, BR3	Yes, #5	Yes
W	2012-2013	Middle (grades 6-8)	(C) Urban Stormwater Management Curricular Unit	(I) (P) Green Space Based Learning (GSBL): Implementation of Urban Stormwater Curricular Unit	Yes	No	No	Yes ($4,300)	Host: BR1, BR2, BR3	Yes, #10	Yes
B	2013	High (grades 9-12)	(C) Urban Stormwater Management Curricular Unit	(I) (P) Green Space Based Learning (GSBL): Implementation of Urban Stormwater Curricular Unit	Yes	No	No	No	N/A	Yes, #10	Yes
M	2013	Middle (grades 6-8)	(L) Demystifying Civil and Environmental Engineering: Unveiling the mystery behind the profession	(F) (P) Green Space Based Learning (GSBL) Framework Implementaiton	Yes	Yes	Yes	Yes ($3,100)	Host: BR6; Participated: BR4	No	No
N	2103	High (grades 9-12)	(L) Grand Engineering Challenges: Manage the Nitrogen Cycle and Restore and Improve Urban Infrastructure (A) Leaf Stomata Lab	(F) (P)Green Space Based Learning (GSBL): Stomata Quantities of Florida Native Plant Species	Yes	Yes	No	Yes ($500)**	Host: BR7; Participate: BR4, BR5	No	No
S	2014	Middle (grades 6-8)	(L) Using Existing Green Infrastructure to Understand the Engineering Design Process	(P) Understanding the Engineering Design Process within the Local Watershed	Yes	No	No	No	Participated: BR4, BR7	No	No
J	2014	High (grades 9-12)	(L) Rain Gardens Air Quality Impact of Rain Gardens	(F) (P) Weather Stations and Rain Gardens: Linking Climate Change and Adaptation	Spring 2015	Spring 2015	Yes	Yes ($300)**	Anticipated: Spring 2015; Participated: BR4, BR5	No	No
K	2014	High (grades 9-12)	(L) Reducing Flooding in Urban Green Spaces: An Analysis of Media Fill Composition	(F) (P) Reduce Flooding in Urban Green Spaces Using Rain Gardens: An Analysis of Media Fill	Spring 2015	Spring 2015	Yes	Yes (2,000)	Anticipated: Spring 2015; Participated BR4, BR5	No	No
T	2014	Middle (grades 6-8)	(L) Water Quality of Urban Rain Gardens	(F) (P) Water Quality Analysis of Urban Rain Gardens	Yes	Spring 2015	Yes	Yes ($1,700)	Anticipated: Spring 2015; Participated BR4, BR5	No	No
S[#]	2014	Middle (grades 6-8)	(C) Urban Stormwater Management Curricular Unit	(I) Green Infrastructure Science Summer Camp	Yes	Yes	N/A*	Yes ($1,000)	Host: BR4	Yes, #30	N/A
D[#]	2014	Middle (grades 6-8)	(C) Urban Stormwater Management Curricular Unit	(I) Green Infrastructure Science Summer Camp	Yes	Yes	N/A*	Yes ($1,000)	Host: BR5	Yes, #15	N/A

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Only two RET participants transferred their material into published material on teachengineering.org (Locicero et al., 2014a). However, each teacher either piloted or plans to pilot their lessons with their students during the academic year and therefore meet the requirements for submitting to the teacher training resource. Five RET participating teachers have either implemented or plan to implement a student driven green infrastructure project on their campus. 50% of the participants applied for external funding for their projects and all but one received financial support as of Spring 2015. In addition, all conceptualized green infrastructure improvement projects have been fully funded by outside sources or partially funded as part of the RET program.

3.5.1 Urban Stormwater Management Curricular Unit

The main learning materials, Urban Stormwater Management Curricular Unit (USMCU), developed to date has been used in both formal and informal education settings with middle and high school students. The USMCU includes 2 lesson plans and 5 associated activities (Locicero et al., 2014a-g). GSBL participants B#, P#, W, and B (Table 6) developed the USMCU between 2011 and 2013 during two 7th and 8th grade math research classes and two 6th grade agriculture classes. The curricular unit was also used as instructional material for the 2013 and 2014 GI Science Summer Camp and submitted under the direction of the author of this paper to teacher training resource by GSBL participants W and B after their 6-week summer 2013 RET program. The goal of the USMCU is to advance students' understanding of urban hydrology and green infrastructure practices, providing them with a real world application for solving the NAE-GEC. This curricular unit was designed to meet state mandated standards and to be taught within the constraints of the academic year (Table 7). The USMCU introduces students to the sub-units of the

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hydrologic cycle and urban stormwater management through two lessons: Natural and Urban "Stormwater" Water Cycles and Green Infrastructure and Low-Impact Development Technologies.

Table 7: Urban Stormwater Management Curriculum state and national mandated standards

Urban Stormwater Management Curriculum	Next Generation Science Standard Florida Next Generation Sunshine State Mathematics Common Core
Natural and Urban "Stormwater" Water Cycle	MS-LS1-6, MS-ESS3-4, MS-ESS2-4, SC.6.E.7.ln.2, SC.7.E.6.6, SC.7.L.17.3, SC.8.L.18.1 (Locicero et al., 2014a)
Natural and Urban "Stormwater" Water Cycle Model	MS-ESS2-4, SC.6.E.7.ln.2, SC.7.E.6.6 (Locicero et al., 2014b)
Green Infrastructure and Low-Impact Development Technologies	MS-LS-2-5, MS-ESS3-4, MS-ETS1-1, SC.7.E.6.6 (Locicero et al., 2014c)
Just Breathe Green: Measuring Transpiration Rates	MS-LS2-5, MS-LS1-6, MS-ESS3-3, MS-ESS2-4, MS-ETS1-1, MS-ETS1-3, 6.RP.A.1, 6.RP.A.3, 7.RP.A.2, 8.EE.B.5, 8.F.B.4, 8.SP.A.2, SC.6.E.7.ln.2, SC.7.E.6.6, SC.7.L.17.3, SC.8.L.18.1, SC.8.P.8.4 (Locicero et al., 2014d)
Does Media Matter? Infiltration Rates and Storage Capacities	MS-ESS3-3, MS-ESS2-4, MS-ETS1-1, MS-EST1-2, MS-ETS1-3, 6.RP.A.1, 6.RP.A.3, 7.RP.A.2, 8.EE.B.5, 8.F.B.4, 8.SP.A.2, SC.6.E.7.ln.2, SC.7.E.6.6, SC.7.L.17.3, SC.8.L.18.1, SC.8.P.8.4 (Locicero et al., 2014e)
Making "Magic" Sidewalks of Pervious Pavement	MS-ESS3-3, MS-ESS2-4, MS-EST1-2, MS-ETS1-3, 6.RP.A.1, 6.RP.A.3, 6.SP.B.5, 7.RP.A.2, SC.6.E.7.ln.2, SC.7.E.6.6, SC.7.L.17.3, SC.8.L.18.1, SC.8.P.8.4 (Locicero et al., 2014f)
A Guide to Rain Garden Construction	MS-LS2-5, MS-LS1-6, MS-ESS3-3, MS-ESS3-4, MS-ESS2-4, MS-ETS1-1, MS-ETS1-2, MS-ETS1-3, MS-ETS1-4, 6.RP.A.1, 6.RP.A.3, 6.SP.B.5, 7.RP.A.2, 7.NS.A.3, 7.EE.B.4, 7.G.B.6, 8.G.C.9, SC.6.E.7.ln.2, SC.7.E.6.6, SC.7.L.17.3, SC.8.L.18.1, SC.8.P.8.4 (Locicero et al., 2014g)

Through the two lessons in this unit, students are introduced to green infrastructure (GI) and low-impact development (LID) technologies, including green roofs and vegetative walls, bioretention or rain gardens, bioswales, planter boxes, permeable pavement, urban tree canopies, rainwater harvesting, downspout disconnection, green streets and alleys, and green parking. Student teams take on the role of stormwater engineers through five associated activities. Students are introduced to the EDP, design optimal solutions to media type, pervious pavement mix combinations, and plant selection. They first approach the water cycle, and then measure transpiration rates and compare native plant species. They investigate the differences in infiltration rates and storage capacities between several types

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of planting media before designing their own media mixes to meet design criteria. Then they design and test their own pervious pavement mix combinations. In the culminating activity, teams bring together all the concepts as well as many of the materials from the previous activities in order to create and install personalized rain gardens (Figure 7). The unit prepares the students and teachers to take on the design and installation of a bigger green infrastructure project to manage stormwater at their school campuses, homes and communities.

Figure 7: Urban Stormwater Management Personal rain garden activity

GSBL participants B#, P#, W, B, S#, and D# took part in three GI Science Summer Camps, implementing ~ 50 personal rain gardens and two field scale bioretention systems. Two teachers, T and K installed GI at their home after participating in GSBL program and two GSBL participants, N and M conducted Campus Green Infrastructure Challenges utilized components of the USMCU to design and install bioretention cells, BR-6 and BR-7 at their campus.

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3.5.2 Campus Green Infrastructure Challenge

A second output of the GSBL Primary Phase developed to date includes the Campus Green Infrastructure Challenge. The Campus Green Infrastructure Challenge was modified from the EPA RainWorks Challenge 2012 first prize winner, The University of Florida (EPA, 2012b). Student participants were presented with a campus site map (Figure 8), plant selection list, and index cards to record responses to prompted questions. The students selected the site location, debated pros and cons of their concept designs, used a scale drawing to layout their design, excavated the site, integrated vegetative and engineered media layers and installed native and regionally friendly vegetation.

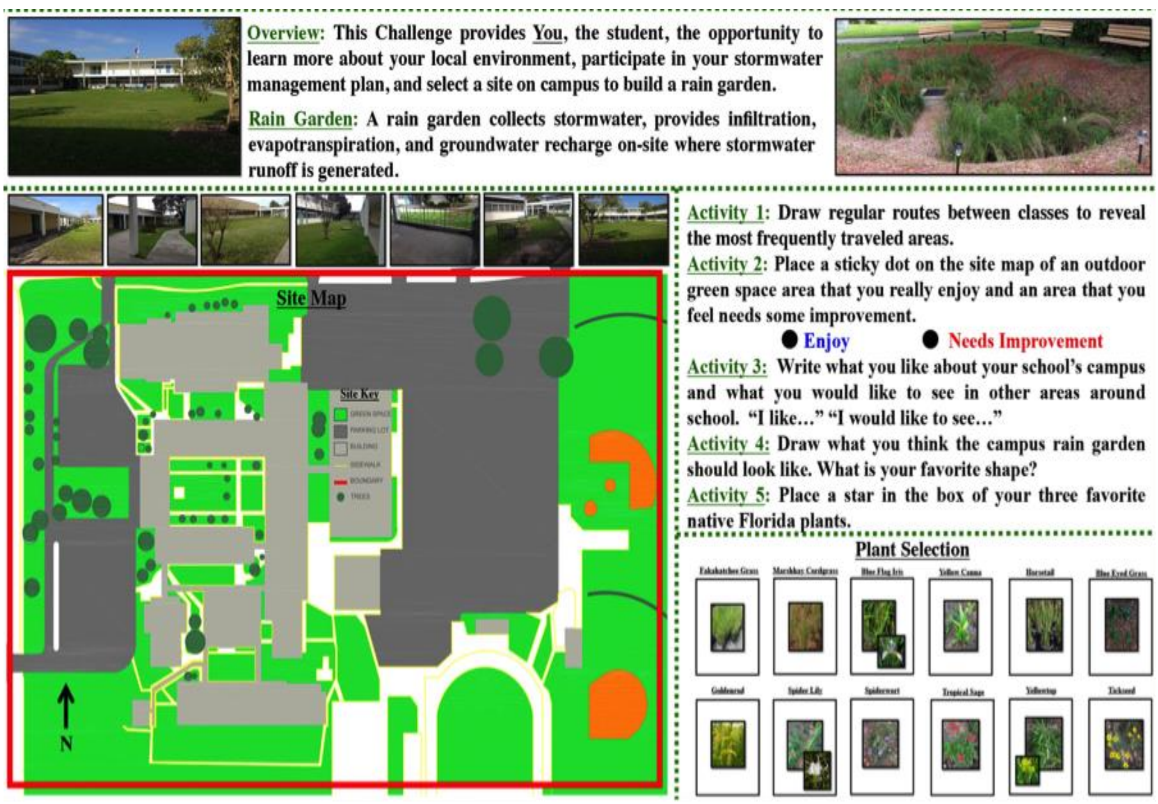

Figure 8: Campus Green Infrastructure Challenge Activity

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3.5.3 Individual Teacher Profile: Nymeria

Nymeria is a high school pre-International Baccalaureate Biology and Chemistry teacher whom participated in the GSBL approach Primary and Secondary Phases between summer 2013 and summer 2015. Nymeria was directly mentored by the author of this dissertation and began her first 6-week research experience by reviewing current literature on bioretention systems and their applicability to solving grand engineering challenges. Nymeria's second task was to work in the field at a bioretention research site collecting water quality samples from a synthetic stormwater runoff. These samples were returned to the university environmental engineering research laboratory and processed for TN, NH_4^+, and NO_3^- concentrations. Nymeria continued to show interest in the research subject, requesting bioretention overview articles and laboratory-based research assignments. She was then given the opportunity to design a sampling port for a field-scale evapotranspiration experiment to measure transpiration rates of native plant species. She took initiative and completed the task successfully. Her fourth objective was to develop a hands-on activity that would compare transpiration rates between native plant species that were currently being studied for quantitative performance. Nymeria had experience with teaching a microscope lab and developed a method for casting plant stomata using acetone and acetate, creating a surface that could be viewed under a 400X microscope. She developed the Leaf Stomata Lab which compliments the USMCU activity 2: Just Breathe Green: Measuring Transpiration Rates. The Stomata Lab allows students to evaluate the stomata density of different plant species and draw conclusions on shape, size, and quantity of stomata and the relationship to transpiration rates. This lab was intended to compliment the evapotranspiration research study at the university and field-scale

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bioretention site, connecting her students with university level graduate research. In Nymeria's final week in the summer program she finished installing the evapotranspiration experiment at the University Botanical Gardens and disseminated her experience during a poster symposium. Nymeria described this summer research experience as allowing her to connect with her students in a different way.

"I engaged them (students) with enthusiasm and in the beginning of the year I told them about working with USF and I have pictures of me with my goggles on, so showing them that I was in school over the summer and that I actually get to use it in the classroom… I emphasized that this is for research and a lot of them want to be doctors and in science so that helped them as well."

Nymeria successfully implemented both the lesson: Grand Engineering Challenges Restore and Improve Urban Infrastructure and Manage the Nitrogen Cycle, and activity: Leaf Stomata Lab that she developed. Having significant buy-in from the teacher and traction within the school district prompted the author of this dissertation to further engage Nymeria's high school as a potential future field research site and location for a Campus Green Infrastructure Challenge. Here, both USF doctoral candidate (dissertation author) and direct advisor met with the principal, Nymeria, and campus facilities to explain the benefits of green infrastructure and the GSBL approach to provide solutions to both educational and infrastructure challenges. This conversation led to an open dialogue on how this approach could benefit the community and a site evaluation was subsequently conducted. The site evaluation provided valuable insight into some of the stormwater related challenges the school currently faced, locating areas on the school campus that both the principal and facilities felt would be appropriate for green infrastructure application.

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Five areas were identified, (Figure 9) as "hotspots" or potential area for green infrastructure implementation and a permit was filed with the local water management district as is required when altering the flow path of stormwater runoff. The university research staff was granted permission by the local school district to apply for a permit on their behalf and was granted a *de minimis* exemption for proposed bioretention per section 373.406(6), F.S., "Any district or the department may exempt from regulation under this part those activities that the district or department determines will have only minimal or insignificant individual or cumulative adverse impacts on the water resources of the district."

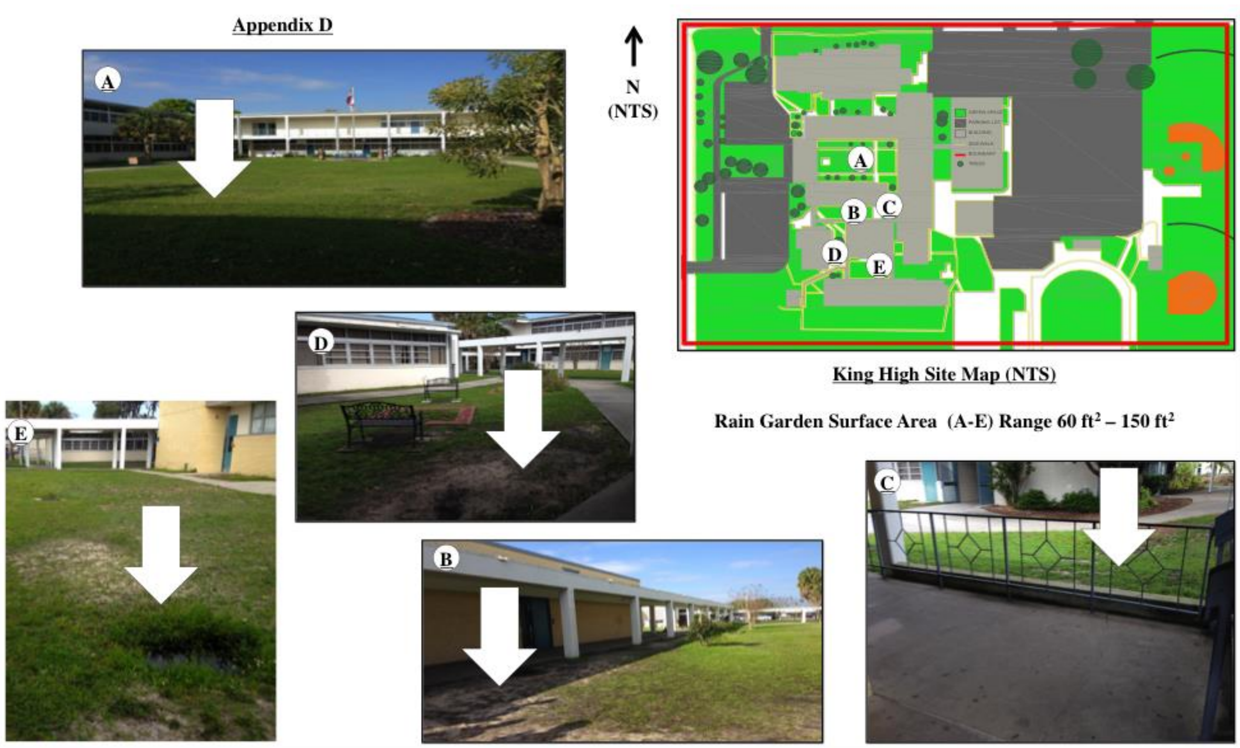

Figure 9: Campus site evaluation "hotspot" locations for future green infrastructure applications.

The students were then charged with the task of identifying an area on their campus that would benefit from a green infrastructure improvement project, and took part in a Campus Green Infrastructure Challenge. Students were directed through several activities

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that included drawing regular routes between classes to reveal the most traveled areas, identifying areas on their campus areas that they really enjoyed and areas that they felt needed improvement; they were the asked to write what they liked about their schools campus and what they didn't like, and finally they were asked to draw what they would like their green infrastructure to look. This started the conversation on implementation and design and built off of their stomata lab, which provided students the opportunity to utilize the engineering design process to select plants based on assumptions of evapotranspiration rates. Over 100 students participated in the design and construction, diplomatically selecting their school mascot (Figure A.5) as the shape for their system, finishing construction of the project within one school day.

In her own words, Nymeria describes the experience, "They (students) chose the plants based on their characteristics… They had to make inferences based on the collected data and figure out what to use… they looked at every design from every student and selected their 2 favorites per table." "I was a facilitator for the *Campus Green Infrastructure Challenge,* we walked around campus… they did pretty good at knowing where we were located (on map)… the map was easy for giving them perspective of things… we did the plant part ahead of time with a previous lesson… and they chose the amounts based on the information… They had to choose a location based on where it was needed."

Nymeria expressed the value of working on a project that provided a solution to a real world challenge with local context. In addition, her students were more engaged with the design and construction of the bioretention system than any other project presented to them over the course of the year.

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"Being able to actually build the rain garden was an experience that I absolutely enjoyed as well as the kids; they got to feel like engineers. The excitement is the biggest thing; I was actually surprised how excited they were. They were so excited… It made it a more real world application type of thing… it (bioretention system) was something bigger that I could use; it was something they could be proud of and see through the next four years… That's something they can see and say, "I made that.""

"They (students) were more *engaged with* this activity than other lessons/activities… They had a blast, when you have IB kids who are willing to come when they have the opportunity to do their homework during school and they rather do it at home because they want to build a *bioretention system*, that's buy in."

In her second year, Nymeria took on the role of a mentor in the research group, showing interest in facilitating the outputs of the GSBL approach to other program participants. "I feel like I'm more of a mentor… I've helped out a lot of people this year… From doing it last year, I don't feel as stressed about the lesson plans or the poster because I know exactly what I'm going to be doing."

During the Secondary Phase of the GSBL approach Nymeria is investigating the system function of the implemented bioretention system installed during the Primary Phase Green Infrastructure Challenge. Her lesson: Rain Garden Performance: Vegetative Monitoring looks at the performance of plant species selected and monitors quantitative performance characteristics (e.g. height, canopy area, # leaves, # shoots) over the course of the academic year. In addition, Nymeria is developing educational signage for the installed bioretention system and working with another GSBL participant whom received external funding to install a second green infrastructure project on their school campus in the

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spring of 2015. Nymeria has shown interest in continuing working with USF on curriculum development and engage her student's interest in science after RET program and is a valuable partner in mainstreaming green infrastructure within the K-12 community.

3.6 Discussion: GSBL Stakeholder Groups

At its full implementation, GSBL would combine K-12 students, teachers, and community members with local scientists, engineers, planners, municipalities, design professionals, graduate students and professors in evolving transdisciplinary community-based participatory research projects with multiple symbiotic outcomes. Similar to Multiple Outcome Interdisciplinary Research Learning (MOIRL) and research by Talley (2013), these stakeholders would combine university-based academic research with citizen science to develop and implement real world solutions to the National Academies of Engineering Grand Engineering Challenges (NAE-GEC) (Feldman, 2012; NAE 2014). The GSBL Framework dependent groups are K-12 schools and a university or college with a National Science Foundation (NSF) funded RET summer teacher program. The RET program provides an opportunity for graduate students and professors to share their field of knowledge with the teacher participants. This content knowledge may then be translated by the participating teachers into grade specific lessons that support the development of interactive green spaces within their school campus. The participation of the subsequent stakeholder groups benefits the longevity and resilience of GSBL, however group participation is independent of the potential success of outcomes from a science educator's perspective. Here we are specifically interested in how teacher and student participants are affected by GSBL projects.

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The benefits (Table 8) of GSBL can be realized from a K-12 school perspective through teacher professional development, reduction in maintenance and energy demands, and promoting innovative educational experiences for attracting students. School campuses are typically underutilized community space and innovative locations for research.

Table 8: Green Space Based Learning approach stakeholder benefits

Green Space Based Learning Stakeholders	Stakeholder Benefits
K-12 Schools (multiple school participation preferred but not required)	Teacher Training and Professional Development, Administration Attracting Students, School Board Site Maintenance, Heating and Cooling Savings
Universities and Colleges (RET program required for teacher training)	Community Participatory Research, Support Innovation, Long-term Monitoring, Thesis and Data Collection, Educational Outreach
Consultants	Competitive Marketing Strategy, Attract Clients and Federal and State Projects, Connect with Research University or College, Implement New Design and Construction Practices (low risk)
Municipality	National Pollutant Discharge Elimination System (NPDES) Annual Reporting, Total Maximum Daily Loads (TMDL) Requirement, New Numeric Nutrient Criteria Regulation
Water Management District	Educational Outreach, Long-term Monitoring For Reliability, Resilience, Vulnerability
Department of Environmental Protection	Educational Outreach, Long-term Monitoring For Reliability, Resilience, Vulnerability
County Extension Services	Educational Outreach, Homeowner Implementation and Workshops
Special Interest Groups	Educational Outreach, Water Quality Monitoring, Improved Community Space

Universities and colleges may benefit from K-12 student driven data collection through field research sites. Consultants can utilize the partnership as a marketing mechanism for attracting new clients and to obtain funding while at the same time participate in exploratory design and implementation for future projects in a low-risk environment. Municipalities may benefit from regulatory compliance through reducing

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stormwater runoff and improving water quality. Water management districts, environmental protection offices and county extension services benefit may be realized as a result of increased educational outreach, homeowner implementation, and long-term monitoring of the systems for use in future permitting.

3.7 Conclusions

The Green Space Based Learning (GSBL) approach is intended to provide K-12 teachers with a university research experience that supports the development of lessons and activities that introduce students to the engineering design process and scientific inquiry. The lessons/activities are intended to support a Campus Green Infrastructure Challenge that allows students to select a type of green infrastructure, debate their design, and construct a green infrastructure improvement project within their campus to solve real world *Grand Engineering Challenges*.

Evaluation of the GSBL approach is defined as the successful implementation of one or more of the GSBL approach outputs: implementation of green infrastructure curriculum, Campus Green Infrastructure Challenge, installation of personal rain gardens, apply for/received funding to construct green infrastructure, field-scale green infrastructure construction on school campus, and submit curriculum to a teacher training resource. With approximately 400 K-12 students and teachers engaged in both formal and informal educational activities, the GSBL approach has been enacted to successfully design and construct seven field-scale bioretention systems, two Campus Green Infrastructure Challenges, the publication of the Urban Stormwater Management Curricular Unit, secured funding for 3 green infrastructure projects, 100% lesson development and implementation, and approximately 70 personal bioretention systems. In doing so, the GSBL approach has

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successfully engaged nine in-service middle school teachers (grades 6-8), four in-service high school teachers (grades 9-12), three pre-service teachers, and a LEAD teacher from five different schools within the district. In addition, the formal GSBL approach outputs USMCU, Campus Green Infrastructure Challenge, and field-scale green infrastructure construction were used as instructional material for 3 Green Infrastructure Science Summer Camps. These camps took place in the summer of 2013 and 2014 and were used to attract incoming 6th grade students to and returning 7th grade students to pursuing STEM subjects.

Individual teacher experience with the GSBL approach has provided positive feedback from both the in-service teacher and student population. The teacher successfully completed many of the GSBL outputs, including the development and implementation of both lessons and activities that support green infrastructure, facilitated a Campus Green Infrastructure Challenge, a student drive design and construction of a bioretention system on their school campus, and developed lessons for evaluating the performance of the installed system as a continuation of original design project. This experience was something that the teacher as well as students expressed as something they enjoyed and were excited to take part in, working outside of the traditional classroom setting and solving real world problems.

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CHAPTER 4: COMMUNITY ENGAGEMENT AND THE COST OF BIORETENTION INSTALLATION THROUGH EDUCATIONAL ACTIVITIES

4.1 Introduction

Looming large in the US is how to fill, by 2018, a million more (STEM) jobs to retain the US's historical preeminence in science and technology (PCAST, 2012). In any given year approximately 15% of the US population is engaged with K-12 education. Forty-five states, four territories and the District of Columbia, recently adopted the Common Core State Standards, the first national standards for mathematics and English language competency in the U.S. designed to be robust, relevant to the real world, and reflective of the knowledge and skills needed for success in college and careers, these standards overlap with 50% of the Next Generation Science Standards (NGSS) that are currently under evaluation by 26 states. Sponsored by the National Research Council and supported by many professional science organizations, the NGSS present four disciplinary core ideas (Physical Sciences, Life Sciences, Earth and Space Sciences, Engineering, Technology, and Applications of Science) with many subthemes that intersect with engineering and design challenges facing urban infrastructure for stormwater management.

Urbanization coupled with climate change, ageing infrastructure, and more stringent water quality standards, present major challenges for stormwater management (EPA, 2013). Green infrastructure (GI) for stormwater management has been gaining traction with rain gardens, bioretention, pervious pavement, and rain barrels, approved by

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the US Environmental Protection Agency as best management practices that are seen as most applicable at residential scales (Kertesz et al., 2014). Green infrastructure for stormwater management can be implemented throughout a watershed at smaller "hotspot" plots of private and public land. This approach requires community buy-in and active engagement from multiple property owners across various stakeholder groups (Hottenroth et al., 1999; Dickinson et al., 2012; Shandas and Messer, 2008). Green infrastructure can be used as educational tools (Church, 2015) and educational activities could incentivize residents to implement green infrastructure and cover the costs of that infrastructure (Thurston et al., 2010; Green et al., 2012). Very little information exists on sustainable mechanisms for these educational activities, especially ones that include university researchers who simultaneously engage with research on green infrastructure.

Green infrastructure incentives for land owners in Tampa, FL do not exist. Various researchers have investigated incentive programs for land owners (Doll et al., 1998; Parikh et al., 2005; Thurston et al., 2010; Kertesz, 2014) and Table 9 lists examples of incentive programs for rain garden implementation on single-family residences in the US that could be adopted in Tampa. Kertesz et al. (2014) modeled the economic and hydrological efficacy of residential credit programs in Cleveland (OH), Portland (OR), Fort Myers (FL), and Lynchburg (VA) and found inconsistencies between the percentage of annual runoff reduced and the percentage of residential fee reduced for stormwater management. For their study each location had varying levels of educational material and homeowners received no economic assistance for their installations. Despite these discrepancies the authors concluded that there was an overall benefit to the stormwater utility for supporting the incentive program.

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Table 9: Utility incentives for green infrastructure for stormwater management in the US

Location	Type of incentive
Roanoke, VA	10% credit per category, level 1 Rain barrel, vegetative filter strip, roof drain disconnect, grass channel 25% credit per category, level 2 Pervious pavement, rain garden, cistern, green roof, infiltration practice Link:http://www.roanokeva.gov/85256A8D0062AF37/vwContentByKey/3F44F163F37545BF85257DB3004D3407/$File/FY15CreditAppSingle.pdf
Richmond, VA	Maximum credit of 50% for a combination of rain gardens, on-site stormwater storage, vegetative filter strips, and pervious pavement. A single application is 20% credit. Link: http://www.richmondgov.com/dpu/documents/SWcreditmanual.pdf
Spring Hill, TN	A 15% maximum credit may be applied for the on-site treatment of all impervious surfaces. The credit will be granted for the portion of impervious area that drains to the approved BMP and which removes at least 80% of the TSS during the first, 1/2 inch rainfall, flush volume. Link: http://www.springhilltn.org/DocumentCenter/View/428
Montgomery County, MD	Residential Credit Calculator: $WQPC\ Credit = \frac{Volume\ Provided}{ESDv\ Required}\ x\ 50\%\ Maximum\ Credit$ The water quality credit (WQPC) is calculated as the volume of storage provided by GI practices divided by the required volume of storage for the site (based on soil group and percent impervious) with a maximum single family residential credit of 50% Link:https://www.montgomerycountymd.gov/DEP/Resources/Files/downloads/water/wqpc/How-Is-My-WQPC-Credit-Calculated-Guide.pdf
Washington, DC	Reimbursement set at $1.25 per square foot of routed impervious area Link: http://green.dc.gov/node/122602
Greater Elkhart County, IN	$250 plant rebate Link:http://www.stormwaterelkco.org/docViewer.php?item=00160-Incentive%20Program%20Brochure%202014.pdf

Thurston et al. (2010) used reverse auctions to incentivize homeowners to contribute to N reduction through a subsidized rain garden on their properties with the program paying the 81 homeowner participants anywhere from $0 to $500. For that study, the homeowner had little choice in the design of the rain garden that the program paid a contractor $1500 to install. The fact that 55% of the homeowners requested no payment for having a rain garden installed on their property led the authors to propose that education could be used to promote buy in provided the utility helped with the construction costs. No discussion was provided on the contractor/s used to install the rain

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gardens and there was no discussion on any educational activity that was incorporated into the actual design, implementation, and publicity of the rain garden.

This chapter integrates the implementation of green infrastructure with educational and research activities that address STEM needs with the motivation for the work mainly driven by community engagement to broaden participation in STEM and provide innovative training for engineering students. It does this by focusing on a local community in Florida, East Tampa, where research and education funded projects led by a research I and Carnegie classified community engaged university, are piloting green infrastructure and approaches to mainstream its implementation as a means to broaden participation in STEM while improving water quality of the local watershed. The study site and methods used to assess the hydraulic performance and water quality performance of implemented bioretention systems are first described. The implemented bioretention systems are then reviewed for their community engagement and rationale for green infrastructure location identification "hotspot", design specifications, material costs, and projected performance at stormwater management. The applicability of the installed systems and opportunities for expansion are placed within the socio-cultural context of the community to shed light on their potential impact on social/human capital.

4.2 Methods

4.2.1 Study Area

Located within the City of Tampa in Hillsborough County, Florida, East Tampa is a densely populated majority African American neighborhood with 5,565 households, and a population of 16,355 persons (Table 10). The population density is approximately 14 times that of the state of Florida and 2.4 times that of the city of Tampa. Compared to the

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county, the per capita income in East Tampa, $11,786, is 43% lower, with 3 times as many households whom receive public assistance and 2.8 times are female headed. Thirty three percent of the households have children under the age of 18. The area has 4 elementary schools, 4 middle schools, and 1 high school within Hillsborough County Public Schools (HCPS). HCPS, the 9th largest school district in the US, has adopted Common Core standards, and through a Race to the Top grant, has developed its curriculum to satisfy NGSS (USDOE, 2010).

Table 10: Demographics of East Tampa Business & Civic Association, Woodland Terrace, Hillsborough County, and Florida. Based on 2010 census data, taken from the Hillsborough County Community Atlas (2015).

	East Tampa BCA Inc.	Woodland Terrace	City of Tampa	Hillsborough County	Florida
Population	16,355	858	333,073	1,229,226	18,801,310
% African American	84	89	26	17	16
% Hispanic or Latino	11	6	23	25	22
% White	10	8	63	71	75
Persons per square mile	4,447	4580	1,862	1,082	321
Households	5,565	317	134,393	474,030	7,420,802
Per capita income $	11,786	16,045	28,891	27,282	26,733
% Households receiving food stamps*	92	65	39	31	
% 1 person households	27	27	33	27	27
% Households with children under 18	33	24	27	30	26
% Female householder (no husband present)	39	32	17	14	13
Size (sq mile)	3.68	0.19	179	1,136	
% urban & built	94.19	99.71	68.93	46.16	N
% residential	60.06	81.69			

* 2013 data
East Tampa BCA has 4 elementary, 5 middle, and 1 high schools and Woodlands Terrace has 1 elementary school. Of these 11 schools, one received a grade B in 2012-2013, the rest scored C and below.

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East Tampa is 19.5 km^2 highly urbanized coastal area (Figure 9) that drains to McKay Bay, an impaired waterway for nutrients and dissolved oxygen (EPA, 2012a, 2013b). McKay Bay discharges into Hillsborough Bay, one of seven subsections of Tampa Bay with a contributing watershed of approximately 3318 km^2 (USF Water Institute, 2015). Tampa Bay receives an annual loading of approximately 3,666 tons of TN per year with Hillsborough Bay receiving the highest loading on a percentage basis (1,369 tons TN per year, 37% of total annual loading) (Janicki et al., 2001). The major contributor of nutrient loading within the Hillsborough Bay is from non-point sources (487 tons/year).

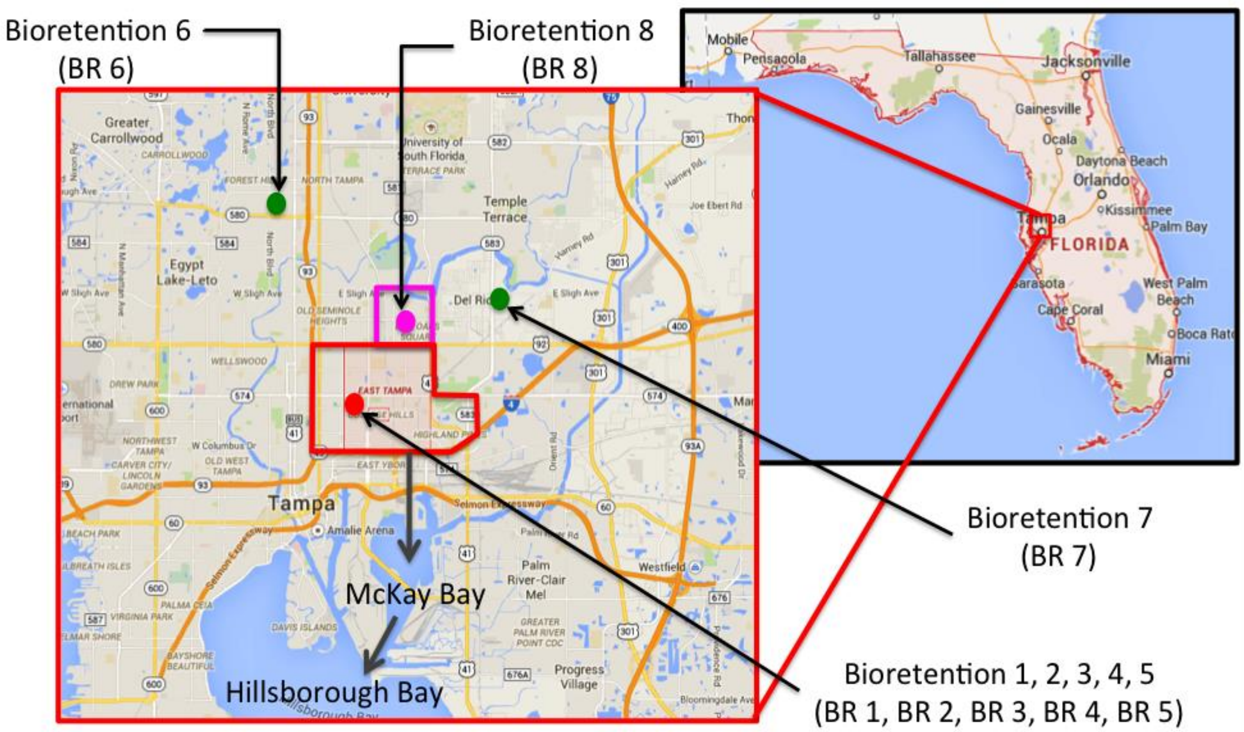

Figure 10: East Tampa Business and Civic Association (red), educational sites outside East Tampa (green), and residential site within Woodland Terrace (magenta). Image modified from Google Maps.

Between December 2012 and March 2015, six bioretention systems were installed as a part of curriculum on green infrastructure targeting K-12 and vocational students in the East Tampa Business and Civic Association area with five (BR 1 – BR 5) at a middle

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school, and one (BR 8) at a residence within Woodland Terrace. Woodland Terrace is a community outside of the East Tampa and Civic Association area however it is a neighborhood that is part of the East Tampa Community Revitalization Partnership and therefore included in this study. Bioretention systems 6 and 7 (BR 6 and BR 7) are shown here as successful applications of the GSBL approach used various parts of the Urban Stormwater Management Curricular Unit (USMCU) and the Green Infrastructure Bioretention Challenge described in Chapter 3 (Locicero et al., 2014 a-g). The curriculum used included multiple funded projects awarded to the university researchers provided financial support to pilot green infrastructure research and educational projects in East Tampa. These grants build on a longer-term engagement with this community by the engineering researchers, some of which Mihelcic and Trotz (2010) describe in their example on incorporating sustainability into engineering curriculum. Construction costs for projects implemented at the schools were supported mainly through a National Science Foundation (NSF) Research Experience for Teachers (RET) program grant for teachers with the Hillsborough County Public Schools (HCPS) being the main partner. Tampa Bay Estuary Program and Southwest Florida Water Management District funded the project that implemented at the residential site and a portion of the systems installed at the school in East Tampa with the main partner being the Corporation to Develop Communities of Tampa Inc. (CDC).

Table 11 lists criteria used to identify stormwater "hotspots" within East Tampa as a part of this project to fuse broadening participation in STEM education and the mainstreaming of green infrastructure. Table 10 and Table 11 provide context for discussion of the results from the construction of the bioretention systems.

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Table 11: Rationale for locating green infrastructure within East Tampa, Florida

Green Infrastructure Hotspot Factors	Rationale
Localized areas of flooding	A person will more likely support green infrastructure if they experience flooding.
Presence of learning space, community center, committed educator	Implementation on these properties can be used to engage with a larger segment of the population. Proximity to schools also means that K-12 curriculum can use the bioretention system for scientific inquiry, and contribute to its improvement and maintenance. A committed educator, whether a teacher or a property owner is critical for the sustained education of others on green infrastructure.
Willingness to pay	Constructing and maintaining bioretention cells will require funding and a property owners' willingness to pay could affect the size of a system if implementation is selected. East Tampa does not receive reclaimed water from the city and multipurpose stormwater-landscape feature (i.e. bioretention cell) could reduce the irrigation bill.
Presence of green infrastructure	A property that already has green infrastructure (e.g. rain barrels) may be open to other interventions.
Property ownership	The decision to implement green infrastructure may vary if the city or a private individual owns the property, whether as a residence or business.
Visibility of location	Greater visibility of a bioretention system will engage with a larger segment of the population.
Positive Stormwater Intervention	Given the community's decision to fund three beautification projects with their property taxes years ago, areas closer to these sites might have property owners who are more familiar with positive stormwater interventions.

4.2.2 Maintenance Requirements

Construction costs of the bioretention systems were deducted from actual purchases made during installation. Maintenance costs of the bioretention systems were estimated from the performance of one of the bioretention system. Table 12 summarizes these costs which are associated with: (1) the surrounding berm of each system, (2) weeding of invasive species and clearing of debris once per month, (built up silt/fines are to be removed from influent pipe as part of weeding and debris process as needed), (3)

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harvesting of plant species once between midsummer peak and fall equinox and again prior to spring equinox as needed, and (4) application of mulch following the fall and spring harvest schedule. The associated costs for weeding and removal of fines/silt is figured as one half-hour per 9.29 m^2, harvesting costs 1-hour per 9.29 m^2, and a 1-hour flat fee for mulch with a capital cost of $25 per 9.29 m^2. Total maintenance costs are based on 1 person performing each of the activities and are approximated at $110 per 9.29 m^2 annually. Costs are based on an assumed minimum wage salary of $8.50/hr and exclude plant die-off or cost associated with replanting.

Table 12: Recommended maintenance and frequency of task associated with bioretention systems.

Task	Description	Frequency	Unit Rate	Total Annual Cost
1	Maintain bioretention berm as part of typical grounds maintenance protocol	Every 1 to 4 weeks as needed	Established	No additional cost
2	Weed of invasive species, remove silt/fines from influent, and clear of debris	Monthly	\$ 4.25 / 9.29 m^2	\$ 51.00 / 9.29 m^2
3	Harvest plant species at fall and spring equinox as specified	Annually / semi-annually	\$ 8.50 / 9.29 m^2	\$ 17.00 / 9.29 m^2
4	Re-apply mulch after fall and spring harvest	Semi-annual	Flat \$25 / 9.29 m^2 \$ 8.50 / 9.29 m^2	\$ 42.00 / 9.29 m^2
Total				\$110.00/9.29 m^2

4.2.3 Hydraulic and Water Quality Performance

The Soil Conservation Service (SCS) method was used to calculate runoff volume from five consecutive years of rain events from March 2010 to March 2015. During this time period, East Tampa registered 496 rain events with an average precipitation of 141 cm/yr. Individual rain events greater than 0.254 cm were applied to each of the

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constructed bioretention systems to determine percent runoff captured, volume of runoff captured, nitrogen attenuation, and capital cost per kg of nitrogen removed from traditional stormwater infrastructure over a 20-year life of the system. Assumptions included, initial abstraction of 0.254 cm, the full restoration of field capacity prior to subsequent storm event, and uniform porosity of 0.25, 0.5, and 0.35 for sand, gravel, and mixed combinations of media respectively. The Soil Conservation Service method was used to calculate the total runoff generated by a rainfall event, R_i = rainfall event (cm). The total rainfall excess, Q_R (cm) is a summation of the rainfall excess from directly connected impervious area (DCIA) (%), Q_{DCIA} (cm), and non-DCIA, (Q_{nDCIA}) (cm):

$$Q_R(cm) = \frac{\big((100 - DCIA) \times Q_{nDCIA}\big) + (DCIA \times Q_{DCIA})}{100} \tag{4}$$

The non-DCIA curve number (CN) for pervious area, percent impervious surfaces (IMP) (%), and DCIA is given by the following:

$$nDCIA\ CN = \frac{CN(100 - IMP) + 98(IMP - DCIA)}{100 - DCIA} \tag{5}$$

Soil Storage, S (cm) is given by the following:

$$S = \left(\frac{1000}{nDCIA\ CN} - 10\right) \tag{6}$$

Rainfall excess (Q_{nDCIA}) (cm) for non-DCIA is given by the following:

$$Q_{nDCIA} = \frac{(R_i - 0.2S)^2}{(R_i + 0.8S)} \tag{7}$$

Rainfall excess (Q_{DCIA}) (cm) for DCIA is given by the following:

$$Q_{DCIA}(cm) = (R_i - 0.1) \tag{8}$$

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The site-specific constraints (i.e. impervious surface area, soil type, curve number, storage volume, media layering) for each bioretention cell were used to calculate the runoff generated from each storm event (Appendix B). The runoff volume was then compared to the total storage volume to determine the percent runoff captured by each system over the course of the 5-year study period. The land use for each site, low-intensity commercial (n = 9) of 1.18 mg N/l for K-12 schools and single-family residential site (n = 17) of 2.07 mg N/l was obtained from Florida stormwater runoff studies was used to estimate total nitrogen runoff concentrations (Harper and Baker, 2007). These literature-based runoff concentration values for total nitrogen were combined with the total volume retained within each bioretention system to calculate nitrogen attenuation. Capital cost per kg of nitrogen removed from traditional stormwater infrastructure over a 20-year life of the system were calculated and compare to the SWFWMD database of > 130 permitted coastal LID and general projects the District permitted between 1993 and 2015. This database is used to: (1) track the amount of work that the section completes each year for our Annual Report (acres treated, TP, TN and TSS removed), (2) look at historical project costs as a benchmark for proposed projects, and (3) track project operation and maintenance by using the contact data to follow-up with project partners who are responsible for O&M (Norton, 2014 Personal Communication). The numbers $1424/kg TN and $494/kg TN are benchmark values that SWFWMD uses to calculate capital cost/kg TN removed over a 20 year life (Seachrist, 2014 Personal Communication). These values are compared to capital costs/kg TN removed over a 20-year life for BR 1 – BR 8 to determine the cost benefit of bioretention compared to other BMP's that have been implemented to date through SWFWMD.

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4.3 Results & Discussion

4.3.1 Education, Human, and Economic Considerations of Bioretention System Installation in East Tampa

Table 13 provides a summary of bioretention systems installed in East Tampa using the Urban Stormwater Management Curricular Unit (USMCU) and the Green Infrastructure Bioretention Challenge. Two additional systems, BR 6 and BR 7, are included though they were installed at schools outside of East Tampa. The targeted population of learners varied from entering sixth graders to vocational students and included activities aligned with formal (during the regular class time) and informal (outside of regular class time) activities. BR 1 – BR 5 were constructed in areas of localized flooding identified by stakeholders, and on a school campus adjacent to a stormwater pond that was beautified through East Tampa's tax incentive fund. Figures 7-10 provide images of the East Tampa sites before and after construction and detailed site information on site specific characteristics (i.e. catchment area, impervious/pervious area, soil classification, plants installed, media layers, and runoff capture volume), is included in Appendix B. BR 8 was constructed in a highly visible part on a residential property belonging to a single, female head of household who was an influential community leader and educator. The residential site selected did not experience major flooding, however, it was highly visible and was designed to capture roof runoff from 2.54 cm storm event and provided a good location for educational outreach to neighbors by the property owner.

BR1, BR 2, and BR 3 were designed to serve as engineering research sites with diverse media mixes and sampling ports, and were constructed during the developmental phase of the Urban Stormwater Management Curricular Unit (USMCU). The media mixes

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are common to what is found within the literature and include sand ($27/yard), topsoil ($25/yard), hardwood mulch ($22/yard), clinoptilolite ($165/yard), tire crumbs ($173/yard), and limestone ($43/yard). BR 1 engineered media mix is comprised of 8 parts sand, 2 parts tire crumb, 1 part clinoptilolite, and 2 parts limestone; BR 3 engineered media layer consist of 7 parts sand, 4 parts tire crumb, and 2 parts clinoptilolite; whereas, BR 2 utilized a more conventional media mix of 2 parts sand, 2 parts topsoil, and 1 part mulch for an overall engineered media mix cost of $289, $430, and $93 respectively.

Materials were delivered in bulk, which helped to reduce costs and significantly smaller portions of the media mix were comprised of specialized materials with higher associated costs (i.e. clinoptilolite and tire crumb). Bulk materials however require more time for mixing and transfer to the system and should be evaluated based on the labor source when determining delivery method (i.e. students, contractor). Field-scale research sites are important to determine the cost benefit of installing bioretention systems with specialized media vs conventional media for nutrient removal allowing for researchers to provide recommendations to decision makers on future funded projects as was the rational for selecting media materials for BR 1 and BR 3. These sites took several months to construct and required mechanized equipment to assist with the excavation given that these cells were implemented during regular classroom hours by students, intended to be used as research data collection sites, and were used as a pilot site for determining effective construction practices. BR 4 – BR 8 were installed by K-12 students, TVI students, teachers, RET participants, Research Experience for Undergraduate (REU) participants, and volunteers from the community, taking one to two days to construct after completing the Green Infrastructure Bioretention Challenge.

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Table 13: Community engagement, design, material costs, and projected performance of seven K-12 (BR 1-BR 7) and one residential (BR 8) bioretention systems. BR 6 and BR 7 located on school campuses outside of East Tampa.

	BR 1	BR 2	BR 3	BR 4	BR 5	BR 6	BR 7	BR 8
Target Population	6^{th}-8^{th} grade	6^{th}-8^{th} grade	6^{th}-8^{th} grade	Pre-6^{th} grade	Incoming 7^{th} grade	6^{th} & 7^{th} grade	9^{th} and 10^{th}	TVI
Formal	X	X	X			X	X	X
Informal				X	X	X		
Engagement	HCPS, Principal, Teacher, Facilities/Grounds	HCPS, Principal, Teacher, Facilities/Grounds	HCPS, Principal, Teacher, Facilities/Grounds	HCPS, Principal, Teacher, Facilities/Grounds	HCPS, Principal, Teacher, Facilities/Grounds	HCPS, Principal, Teacher, SWFWMD, Facilities/Grounds	HCPS, Principal, Teacher, SWFWMD, Facilities/Grounds	Resident, Landscape Maintenance
Catchment Area (m^2)	291.08	232.90	291.08	241.64	297.40	1006.82	227.70	185.87
Depth (cm)	109	109	109	61	61	61	61	61
Surface Area (m^2)	11.62	9.29	11.62	45.07	25.56	30.20	9.11	8.64
Surface Volume (m^3)	1.74	1.39	1.74	4.18	2.23	4.53	1.37	1.30
Vegetative Media (m^3)	3.54	2.83	3.54	3.68	4.54	1.12	2.30	1.53
Engineered Media (m^3)	3.54	2.83	3.54	0.42	0.70	0.56	0.24	0.75
Storage Volume (m^3)	4.22	3.38	3.87	5.31	3.71	5.09	2.06	2.06
% Impervious	30	25	35	85	90	20	65	45
Design Storm (cm)	2.54	2.54	2.54	2.25	1.27	2.25	1.65	2.54
Materials Used	Hardwood Mulch,Tire Crumb, Zeolite, Limestone, Sand, Topsoil	Hardwood Mulch, Sand, Topsoil	Hardwood Mulch, Tire Crumb, Zeolite, Limestone, Sand	Hardwood Mulch, Sand, Topsoil, Gravel	Hardwood Mulch, Sand, Topsoil, Gravel	Hardwood Mulch, Sand, Topsoil, Gravel	Hardwood Mulch, Sand, Topsoil, Gravel	Hardwood Mulch, Sand, Gravel
# Plants	126	90	126	114	98	100	51	70
Cost of Plants	$ 453.60	$ 324.00	$ 453.60	$ 365.00	$ 288.00	$ 400.00	$ 204.00	$ 240.00
Cost of Materials	$ 431.30	$ 186.67	$ 576.38	$ 505.74	$ 686.97	$ 543.83	$ 244.48	$ 136.20
Other Costs	$ 623.33	$ 623.33	$ 623.33	-	-	$ 100.00	$ 65.00	$ 543.79
Total Costs	$ 1,508.23	$ 1,134.00	$ 1,653.31	$ 870.74	$ 974.97	$ 1,043.83	$ 513.48	$ 919.99
# Students	144			25	30	66	100	14
Mean Landuse N Concentration (Location: Florida) (mg/l)	Low-Intensity Commercial (1.18)	Low-Intensity Commercial (1.18)	Low-Intensity Commercial (1.18)	Low-Intensity Commercial (1.18)	Low-Intensity Commercial (1.18)	Low-Intensity Commercial (1.18)	Low-Intensity Commercial (1.18)	Single Family Residential (2.07)
Percent Runoff Capture	56%	56%	53%	67%	49%	31%	41%	56%
Capture Volume (m^3) yr^{-1}	112.2	86.5	110.7	262.2	189.7	146.5	82.7	64
N Attenuation (mg) yr^{-1}	132,400	102,500	130,600	226,100	223,900	172,800	97,500	132,600
Capital Cost/ kg TN Removed 20 Year Life	$ 333	$ 260	$ 395	$ 192	$ 218	$ 273	$ 229	$ 346
20 Year Cost Savings Compared to SWFWMD Coastal/LID Benchmark Values	$ 21,822	$ 23,277	$ 20,587	$ 24,644	$ 24,115	$ 23,013	$ 23,894	$ 21,557

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BR 4 and BR 5 were completed during a summer program at the school and served as a training site for other teachers who were participants in a Research Experience for Teachers, which allowed for a longer construction time. Materials were not purchased in bulk and though this increased costs, it reduced construction time and labor demands on student participants. BR 6 and BR 7, though not in East Tampa, were included to provide examples of the implementation via formal education pathways with materials not delivered in bulk. BR 6 was constructed on a Saturday with student and adult volunteer help, and BR 7 took 1 day to construct. Adult vocational students and university researchers constructed BR 8 in one day at the residential site. The materials were delivered in bulk, reducing overall costs of the residential system.

In addition to the university researchers and official project partners (HCPS, CDC), the systems installed in the East Tampa middle school directly engaged a school Principal, teachers at a middle school responsible for all grade levels, caretakers and approximately 200 students. The residential system engaged 14 vocational students, the homeowner, and a caretaker. The follow up actions of the key decision makers at each site (teachers and homeowner) do provide evidence that the process encouraged further action to replicate green infrastructure systems. After BR 1, BR 2, and BR 3 were installed during regular class hours, teachers leading summer programs at the school opted to use the curricular materials for their summer program and installed BR 4 and BR 5. After BR 8 was installed the homeowner volunteered to host a community event at her house, covering costs for food and drinks, to showcase the green infrastructure and encourage others to also implement.

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Figure 11: Bioretention BR 1, BR 2, BR 3 pre-construction (top) and post-construction (bottom)

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Figure 12: Bioretention BR 4 pre-construction (top) and post-construction (bottom)

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Figure 13: Bioretention BR 5 pre-construction (top) and post-construction (bottom)

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Figure 14: Bioretention BR 8 pre-construction (top) and post-construction (bottom)

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4.3.2 Bioretention System Water Quality and Water Quantity Performance

Over the course of the 5 year evaluation period (March 2010 – March 2015), East Tampa registered (n=496) storm events with (n=354) greater than 0.254 cm. These storm events combined for an average of 141 cm of rainfall with a minimum of 0.01 cm and maximum 8.29 cm. Each of the rain gardens surface area (SA) constraints were designed based on recommendations within the literature of 2% to 5% of total catchment area (CA), with higher percent impervious areas receiving a larger SA:CA ratio than higher percent pervious areas (Hunt et al., 2012). Each of the systems are capable of retaining a minimum 1.27 cm storm event and four of the eight systems are designed to manage runoff from a 2.54 cm storm event.

A direct relationship between design storm event and percentage of overall runoff captured by the system was not found. For instance, BR4 and BR5 capture runoff from an 85% and 90% impervious area and are designed to manage a 2.25 cm and 1.27 cm design storm event, capturing 67% and 49% of stormwater runoff respectively. This is compared directly to BR3 and BR6 that capture runoff from a 35% and 20% impervious area, designed to manage 2.54 cm and 2.25 cm design storm and capture 53% and 31% of stormwater runoff. This comparison demonstrates that importance of properly locating bioretention systems in areas that intercept high runoff volumes of stormwater runoff (i.e. DCIA). Over the course of this study BR4 and BR5 were capable of attenuating 226,100 and 223,900 mg TN/yr from 191.6 m^3 and 189.7 m^3 of collected stormwater runoff annually.

4.3.3 Mainstreaming of Green Infrastructure in East Tampa

The costs of implementing the bioretention systems presented in Table 13 do not include equipment (shovels, wheel barrows, etc.) nor labor costs. This includes researcher

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staff (university professor, graduate, or undergraduate researchers) or professional (teacher, CDC staff) involved with the project. There were no labor costs associated with the target student populations or volunteers who expended the most energy on the actual construction activity. This approach of tying green infrastructure implementation with student learning makes sense for K-12 campuses, but becomes difficult with the TVI program as there are potentially 5,565 residential sites in the East Tampa BCA and the TVI students spend just one week with the green infrastructure project.

The construction costs presented varied from $513 to $1653 with the method of delivery of the media materials having a large impact. Installed plants sourced from retail nurseries averaged $4 per plant. The low per capita income in East Tampa coupled with the poor overall performance of many of the schools in the area, forces one to consider not only the most affordable bioretention systems to install, but also approaches that would create student interest in STEM and that would contribute to the economy and local job creation. Sourcing native plants from the local community is possible and may be less expensive as many yards already have some of them and they are seen as weeds. Creating local nurseries with the native plants could also provide economic support for a resident or school program provided there is a growing request for green infrastructure projects. The stakeholders recognize the sourcing of native plants in East Tampa a viable hobby, educational or business activity that could reduce installation costs. The sourcing of local media materials is yet to be explored and this could also reduce installation costs. Based on the data in Table 13, bioretention installation costs in East Tampa through educational activities could potentially save the district between $20,500 AND $23,300 over the design life of the system for (BR 1, BR 2, BR 3), approximately $21,500 for non-research

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residential systems (BR 8), and $24,000 to $24,500 for the two systems capturing significantly greater portions of impervious area (BR 4 and BR 5) compared to traditional BMP practices. For the residential site (BR 8), the materials cost included roof guttering and pipes to channel the stormwater into the bioretention system. Given that a goal of the vocational program is job placement for students and the green infrastructure module anticipates green job availability, there is an opportunity to pay the TVI graduates for implementing residential bioretention systems and this would have to be factored into the cost that the utility or another funding source would provide. While 14 TVI students were engaged with the design and construction of BR 8, the day of construction had a more reduced number plus the university researchers. Assuming a team of five could complete a residential site in a day, and that each person is paid an hourly rate of $8.50, that adds $340 to the installation cost bringing the total to $1,260. Multiple teams of TVI graduates and other local contractors would have to be supported to install these systems in East Tampa in a timely manner. Assuming that costs can be reduced for materials and plants so that the overall cost of installation is lowered to $1,000 for a residential sized system without monitoring equipment (e.g. flow meters, temperature probes, soil moisture probes) and $1500 per installation with monitoring equipment, the cost to the utility would range from $5.50 million to $8.25 million dollars for all households within the East Tampa BCA in Florida.

The McKay Bay watershed contributes to the larger Hillsborough Bay watershed, receiving 1,366 tons TN/year, 487 tons of which is associated with non-point source pollution. East Tampa is approximately 0.58% of the total watershed area, contributing to equivalent non-point source pollutant loading of 2.82 tons TN/year to Hillsborough Bay.

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This study provided an average removal of 158,000 mg TN/year (0.16 kg TN/year) removed per bioretention system. Assuming that residential installation of bioretention systems ranges from partial installation (25%) to full implementation (100%) we estimate TN removal of East Tampa as 0.24 – 0.97 tons, capturing 8.5 to 34 % of the nitrogen loading entering Hillsborough Bay from East Tampa. This removal of TN from the watershed is further extrapolated to include a potential savings of $1,570,000 to $6,270,000 per year to the utility over a 20-year life when compared to current BMP practices installed.

During the design of the residential bioretention system BR 8, the potential to reduce irrigation requirements was highlighted as important to the homeowner. It is possible that residents would be willing to offset some of the costs of the bioretention system installation if the installation aligns with something they value (savings on irrigation bills, production of useful vegetation, creation of a neighborhood asset). Given the educational based approach used in this work it is also possible to raise funding for the program's expansion through non-traditional methods like online campaigns and community-based events. Sustaining university engagement with the project also requires inclusion in established classes and support from student groups and other university programs or offices. In terms of continued implementation on school campuses, while funding for construction can come from the local utility, results from the GSBL in chapter 3 show that teachers have successfully sourced external funds for their green infrastructure projects. An added cost to the school would be the maintenance of the systems by ground staff. Using an estimated annual maintenance cost of $110/9.29 m^2 of which only $25 was not for wages, inclusion of maintenance activities as a regular part of the job description would eliminate the need to find additional funding for this activity.

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4.4 Conclusions

Green infrastructure for nitrogen management could make communities more resilient to wet weather storm events, provide access to community green space, provide valuable use of stormwater runoff, and increase STEM engagement. On average, the six (BR 1-5 and BR 8) installed bioretention systems in East Tampa removed a total of 950,000 mg of N from entering traditional stormwater infrastructure per year. This results in an capital cost per kg TN removed of $290 over the 20 year life of the designed bioretention systems compared to the $1,424 benchmark value SWFWMD currently uses to estimate the cost benefit of coastal LID implementation based on a historical average of >130 permitted projects between 1993 and 2015. These numbers can be extrapolated across the East Tampa watershed of 19.5 km^2 with implementation goals ranging from 25 % to 100 % over 5,500 residential sites resulting in a capture efficiency of 8.5 to 34 % of the contributing nitrogen loading entering Hillsborough Bay. The residential installation of bioretention systems utilizes private property to manage stormwater runoff with a potential return on capital investment of $1,570,000 to $6,270,000 per year to the utility over a 20-year life when compared to current coastal LID/BMP practices installed. This savings may be passed on to residents in the form of an incentive package to cover installation costs.

Uncertainty associated with this calculation is attributed to the success of the GSBL approach, utilizing the case study year to predict future years nitrogen loading, method for calculating $/kg N removed, actual TN entering into bioretention systems, treatment efficiency associated with bioretention design, and the percentage of TN entering into groundwater supply as a result of implementation. In addition, human, social, and ecological factors associated with installation of bioretention systems (i.e. increased

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biodiversity property value, health of residents, educational opportunities, STEM engagement, and reduction in crime) are not included in the overall cost benefits calculation. The educational approach used with K-12 and vocational students to install the bioretention systems discussed here, engaged with multiple stakeholders who likely benefited from the educational activities. The interest of the teachers and the residential owner in expanding the process to summer programs and through community activities, demonstrate the success of the approach to continue educating others on green infrastructure. Engagement with local utilities that would benefit from the reduced stormwater loads to McKay Bay is needed to explore funding mechanisms and incentives to cover the costs of implementation in an expanded program.

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CHAPTER 5: FIELD EVALUATION OF BIORETENTION ABILITY OF SELECTED PLANT SPECIES NATIVE TO SUBTROPICAL FLORIDA

5.1 Introduction

Green Infrastructure (GI), a type of low impact development technology, promotes infiltration, evapotranspiration, and vegetative growth within decentralized attenuation areas. The goal of GI is to manage runoff at the source and reduce the overall volume of stormwater discharging into existing storm drain or combined sewer infrastructure. This can improve water quality by reducing the overall nutrient loading to downstream ecosystems and reducing the potential for combined sewer overflows (Hunt et al., 2006; Li et al., 2009; EPA, 2013a).

Bioretention has become an increasingly popular GI technology for the localized management of urban stormwater runoff (Davis et al., 2009). Located in areas that either collect or intercept runoff during storm events, such systems are comprised of a ponding area, a bioretention cell, and related infrastructure used for bypass or overflow. A traditional bioretention cell is constructed with naturalized vegetation contained within a ponding area, a high-permeability media layer capable of supporting vegetative growth and an engineered media layer for additional storage and managing pollutants specific to the site (Roy-Poirier et al., 2010; Hunt et al., 2012). The selected vegetation for these systems should consist of terrestrial and in certain cases emergent aquatic plant species that are native and acclimated to environmental and biological stresses for a geographical region.

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Native vegetation increases the likelihood of self-sustaining system maintenance, survivability and performance for the designed life of the system. These vegetative bioretention systems provide short-term and long-term storage of nutrients within aboveground (AG) and belowground (BG) biomass that can be harvested to remove undesirable nutrients from the watershed.

Vegetated bioretention systems play a significant role in improving water quality, especially reduction of nitrogen and phosphorous, when compared to unvegetated systems, in both laboratory (Fraser et al., 2004; Davis et al., 2006; Henderson, 2007; Read et al., 2008, Bratieres et al., 2008; Lucas & Greenway, 2008; Lucas & Greenway, 2011; Zhang et al., 2011; Barrett et al., 2013) and field studies (Dietz & Clausen, 2005; Davis et al., 2006; Hatt et al., 2008; Read et al., 2009; Luell et al., 2011). Plants, considered the major biological component of bioretention systems, assimilate pollutants directly into their tissues, influence environmental diversity within the rhizosphere, and promote a variety of chemical and biological reactions that enhance pollutant removal and overall system performance (Zhang et al., 2007, 2011). Additionally, plants exhibit interspecific difference in nutrient uptake (Greenway & Lucas, 2010; Read et al., 2008, 2009) that can be utilized to maximize nutrient removal (Bratieres et al., 2008; Read et al., 2009).

It is critical to evaluate the ability of individual plant species for improving effluent water quality and suitability. Plant species often have limited geographical ranges, thus it is desired to identify species for individual climate zones. Studies have been conducted for various climates within Australia; however, plant performance and selection are poorly documented in the United States (Read et al., 2009). This study investigated quantifiable attributes associated with 12 Florida native plant species within a field-scale bioretention

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system. Each plant species was evaluated based on performance and applicability to the subtropical conditions of the Tampa metropolitan area.

5.2 Methodology

5.2.1 Study Site

The Tampa Bay estuary is listed as an impaired waterway for nutrients and dissolved oxygen (EPA, 2012a, 2013b). Three bioretention cells were installed in December 2012 in Tampa, Florida (27.9N latitude and -82.4W longitude) to study qualitative and quantitative design attributes of 12 selected Florida native plants species. The study site (Figure 10) is considered a highly urbanized coastal area with sandy soils overlying the Upper Floridan aquifer and surficial aquifer systems that act as a major municipal water source for the region (NOAA, 2013; Nachabe et al., 2012). The annual rainfall from March 2013 to March 2014 was approximately 152.9 cm. The overall bioretention system, (BR 1, BR 2, and BR 3) was designed to collect 365.6 m^3 of stormwater and 431,486 mg N annually that would otherwise have collected as runoff and discharged into an existing storm drain from the McKay Bay watershed into the Tampa Bay Estuary.

The overall bioretention system was designed and constructed with K-12 students as part of the Urban Stormwater Management Curricular Unit in conjunction with the University of South Florida (USF) - Water Awareness Research and Education (WARE) program and the Green Space Based Learning (GSBL) approach for transforming green spaces on school campuses into multi-use educational environments (Chapter 3). The characteristics of the three bioretention cells and contributing catchment area are shown in Table 14. Briefly, each cell was installed with a 30.5 cm vegetative and engineered media layer consisting of either a homogeneous mix or layered combination of several recycled

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and locally sourced naturally available materials representative of the types of mixes found within the literature (Chapter 2). A ponding area with a freeboard of 15.24 cm was established above a 7.62 cm layer of hardwood mulch to capture and store runoff from the contributing 815-m^2 catchment area. An existing drainage structure and weir configuration, 30.50 cm (w) x 10.16 cm (h) was used to establish the top of ponding area and overflow elevation for the bioretention system.

Table 14: Field-scale bioretention system characteristics

Characteristics	BR 1	BR 2	BR 3
Native plant species [a]	CF, CL, EH, FL, HL, IV, SC, SA, SF, SP, TO	CL, EH, FL, IV, SC, SA, SP, TO	CF, CL, EH, FL, HL, IV, SC, SA, SF, SP, TO
No. of plants installed	126	90	126
Excavation volume	12.7 m^3	10.1 m^3	12.7 m^3
Bioretention surface area (SA)	11.6 m^2	9.3 m^2	11.6 m^2
Ponding area storage volume	1.8 m^3	1.41 m^3	1.8 m^3
Total catchment area	291.1 m^2	232.9 m^2	291.1 m^2
Catchment SA to bioretention SA		25:1	
Total system depth		109 cm	
Depth to seasonal high water table		>140 cm	
Catchment percent impervious		30	
Catchment soil classification		Sandy Clay Loam	
Existing soil media characteristic group [d]		C/D	
Weighted curve number [d]		50	
Vegetative media layer composition	2:2:1 [b] sand:topsoil:mulch	2:2:1 [c] sand:topsoil:mulch	4:1 [c] sand:mulch
Engineered media layer composition	8:2:2:1 [b] sand:crumb: limestone:zeolite	2:2:1 [b] sand:topsoil:mulch	7:4:2 [b] sand: tirecrumb:zeolite

[a] plant species ID can be found in Table 19. [b] homogeneous media mix. [c] layered media mix. [d] USDA (1986).

5.2.2 Plant Selection

The bioretention system was planted, (March 21, 2013) based on plant species that are commonly found in environments that mimic the conditions particular to the given site and design parameters, (Table 15). Ten of the twelve species were part of the initial plant installation (excluding *Tripsacum dactyloides* and *Solidago fistulosa*), and obtained as three-

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to six-month old seedlings from a local native nursery. Plants were transplanted from 1-gallon containers into equally distributed clusters spaced approximately 30.5 cm on center within each cell.

Table 15: Selected plant scientific name, common name, and plant species coding

Scientific Name	Common Name	Code
Coreopsis leavenworthii	Tickseed	CL
Flaveria linearis	Yellowtop	FL
Salvia coccinea	Red Salvia	SC
Solidago fistulosa	Goldenrod	SF
Canna flaccida	Yellow Canna	CF
Hymenocallis latifolia	Spider Lily	HL
Iris virginica	Blue Flag Iris	IV
Sisyrinchium angustifolium	Blue Eyed Grass	SA
Spartina patens	Marshaay Cordgrass	SP
Tradescantia ohiensis	Spider Wort	TO
Tripsacum dactyloides	Fakahatchee	TD
Equisetum hyemale	Horsetail	EH

Bioretention cells BR 1 and BR 3 have differing surface dimensions and a similar surface area of 11.6 m^2 with 126 plant species within each cell, and bioretention cell 2 has an approximate surface area of 9.3 m^2 with 90 plant species. *Spartina patens* were used to stabilize the side slopes of the bioretention system and were installed around the perimeter of the system and along a dividing berm between each cell. As a result of significant plant mortality of both *S. patens* and *Hymenocallis latifolia*, two additional species, *Solidago fistulosa* and *Tripsacum dactyloides* were selected, tested for baseline nitrogen concentration data as described below and installed within the affected bioretention cells in February 2014 and July 2014, respectively. *Tripsacum* dactyloides was not evaluated for field performance as a result of insufficient acclimation period with respect to overall system seasonal harvesting.

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5.2.3 Baseline Plant Data Collection

The baseline above ground (AG) and below ground (BG) biomass was collected in duplicate from a random selection of three to six-month-old 1-gallon seedlings from each plant species. Three randomly selected shoots from each 1-gallon sample were cut at the soil surface and partitioned into leaves, stems, and reproductive structures. Individual species were classified based on their physiological traits as having both leaves and stems (*Coreopsis leavenworthii*, *Flaveria linearis*, *Salvia coccinea*, *Solidago fistulosa*, *Canna flaccid*a, *Tradescantia ohiensis*, and *Tripsacum dactyloides*), leaves without stems (*Hymenocallis latifolia*, *Iris virginica*, and *Sisyrinchium angustifolium*) or stems without leaves (Spartina *patens* and *Equisetum hyemale*). Only four of the twelve species (*Coreopsis leavenworthii*, *Salvia coccinea*, *Tradescantia ohiensis*, and *Tripsacum dactyloides*) were sampled for their reproductive structure as a result of seasonal flowering conditions at the time of sampling. Therefore reproductive structures was weighted into the overall nutrient uptake capacity, but not explicitly reported in this study. The BG biomass for each sample was placed over a #10 sieve and washed to remove all soil and particulate debris prior to drying.

5.2.4 Harvested Plant Data Collection

Harvesting of AG biomass in the bioretention system occurred two growing seasons (July 2014) after initial planting. This corresponded to a point between the mid-summer peak and early autumn of the second growing season to allow for sufficient plant community acclimation. Three plants from each growth type were selected using a random number generator and harvested from bioretention cell 1 at approximately 5.0 cm (*Tradescantia ohiensis, Sisyrinchium angustifolium*), 12.25 cm (*Canna flaccida, Flaveria*

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linearis, Equisetum hyemale), and 25.4 cm (Solidago fistulosa, Spartina patens, Iris virginica, Salvia coccinea, Coreopsis leavenworthii) above the media layer. Once collected, samples were placed into a cooler (4°C) and transported to the laboratory for total AG nitrogen analysis.

5.2.5 Total Nitrogen Analysis

Baseline and harvested samples were oven-dried for 24 to 48 hours at 105°C to a constant weight and ground to pass a #40 sieve before being placed into sealed polypropylene bag with a 2 g silica gel desiccant pack. Samples were stored in a cool, dark, and dry laboratory environment for a maximum of 60 days prior to total nitrogen analysis. Total nitrogen analysis was performed using a Total Nitrogen Analyzer, model TN 3000 (Thermo Electron Corporation, Waltham, MA). The National Institute of Standards and Technology (NIST), Standard Reference Material (SRM), apple leaves (SRM-1515) was used as a reference standard for total nitrogen (22.5 mg N/g). Appendix B provides the data collected and results from total nitrogen analysis.

5.2.6 Monitoring and Surveying

Supplemental watering was provided during the first two weeks of establishment and in 22 instances where the mean antecedent dry periods for rain events was exceeded (> 4.65 days for dry season and > 1.93 for wet season), to reduce plant stress and mortality rate (Harper & Baker, 2007). Each bioretention cell was visually inspected and photographed to document the overall health (i.e. vigor, necrosis, new growth, spread) and aesthetics (i.e. presence of reproductive parts, structure, shape) of the installed plant species (Denich et al., 2013, Welker et al., 2013).

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A plant survey was conducted to determine plant species establishment and propagation at the end of the first growing season (Fall 2013), the winter between the first and second growing season (Spring 2014), and prior to biomass harvesting (Summer 2014) to gauge the adaptability of selected species to the bioretention environment. The position of each species within the three-bioretention cells was recorded, and long lived perennials (LLP) and short lived perennials (SLP) that died-off between subsequent surveys were noted. Propagation values were based on the net number of plants within each of the three-bioretention cells compared to the initial quantity installed. Plant species that are classified as annuals considered establishment as a propagation rate with respect to initial planting, and propagation as the number of individual species greater than the initial planted or previous season.

5.2.7 Mean Total Nitrogen Density

Differences in plant size may affect the ability of a species to remove influent nitrogen loading. Therefore, area-based total nitrogen concentration, or mean total nitrogen density, $(\overline{\sigma}_{TN})$ is typically reported so that surface area requirements align properly with targeted design goals (Iamchaturapatr et al., 2007, Tanner, 1996). The canopy of each plant was surveyed at the same increments as the plant mortality survey to determine the area occupied by each plant species. These data were extrapolated to determine mean total nitrogen accumulated per square meter. The mean total nitrogen density is:

$$\overline{\sigma}_{TN} = \frac{1}{n}\sum_{i=0}^{n}\left(\frac{D_B \times \overline{TN}_{Acc}(x_i)}{A_C}\right) \quad (9)$$

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where:

$\overline{\sigma}_{TN}$ = mean total nitrogen density (mg N/m^2)

D_B = Biomass sample dry weight (g biomass)

$\overline{TN}_{Acc}(x_i)$= Mean TN concentration of sample plant species (mg N/g biomass)

A_C = Canopy area (m^2)

A one-way ANOVA and post-hoc test was used with baseline plant allocation and harvested nitrogen concentration data to determine statistical differences between means of: (1) baseline and harvested plants of the same species and (2) harvested plant samples of different species. IBM SPSS Version 21 was used for analysis with a critical value of α = 0.05.

5.2.8 Stomata Density

Stomata density is a measure of plants microscopic pores that allow water and gaseous exchange to occur and can be related to mean actual evaporation potential rate of a plant species. Stomata density was collected from 10 of the 12 selected plant species, *Spartina patens, Flaveria linearis, Equisetum hyemale, Sisyrinchium angustifolium, Canna flaccida, Hymenocallis latifolia, Iris virginica, Coreopsis leavenworthii, Salvia coccinea,* and *Tradescantia ohiensis.* A 0.1 cm film of acetone was applied to a 1.0 cm x 1.0 cm of plant species leaf surface area. The leaf surface is covered in a 2.54 cm x 1.26 cm section of acetate tape and removed. The acetate tape is then viewed under a microscope with a 40X objective and 10X eyepiece for an overall 400x magnification. Stomata density is taken in triplicate as the average number of stomata from the field view for each of the tested species.

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5.3 Results & Discussion

5.3.1 Baseline Total Nitrogen Allocation

Plants display interspecific differences in their ability for luxury concentration of nutrients within their above and below ground biomass (Kadlec and Wallace, 2009). Figure 14 summarizes weighted total nitrogen allocation of the 12 native Florida plant species of this study. Baseline plant allocation data revealed nearly a four-fold range between *T. ohiensis, (29.20 ± 8.13 mg N/g)* and *S. patens (7.65 ± 0.54 mg N/g)* species with an average total nitrogen uptake of 18.25 ± 5.77 mg N/g across all species. Similar to Lai et al. (2012), total nitrogen uptake of individual component parts (i.e. leaves, stems) remained similar between component parts of the same species. Plant production and nitrogen allocation varied widely among species and may be attributable to relative differences in initial nutrient loading (i.e. fertilizing) as well as from intrinsic species and ecotype growth characteristics (Zhang et al., 2011).

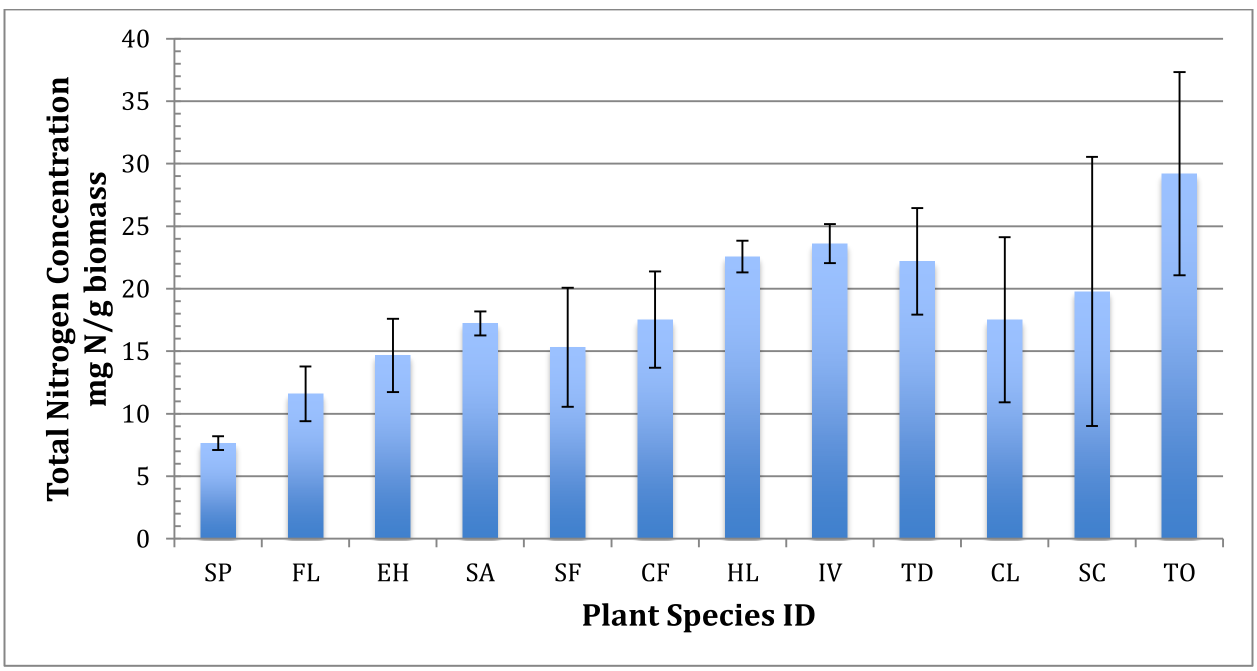

Figure 15: Initial planted above ground total nitrogen concentration of 12 plant species based on weighted values of concentration in stems and leaves.

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5.3.2 Above-Ground Harvested Total Nitrogen Concentration

The AG harvested total nitrogen concentration data for the field bioretention site ranged from 9.14 ± 1.45 mg N/g (*S. patens)* to 15.30 ± 0.22 mg N/g (*F. linearis*) as shown in Figure 13. The difference in nitrogen uptake between baseline plant and harvested plant performance data was similar (α<0.05) among *Flaveria linearis, Sisyrinchium angustifolium, Solidago fistulosa, Canna flaccida, Salvia coccinea, Spartina patens*, and *Coreopsis leavenworthii* plant species after the second growing season. Confirming that plant species display similarities between baseline and harvested plant performance data as well as a statistical difference between means (α>0.05) for *Equisetum hyemale, Iris virginica, Salvia coccinea, Tradescantia ohiensis* when considering initial installation and acclimation period.

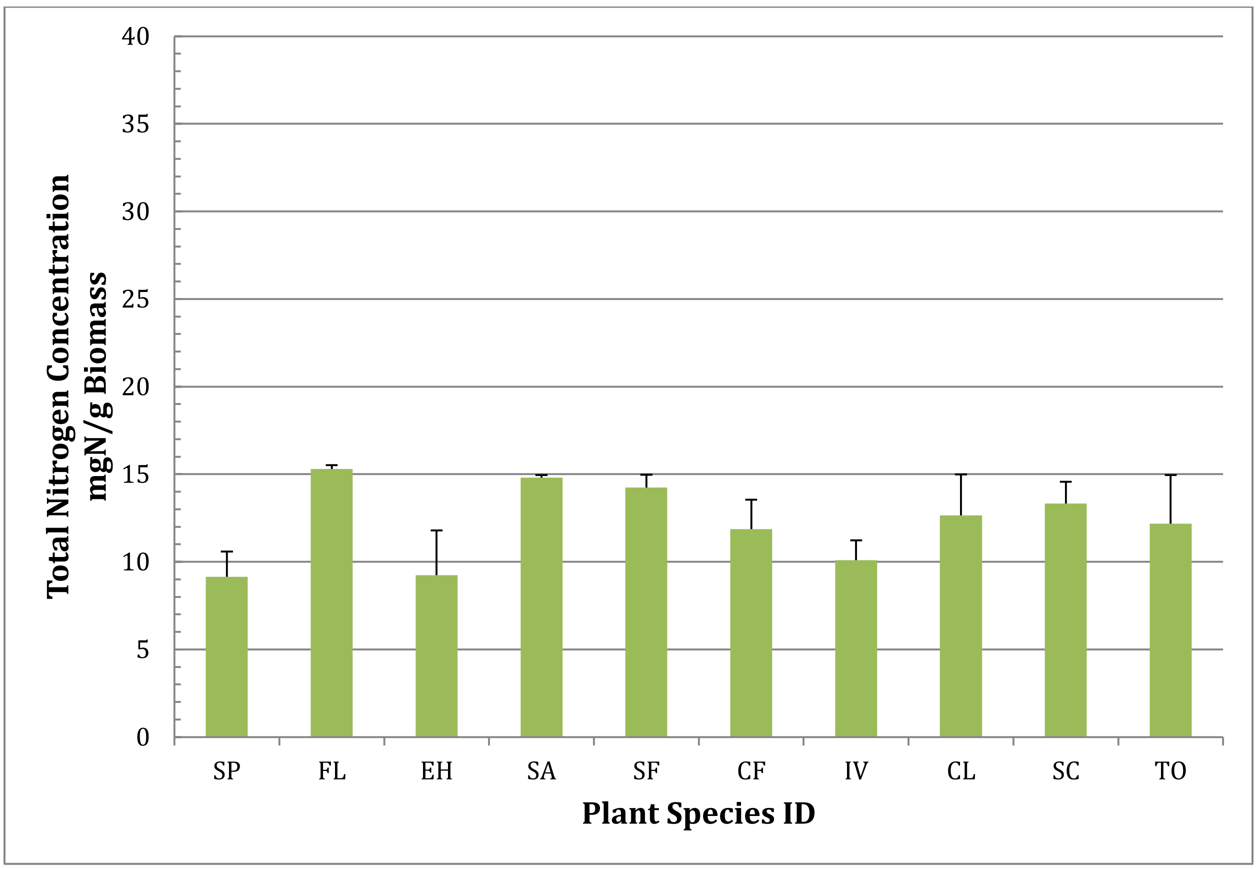

Figure 16: Field bioretention harvested total nitrogen concentration (July, 2014).

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The total nitrogen mean harvested concentration data can be further visualized with Figure 16, dividing similarities in nitrogen concentration within plant species across three statistically significant cluster groups. The clusters have been grouped into low-range (*Spartina patens, Equisetum hyemale, Iris virginica*) 9.14 ± 1.45 mg N/g to 10.10 ± 1.12 mg N/g, mid-range (*Iris virginica, Canna flaccida, Tradescantia ohiensis, Coreopsis leavenworthii, Salvia coccinea*) 10.10 ± 1.12 mg N/g to 13.33 ± 1.23 mg N/g, and high-range (*Salvia coccinea, Solidago fistulosa, Sisyrinchium angustifolium, Flaveria linearis*) 13.33 ± 1.23 mg N/g to 15.30 ± 0.22 mg N/g, overlapping between each cluster for *Iris virginica* and *Salvia coccinea* species, with a mean total nitrogen concentration of 12.28 *± 2.23* mg N/g across all species.

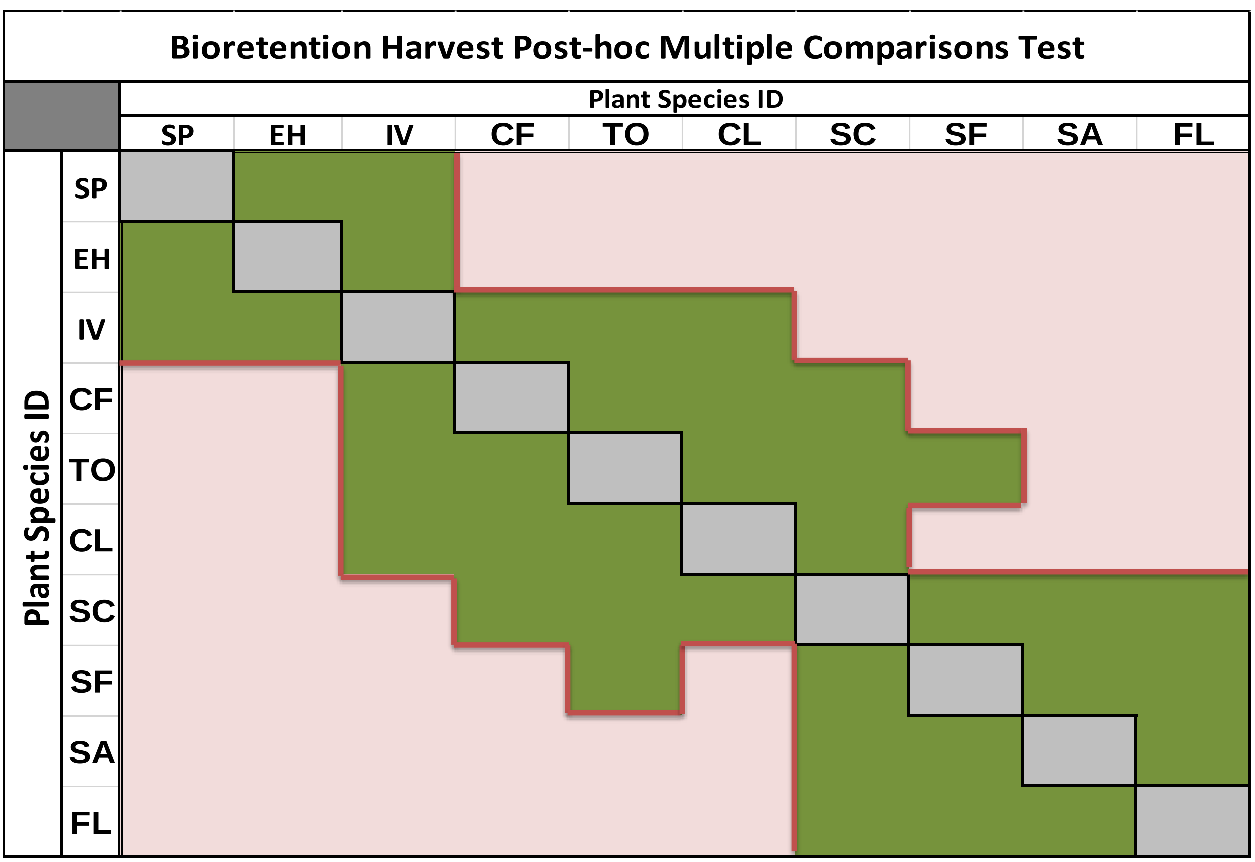

Figure 17: Bioretention Post-hoc Multiple Comparison Test of harvested mean total nitrogen concentrations between plant species. Similarity in mean total nitrogen concentration between species (green).

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There was an 80-fold variation among species in total biomass per sampled plant species with a range of 1.08 g (*C. flaccida*) to 87.30 g (*S. coccinea*) within this study. Table 16 provides a summary of the initial baseline plant allocation data, harvested biomass concentration, plant weight at harvest, percentage survival and propagation, and means total nitrogen density. These data were used to determine mean total nitrogen accumulated per square meter (density) of harvested area, showing a statistical difference between means of two-groups: *Sisyrinchium angustifolium, Equisetum hyemale, Spartina patens, Solidago fistulosa, Salvia coccinea, Coreopsis leavenworthii, Iris virginica* (286 mg N/m^2 to 4,539 mg N/m^2) and *Canna flaccida, Flaveria linearis, Tradescantia ohiensis* (12,428 mg N/m^2 to 15,409 mg N/m^2).

The results for harvested plants are similar to both Miao & Zou (2012) and Zhang et al. (2007). Miao and Zou (2012) evaluated six Florida native species and reported a mean leaf concentration of 8.1 mg N/g and range of 2.0 – 14.0 mg N/g. Zhang, (2011) conducted a 35-column experiment across six-species harvesting AG biomass after a 20-month acclimation period and 16-months of synthetic stormwater application and calculated a mean total nitrogen range of 6.8 - 8.4 mg N/g AG biomass. Zhang's (2011) data fall below the low range of this study and may be attributed to laboratory scale, specific plant characteristics, region of implementation, and/or seasonal harvesting and maturity trends in nitrogen retention (Lucas and Greenway, 2011). Additionally, the percent removal of nutrients increases under low nutrient loading, increased retention times, and as a result of regular harvesting, making a case for field scale bioretention plant performance to have higher total nitrogen concentration (Lucas & Greenway, 2011; Zhang et al., 2011; Borin & Salvato, 2012).

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Table 16: Baseline and harvested mean total nitrogen concentration, mean total density, harvest height, harvest weight, establishment, and propagation for 12 selected plant species.

Plant Species ID	Baseline Leaves TN Accumulation mg N/g biomass	Baseline Stems TN Accumulation mg N/g biomass	Baseline Roots TN Accumulation mg N/g biomass	Initial Weighted TN Accumulation mg N/g biomass	Harvested AG TN Accumulation mg N/g biomass	Mean TN Density mg N/m^2	Harvest Height cm	Harvest weight g	Establishment %	Propagation %
SP	n/a	7.58 ± 0.54	7.78 ± 0.92	7.65 ± 0.54	9.14 ± 1.45	1622 ± 1007	91 ± 6.3	17.92 ± 6.41	60 ± 5	0 ± 0
FL	12.80 ± 2.32	9.93 ± 1.10	16.12 ± 0.22	11.59 ± 2.18	15.30 ± 0.22	12497 ± 7773	57.0 ± 19.0	6.59 ± 6.29	55 ± 26	26 ± 5
EH	n/a	15.33 ± 2.93	9.84 ± 1.44	14.67 ± 2.93	9.23 ± 2.56	625 ± 438	72.3 ±44.7	5.98 ± 3.06	100 ± 0	118 ± 43
SA	17.23 ± 0.97	n/a	8.04 ± 0.27	17.23 ± 0.97	14.81 ± 0.14	286 ± 140	25.3 ± 4.6	6.82 ± 2.76	95 ± 8	5 ± 8
SF	19.70 ± 1.41	12.79 ± 2.61	14.89 ± 2.05	15.31 ± 4.76	14.24 ± 0.72	1935 ± 728	85.0 ±36.0	20.01 ± 18.26	n/a	n/a
CF	20.51 ± 1.76	14.99 ±1.69	15.91 ± 0.48	17.53 ± 3.85	11.86 ± 1.67	12428 ± 7859	44.3 ± 11.6	2.79 ± 2.20	32 ± 45	0 ± 0
HL	22.67 ± 1.26	n/a	12.82 ± 0.41	22.58 ± 1.26	n/a	n/a	n/a	n/a	10 ± 16	0 ± 0
IV	23.43 ± 1.56	n/a	14.56 ± 3.68	23.60 ± 1.56	10.10 ± 1.12	4539 ± 5139	83.7 ±10.1	9.33 ± 5.56	100 ± 0	10 ± 16
TD	24.01 ± 1.79	16.80 ± 2.12	16.45 ± 0.33	22.19 ± 4.26	n/a	n/a	n/a	n/a	n/a	n/a
CL	25.19 ± 1.21	12.20 ± 2.34	8.33 ± 0.93	17.52 ± 6.60	12.65 ± 2.34	2516 ± 1153	86.0 ± 7.0	5.72 ± 2.42	10 ± 16	86 ± 14
SC	29.16 ± 1.75	18.02 ± 2.34	n/a	19.78 ± 10.76	13.33 ± 1.23	2320 ± 935	108.7 ± 17.0	60.30 ± 26.60	100 ± 0	218 ± 40
TO	29.86 ± 8.12	31.87 ± 9.87	18.17 ± 12.84	29.20 ± 8.13	12.17 ± 2.78	15409 ± 7251	47.0 ± 7.9	4.09 ± 1.93	82 ± 20	37 ± 8

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5.3.3 Establishment and Propagation

Visual inspection and photographs coupled with a thorough plant inventory after the initial establishment period and mid-summer peak uptake (March 2013 – August 2013) revealed that all species except *H. latifolia* had acclimated to the bioretention system. *H. latifolia* was a preferred food for eastern lubber grasshopper (*Romalea microptera),* and *R. microptera* was not properly eradicated from the system. The second plant inventory performed in January and February 2014 revealed several species dependent trends. As expected with ephemeral grasses and annuals, the above ground biomass of both *T. ohiensis* and *C. leavenworthii* were either standing dead, litter fall, or had been completely eliminated from the system. *S. patens* displayed a pattern of die-out within each cell that had ≥ 50% shade conditions, a plant characteristic that was not anticipated. A final plant inventory, pre-harvest (July 2014), revealed that *C. leavenworthii, E. hyemale*, *S. coccinea, T. ohiensis* and *I. virginica* had propagated via reseeding, propagules, and below ground rhizomes. All *S. coccinea*, *E. hyemale*, and *I. virginica* individuals survived the second growing season (0% mortality), whereas *H. latifolia* and *C. leavenworthii* is an annual species with a mean mortality rates were 90%. However, *Coreopsis leavenworthii* is an annual that reseeds at a rate equal to its mortality.

5.3.4 Individual Plant Species Performance

Appropriately selected vegetation increases the likelihood of self-sustaining system maintenance, survivability and performance for the designed life of the system. These vegetative bioretention systems provide short-term and long-term storage of nutrients within aboveground and belowground biomass that can be harvested to remove

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undesirable nutrients from watershed. The 12 species selected for this study are described in detail.

5.3.4.1 *Spartina patens*

Spartina patens spreads by underground roots, reseeds and is salt tolerant preferring full sun and dry to wet soil conditions (Schiller, 2012). *S. patens* had a growth rate of 91 ± 6.3 cm and displayed an increase in total nitrogen concentration between initial, 7.65 ± 0.54 mg N/g and harvested, 9.14 ± 1.45 mg N/g AG total nitrogen concentration. The harvested AG nitrogen concentration is similar to the AG concentration, (10.70 mg N/g) reported for natural coastal marshes by Tobias et al. (2014). This species showed very poor establishment and growth in this study and was nearly eliminated from the system after the second growing season, with a mean survival and propagation rate of 60 ± 5% and 0 %, respectively. This is potentially due to a fluctuation in water levels as Broome (1995) showed limited tolerance of *S. patens* to excessive waterlogging and sustained water levels greater than 30 cm. The seasonal die-back shown by *S. patens*, and lack of establishment of new growth, and inability to provide embankment stabilization within this study suggest it is not likely to be a plant species for bioretention system design.

5.3.4.2 *Flaveria linearis*

Flaveria linearis, an erect to sprawling perennial wildflower with yellow flowers mostly in the fall can survive wet to dry soil moisture conditions and tolerate full sun (Schiller, 2012). *F. linearis* displayed a moderate growth rate of 57 ± 19 cm based on anticipated growth conditions. The baseline weighted AG total nitrogen concentration of 11.59 ± 2.18 mg N/g was low relative to the other test species, but was greatest (15.30 ± 0.22 mg N/g) among all species after two growing seasons. The attributes that make *F.*

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linearis a potentially useful plant for bioretention include: mean total nitrogen concentration of (12,497 ± 7,773 mg N/m^2), more than twice the average recorded for plants growing at the field site, its moderate propagation rate 26 ± 5%, and ability to create habitat by attracting various types of butterflies and pollinators.

5.3.4.3 *Equisetum hyemale*

Equisetum hyemale is an evergreen perennial with a jointed stem and cone shaped flower at its tips, preferring full sun to partial shade and wet to saturated soils (Schiller, 2012). Baseline AG and harvested total nitrogen concentration of 14.67 ± 2.93 mg N/g and 9.23 ± 2.56 mg N/g was similar to the mean of all tested species; however, area based concentration of 625 ± 438 mg N/m^2 performed well below average when compared to the mean of test species. The rhizomes and roots (9.84 ± 1.44 mg N/g) of *E. Hyemale* are capable of penetrating the surface media layers to depths of 60 cm or more in sandy soils and may improve hydraulic performance. Uchino et al., (1984) suggested a potential drawback to implementation, nitrogen fixation associated in *Equisetum Species*. This study showed high growth rates, 72.3 ± 44.7 cm and superior survival 100 % and propagation 118 ± 43% rates, highlighting the need for evaluating the net positive and negative effects of nitrogen fixation within the constraints of a bioretention system when compared to potential benefit of harvesting. For instance, the stems of the equisetum are made up of mesoporous silica with high surface area that can be used in biomorphous materials, an attractive alternative to synthetically produced silica (Sapei et al., 2008)

5.3.4.4 *Sisyrinchium angustifolium*

Sisyrinchium angustifolium is an herbaceous perennial that displayed a moderate growth rate of 25.3 ± 4.6 cm for a flowering groundcover. Its stems are two edged with

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narrow leaves and pale blue, yellow centered flowers for 6-weeks per year. *Sisyrinchium spp*. can thrive in full sun to partial shade, are tolerant of drought and anaerobic conditions, moist-acidic soils, and have a shallow root depth (Schiller, 2012). *S. angustifolium* has several known medicinal uses; the roots and leaves can be made into a tea to treat for diarrhea, worms, and stomach aches (Church, 2006). This species showed excellent establishment (95 ± 8%) and high AG nutrient concentration (14.81 ± 0.14 mg N/g), unlike a study by O'Neill and Davis (2011), where the mortality was 100% after 53 days, although the cause of stress and die-out were not determined. It is unlikely to be competitive in species rich ecosystems, where it may be out competed for light and susceptible to weeds due to its low stature and productivity (286 ± 140 mg N/m^2). However, it may have potential for specialist applications as a side-slope ground cover or in other GI applications (e.g. green roofs, vegetative walls), where high visual maintenance is desired.

5.3.4.5 *Solidago fistulosa*

Solidago fistulosa is a perennial wildflower that can grow in full sun to partial shade and is found in open fields throughout the eastern United States. *Solidago Species* is sought out for its aesthetics and as a nectar source with bright yellow, spike like flowers that bloom between summer and fall. *Solidago fistulosa* is viewed as a beneficial plant that should be enhanced throughout the natural environment and at the same time can be an undesirable species if not properly controlled and managed. *S. fistulosa* displayed moderate concentrations in area-based density (1935 ± 728 mg N/m^2) and high in harvested total nitrogen concentration (14.24 ± 0.72 mg N/g) when compared to the other species in this study. Solidago has high growth rate characteristics (85 ± 36 cm) and a survival rate of ~100%, performing well as an ornamental under field-scale application.

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5.3.4.6 *Canna flaccida*

Canna flaccida is a perennial wildflower that prefers full sun to light shade, wet soils, and can grow up to 120 cm with large, showy, lightly perfumed yellow flowers (Schiller, 2012). *C. flaccida* harvested AG total nitrogen concentration was 32% less than the initial AG total nitrogen concentration, with average overall performance when compared to the other species in this study. This aquatic emergent species displayed poor growth of 44.3 ± 11.6 cm when compared to expected growth characteristics. However, *C. flaccida* showed very high area-based density (12,427 ± 7859 mg N/m2), which aligned with a study by White (2013), where *C. flaccida* accumulated 16,800 mg N/m2. This was also supported by Debusk et al. (1995), who found *C. flaccida* to out perform 10 emergent plant species in daily area-based nutrient uptake. This experiment found almost complete die-out in one cell that may have been caused by influent loading and sedimentation as shown by Naralla et al. (1999) finding non-uniform growth across a field experiment with plant height increasing the farther from influent source. *Canna flaccida* has several agricultural uses that distinguish it from a strictly ornamental species. The leaves, roots, and stems of this species can be used as a wrap for cooking food in, produce alcohol, and make strong fibrous material. Despite its high area-based concentration rate, *C. flaccida* experiences significant die-back and high mortality rate making this species less than desirable for well drained soils and may not be suitable for bioretention application.

5.3.4.7 *Hymenocallis latifolia*

Hymenocallis latifolia is a bulbous perennial flower, with showy, white blooms from spring to fall. This species is salt tolerant, can grow to a height of 90 cm 60 cm wide, prefers moist to dry soil conditions and full sun (Schiller, 2012). Initial weighted AG total

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nitrogen concentration of 22.67 ± 1.26 mg N/g ranked it moderately high when compared to the 12 species tested in this study. *H. latifolia* showed promising establishment and growth within the first 60 days of this study, but only resulted in a mean survival and propagation rate of 10 ± 16 % and 0 %, respectively. *R. microptera*, (eastern lubber grasshopper) preferred the leaves of H. latifolia as a food source. Therefore, *H. latifolia* is not recommended in areas where pest species may be present. However, anecdotal inspection of two other bioretention applications planted the following year show significant yields in biomass production with the absence of *R. microptera*.

5.3.4.8 *Iris virginica*

Iris virginica is an emergent perennial that grows in marshes, swales, ditches, streams, and along the shores of ponds and lakes. This species has showy, blue flowers with dark green sword-like leaves, prefers full sun to partial shade, moist to poor drained soils, and can grow between 90 cm to 150 cm (Schiller, 2012). *I. virginica* has been used as an anti-inflammatory and an ointment to soothe the surface of the skin from minor irritation. This species showed rapid establishment, growth rate of 83.7 ± 10.1 cm and 100% survival rate. The initial AG total nitrogen concentration (23.60 ± 1.56 mg N/ g) was more than twice that of the field harvested samples (10.10 ± 1.12 mg N/g). This species was limited to 10 ± 16 % propagation due to designed bioretention components, spacing, and timing of harvest. Seed capsules begin to dehisce in August and September and germinate at the surface of organic substrates devoid of vegetation and liter in May and June the following year (Morgan, 1990). Despite its significant seasonal die-back, *I. virginica* eventually forms tall dense strands that if harvested in concert with peak uptake would appear to be a preferred plant for bioretention systems. It is also recommended to

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plant species in less well-drained soils within the bioretention configuration. This provides sufficient space for seedling establishment and clearing of the ponding area surrounding the plants in early fall (August and September) and summer (May and June) months.

5.3.4.9 *Tripsacum dactyloides*

Tripsacum dactyloides (TD) is commonly found in tallgrass prairies throughout North America and is well suited for growing along pond edges. This species is drought tolerant, grows to a maximum height of 150 cm, can survive in full sun or shade, tolerates dry to moist soil conditions and may be harvested multiple times per year (Schiller, 2012). The high potential productivity, extensive root network, and easy propagation of this perennial grass have made this species ideal for slope stabilization and for meeting stormwater management criteria (Moyer & Sweener, 2008). In this study, baseline total nitrogen concentration was moderately high with 22.19 ± 4.26 mg N/g allocated to AG biomass. This species is adapted to the influent pollutant loading and maintenance recommendations for bioretention systems, requiring application of nutrients and multiple annual cuttings to increase its yield potential (Douglas et al., 2002). Although *T. dactyloides* was not evaluated for field scale performance, its anticipated growth rates and high nitrogen allocation suggest it may be an ideal plant for bioretention systems.

5.3.4.10 *Coreopsis leavenworthii*

Coreopsis leavenworthii is the Florida state flower, an annual wildflower with dark-yellow to light-yellow ray flowers and needle like leaves capable of growing well throughout the state (Czarnecki et al., 2008). This species has significant reseeding potential in areas of minimum ground surface cover and is an attractor of various butterfly species. *C. leavenworthii* prefers average to moist soils, full sun, and can grow between 30

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cm and 90 cm (Schiller, 2012). It displayed rapid establishment followed by seasonal die-back and was shown to be a successful cover in landfill applications, where it significantly outperformed 10 competing wildflower species (Sabre et al., 1997). *C. leavenworthii* growth rate of 86 ± 7 cm, resulting in a net establishment of 86 ± 14 %. It displayed intermediate area-based and field-scale harvested concentration when compared to other species, 2,516 ± 1,153 mg N/m^2 and 12.65 ± 2.34 mg N/g. A significant amount of initial allocation of nutrients occurs in AG biomass making C. leavenworthii a potential successful candidate for bioretention plant selection. Similar to I. virginica, sufficient space for seedling establishment and clearing of the ponding area surrounding the plants are recommended.

5.3.4.11 *Salvia coccinea*

Salvia coccinea is native to the southeastern United States, preferring well-drained soils, full sun to partial shade, and it can grow between 60 cm and 90 cm (Niu & Rodriguez, 2006). *S. coccinea* displayed the highest plant growth characteristic of 108.7 ± 17.0 cm, average AG area-based (2,320 ± 935 mg N/m^2), harvested nitrogen concentration (13.33 ± 1.23 mg N/g), and initial total nitrogen concentration of 19.78 ± 10.76 mg N/g. *Salvia* is a reseeding short lived perennial with red, white, or pink showy flowers year round, and is valued as an ornamental and for creating habitat for butterflies and hummingbirds. This species showed high potential for bioretention use, with a mean survival rate 100 % and mean propagation rate 218 ± 40 %, making it a preferred species for bioretention application.

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5.3.4.12 *Tradescantia ohiensis*

Tradescantia ohiensis is an ephemeral perennial with blue flowers, self-seeding, clump forming, and free of pests. This prairie species is a self-incompatible perennial wildflower that flowers early in the morning and wilts in midafternoon attracting beneficial bumblebees and honeybee pollinators (Molano, 2014). It prefers full sun to light shade and can grow to a mature height of 90 cm when competing for resources.

Redistribution of resources was found to result in less allocation to reproduction (Molano, 2014). All of the *T. ohiensis* AG biomass is edible and can be used to reduce the swelling and itch of insect bites, highlighting its ability to meet important qualitative attributes of plant selection. T. ohiensis showed the highest harvested mean and initial AG nitrogen concentration of 15,409 ± 7251 mg N/m2 and 29.20 ± 8.13 mg N/g, respectively. Above ground tissue nutrient concentration was high, but overall area covered was small compared to other species, resulting in low total nitrogen removal from the system with mean harvested height of 47 ± 7.9 cm. *T. ohiensis* can tolerate bioretention components specifically related to well-drained soils and antecedent dry day conditions (Monterusso et al., 2005). This species is capable of acclimating to conditions present in bioretention systems, with mean survival and propagation rates of 82 ± 20% and 37 ± 8%. These are similar to the GI application by Monterusso (2005) who reported survival rates of 100%, 96%, and 56% after two growing seasons. This species has an advantage of being able to harvest multiple times a year, low maintenance, reseeding, and provides significant pollutant removal capacity when planted and allowed to form dense clusters.

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5.4 Conclusions

Quantitative plant species attributes were used to compare the bioretention ability of 12 plant species based on baseline and field scale performance data. This study presents evidence for selecting 7 of the 12 plant species as preferential species for bioretention implementation based on the subtropical climate and design goals typical to the Tampa Bay region. The seven species, Flaveria linearis, Equisetum hyemale, Iris virginica, *Tripsacum dactyloides, Coreopsis leavenworthii, Salvia coccinea,* and *Tradescantia ohiensis* displayed highly desirable results ($>0.20\overline{x}$) on several of the 10 evaluated attributes prior to installation and after the initial acclimation period of two growing seasons. *Flaveria linearis* performed desirably for below ground concentration (16.12 ± 0.22 mg N/g biomass), harvested concentration (15.30 ± 0.22 mg N/g biomass), and mean density (12,497 ± 7773 mg N/m^2); similarly *Equisetum hyemale* showed substantial harvest height (72.3 ± 44.7 cm), establishment (100%), and propagation (118 ± 43%); *Iris virginica* outperformed for above ground biomass concentration (23.60 ± 1.56 mg N/g biomass) and establishment (100%); *Tripsacum dactyloides* showed above ground and below ground concentration of 22.19 ± 4.26 (mg N/g biomass) and 16.45 ± 0.33 (mg N/g biomass) respectively; *Coreopsis leavenworthii* harvest height (86.0 ± 7.0 cm) and net propagation (86 ± 14%); *Salvia coccinea* dry weight (60.30 ± 26.60 g biomass), harvest height (108.7 ± 17.0), establishment (100%), and propagation (218 ± 40%) rates were considerably higher than the means across all species*;* and *T. ohiensis* above ground and below ground concentration of (29.20 ± 8.13 mg N/g biomass) and (18.17 ± 12.84 mg N/g biomass), mean density (15409 ± 7251 mg N/m^2), and establishment (82 ± 20%) performed desirably.

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This study found a similarity in mean total nitrogen concentration between baseline and harvested plant species for *Flaveria linearis, Sisyrinchium angustifolium, Solidago fistulosa, Canna flaccida, Salvia coccinea, Spartina patens* and *Coreopsis leavenworthii* and a differences in means for *Equisetum hyemale, Iris virginica,* and Tradescantia ohiensis. Harvested plant samples of different species showed similarities in nitrogen concentration within plant species across three statistically significant groups. These groups were categorized as low-range (*Equisetum hyemale, Spartina patens, Iris virginica)* 9.14 *± 1.45* mg N/g to 10.10 ± 1.12 mg N/g, mid-range (*Iris virginica, Canna flaccida, Tradescantia ohiensis, Coreopsis leavenworthii, Salvia coccinea)* 10.10 ± 1.12 mg N/g to 13.33 ± 1.23 mg N/g, and high-range (*Salvia coccinea, Solidago fistulosa, Sisyrinchium angustifolium, Flaveria linearis)* 13.33 ± 1.23 mg N/g to 15.30 ± 0.22 mg N/g performance, with a mean total nitrogen concentration of 12.28 *± 2.23* mg N/g across all species. These harvested data were used to determine mean total nitrogen concentration per square meter, providing a relationship between *Sisyrinchium angustifolium, Equisetum hyemale, Spartina patens, Solidago fistulosa, Salvia coccinea, Salvia coccinea, Coreopsis leavenworthii, Iris virginica)* (range: 286 mg N/m^2 to 4,539 mg N/m^2) and *Canna flaccida, Flaveria linearis, Tradescantia ohiensis* (range: 12,428 mg N/m^2 to 15,409 mg N/m^2).

This research highlights the need for developing a method for scoring plant species based on both qualitative and quantitative metrics for plant selection as bioretention systems continue to become an ever-increasing green infrastructure practice and commonly used within urban environments for stormwater management. A scoring metric will allow for decision makers to define weight and ranking importance of individual characteristics to satisfy site constraints typical to region and climate of implementation.

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CHAPTER 6: BIORETENTION PLANT SELECTION INDEX: SUBTROPICAL TAMPA BAY REGION CASE STUDY

6.1 Introduction

Green Infrastructure (GI) is a type of low impact development technology designed to mitigate both hydrologic and water quality impacts associated with anthropogenic development (Hunt et al., 2006; Li et al., 2009). Over the past two decades bioretention has become an alternative and increasingly popular green infrastructure technology for managing stormwater runoff (PGC, 1993; Davis et al., 2009; Ergas et al., 2010; Hunt 2012). These systems are designed to capture stormwater runoff at a decentralized scale from a catchment area less than two acres and preferably less than one acre (PGC, 2000). Located in areas that intercept runoff, a conventional bioretention system has several components, including a ponding area or depression for attenuating runoff, vegetation, a vegetative root layer, and engineered media layer.

Vegetation is considered an important component of bioretention design, the role of which is multifaceted. Plants have been shown to enhance nutrient removal through both morphological and physiological plant characteristics, and increasing filtration, sedimentation, and uptake of influent stormwater pollutant loading (Brix, 1997, Zhang et al., 2011, Zinger et al., 2013). Plants naturally abate nutrients and heavy metals, promote evapotranspiration, and reduce clogging within the planted media layers. Nutrients, such as nitrogen, are transformed in the rhizosphere from ammonia (NH_3) to nitrate (NO_3^-), and

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within engineered media layers as leaf and plant detritus or media layer mix provides a carbon source for heterotrophic denitrifying bacteria (Fraser et al., 2004; Le Coustumer et al., 2007; Read et al., 2009). Plants promote the filtration of particulate-bound phosphorus and acidic environments for chemical sorption of dissolved phosphorus to occur.

Vegetation within bioretention systems has been shown to significantly improve the water quality when compared to non-vegetated systems in both laboratory (Davis et al., 2006, Barrett et al., 2013) and field-scale research (Davis et al., 2006; Brown & Hunt, 2011a, 2011b; Welker et al., 2013). However, performance characteristics of individual plant species have not been previously directly quantified within these US based studies. Instead, the presence of vegetation contributed indirectly to an increase in overall system performance. The only comprehensive plant performance studies within the bioretention literature are for regions of Australia. Table 17 summarizes these studies, focusing on the role that plant species play in promoting media permeability, improving nitrogen removal and uptake, extending nitrogen removal life expectancy, and increasing aerobic and anaerobic processes such as nitrification and denitrification.

Plant selection is indeed regionally specific, must take into consideration site-specific environmental factors as well as the desired functional and aesthetic uses of the system. In particular, the role that plants play has been overlooked by researchers studying bioretention performance in the United States, with no plant selection criteria significantly documented within the literature. This paper presents a comprehensive set of criteria to select and evaluate bioretention plant species and applies the set of qualitative and quantitative set of attributes as an example for selecting plants within the subtropical Tampa Bay region. This is achieved by (1) performing a critical literature review of

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qualitative and quantitative attributes associated with plant performance, plant characteristics, overall bioretention system performance, and sustainable stormwater management, (2) constructing a plant selection utility index (PSI) from the linear-additive form of the multiattribute utility function, (3) evaluating a selected set of 26 Tampa Bay native and regionally friendly plant species based on qualitative attributes, and (4) assigning field-scale performance metrics to 11 of the 26 selected species based on quantitative attributes (Chapter 5).

Table 17: Significant findings from bioretention studies with nitrogen species removal efficiency data.

Reference	Plant Species	Significant Finding
(Zhang et al., 2011)	*B. juncea* *B. rubiginosa* *J. subsecundus* *M. lateritia*	Macrophytes increase nitrogen species removal SZ increase NO_3^- and TN Removal NH_4^+ removal constant (SZ vs. NSZ) NH_4^+ removal > 90%
(Zhang et al., 2011)	*P. alapecurioides* *C. pachyphyllus* *M. thymifolia* *C. apressa* *F. nodosa*	TN and NO_3^- removal due to mature plant species (>18 mo), regular harvesting, increased retention time, high root density, and plant uptake TKN values similar vegetative and non-vegetative
(Lucas and Greenway, 2008)	*P. alopecurioides* *D. brevipedunculata* *B. integrefolia* *C. pachyphyllus*	NO_3^- removal due to mature vegetation and loam media composition NO_3^- removal >70% high influent concentration NO_3^- removal > 90% typical stormwater concentrations
(Read et al., 2008)	*Carex apressa* *Dianella revolute* *Ficinia nodosa* *Juncus amabilis* *Juncus flavidus* *Lomandra longifolia* *Microlaena stipoides* *Poa labillardierei* *Acacia suaveolens* *Banksia marginata* *Correa alba* *Dodonaea viscosa* *Goodenia ovate* *Hibbertia scandens* *Kunzea ericoides* *Leucophyta brownii* *Melaleuca ericifolia* *Myoporum parvifolium* *Pomaderris paniculosa* *Pultenaea* *Daphnoides*	Vegetative columns outperform non-vegetative columns Nitrogen removal due to microbial uptake, assimilation, and/or sorption processes Significant reduction in TN: C. apressa, F. nodosa, J. amabilis, J. flavidus, G. ovate Significant reduction in NH_4^+: C. apressa, J. amabilis, J. flavidus, G. ovate, M. ericifolia Significant reduction in NOx: C. apressa, F. nodosa, J. amabilis, J. flavidus, C. alba, G. ovate, H. scandens, L. brownii, M. ericifolia, M. parvifolium Species recommended to significantly reduce stormwater constituents: C. apressa, J. amabilis, J. flavidus, G. ovate, and M. ericifolia
(Read et al., 2009)	Same as Read eta al., 2008	Specific plant traits found to correlate with nitrogen species removal: root soil depth, longest root, percent root mass, root mass, and total root length. Biofilter nitrogen species performance improves as root depth increases

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6.2 Methods

6.2.1 Plant Selection Criteria Literature Review

Electronic journal databases (Web of Science and Science Direct) were searched using the keywords: bioretention, bioinfiltration, rain garden(s), and wetland(s) to generate a list of applicable literature. At this stage only peer-reviewed publications were selected including the Journal of Environmental Engineering (n=33), Ecological Engineering (n=18), and Journal of Hydrologic Engineering (n=18). Additional book publications and personal communication with authors were included within this review.

172 articles, (Table 18) were evaluated and reviewed for applicability to plant selection, performance, bioretention system design, and sustainable stormwater management. The complex nature of non-point sources makes it difficult to standardize how stormwater performance is presented and analyzed (Davis, 2007). Individual studies often include different constituents and use a range of methods for collecting and analyzing data, as well as report various degrees of information on the design and inflow/outflow characteristics (Bratieres et al., 2008; Davis et al., 2006; Hunt et al., 2012; Strecker et al., 2001). A wide range of bioretention system "effectiveness" is reported in the literature and it is impossible to combine individual studies to statistically assess the effectiveness of individual design factors (Strecker et al., 2001). Therefore this critical literature review focuses on performance based association rather than causation.

The literature review revealed a number of themes and relationships that relate to the overall aim of improving bioretention system performance and plant selection. These themes were grouped into either qualitative or quantitative categories. Numeric values

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were then applied to these criteria and the data presented as target plots as a tool for comparison.

Table 18: Reviewed literature journal frequency (n=172). The following journals received a frequency of (n=1) and were not included within table 21: Chemosphere, Environmental Management, Environmental Progress & Sustainable Energy, Environmental Technology, Hydrologic Sciences Journal, International Journal of Phytoremediation, Journal of Biogeography, Journal of Freshwater Ecology, Journal of Hazardous Toxic Radioactive Waste, Journal of Soil and Water Conservation, Soil Science, Research Journal of Chemistry and Environment, Soil Science, Water Environment Federation, Water Resource Technology, Water SA, World Environmental and Water Resources Congress, World Water Congress.

Journal	Frequency	Journal	Frequency
Bioresource Technology	3	Journal of Water Resources Planning and Management	5
Ecological Engineering	18	Landscape and Urban Planning	3
Environmental Engineering Science	2	Landscape Architecture	3
Environmental Science & Technology	8	Science of the Total Environment	4
Journal of American Water Resources Association	5	Water Air and Soil Pollution	5
Journal of Environmental Engineering	33	Water Environment Research	12
Journal of Environmental Science and Health	2	Water Research	5
Journal of Hydrologic Engineering	18	Water Science and Technology	9
Journal of Hydrology	2	Water Quality Research Journal of Canada	2
Journal of Irrigation and Drainage Engineering	15		

6.2.2 Initial Plant Selection

Staff from over 70 native nurseries, part of the Florida Association of Native Nurseries, were contacted to act as subject matter experts in identifying plant species that were applicable to the plant selection criteria identified in this study. One of the contacted nurseries became actively involved with our goal of developing plant selection criteria and acted as a partner in this research. This partnership evolved through the installation of eight field-scale bioretention systems and ultimately developed a list of 26 native and

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regionally friendly plant species (Schiller, 2012). The 26 selected plants, (Table 19) were chosen for their ability to meet various levels of the qualitative criteria for the subtropical climate of Tampa Bay.

Table 19: Twenty-six selected plant species

Scientific Name	Common Name	Code	Scientific Name	Common Name	Code
Coreopsis leavenworthii	Tickseed	CL	***Mimosa strigillosa***	Sunshine Mimosa	MS
Flaveria linearis	Yellowtop	FL	***Callicarpa americano***	Beauty Berry	CA
Salvia coccinea	Red Salvia	SC	***Penta lanceolata***	Pentas	PL
Solidago fistulosa	Goldenrod	SF	***Chamaecrista fasciculata***	Partridge Pea	CH
Canna flaccida	Yellow Canna	CF	***Monardo punctate***	Spotted Horsemint	MP
Hymenocallis latifolia	Spider Lily	HL	***Muhlenbergia capillaris***	Muhly Grass	MC
Iris virginica	Blue Flag Iris	IV	***Helianthus debilis***	Dune Sunflower	HD
Sisyrinchium angustifolium	Blue Eyed Grass	SA	***Glandularia tampensis***	Tampa Vervain	GT
Spartina patens	Marshaay Cordgrass	SP	***Silphium asteriscus***	Starry Rosinweed	SR
Tradescantia ohiensis	Spider Wort	TO	***Stachytarpheta jamaicensis***	Blue Porterweed	SJ
Tripsacum dactyloides	Fakahatchee	TD	***Myrcianthus fragrans***	Simpson Stopper	MF
Equisetum hyemale	Horsetail	EH	***Zamia puila***	Coontie	ZP
Arachis glabrata	Perennial Peanut	AG	***Coreopsis lanceolata***	Lanceleaf Coreopsis	C

Of the 26 plants, 11 were installed in a field scale bioretention system and used to evaluate the five quantitative plant selection utility index attributes. Briefly, the bioretention system was designed with a 15-cm ponding area, 30.5-cm vegetative root layer, and 30.5-cm engineered media layer. The media layers were similar to that which is

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found within the literature and designed to readily drain stormwater runoff from the system. The overall bioretention system area was 32.5 m^2 and was installed with a minimum of 19 samples of each plant species. The 11 species, (*Coreopsis leavenworthii, Flaveria linearis, Salvia coccinea, Solidago fistulosa, Canna flaccida, Hymenocallis latifolia, Iris virginica, Sisyrinchium angustifolium, Spartina patens, Tradescantia ohiensis, and Equisetum hyemale*) were evaluated for initial nitrogen content as 1-gallon 3 to 6-month seedlings.

6.2.3 Plant Selection Index Multiattribute Utility Function

There are three forms of the multiattribute utility functions, linear-additive, multiplicative, and multilinear used to synthesize numerous factors into one given factor or index score (Keeney & Raiffa, 1993). The multiattribute plant selection utility index (PSI) was constructed by (1) reviewing relevant literature to identify qualitative and quantitative attributes, (2) defining a set of qualitative level descriptions and converting raw quantitative data into a 0.00 to 1.00 level score, (3) determining a set of weights and rankings based on user defined importance of each indicator, and (4) defining the appropriate utility function that combines and weights the relative importance of each indicator (Hajkowicz, 2005).

This study will focus in on the most commonly used linear-additive form of the multiattribute utility function. The PSI calculates scores on a conventional utility scale of 0 to 100. The PSI additive utility function, *u(x)* is used to calculate both the seven qualitative and five quantitative attributes associated with the plant selection, criteria and is written as:

$$u(x) = \left[\frac{2}{n+1}\right]\left[\sum_{i=1}^{n} k_i w_i v_i(x_i)\right] \qquad (10)$$

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where:

$u(x)$ = Additive utility function (plant selection utility index score)

$v_i(x_i)$ = Single attribute utility function (qualitative level score = 0 or 1)

w_i = User defined weighting factor

k_i = Function parameter

the PSI function parameter k_i is given by:

$$k_i = \frac{(n+1)-k}{n} \tag{11}$$

where:

k = User assigned integer ranking (k = 1,2,3… n)

The single-attribute utility function, $v_i(x_i)$ reflects the individual utility attached to each level on 0.00 to 1.00 scale for attributes *i*. Each of the singular attributes may be comprised of one or more level scores. The qualitative level score is either yes or no, or (1.0 or 0.0) for each level of a given attribute. The quantitative level score ranges from 0.00 to 1.00 in 0.25 increments based on a positive or negative deviation from the mean of plant species considered at that level. In the instance where raw data produces an extreme outlier, this point will be removed from the mean calculation and assigned a level score of 1.0. The function f(x) for calculating the quantitative level score is:

$$f(x) = \begin{cases} v_i(x_i) = 1.00, & x_i > 1.2\bar{x} \\ v_i(x_i) = 0.75, & x_i > 1.1\bar{x} \\ v_i(x_i) = 0.50, & 1.1\bar{x} \geq x_i \geq 0.9\bar{x} \\ v_i(x_i) = 0.25, & x_i \leq 0.9\bar{x} \\ v_i(x_i) = 0.00, & x_i \leq 0.8\bar{x} \end{cases} \tag{12}$$

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where $\bar{x}$ bar is the mean of the values for all plants under consideration. Weighting factor, w_i provides the option to attach a 0.00 to 1.00 scale to each utility. Function parameters k_i allows the user to assign an integer ranking (k = 1, 2, 3… n) among attributes with one level for each of the attributes.

6.3 Results and Discussion: Qualitative and Quantitative PSI Attributes

6.3.1 Qualitative Selection Criteria

The seven plant selection attributes and design rationale for the qualitative thematic grouping is shown in Table 20. The qualitative criteria are classified as: (1) native to geographical region, (2) harvestable, (3) mimic environment, (4) root network, (5) species rich ecosystem, (6) human, social, and economic impacts, and (7) create habitat.

Table 20: Qualitative selection criteria and design rational

Attribute Code	Attribute	Design Rational	Reference
NGR	Native to Geographical Region	Established prior to significant human impact, no negative impact on natural ecology	Tanner, 1996; Roy-Poirier et al., 2010; Welker et al., 2013
H	Harvestable	Remove nutrients and target pollutants from watershed	Lucas and Greenway, 2011; Borin and Salvato, 2012
ME	Mimics Environment	Closest natural conditions that simulate rain garden design criteria to increase survivability under fluctuation in water levels, wetting and drying cycles, and well-drained soils.	Davis et al., 2006; Read et al., 2008
RN	Root Network	Promote media permeability; increase aerobic processes, infiltration, and uptake; supports diverse microbial community	Davis et al., 2009; Fraser et al., 2004; Lucas and Greenway, 2008
SRE	Species Rich Ecosystem	Improved removal w/competition, pest abatement, phytoremediation of other pollutants, increased tolerance to abiotic stress, and increased performance under lower loading concentrations	Fraser et al., 2004; Read et al., 2008; Liang et al., 2011
HSE	Human, Social, and Economic Impacts	Improving green space within urban environments, aesthetics, homeowner and community acceptability; increase in property value, provides goods and services to local community	Brix, 1997; Carmen and Crossman, 2001; Fraser et al., 2004; EPA, 2013a
CH	Create Habitat	Promote ecosystem health, establish native wildlife, attract beneficial wildlife	Kazemi et al., 2009; Welker et al., 2013

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6.3.1.1 Native to Geographical Region

Selected plant species should be native to the geographical region, established prior to significant human impact, and therefore free of negative impact on natural ecology (Tanner, 1996; Roy-Poirier et al., 2010; Welker et al., 2013). The native vegetation, either short-lived (SLT) or long-lived terrestrial (LLT) species should be selected based on their ability to adapt to conditions associated with bioretention design and aptitude for promoting ecosystem health. Ecosystem health in general is the occurrence of "normal" ecosystem processes and functions (Costanza, 1992). Normal ecosystem processes are traditionally free from distress and degradation, maintain organization and autonomy over time and are resilient to the environment of implementation (Costanza, 1992; Mageau et al., 1995; Costanza, 1998; Rapport et al., 1998). The Native to geographical region level value ranges from 0.00 to 1.00 for utility function coding (Table 21).

6.3.1.2 Harvestable

Frequency of harvesting maximizes overall pollutant uptake (Tuncsiper et al., 2006), therefore harvesting should occur at various periods annually and in sequence with the cyclical nature of peak nutrient assimilation (Lucas and Greenway, 2011). Plant species typically experience peak uptake between midsummer and fall equinox prior to nutrients being returned to the substrate via litter fall, standing dead, and nutrient retranslocation (Kadlec and Wallace, 2009; Gottschall et al. 2007). Lucas (2011) found that plant maturation and naturalization of a constructed ecosystem requires a minimum of one-year to reach a homeostasis between the structure and function of the overall system (Sistani et al., 1996; Lucas and Greenway, 2011). Figure 17 provides an example of the projected harvestable seasonal trend in immobilization/uptake and timescale required to meet

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designed mature pollutant removal capacity for *Salvia coccinea* species. Harvestable utility function coding values are set at 0.00, 0.50, and 1.00 for non- or insignificant, annual, and semi-annual harvest respectively (Table 21).

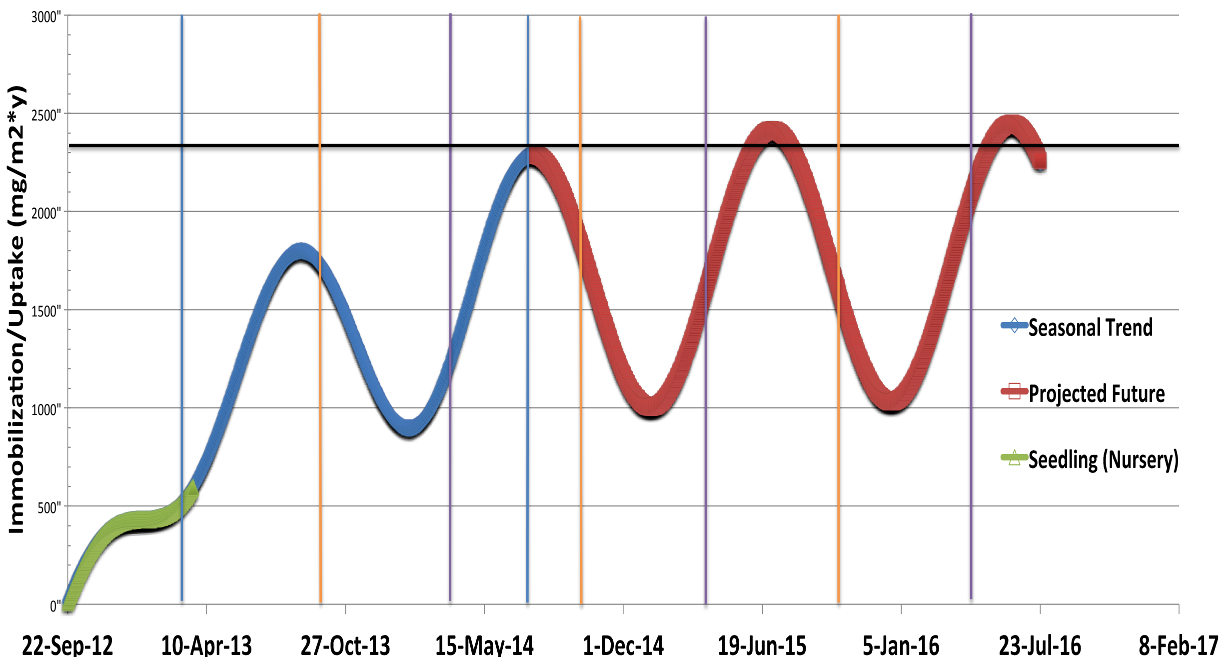

Figure 18: Retrospective, actual, and projected future immobilization and uptake of total nitrogen by *Salvia coccinea* species. Solid line on x axis represent beginning and end of acclimation period (blue), Equinox and Solstice (orange and purple), Solid line on y-axis is the harvested total nitrogen uptake.

6.3.1.3 Mimics Environment

Environmental mimicry criterion identifies plants that are found in similar environmental conditions associated with constructed bioretention systems. These natural environments may include but are not limited to coastal dunes, scrublands, grasslands, meadows, natural wetlands, hammocks, woodlands, shorelines, and fatwoods. Plant species should be naturally adapted to well-drained soils, experience wetting and drying cycles, and adapted to drought conditions for a given geographical region (Davis et al., 2006; Read et al., 2008).

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Bioretention systems are designed to experience inundation of water up to and exceeding the ponding area and with porous media allowing for the water level to drain quickly from the system. Therefore a higher level value is assigned to plant species that are naturally adapted to these conditions and a level value of 0.00 is assigned to species that would readily die out or remain stressed under these conditions (Table 21). It is possible that the plant species' environmental preference satisfies a positive non-zero level value and 0.00 level value at the same time, and in that case the 0.00 value will be the single attribute utility used to calculate the PSI score.

6.3.1.4 Root Network

A plant's root structure increases aerobic processes such as nitrification, promotes media permeability, and supports productive microbiological populations (Davis et al., 2009; Faulwetter et al., 2009; Le Coustemer et al., 2012; Hunt et al., 2012). In addition, the surface area of a plant's root and stem structure provides a surface for biofilm formation (Fraser et al., 2004). For example, Carex Sp. has a high number of microscopic hairs that greatly increase the rhizosphere surface area per volume of soil contact area and intercepts soluble interstitial nitrogen species (Lucas & Greenway, 2008; Bratieres et al., 2008). Liang (2011) found a dense root structure to better facilitate nitrification. Similarly, Lai et al. (2012) found that a fibrous root biomass correlated closely with overall nutrient removal. Tanner (1996) found *Bolboschoenus fluviatilis* to have a below ground (BG) to above ground (AG) biomass ratio to be 3.35, with BG comprising primarily of bulbous tubers or tap roots that increased the effective pore space and reduced clogging. Symbiotic relationships between the rhizosphere microbial community and plant species often occur and may increase the absorptive surface of the plant root system as with Arbuscular

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mycorrhizal fungi, found within the roots of Melaleuca (Smith et al., 1997). The depths of mature root structure should also be considered when designing systems with liners or internal water storage zones. Mature fibrous and tap roots are recommended for improving treatment and hydraulic performance respectively and should be identified to satisfy this criterion.

The root network utility function level value is set at 0.00 for a root network that supports microbial populations that are associated with nitrogen fixation and 1.00 for root structure that support nutrient removal, hydraulic performance, or a combination of both (Table 21). This allows for the user to define a weighted value on the type of root network applicable to their design scenario. Under this scenario it is possible for a root network to satisfy a level value of 1.0 and 0.00, and in this case the 0.00 value will be the single attribute utility used to calculate the PSI score.

6.3.1.5 Species Rich Ecosystem

Studies from wetlands suggest that species-rich ecosystems had an increase in effective root distribution, were less susceptible to seasonal variations, and supported more diverse microbial populations when compared to monoculture systems (Bachand and Horne, 2000; Coleman et al., 2001; Engelhardt and Ritchie, 2001; Karathanasis et al., 2003; Fraser et al., 2004; Picard et al., 2005; Amon 2007; Zhang et al., 2007). Species-rich ecosystems are considered more resilient, biodiverse, and resistant to invasive species due to their ability to use available resources more effectively than monocultures (Loreau et al., 2002). These heterogeneous bioretention system configurations have a higher productivity than simplified ecosystems. This provides an overall improved urban

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ecosystem health through increased availability to food sources, water services, comfort, amenities, and cultural values particularly if they are well managed (Tzoulas et al., 2007).

The species rich ecosystem utility function level value ranges from 0.50 to 1.00 (Table 21). Plant species can be classified into three categories depending on their lifespan, long lived perennials (LLP) with longevity of three years or greater; short lived perennials (SLP) with a lifespan of one to three years; and annuals (A) which die out after 1 year. The likelihood of an ecosystem remaining heterogeneous is a combination of planted species lifespan and reproductive traits with seed >> than rhizome propagation. Therefore, a species level value depends on longevity and type of propagation. For example, a LLP with rhizome propagation (level value 0.90) will allow for species competition at a greater rate than a SLP that reproduces through seed and spores (level value = 0.60).

6.3.1.6 Human, Social, and Economic Impacts

Bioretention systems can be used to improve underutilized green spaces within urban environments and have the potential to foster conservation through increased biodiversity (Aldous, 2007; Kazemi et al., 2009). Implementation of bioretention systems increases green corridors, improves the connectivity of residents by providing access to exercise trails, improved aesthetics, increased property values, reduction in crime rates, and provides sites for producing goods and services (Brix, 1997; Carmen & Crossman, 2001; Fraser et al., 2004; EPA, 2013a). Bioretention systems provide an opportunity to produce products that have cultural significance to local communities, improve health of residents, provide supplemental income or subsistence practices, and increase livability and sense of community. Furthermore, these urban ecosystems provide educational platforms for residents to immerse themselves with green infrastructure technology and

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experience more sustainable human quality of life practices (Hostetler et al., 2011). Costs associated with initial plant installation are not considered as capital costs of plants. The may be offset through harvesting of plants to the local community, incentives from local municipality, production of edibles (i.e. fruits and vegetables), and hard to quantify areas (i.e. birding and butterfly viewing). Plants that require limited maintenance, provide subsistence, textile, industrial, or medicinal value may be weighted by the user to score one plant species higher than another based on intended bioretention design preferences (Table 21).

Aesthetics play an important role in initial plant selection, but were not included in the qualitative plant selection criteria as this is something that is independent of any research based on the plant behavior in the field.

6.3.1.7 Create Habitat

Plants play an important role in urban aesthetics, increasing property value, livability, human health, social adaptation, and attracting beneficial wildlife (Brix, 1997; Carmen and Crosman, 2001; Fraser et al., 2004; EPA, 2013a; Tilman, 1997; Kuo and Sulivan, 2001; Tzoulas, 2007; Davis, 2012). Birds in particular provide a number of unique habitats and ecosystem services. They regulate pest populations, disperse seeds, provide aesthetic and recreational value and enhance visitors' experiences in urban parks and open spaces (Sekercioglu et al. 2004; Brenneisen, 2006; Fuller et al. 2007; Whelan et al. 2008; Dallimer et al. 2012).

The Create Habitat utility function level value is set at 1.00 for attracting beneficial wildlife (i.e. birds, bees, hummingbirds, butterflies, provide cover and perching) and 0.00 for not attracting beneficial wildlife, Table 21.

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Table 21: Qualitative plant selection utility function coding with level values, level codes, and level description

Attribute	Level Value	Level Code	Level Description
Native to Geographical Region	1.00	NS	Native species free of pests and disease
	0.80	RF	Regionally friendly species free of pests and disease
	0.50	NMI	Native species with minimal impact from pests and disease.
	0.30	RMI	Regionally friendly species with minimal impact from pests and disease.
	0.00	SI	Invasive species
	1.00	NS	Native species free of pests and disease
Harvestable	1.00	Q2	Semi-annually
	0.50	Q1	Annually
	0.00	UH	Unable to harvest annually or insignificant harvest
Mimics Environment	1.00	DW	A terrestrial or aquatic species that equally tolerates well drained to wet soil conditions
	0.75	WD	A terrestrial or aquatic species that prefers well drained soil conditions
	0.50	MS	A terrestrial or aquatic species that prefers moist soil conditions
	0.00	NF	A terrestrial plant species that will not tolerate fluctuations in water levels
	0.00	HM	A aquatic species that may be classified as submerged or floating; or emergent vegetation that will not readily survive in dry conditions
Root Network	1.00	FR	A fine root biomass with fibrous root structure
	1.00	TR	A bulk root biomass with tap root structure
	1.00	FT	A mix of fibrous and tap roots
	0.00	NF	A root network that harbors nitrogen fixing bacteria
	0.50	HA	Harvested concentration
Species Rich Ecosystem	1.00	SPR	SLP or A that reproduces via rhizome propagation
	0.90	LPR	LLP that reproduces via rhizome propagation
	0.80	SPSP	A SLP or A that reproduces via seeds and rhizome propagation at equal rates
	0.70	LPSP	A LLP that reproduces via seed and rhizome propagation at equal rates
	0.60	SLSS	A SLP or A that reproduces via seed or spores
	0.50	LLSS	A LLP that reproduces via seed or spores
Human Social and Economic Impact	1.00	LM	Limited maintenance
	1.00	SV	Subsistence value, including resale for more bioretention systems
	1.00	TIV	Textile or industrial value
	1.00	MV	Medicinal value, including reduced mosquito breeding
Create habitat	1.00	BWL	Attracts beneficial wildlife
	0.00	XBWL	Does not attract beneficial wildlife

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6.3.2 Quantitative Plant Selection Criteria

Table 22 lists the five plant selection criteria and design rational for the quantitative thematic grouping. The quantitative criteria are classified as: (1) initial pollutant removal capacity, (2) acclimated pollutant removal capacity, (3) evapotranspiration capacity, (4) rapid growth rate, and (5) successful establishment and propagation rate.

Table 22: Quantitative plant selection criteria

Attribute Code	Attribute	Design Rational	Reference
IPRC	Pollutant Removal Capacity (Initial)	Target constituent loading for initial and harvested pollutant removal based on concentration-metric and/or spatial-metric	Zhang et al., 2011; Brison, 2009; Tanner, 1996; Bratieres et al., 2008
APRC	Pollutant Removal Capacity (Acclimated)	Target constituent loading for harvested pollutant removal based on concentration-metric and/or spatial-metric	Zhang et al., 2011; Brison, 2009; Tanner, 1996; Bratieres et al., 2008
EC	Evapotranspiration Capacity	Restore field capacity of bioretention system, enhance antecedent dry day performance, improve hydrologic and water quality performance	Davis et al., 2006; Brown and Hunt, 2011
RGR	Rapid Growth Rate	Increased uptake rate and removal of nutrients	Lucas and Greenway, 2008; Brison, 2009; Zhang et al., 2011; Tanner, 1996
EPR	Establishment and Propagation Rate	Increased density, improved system performance and resiliency, balances plant mortality rate, resiliency	Lucas and Greenway, 2008; Tanner, 1996

6.3.2.1 Pollutant Removal Capacity (Initial and Acclimated)

The relationship between initial pollutant removal capacity and acclimation period remains an important factor for streamlining plant selection (Tanner, 1996; Bratieres et al., 2008; Brison, 2009; Zhang et al., 2011). In addition, the pollutant removal capacity of plant species is considered to vary significantly across species. For instance, Read (2008) showed a difference in AG pollutant removal capacity between plant species to range several fold. Mean harvested biomass concentration (mg/g) and mean total nitrogen density (mg/m^2) removal rates are typically reported so that system surface area

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requirements align with targeted design goals (Iamchaturapatr et al., 2007, Tanner, 1996). The mean harvested AG biomass concentration concentration-metric is used to measure the efficiency of each plant species per g of biomass. The density-metric takes into consideration the efficiency of the select plant species with respect to the area in which it occupies at various stages in its maturation process. The density-metric considers the overall mass, footprint, and canopy area. This is important to consider when designing and sizing the bioretention surface area and for determining the appropriate number of plants to meet design requirements. Acclimation should be taken into consideration when calculating the first year overall nutrient removal efficiency from harvestable AG biomass.

The initial pollutant removal utility function level value is set at 0.80 and 0.20 for baseline above ground and below ground concentration respectively (Table 23). The values assigned to above ground and below ground concentration are associated with non-destructive and destructive harvesting methods. A modification to assigned values may be appropriate in instances where destructive harvesting or removal of the entire plant from the bioretention system is warranted.

Table 23: Quantitative plant selection utility function coding with level values, level codes, and level description

Attribute	Level Value	Level Code	Level Description
Initial pollutant removal capacity	0.80	BAG	Baseline above ground concentration
	0.20	BBG	Baseline below ground concentration
Acclimated pollutant removal capacity	0.50	MD	Mean density
	0.50	HA	Harvested concentration
Evapotranspiration capacity	0.80	MAE	Mean actual evapotranspiration
	0.20	SD	Stomata density
Growth rate	0.50	DW	Dry weight
	0.50	HH	Harvest Height
Establishment and propagation	0.80	E	Establishment
	0.20	P	Propagation

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The acclimated pollutant removal utility function level values are equally weighted at 0.50 for mean density and harvested concentration (Table 23). The mean density calculation takes into account the plant species acclimated canopy area, where a higher level score results in greater removal efficiency per surface area when compared to other species. The acclimated harvested concentration level value is equally important for overall plant species removal efficiency and should be ranked appropriately with respect to growth rate when considering a species for removing specific pollutants.

6.3.2.2 Evapotranspiration Capacity

Evapotranspiration (ET) is a hydrologic property that improves the overall water quality performance. Stormwater runoff is taken up from the vegetative and engineered media layers through a plant's root structure, transpired through leaf stomata, and evaporated to the atmosphere. This process restores the field capacity of bioretention systems during antecedent dry days, allowing for the vadose or un-saturated media layers to absorb influent stormwater runoff. Restoring the field capacity is of critical importance for improving the overall removal efficiency of influent loading, approaching 100 percent mass removal efficiency under a zero discharge storm event (Davis et al., 2001, 2006). Plant species individual ET rates are rarely documented; rather ET is typically estimated for a given region of implementation through one of the various methods found within the literature (Thornthwaite, 1948; Hamon, 1963; Hargreaves & Samani, 1985; Priestley-Taylor, 1972). When applicable, individual ET and extents of root network should be considered when designing both vegetative and engineered media layer.

The actual ET rate of a plant species is weighted significantly higher than stomata density due to the fact that it links specific hydrologic data with a given plant. However,

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stomata density is easier to obtain, considering the vast number of plant species for a given region and is provided here to quantify this utility function. Table 23 provides the evapotranspiration utility level values for mean actual evapotranspiration (MAE) and stomata density (SD) as 0.80 and 0.20. Further research may prove advantageous, linking stomata density to mean actual evapotranspiration rates.

6.3.2.3 Growth Rate

Research has shown a high correlation between plant growth and nutrient removal (Kyambadde et al., 2004; Cheng 2009). Constructed wetland studies were evaluated and found to base plant selection on established practices where individual species are assumed to be adequate as long as they have a rapid growth rate (Brisson & Chazarenc, 2009, Faulwetter et al., 2009; Read et al., 2008; Smith & Read, 1997). A rapid growth rate increases the mass based uptake of loading from influent runoff, improving the overall system performance, and increasing the lifetime removal efficiency of a system (Lucas and Greenway, 2008, Brison, 2009; Zhang et al., 2011; Tanner, 1996). Plant species with a greater annual growth rate and harvested dry weight when compared to other plant species are therefore advantageous for improving water quality and restoring the hydrology to that of pre-development conditions.

The growth rate utility function level values are set at 0.50 for dry weight and harvest height, Table 23. Both dry weight and harvest height are quantitative measurements that describe the performance and health of a given plant species. The dry weight provides a method for calculating the total removal capacity of a pollutant from a system with a higher value signifying a greater potential for removal when compared to other test species. The harvest height is a measure of how well a species is performing

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with respect to its intended growth characteristics. This attribute is also an indicator of plant species health as a result of frequency of harvesting.

6.3.2.4 Establishment and Propagation Rate

Successful establishment and sustainable propagation rates should be considered when selecting plant species for bioretention application. Sustainable propagation refers to the ability of a species to naturalize and to maintain heterogeneity within the designed system. A large body of wetland research has developed theories for spatial dynamics of plant populations to decipher the process that promotes spatial heterogeneity within densely vegetative populations (Hanski & Gilpin, 1997; Tilman, 1997; Hanski, 1999; Keeling, 1999). The dynamic theory of island biogeography (DTIB) describes the importance of ecological connectivity and the relationship between expected number of species in a fragmented habitat, species mobility, and continuation of genetic exchange. DTIB theorizes that the smaller the green space the greater the turnover of species as a result of extinction and the greater the chance that a species will become extinct before naturalizing to system conditions. Quantitatively evaluating plant species that readily establish and propagate at a rate that allows for adequate competition between species, naturalization, and maintenance of heterogeneity will satisfy this criterion.

The establishment and propagation utility levels are set at 0.80 and 0.20 respectively for this attribute, (Table 23). Indeed, establishment is relatively important, quantifying the ability of LLP and SLP to acclimate to the designed system. Plant species that are classified as annuals should calculate establishment as a propagation rate with respect to initial planting, and propagation as the number of individual species greater than

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the initial planted or previous season. Propagation is weighted significantly less to account for species richness and ecosystem heterogeneity.

6.4 Results and Discussion: Qualitative and Quantitative PSI Scores

The qualitative PSI scores for the 26 plant species identified in this study ranged from 63 (*Spartina patens, Equisetum hyemale, and Myricianthus fragrans*) to 91 (*Tripsacum dactyloides*). Table 24 displays the user-defined weighting factors, ranks, level scores, and qualitative plant selection utility index scores for each of the Tampa Bay native and regionally friendly selected plant species. The mimics environment attribute was ranked first followed by harvestable, species rich ecosystem, root network, create habitat, native to geographic region, and human social and economic impacts. The rational for ranking is based firstly on a plant species' natural ability to adapt and acclimate to conditions found within a bioretention system followed by watershed design goals specific to the Tampa Bay region.

Tampa Bay is listed as impaired for nitrogen and dissolved oxygen and therefore attributes that promote nitrogen removal were ranked higher in relation to other attributes. The qualitative PSI scores allowed for the 26 selected plant species to be categorized as highly desirable (n=4, PSI ≥ 80), moderately desirable (n=15, 80 > PSI ≥ 65), and least desirable (n=8, PSI < 65) for the regionally specific design goals of Tampa Bay. It is noted that weighted and ranking values will differ significantly based on region of implementation, site constraints and assumptions, design goals, and stakeholder preference. The PSI score provides a convenient method for ranking multiple plant species attributes and plant performance characteristics based on the design constraints associated with bioretention systems. An individual plant species' intended performance

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might be better visualized by using target plots, examining its results with respect to the 7 qualitative attributes of the plant selection utility index as shown in Figure 18-20. Plant species *Flaveria linearis, Tripsacum dactyloides, Salvia coccinea, and Chamaecrista fasciculata* were classified as highly desirable and displayed very similar attribute level scoring, all scoring 1.0 on four of the 7 attributes. *Iris virginica, Myrcianthus fragrans, Equisetum hyemale, Coreopsis leavenworthii, Sisyrinchium angustifolium, Spartina patens,* and *Canna flaccida* on the other hand were least desirable of the evaluated species, each with very different attribute scoring.

Table 24: Qualitative plant selection utility index scoring for 26 Tampa Bay native and regionally friendly plant species

Attribute Code	Weight	Rank	Level Value	Level Code	Plant Species Level Score																									
					TD	SC	CH	FL	MP	TO	SJ	MS	HL	SR	AG	CA	HD	GT	MC	C	CF	PL	SF	SA	IV	SP	EH	MF	ZP	CL
NGR	1.0	6	1.00	NS	Y	Y	Y	Y	Y	Y	Y	Y		Y		Y	Y	Y	Y	Y				Y		Y	Y	Y	Y	Y
			0.80	RF											Y							Y								
			0.50	NMI									Y								Y		Y		Y					
			0.30	RMI																										
			0.00	SI																										
H	1.0	2	1.00	Q2	Y	Y	Y	Y					Y									Y					Y			
			0.50	Q1					Y	Y	Y					Y	Y	Y	Y		Y		Y		Y	Y		Y	Y	
			0.00	UH								Y		Y	Y					Y				Y						Y
ME	1.0	1	1.00	DW	Y							Y	Y	Y	Y	Y				Y				Y				Y		
			0.75	WD		Y	Y		Y	Y	Y						Y	Y	Y			Y	Y			Y			Y	
			0.50	MS				Y													Y				Y		Y			Y
			0.00	NF													Y													
			0.00	HM																	Y									
RN	1.0	4	1.00	FR	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y		Y	Y	Y	Y	Y		Y	Y		Y	Y			Y
	0.5		1.00	TR									Y			Y									Y			Y	Y	
	0.5		1.00	FT																		Y								
	0.0		0.00	NF																							Y			
SRE	1.0	3	1.00	SPR																										
			0.90	LPR				Y				Y	Y	Y	Y						Y	Y		Y	Y					
			0.80	SPSP					Y																					
			0.70	LPSP	Y					Y	Y					Y				Y						Y		Y	Y	
			0.60	SLSS		Y	Y										Y	Y												Y
			0.50	LLSS															Y				Y				Y			
HSE	1.0	7	1.00	SV		Y			Y	Y											Y									
	0.8		1.00	MV																				Y	Y					
	0.5		1.00	TIV																							Y			
	0.3		1.00	LMG								Y			Y															
CH	1.0	5	1.00	BWLF	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y		Y		Y		Y			Y
			0.00	BWLS									Y									Y		Y		Y		Y	Y	
Qualitative PSI Score:					91	87	83	82	79	78	74	74	73	73	73	73	72	72	71	70	70	69	67	65	64	63	63	63	56	55

The quantitative PSI scores further illuminate the complex nature and selection challenges between plant species. Take, for example, the difference between *Tradescantia ohiensis* and *Salvia coccinea* (Figure 18)*, and Spartina patens* and *Flaveria linearis* (Figure

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19). *Salvia coccinea*, with a PSI of 73 scores 1.0 for dry weight, harvest height, establishment, and propagation; and *Tradescantia ohiensis* with a PSI of 70 scores 1.0 for baseline above ground concentration, baseline below ground concentration, mean density, and establishment, are highly recommended species. Whereas, *Spartina patens* with a PSI of 40 scores 1.0 for stomata density, dry weight, harvest height; *and Flaveria linearis'* with a PSI of 43 scores 1.0 for below ground concentration, harvested concentration, and mean density are not recommended species. Both highly recommended species (SC and TO) and species not recommended (SP and FL) score maximum values in at least three of the seven categories bringing further evidence to the importance placed on ranking and weighting factors.

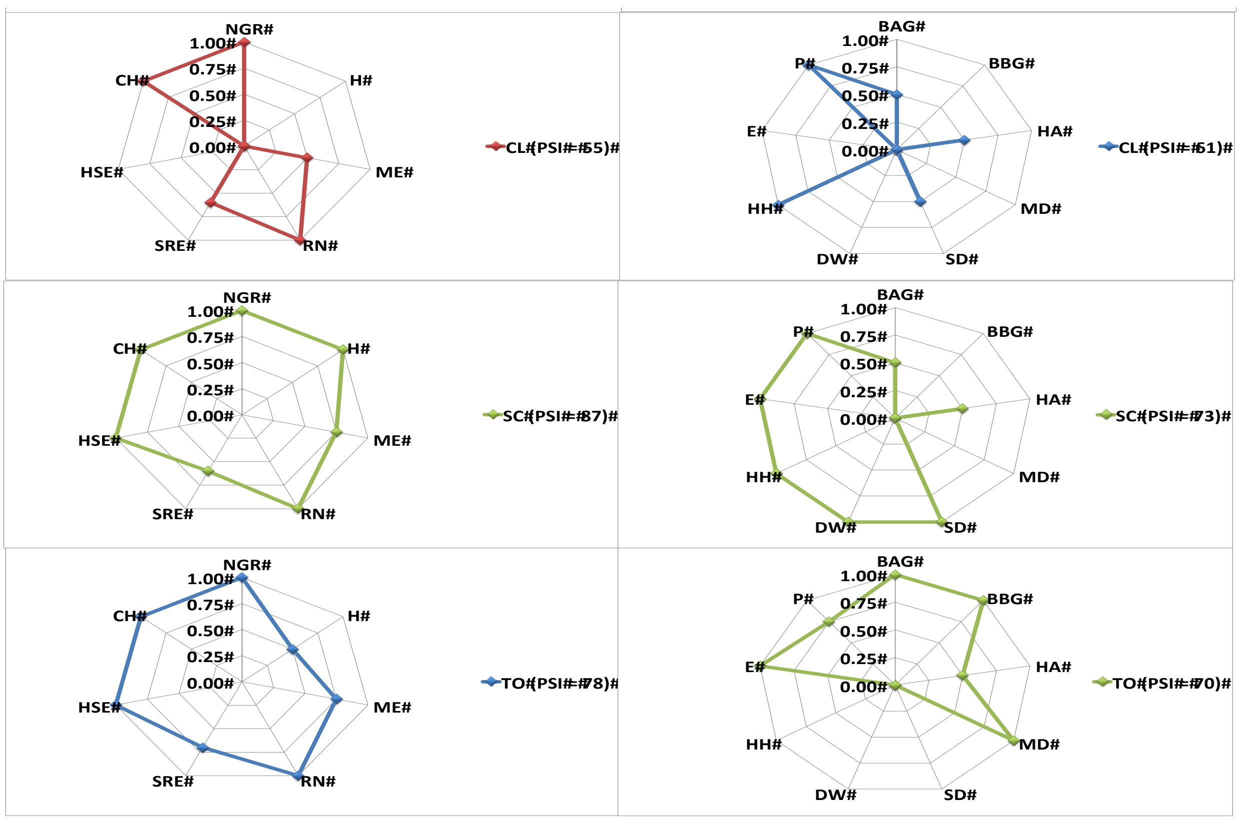

Figure 19: Qualitative (left) and quantitative (right) utility attributes and PSI scoring for *Coreopsis leavenworthii (CL)*, *Salvia coccinea (SC)*, and *Tradescantia ohiensis (TO)*. Highly desirable (green), moderately desirable (blue) and least desirable (red) for bioretention application.

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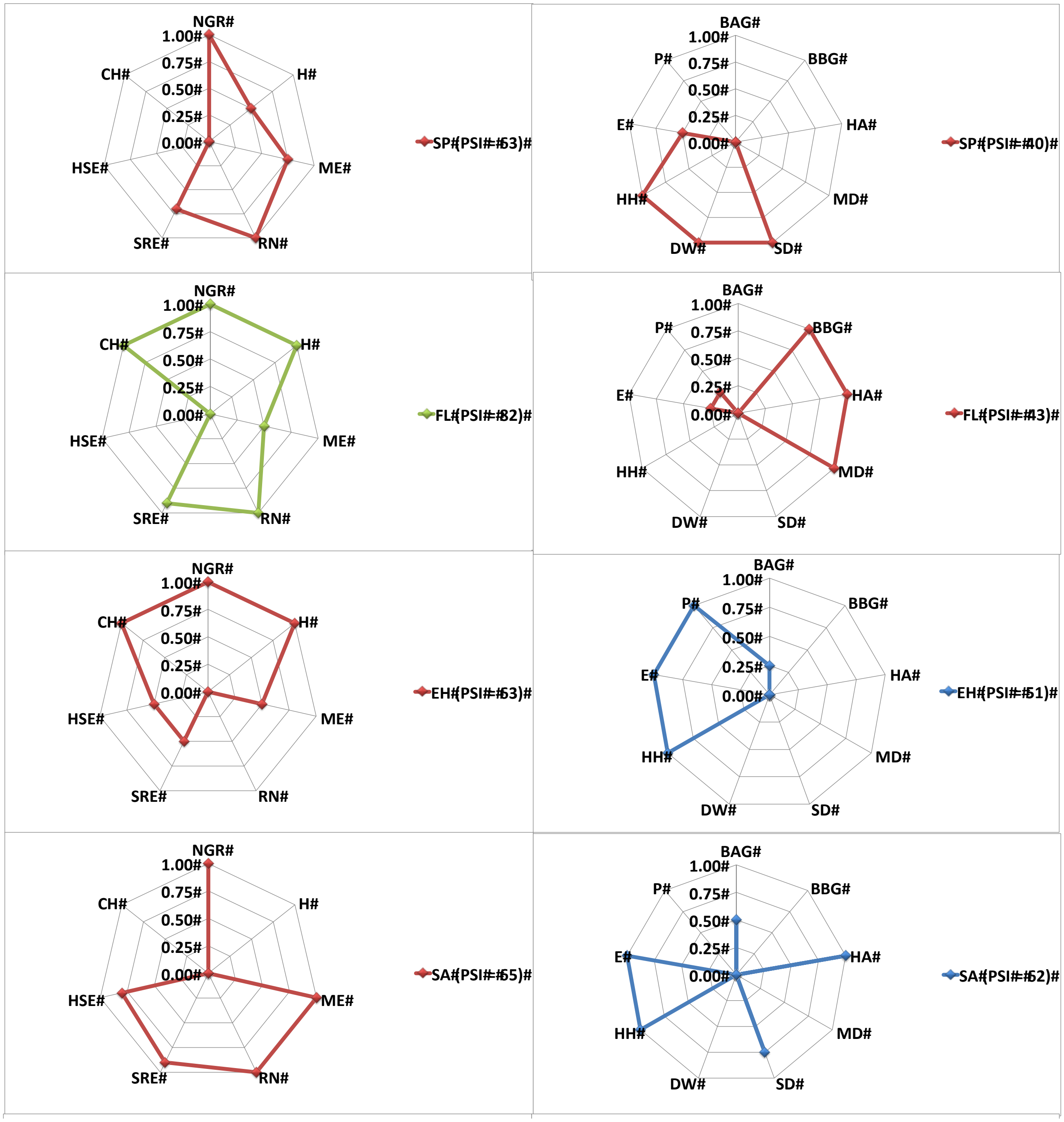

Figure 20: Qualitative (left) and quantitative (right) utility attributes and PSI scoring for *Spartina patens (SP), Flaveria linearis (FL), Equisetum hyemale,* and *Sisyrinchium angustifolium.* Highly desirable (green), moderately desirable (blue) and least desirable (red) for bioretention application. Qualitative attributes: native to geographical region (NGR), harvestable (H), mimic environment (ME), root network (RN), species rich ecosystem (SRE), human, social, and economic impacts (HSE), and create habitat (CH). Quantitative attributes baseline above ground concentration (BAG), baseline belowground concentration (BBG), harvested concentration (HA), mean density (MD), stomata density (SD), dry weight (DW), harvest height (HH), establishment (E), and propagation (P).

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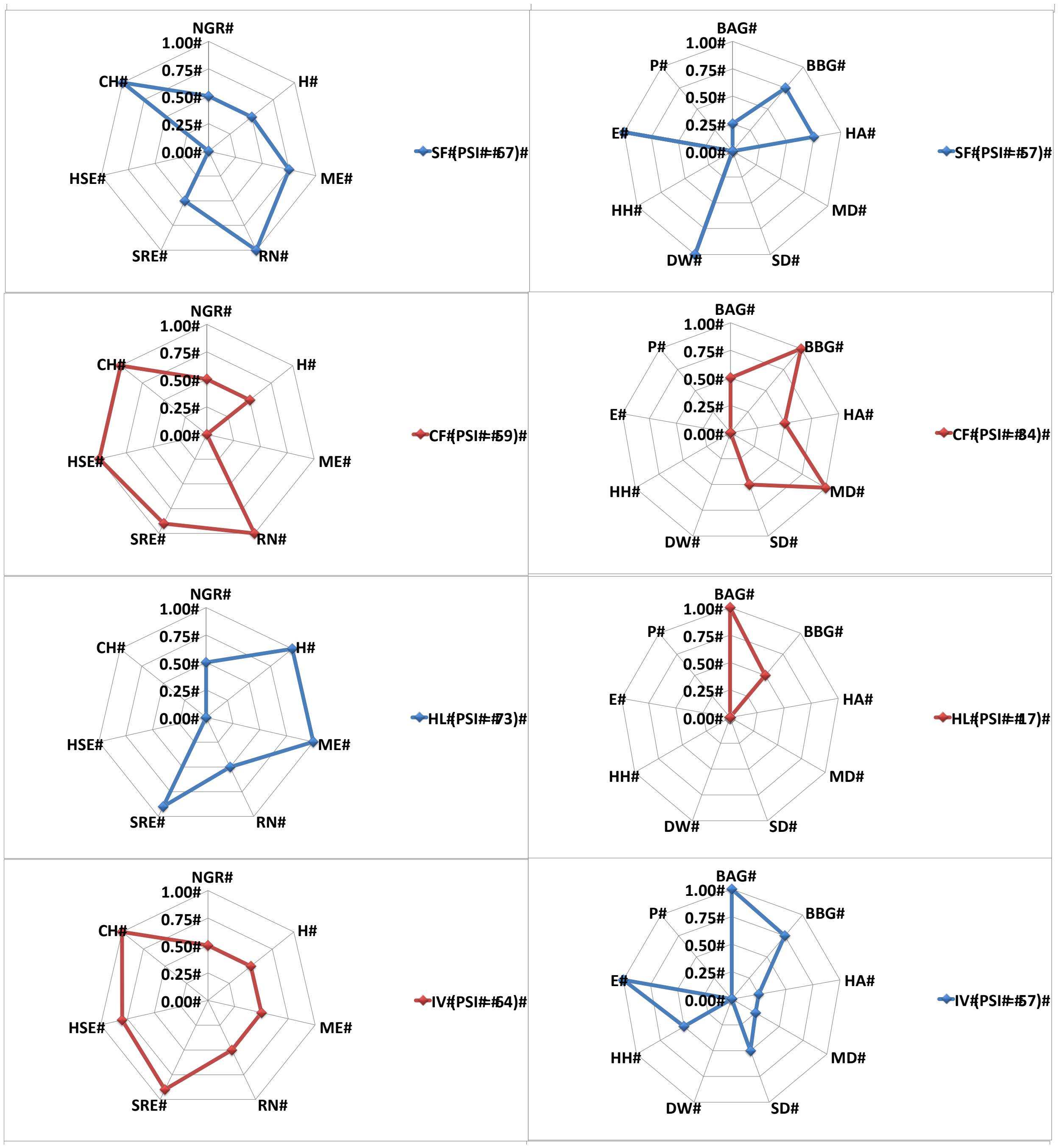

Figure 21: Qualitative (left) and quantitative (right) utility attributes and PSI scoring for *Solidago fistulosa (SF), Canna flaccida (CF), Hymenocallis latifolia (HL),* and *Iris virginica.* Moderately desirable (blue) and least desirable (red) for bioretention application. Qualitative attributes: native to geographical region (NGR), harvestable (H), mimic environment (ME), root network (RN), species rich ecosystem (SRE), human, social, and economic impacts (HSE), and create habitat (CH). Quantitative attributes baseline above ground concentration (BAG), baseline belowground concentration (BBG), harvested concentration (HA), mean density (MD), stomata density (SD), dry weight (DW), harvest height (HH), establishment (E), and propagation (P).

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The quantitative plant selection utility index scoring ranged from 17 (Hymenocallis latifolia) to 73 (Salvia Coccinea) for the eleven evaluated plant species, Table 25. This study did not evaluate actual evapotranspiration capacity and therefore did not negatively weight quantitative PSI scores for not satisfying this utility level attribute. Similar to the qualitative PSI scores, the quantitative PSI scores allowed for the 11 selected plant species to be categorized as highly desirable (n=2, PSI ≥ 70), moderately desirable (n=5, 70 > PSI ≥ 50), and least desirable (n=4, PSI < 50) for the site specific characteristics of this particular bioretention application. It should be noted that two of the four species that scored less favorably, Flaveria linearis and Hymenocallis latifolia experienced stress within their first growing season as a result of improper harvesting techniques and invasion from a Romalea microptera (lubber grasshopper) pest species.

Table 25: Quantitative plant selection utility index scoring for 11 of the 26 selected plant species. Initial pollutant removal capacity (IPRC), acclimated pollutant removal capacity (APRC), evapotranspiration capacity (EC), growth rate (GR), and establishment and propagation rate (EP).

Attribute Code	Weight	Rank	Level Code	Plant Species Level Score										
				SP	FL	EH	SA	SF	CF	HL	IV	CL	SC	TO
IPRC	0.8 0.2	4	BAG BBG	0.00 0.00	0.00 1.00	0.25 0.00	0.50 0.00	0.25 0.75	0.50 1.00	1.00 0.50	1.00 0.75	0.50 0.00	0.50 1.00	1.00 1.00
APRC	0.5 0.5	2	HA MD	0.00 0.00	1.00 1.00	0.00 0.00	1.00 0.00	0.75 0.00	0.50 1.00	n/a n/a	0.25 0.25	0.50 0.00	0.50 0.00	0.50 1.00
EC	0.8 0.2	5	AET[a] SD	n/a 1.00	n/a 0.00	n/a 0.00	n/a 0.75	n/a n/a	n/a 0.50	n/a 0.00	n/a 0.50	n/a 0.50	n/a 1.00	n/a 0.00
GR	0.5 0.5	3	DW HH	1.00 1.00	0.00 0.00	0.00 1.00	0.00 1.00	1.00 0.00	0.00 0.00	n/a 0.00	0.00 0.50	0.00 1.00	1.00 1.00	0.00 0.00
EP	0.8 0.2	1	E P	0.50 0.00	0.25 0.25	1.00 1.00	1.00 0.00	1.00 0.00	0.00 0.00	0.00 0.00	1.00 0.00	1.00 1.00	1.00 1.00	1.00 0.75
Quantitative PSI Score:				40	43[b]	51	62	57	34	17[c]	57	61	73	70

[a] Actual evapotranspiration capacity was not evaluated as part of this study. [b] *Flaveria* linearis was improperly harvested after the first growing season, resulting in a reduced growth rate and establishment and propagation single attribute utility value. [c] *Hymenocallis latifolia* was observed to be a preferential food source for *Romalea microptera* severely reducing its overall utility score.

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This illuminates the unpredictable nature of actual field-scale implementation and places increased emphasis on the importance of collecting field scale data to better assess bioretention performance for appropriate plant selection. In a similar application (not evaluated for this study) both *Flaveria linearis* and *Hymenocallis latifolia* performed significantly better with respect to both growth rate and establishment and propagation single utility attributes.

Quantitative PSI scores are directly linked to the level value and rank assigned to each attribute. Given the diversity of environments and applications, there will never be full agreement on a universally applicable set of level values for the aggregation of the 7 qualitative and 5 quantitative PSI attribute scores. Users may find the need to add or remove attributes from the PSI. In some regions, nutrient management may be the most pressing concern, in others the priority may shift to hydrologic functioning as municipalities face longer-term fiscal challenges associated with combined sewer overflows, resource recovery, stormwater treatment and the protection of biodiversity. The plant selection criteria can be applied to any region, as plants are regionally specific. The qualitative PSI score was calculated based on conversations with experts in the field on how plants perform based on the 7 attributes identified. For example, a botanist or ecologist familiar with plant species characteristics state side (e.g. California, Pennsylvania, Michigan) or internationally where plant performance data has been collected for bioretention systems (i.e. Australia) would need to be consulted to evaluate region specific plant species qualitatively, resulting in regionally specific PSI scoring. Furthermore, the qualitative PSI data could be evaluated by researchers in Australia, whom have conducted quantitative field data on plant performance, comparing anticipated qualitative scoring

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with quantitative field performance data. These researchers may decide to add or remove quantitative attributes depending on the field data they have collected, enabling the PSI to be further validated and refined for attributes, level values, and region specific ranking.

6.5 Conclusions

The plant selection index considers 12 attributes consisting of 30 qualitative and 10 quantitative variables to be the building blocks for bioretention plant selection and a template for decision makers and other green infrastructure practices. Each attribute builds on a logic developed by a careful review of the science and the literature in the field of green infrastructure, wetlands research, and the environmental field, as well as thorough consultation with experts in the field. The PSI allows the user to select plant species based on qualitative attributes and individual performance parameters, and provides the option of assigning individual weights and rankings based on site-specific constraints for a given region of implementation.

The qualitative PSI was used to score 26 plant species applicable to the subtropical region of Tampa Bay, finding *Flaveria linearis, Tripsacum dactyloides*, *Salvia coccinea, and Chamaecrista fasciculata* to be highly favorable, and 15 other species to be considered for bioretention application. This plant selection index can be taken a step further by allowing the user to quantitatively evaluate selected plant species based on pollutant removal capacity, evapotranspiration capacity, growth rate, and establishment and propagation. Field-scale plant performance data was collected for 11 of the 26 species across each of the quantitative attributes. The qualitative PSI found *Salvia coccinea* and *Tradescantia ohiensis* to be highly desirable with 5 other species moderately desirable.

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Both qualitative and quantitative scores were combined on a 0-200 scale to provide a list of recommended species based, ranking from high to low: *Salvia coccinea* (PSI=160), *Tradescantia ohiensis* (PSI = 148), *Sisyrinchium angustifolium* (PSI =127), *Flaveria linearis* (PSI = 125), *Solidago fistulosa* (PSI = 124), *Iris virginica* (PSI =121), *Coreopsis leavenworthii* (PSI = 117), *Equisetum hyemale* (PSI = 114), *Canna flaccida* (PSI = 104), *Spartina patens* (PSI = 103), *Hymenocallis latifolia* (PSI =90).

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CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 How Does the Green Space Based Learning Approach Translate a Federally Funded University K-12 STEM Project Into a K-12 Educational Approach That Develops Green Infrastructure on School Campuses?

The Green Space Based Learning (GSBL) approach builds on a long-term partnership between a Research I university, surrounding community, and local school district, transforming underutilized community green space into an interactive educational tool to addresses national infrastructure and educational challenges. The GSBL approach is an educational platform for engaging K-12 and the local community in engineering design and construction of sustainable Green Infrastructure (GI) projects. GSBL was piloted as a part of a federally funded Research Experience for Teachers (RET) program in which teachers participated in two intensive 6-week summer research experiences and two consecutive academic year components.

The summer experience focuses on the development of Science Technology Engineering and Mathematic (STEM) lessons and activities that meet Common Core and Next Generation Science Standards and the dissemination of the RET research experience. Evaluation of the success of the GSBL approach is based on the successful development/implementation of one or more of the anticipated GSBL approach Primary and Secondary Phase outputs:

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- K-12 green infrastructure curriculum development
- Dissemination of 6-week summer research experience
- Implementation of green infrastructure curriculum
- Installation of personal rain gardens or curricular product
- Green Infrastructure Science Summer Camp
- Student driven Campus Green Infrastructure Challenge
- Application for and/or received funding to implement green infrastructure project
- Student drive field-scale green infrastructure construction on school campus
- Submittal and/or acceptance of curriculum to a teacher training resource
- Participatory research project development
- Implementation of participatory research project (i.e. system function, monitoring and performance)
- Dissemination of participatory research project (i.e. signage, community engagement)

GSBL was piloted between Spring 2011 and Summer 2012 and implemented as part of the RET program between Summer 2012 and Spring 2015 with nine in-service middle school teachers (grades 6-8), four in-service high school teachers (grades 9-12), three pre-service teachers, and a Lead teacher from five different schools within the Hillsborough County Public School (HCPS) district. Approximately 400 K-12 students and teachers engaged in both formal and informal educational activities resulting in the design and construction of eight bioretention cells at three HSPS K-12 school campuses, one of which was designed as a field-scale research site, the hosting of three green infrastructure science

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summer camps, the completion of four Campus Green Infrastructure Challenges; the publication of the Urban Stormwater Management Curricular Unit, the installation of approximately 70 personal rain gardens, two home-scale bioretention cells, and the securing of funding for two constructed and three future green infrastructure projects.

Individual teacher experience with the GSBL approach has provided positive feedback from an in-service teacher and student population. The teacher successfully completed many of the GSBL outputs, including the development and implementation of both lessons and activities that support green infrastructure, facilitated a Campus Green Infrastructure Challenge, a student drive design and construction of a bioretention system on their school campus, and developed lessons for evaluating the performance of the installed system as a continuation of original design project.

Recommendations for future studies include continuation of support for HCPS teachers and schools through the writing of future grants and the development of a business model. Funding should include support for dissemination of curricular products, expansion to other subject areas (e.g. arts, technology, programing), evaluation of impact GSBL approach has on students and teachers, as well as the continued expansion of field-scale systems to be used as educational and research sites.

7.2 How Do Educational Activities Developed Through the GSBL Approach Mainstream Green Infrastructure in East Tampa, a Highly Urbanized Community in the Tampa bay Watershed?

Integration of university research with K-12 community engagement using the GSBL curricular products has led to the installation of six bioretention systems in East Tampa, five on one public school campus, and one at the home of a local community leader. These

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sites were selected based on one or more hotspot factors (e.g. localized areas of flooding, access to site, presence of learning space, willingness to pay, property ownership, visibility of location) and designed to restore the hydrology and water quality to pre-development conditions. The bioretention cells were designed for 1.27 cm to 2.54 cm storm-events and cost between $550 and $1,650 to construct depending on the design scope and scale, and installation methods. The installed systems convey stormwater runoff to a ponding area sized to approximately 2-5% of the total catchment area, capture between 31% and 67% of annual runoff (March 2010 – March 2015), and attenuate between 97,500 and 226,100 mg N annually.

On average, the six (BR 1-5 and BR 8) installed bioretention systems in East Tampa removed a total of 950,000 mg of N from entering traditional stormwater infrastructure per year. This results in an capital cost per kg TN removed of $290 over the 20 year life of the designed bioretention systems compared to the $1,424 benchmark value SWFWMD currently uses to estimate the cost benefit of coastal LID implementation based on a historical average of >130 permitted projects between 1993 and 2015. These numbers can be extrapolated across the East Tampa watershed of 19.5 km^2 with implementation goals ranging from 25 % to 100 % over 5,500 residential sites resulting in a capture efficiency of 8.5 to 34 % of the contributing nitrogen loading entering Hillsborough Bay. The residential installation of bioretention systems utilizes private property to manage stormwater runoff with a potential return on capital investment of $1,570,000 to $6,270,000 per year to the utility over a 20-year life when compared to current coastal LID/BMP practices installed.

The educational approach used with K-12 and vocational students to install the bioretention systems engaged multiple stakeholders. The interest of the teachers and the

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residential owner in expanding the process to summer programs and through community activities, demonstrate the success of the approach to continue educating others on green infrastructure. Engagement with local utilities that would benefit from the reduced stormwater loads to McKay Bay is needed to explore funding mechanisms and incentives to cover the costs and benefits of an expanded program. This savings may be passed on to residents in a variety of incentive programs that cover installation costs, provide a water utility credit, or fund green infrastructure job creation. It is recommended that future studies install influent and effluent monitoring equipment; soil moisture, temperature, conductivity, and solar radiation probes; and install Wi-Fi connected weather stations at all field site locations. Social networking is also an important aspect of mainstreaming green infrastructure and should include the use of installed bioretention systems for community outreach and neighborhood workshops; the continued expansion of green infrastructure mobile-applications, one in particular the Hydro-Hero application that has been developed and is currently being piloted at USF; neighborhood scale green infrastructure build events and the promotion of educational outreach sites such as raingardens.us that was developed as part of this research.

7.3 What are the Plant Recommendations for Constructing a Bioretention System Within the Tampa Bay Watershed?

This research developed a plant selection utility index (PSI) that scores plants based on qualitative and quantitative plant selection criteria. This qualitative PSI was used to evaluate 26 native and regionally friendly plant species commonly found within the subtropical Tampa Bay climate to provide an example and act as a template for selecting plant species. The qualitative PSI scores categorized the identified plant species as highly

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desirable (n=4, PSI ≥ 80), *Flaveria linearis, Tripsacum dactyloides*, *Salvia coccinea, and Chamaecrista fasciculata*; moderately desirable (n=15, 80 > PSI ≥ 65), *Solidago fistulosa, Hymenocallis latifolia, Canna flaccida, Tradescantia ohiensis, Arachis glabrata, Mimosa strigillosa, Callicarpa Americana, Penta lanceolata, Monarda punctate, Muhlenbergia capillaris, Helianthus debilis, Glandularia tampensis, Silphium asteriscus, Stachytarpheta jamaicensis, and Coreopsis lanceolata*; and least desirable (n=7, PSI < 65) *Spartina patens, Equisetum hyemale, Sisyrinchium angustifolium, Iris virginica, Coreopsis leavenworthii, Myrcianthus fragrans, Zamia puila*.

The quantitative PSI was used to evaluate attributes of 11 of the 26 species within the 32.5 m^2 field-scale bioretention system after two-growing seasons. The tested species scored as highly desirable (n=2, PSI ≥ 70) for *Salvia coccinea, Tradescantia ohiensis*; moderately desirable (n=5, 70 > PSI ≥ 50) for *Equisetum hyemale, Sisyrinchium angustifolium, Solidago fistulosa, Iris virginica, Coreopsis leavenworthii,* and least desirable (n=4, PSI < 50) for *Spartina patens, Flaveria linearis, Canna flaccida, Hymenocallis latifolia*. Both qualitative and quantitative scores were combined on a 0-200 scale to provide a list of recommended species based, ranking from high to low: Salvia coccinea (PSI=160), *Tradescantia ohiensis* (PSI = 148), *Sisyrinchium angustifolium* (PSI = 127), *Flaveria linearis* (PSI = 125), *Solidago fistulosa* (PSI = 124), *Iris virginica* (PSI =121), *Coreopsis leavenworthii* (PSI = 117), *Equisetum hyemale* (PSI = 114), *Canna flaccida* (PSI = 104), *Spartina patens* (PSI = 103), *Hymenocallis latifolia* (PSI =90).

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APPENDICES

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Appendix A: Bioretention Cells 1-8

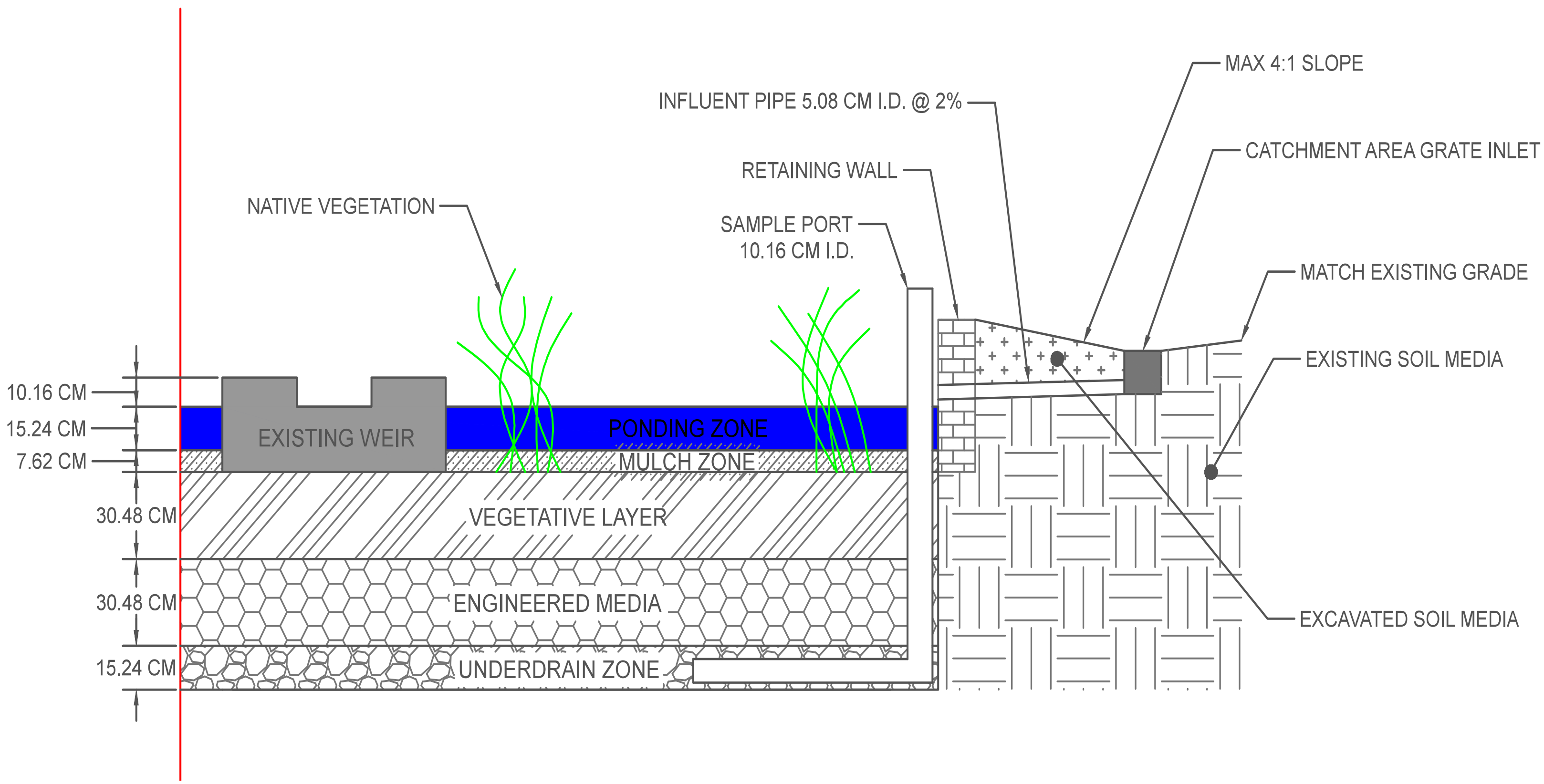

Figure A.1: Bioretention BR 1, BR 2, BR 3 cross-section

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Table A.1: Bioretention 1 (BR 1) design specifications

Bioretention Cell 1	BR 1			
Surface Area:	125	ft2	11.6	m2
Catchment Area	3132	ft2	291.1	m2
Storage Volume			1.7	m3
Vegetative Media Volume			3.5	m3
Engineered Media Volume			3.5	m3
Pervious	2192.4	ft2	203.8	m2
Impervious	939.6	ft2	87.3	m2

Vegetation	# Plants/Species	$/plant	Total	
CF, CL, EH, FL, HL, IV, SC, SA, TO	63	3.60	$226.80	
SP	63	3.60	$226.80	
		Vegetation Total:	$453.60	
		$/SF:	$3.63	

Mulch Layer depth (in)	3			
	Percent	$/yd	Total	Yards
Hardwood Mulch	100	22	$ 25.46	1.16
		Mulch Layer Total:	$ 25.46	
		$/SF:	$ 0.20	

Vegetative Media Layer (in)	12			
	Percent	$/yd	Total	Yards
Construction Sand	40.0	27	50.00	1.85
Topsoil	40.0	25	46.30	1.85
Hardwood Mulch	20.0	22	20.37	0.93
sum	100			
		Vegetative Media Layer Total:	116.67	
		$/SF:	0.93	

Engineered Media Layer (in)	12			
	Percent	$/yd		Yards
Construction Sand	61.5	27	76.92	2.85
Tire Crumb	15.4	173	122.97	0.71
Clinoptilolite (Zeolite)	7.7	165	58.65	0.36
3/8" Limestone	15.4	43	30.63	0.71
sum	100			
		Engineered Media Layer Total:	289.17	
		$/SF:	$ 2.31	

		Total:	$884.90	
		$/SF:	$7.08	

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Table A.2: Bioretention 2 (BR 2) design specifications

Bioretention Cell 2	BR 2			
Surface Area:	100	ft2	9.3	m2
Storage Volume			1.4	m3
Vegetative Media Volume			2.8	m3
Engineered Media Volume			2.8	m3
Catchment Area	2506	ft2	232.9	m2
Pervious	1754.2	ft2	163.0	m2
Impervious	751.8	ft2	69.9	m2
Vegetation	# Plants/Species	$/plant	Total	
CL, EH, FL, HL, IV, SC, SA, TO	40	3.60	$144.00	
SP	50	3.60	$180.00	
		Vegetation Total:	$324.00	
		$/SF:	$3.24	
Mulch Layer depth (in)	3			
	Percent	$/yd	Total	Yards
Hardwood Mulch	100	22	$ 20.37	0.93
		Mulch Layer Total:	$ 20.37	
		$/SF:	$ 0.20	
Vegetative Media Layer (in)	12			
	Percent	$/yd	Total	Yards
Construction Sand	40.0	27	40.00	1.48
Topsoil	40.0	25	37.04	1.48
Hardwood Mulch	20.0	22	16.30	0.74
sum	100			
		Vegetative Media Layer Total:	93.33	
		$/SF:	0.93	
Engineered Media Layer (in)	12			
	Percent	$/yd		Yards
Construction Sand	40.0	27	40.00	1.48
Topsoil	40.0	25	37.04	1.48
Hardwood Mulch	20.0	22	16.30	0.74
sum	100			
		Engineered Media Layer Total:	93.33	
		$/SF:	$ 0.93	
		Total:	$531.04	
		$/SF:	$5.31	

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Table A.3: Bioretention 3 (BR 3) design specifications

Bioretention Cell 3	BR 3			
Surface Area:	125	ft2	11.6	m2
Storage Volume			1.7	m3
Vegetative Media Volume			3.5	m3
Engineered Media Volume			3.5	m3
Catchment Area	3132	ft2	291.1	m2
Pervious	2192.4	ft2	203.8	m2
Impervious	939.6	ft2	87.3	m2
Vegetation	# Plants/Species	$/plant	Total	
CF, CL, EH, FL, HL, IV, SC, SA, TO	63	3.60	$226.80	
SP	63	3.60	$226.80	
		Vegetation Total:	$453.60	
		$/SF:	$3.63	
Mulch Layer depth (in)	3			
	Percent	$/yd	Total	Yards
Hardwood Mulch	100	22	$ 25.46	1.16
		Mulch Layer Total:	$ 25.46	
		$/SF:	$ 0.20	
Vegetative Media Layer (in)	12			
	Percent	$/yd	Total	Yards
Construction Sand	80.0	27	100.00	3.70
Hardwood Mulch	20.0	22	20.37	0.93
sum	100			
		Vegetative Media Layer Total:	120.37	
		$/SF:	0.96	
Engineered Media Layer (in)	12			
	Percent	$/yd		Yards
Construction Sand	53.8	27	67.31	2.49
Tire Crumb	30.8	173	245.93	1.42
Clinoptilolite (Zeolite)	15.4	165	117.31	0.71
sum	100			
		Engineered Media Layer Total:	430.55	
		$/SF:	$ 3.44	
		Total:	$1,029.98	
		$/SF:	$8.24	

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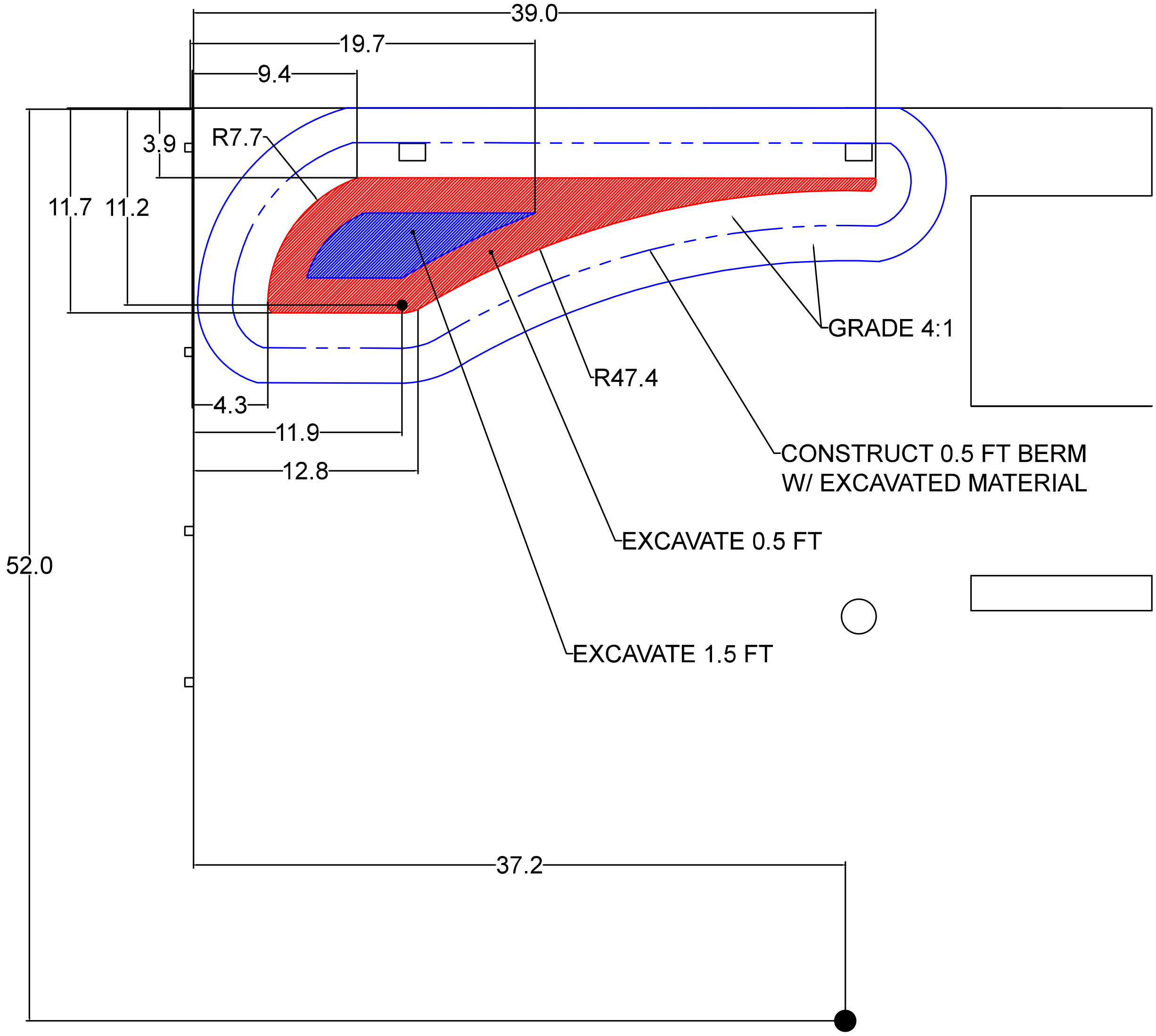

Figure A.2: Bioretention 4 (BR 4) plan view site plan

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Table A.4: Bioretention 4 (BR 4) design specifications

Bioretention Cell 4	BR 4			
Catchment Area	2600	ft2	241.6	m2
Pervious	0	ft2	0.0	m2
Impervious	2600	ft2	241.6	m2
Developed Area	485	ft2	45.1	m2
Storage Volume SA:	300	ft2	27.9	m2
Vegetative Layer SA:	130	ft2	12.1	m2
Engineered Media Layer SA:	30	ft2	2.8	m2

Vegetation	# Plants/Species	$/plant	Total	
SR, SJ, SC	16	5.00	$80.00	
MF, ZP	8	12.00	$96.00	
C	18	2.50	$45.00	
PP, MS	72	2.00	$144.00	
		Vegetation Total:	$365.00	
		$/SF:	$0.75	

Mulch Layer depth (in)	2			
	Percent	$/yd	Total	Yards
Hardwood Mulch	100	41.04	$ 122.87	2.99
		Mulch Layer Total:	$ 122.87	
		$/SF:	$ 0.25	

Vegetative Media Layer (in)	6			
	Percent	$/yd	Total	Yards
Topsoil	50.0	39.69	47.78	1.20
sum	50			
		Vegetative Media Layer Total:	47.78	
		$/SF:	0.10	

Engineered Media Layer (in)	18			
	Percent	$/yd		Yards
Construction Sand	66.67	$203.04	225.60	1.11
Pea Gravel	33.33	$197.10	109.50	0.56
sum	100			
		Engineered Media Layer Total:	335.10	
		$/SF:	$ 0.69	

		Total:	$870.74	
		$/SF:	$1.80	**developed**

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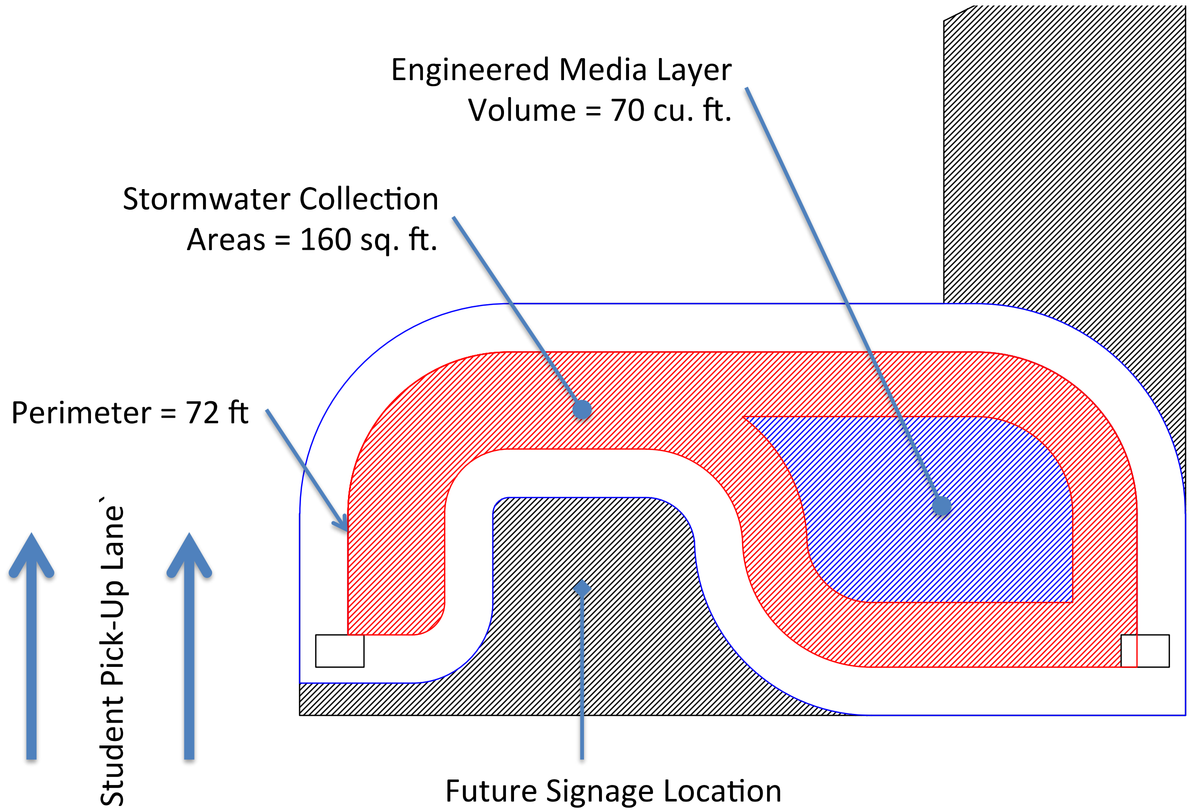

Figure A.3: Bioretention 5 (BR 5) plan view site plan

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Table A.5: Bioretention 5 (BR 5) design specifications

Bioretention Cell 5	BR 5			
Catchment Area:	3200	ft2	297.4	m2
Pervious:	0	ft2	0.0	m2
Impervious:	3200	ft2	297.4	m2
Developed Area:	275	ft2	25.6	m2
Storage Volume SA:	160	ft2	14.9	m2
Vegetative Layer SA:	160	ft2	14.9	m2
Engineered Media Layer SA:	50	ft2	4.6	m2

Vegetation	# Plants/Species	$/plant	Total	
PP, MS, FL, CA, PL, CH, MP, MC, HD, GT	64	2.19	$140.00	
	30	4.00	$120.00	
	4	7.00	$28.00	
		Vegetation Total:	$288.00	
		$/SF:	$1.05	

Mulch Layer depth (in)	2			
	Percent	$/yd	Total	Yards
Hardwood Mulch	100	41.04	$ 69.67	1.70
		Mulch Layer Total:	$ 69.67	
		$/SF:	$ 0.25	

Vegetative Media Layer (in)	6			
	Percent	$/yd	Total	Yards
Topsoil	50.0	39.69	58.80	1.48
sum	50			
	Vegetative Media Layer Total:		58.80	
		$/SF:	0.21	

Engineered Media Layer (in)	18			
	Percent	$/yd		Yards
Construction Sand	66.67	$203.04	376.00	1.85
Pea Gravel	33.33	$197.10	182.50	0.93
sum	100			
	Engineered Media Layer Total:		558.50	
		$/SF:	$ 2.03	

		Total:	$974.97	
		$/SF:	$3.55	**developed**

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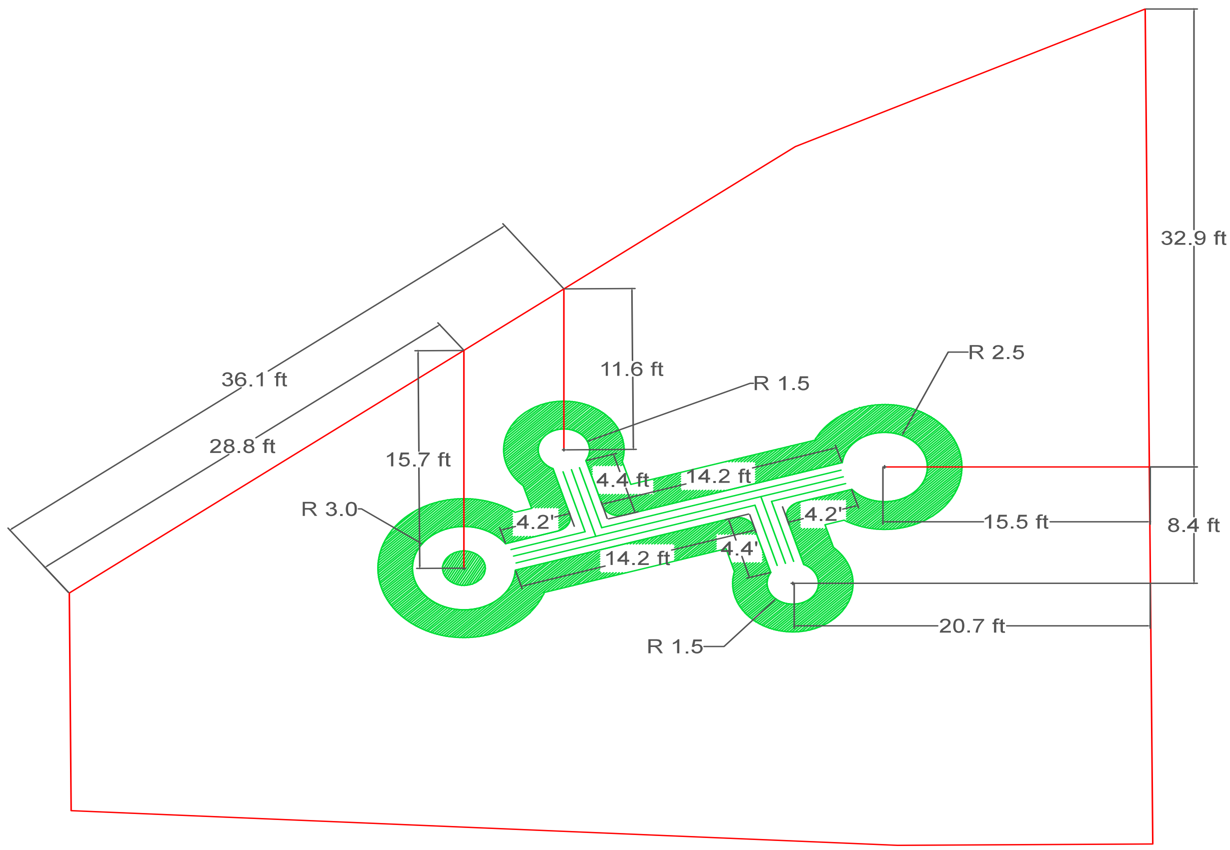

Figure A.4: Bioretention 6 (BR 6) plan view site plan

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Table A.6: Bioretention 6 (BR 6) design specifications

Bioretention Cell 6	BR 6			
Catchment Area	10833	ft2	1006.8	m2
Pervious	8667	ft2	805.5	m2
Impervious	2167	ft2	201.4	m2
Developed Area	325	ft2	30.2	m2
Storage Volume SA:	325	ft2	30.2	m2
Vegetative Layer SA:	40	ft2	3.7	m2
Engineered Media Layer SA:	40	ft2	3.7	m2

Vegetation	# Plants/Species	$/plant	Total	
SP, EH, FL, TO, SC, IV, CF, SA, HL, CL, S	91	4.00	$364.00	
	Vegetation Total:		$364.00	
		$/SF:	$1.12	

Mulch Layer depth (in)	2			
	Percent	$/yd	Total	Yards
Hardwood Mulch	100	41.04	$ 82.33	2.01
	Mulch Layer Total:		$ 82.33	
		$/SF:	$ 0.25	

Vegetative Media Layer (in)	6	graded		
	Percent	$/yd	Total	Yards
Topsoil	50.0	39.69	14.70	0.37
sum	50			
	Vegetative Media Layer Total:		14.70	
		$/SF:	0.05	

Engineered Media Layer (in)	18			
	Percent	$/yd		Yards
Construction Sand	66.67	$203.04	300.80	1.48
Pea Gravel	33.33	$197.10	146.00	0.74
sum	100			
	Engineered Media Layer Total:		446.80	
		$/SF:	$ 1.37	

		Total:	$907.83	
		$/SF:	$2.79	**developed**

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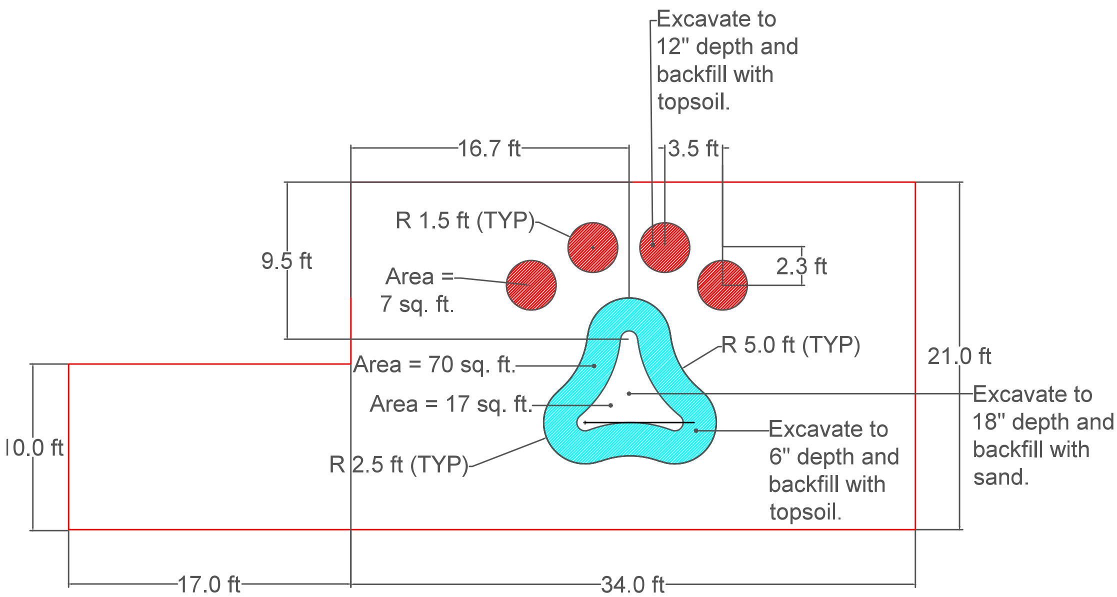

Figure A.5: Bioretention 7 (BR 7) plan view site plan

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Table A.7: Bioretention 7 (BR 7) design specifications

Bioretention 7	BR 7			
Catchment Area	2450	ft2	227.7	m2
Pervious	857.5	ft2	79.7	m2
Impervious	1592.5	ft2	148.0	m2
Developed Area	98	ft2	9.1	m2
Storage Volume SA:	98	ft2	9.1	m2
Vegetative Layer SA:	81	ft2	7.5	m2
Engineered Media Layer SA:	17	ft2	1.6	m2
Vegetation	# Plants/Species	$/plant	Total	
SP, EH, FL, TO, SC, IV, CF, SA, HL, CL, S	46	4.00	$184.00	
		Vegetation Total:	$184.00	
		$/SF:	$1.88	
Mulch Layer depth (in)	2			
	Percent	$/yd	Total	Yards
Hardwood Mulch	100	41.04	$ 24.83	0.60
		Mulch Layer Total:	$ 24.83	
		$/SF:	$ 0.25	
Vegetative Media Layer (in)	6	graded		
	Percent	$/yd	Total	Yards
Topsoil	50.0	39.69	29.77	0.75
sum	50			
		Vegetative Media Layer Total:	29.77	
		$/SF:	0.30	
Engineered Media Layer (in)	18			
	Percent	$/yd		Yards
Construction Sand	66.67	$203.04	127.84	0.63
Pea Gravel	33.33	$197.10	62.05	0.31
sum	100			
		Engineered Media Layer Total:	189.89	
		$/SF:	$ 1.94	
		Total:	$428.48	
		$/SF:	$4.37	**developed**

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Table A.8: Bioretention 8 (BR 8) design specifications

	Start:	2/3/15	Finish:	2/24/15	
Residential #1 (BR 8)					
Surface Area	93	ft2	8.6	m2	
Catchment Area	2000	ft2	185.9	m2	
Pervious	1150	ft2	106.9	m2	
Impervious	850	ft2	79.0	m2	
Developed Area	111.6	ft2	10.4	m2	
Storage Volume SA:	93	ft2	8.6	m3	
Vegetative Layer SA:	54	ft2	5.0	m2	
Engineered Media Layer SA:	54	ft2	5.0	m2	

Vegetation	# Plants/Species	$/plant	Total
HD	32	1.56	$50.00
ZP	2	25.00	$50.00
MC, PL, SJ, CH, C, SC, IV, SR, MP	28	5.00	$140.00
		Vegetation Total:	$240.00
		$/SF:	$2.15

Mulch Layer depth (in)	2			
	# yards	$/yard	Total	Yards
Hardwood Mulch	0.83	41.04	$ 34.20	0.83
		Mulch Layer Total:	$ 34.20	
		$/SF:	$ 0.37	

Vegetative Media Layer (in)	12			
	Percent	$/yd	Total	Yards
Construction Sand	100.0	18	36.00	2.00
		Vegetative Media Layer Total:	36.00	
		$/SF:	0.32	

Engineered Media Layer (in)	6			
	Percent	$/yd		Yards
3/4" Granite	100.00	$66.00	66.00	1.00
		Engineered Media Layer Total:	66.00	
		$/SF:	$ 0.59	

Total:	$376.20	
$/SF:	$3.43	**developed**

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Appendix B: Plant Performance Data

Table B.1: Baseline plant species characteristics

ID	Overall%Height% (mm)	Overall% Circumference% (mm)	#%Leaves	#%Shoots	#%Buds	#%Stems	Stem% Length% (mm)	Stem%Fresh% Weight%(g)	Stem%Dry% Weight%(g)	Bud%Fresh% Weight%(g)	Bud%Dry% Weight%(g)	Leaves% Fresh% Weight%(g)	Leaves%Dry% Weight%(g)
SF#A1			34				505	11.9	2.37			5.76	2.08
SF#A2	505	210	19	11			385	4.94	0.94			2.96	0.96
SF#A3			23				405	6.67	1.27			3.96	1.26
SF#B1			16				315	2.17	0.42			2.06	0.45
SF#B2	425	210	22	6			405	5.25	1.06			2.96	1.07
SF#B3			41				355	7.81	1.29			10.28	2.69
HL#A1	360	90	7					41.32					
HL#A2	330	60	6					25.33					
HL#A3	140	25	2					1.63					
HL#B1	305	50	3					11.71					
HL#B2	260	40	3					9.06					
HL#B3	255	35	2					7.06					
CL#A1					18	14	520	31.69	8.23	1.84	0.31	22.34	3.63
CL#A2	520	480		5	5	1	470	4.43	1.28	0.28	0.01	6.69	1.11
CL#A3					5	1		5.87	1.54	0.17	0.01	6.22	1.08
CL#B1					7	1	650	3.46	0.87	0.33	0.05	3.47	0.5
CL#B2	650	335		29	8	1	590	3.46	0.92	0.21	0.02	3.05	0.45
CL#B3					#	1	520	1.56	0.29	#	#	1.62	0.26
TO#A1			9		4	6	430	13.01	0.58	2.41	0.19	5	0.35
TO#A2	430	190	7	7	1	1	245	4.87	0.18	0.8	0.05	4.27	0.26
TO#A3			4		1	1	395	4.86	0.16	0.57	0.03	4.51	0.28
TO#B1			7		1	1	500	11.62	0.54	2.29	0.07	8.95	0.75
TO#B2	500	170	9	5	#	1	410	3.07	0.16	#		8.74	0.72
TO#B3					#	1	350	1.16	0.06	#		4.41	0.34
SC#A1			15		2	5	515	2.42	0.72	0.42	0.01	0.95	0.16
SC#A2	515	250	39	21	3	6	445	2.13	0.55	0.23	0.04	1.88	0.35
SC#A3			36		2	3	515	5.12	1.15	0.1	0.01	1.75	0.31
SC#B1			12		2	3	260	0.6	0.17	0.13	0.01	0.38	0.05
SC#B2	395	225	14	20	1	5	370	1.39	0.26	0.01	0.01	0.71	0.12
SC#B3			41		2	3	340	1.18	0.32	0.01	0.03	0.88	0.15
IV#A1		55				6						6.99	0.85
IV#A2	425	45		2		2						5.65	0.61
IV#A3		#				#						#	#
IV#B1		65				4						4.82	0.95
IV#B2	250	20		2		3						0.4	0.051
IV#B3		#				#							
TD#A1			4				580	1.42	0.17	0.61		2.75	
TD#A2	580	245	5	20			425	0.89	0.13	0.38		1.5	
TD#A3			4				510	1.4	0.18	0.48		2.03	
TD#B1			5				480	1.29	0.16	0.46		1.9	
TD#B2	540	115	4	10			530	0.77	0.12	0.43		1.37	
TD#B3			3				465	0.73	0.09	0.32		1.33	
EH#A1							415	1.79	0.28				
EH#A2	735	270		47			490	2.12	0.43				
EH#A3							545	2.29	0.38				
EH#B1							335	2.93	0.52				
EH#B2	740	400		48			515	3.04	0.63				
EH#B3							485	3.43	0.72				
FL#A1			9				185	0.69	0.14			1.18	0.11
FL#A2	150	315	14	49			155	0.33	0.06			0.99	0.1
FL#A3			15				150	0.38	0.09			1.7	0.18
FL#B1			16				165	0.44	0.12			1.29	0.15
FL#B2	270	395	21	35			225	1.06	0.28			2.79	0.39
FL#B3			20				280	1.34	0.31			3.3	0.38
CF#A1			1				215	0.61	0.039			0.83	0.087
CF#A2			4	4			305	2.8	0.22			1.88	0.31
CF#A3			5				450	19.92	1.71			15.27	3.11
CF#B1			6		2		560	32.43	3.2	1.62	0.38	20.65	3.53
CF#B2			3	7			415	9.9	1.07			4.22	1.76
CF#B3			3				370	3.97	0.28			7.46	0.79
SA#A1			4				180					0.49	0.048
SA#A2	220	50	3	40			175					0.26	0.037
SA#A3			3				220					0.41	0.057
SA#B1			3				220					0.51	0.066
SA#B2	220	50	3	37			190					0.4	0.054
SA#B3			3				215					0.6	0.081
SP#A1			4				250					0.39	0.163
SP#A2	600	30	5	16			260					0.53	0.213
SP#A3			4				230					0.22	0.099
SP#B1			5				280					0.5	0.214
SP#B2	600	30	5	20			275					0.46	0.193
SP#B3			4				210					0.28	0.072

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Table B.2: Baseline TN 3000 data for CF and TO species

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)
CF_A	140616_CF_A_#1_Leaves_01	5.00	3499.16	0.113400136	2.268002715
	140616_CF_A_#1_Leaves_02	5.20	4301.37	0.145425765	2.796649337
	140616_CF_A_#1_Leaves_03	5.00	4044.18	0.13515829	2.703165795
	140908_CF_A_#1_Leaves_04	5.20	3705.13	0.121622819	2.338900371
	140908_CF_A_#1_Leaves_05	6.50	4322.89	0.146284882	2.25053664
	140617_CF_A_#2_Leaves_01	5.00	3349.02	0.107406284	2.148125674
	140617_CF_A_#2_Leaves_02	5.10	3856.99	0.127685337	2.503634054
	140617_CF_A_#2_Leaves_03	5.10	3246.62	0.103318296	2.025848944
	140908_CF_A_#2_Leaves_04	5.60	3523.9	0.1143878	2.042639284
	140908_CF_A_#3_Stem_01	6.10	3146.33	0.099314543	1.62810727
	140908_CF_A_#3_Stem_02	5.50	2970.95	0.092313066	1.678419389
	140908_CF_A_#3_Stem_03	5.80	3105.02	0.097665376	1.683885791
	140618_CF_A_#2_Stem_01	5.10	3682.35	0.120713402	2.366929446
	140618_CF_A_#2_Stem_02	5.10	3958.18	0.131725019	2.582843509
	140618_CF_A_#2_Stem_03	5.00	3661.75	0.119891014	2.397820272
CF_B	140704_CF_B_#1_Leaves_01	5.10	3194.36	0.101231985	1.984940888
	140704_CF_B_#1_Leaves_02	5.10	3073.63	0.096412232	1.890435922
	140704_CF_B_#1_Leaves_03	5.10	3250.62	0.103477983	2.028980062
	140704_CF_B_#2_Leaves_01	5.10	3065.61	0.09609206	1.884158031
	140704_CF_B_#2_Leaves_02	5.10	3149.38	0.099436305	1.949731468
	140704_CF_B_#2_Leaves_03	5.10	2957.41	0.091772526	1.799461291
	140704_CF_B_#1_Stem_01	5.00	2529.67	0.074696395	1.493927901
	140704_CF_B_#1_Stem_02	5.10	2712.44	0.081992894	1.607703803
	140704_CF_B_#1_Stem_03	5.10	2470.27	0.072325043	1.418138096
	140617_CF_B_#2_Stem_01	5.10	2338.91	0.067080921	1.315312184
	140617_CF_B_#2_Stem_02	5.00	2227.89	0.062648808	1.252976167
	140617_CF_B_#2_Stem_03	5.00	2422.82	0.070430756	1.408615114
	140704_CF_B_#1_REP_01	5.10	3746.45	0.123272386	2.41710561
	140704_CF_B_#1_REP_02	5.10	3802.83	0.125523175	2.461238717
	140704_CF_B_#1_REP_03	5.00	3799.47	0.125389037	2.50778075
CF_A	140911_CF_A_Roots_01	7.30	3485.96	0.112873169	1.546207789
	140911_CF_A_Roots_02	6.70	3501.16	0.113479979	1.693731033
	140911_CF_A_Roots_03	6.20	2881.03	0.088723302	1.431021005
CF_B	140911_CF_B_Roots_01	8.00	3848.75	0.127356381	1.591954769
	140911_CF_B_Roots_02	6.20	3076.63	0.096531997	1.556967698
	140911_CF_B_Roots_03	6.20	3339.9	0.107042197	1.726487053
TO_A	140705_TO_A_#1_Leaves_01	5.10	5261.4	0.183751846	3.60297738
	140705_TO_A_#1_Leaves_02	5.10	5785.58	0.204678031	4.013294727
	140705_TO_A_#1_Leaves_03	5.10	5741.05	0.202900315	3.978437557
	140705_TO_A_#2_Leaves_01	5.00	4990.81	0.172949419	3.458988383
	140705_TO_A_#2_Leaves_02	5.10	5248.42	0.183233662	3.592816902
	140705_TO_A_#2_Leaves_03	5.10	6236.78	0.222690726	4.366484827
	140908_TO_A_#2_Leaves_04	6.10	5843.68	0.206997485	3.393401392
	140704_TO_A_#1_Stem_01	5.20	5409.27	0.189655076	3.647213001
	140704_TO_A_#1_Stem_02	5.10	5603.29	0.197400695	3.870601856
	140704_TO_A_#1_Stem_03	5.10	5494.75	0.193067588	3.785638971
	140705_TO_A_#2_Stem_01	5.00	6409.83	0.229599186	4.591983712
	140705_TO_A_#2_Stem_02	5.00	5889.52	0.208827498	4.176549962
	140705_TO_A_#2_Stem_03	5.10	5820.98	0.206091261	4.04100512
TO_B	140705_TO_B_#1_Leaves_01	5.10	3701.91	0.121494271	2.382240612
	140705_TO_B_#1_Leaves_02	5.10	3726.83	0.122489121	2.401747477
	140705_TO_B_#1_Leaves_03	5.10	3671.51	0.12028065	2.358444116
	140705_TO_B_#2_Leaves_01	5.10	3428.86	0.110593636	2.168502676
	140705_TO_B_#2_Leaves_02	5.00	3451.68	0.111504651	2.230093018
	140705_TO_B_#2_Leaves_03	5.00	3470.99	0.11227554	2.245510799
	140705_TO_B_#1_Stem_01	5.10	3478.85	0.112589325	2.207633822
	140705_TO_B_#1_Stem_02	5.00	3388.82	0.108995169	2.179903389
	140705_TO_B_#1_Stem_03	5.10	3618.05	0.118146433	2.316596725
	140705_TO_B_#2_Stem_01	5.10	3856.07	0.127648609	2.502913897
	140705_TO_B_#2_Stem_02	5.10	3763.94	0.123970618	2.430796423
	140705_TO_B_#2_Stem_03	5.00	3776.22	0.124460857	2.489217134
TO_A	140630_TO_A_#1_REP_01	5.10	5838.02	0.206771528	4.054343682
	140630_TO_A_#1_REP_02	5.10	5081.69	0.176577508	3.46230408

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Table B.3: Baseline TN 3000 data for TO, FL, and SC species

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)
	140630_TO_A_#1_REP_03	5.10	5102.31	0.177400695	3.478444993
TO_A	140626_TO_A_Roots_01	5.00	3815.29	0.1260206	2.520411992
	140626_TO_A_Roots_02	5.10	4253.18	0.143501936	2.813763455
	140626_TO_A_Roots_03	5.10	4285.93	0.144809374	2.839399483
TO_B	140626_TO_B_Roots_01	5.20	1936.36	0.05101042	0.980969607
	140626_TO_B_Roots_02	5.10	1759.6	0.04395385	0.861840205
	140626_TO_B_Roots_03	5.00	1764.5	0.044149467	0.882989341
FL_A	140908_FL_A_#3_Leaves_01	6.00	2259.49	0.063910336	1.065172262
	140908_FL_A_#3_Leaves_02	5.20	2036.9	0.055024153	1.058156782
	140908_FL_A_#3_Leaves_03	6.20	2052	0.055626971	0.897209212
	140908_FL_A_#3_Leaves_04	6.50	2347.58	0.067427043	1.037339123
	140702_FL_A_#1_Stem_01	5.10	1982.66	0.052858797	1.036446995
	140702_FL_A_#1_Stem_02	5.10	2203	0.061655156	1.208924625
	140702_FL_A_#1_Stem_03	5.10	2008.77	0.053901154	1.056885367
	140908_FL_A_#3_Stem_01	5.60	1920.42	0.050374067	0.899536908
	140908_FL_A_#3_Stem_02	5.30	1780.68	0.044795401	0.845196246
	140908_FL_A_#3_Stem_03	5.10	1012.26	0.014118727	0.27683779
	140908_FL_A_#3_Stem_04	5.50	1894.2	0.049327318	0.896860336
FL_B	140704_FL_B_#1_Leaves_01	5.10	2589.17	0.077071739	1.511210576
	140704_FL_B_#1_Leaves_02	5.10	2593.76	0.07725498	1.514803534
	140704_FL_B_#1_Leaves_03	5.10	2608.77	0.077854206	1.526553054
	140704_FL_B_#2_Leaves_01	5.10	2208.58	0.061877919	1.213292535
	140704_FL_B_#2_Leaves_02	5.10	2448.92	0.071472713	1.401425755
	140704_FL_B_#2_Leaves_03	5.10	2181.8	0.060808815	1.1923297
	140704_FL_B_#1_Stem_01	5.10	1840.42	0.047180327	0.925104442
	140704_FL_B_#1_Stem_02	5.10	1898.73	0.049508164	0.970748314
	140704_FL_B_#1_Stem_03	5.10	1759.5	0.043949858	0.861761927
	140704_FL_B_#2_Stem_01	5.00	2019.64	0.054335103	1.086702064
	140704_FL_B_#2_Stem_02	5.00	2006.91	0.053826899	1.076537986
	140704_FL_B_#2_Stem_03	5.10	2007.58	0.053853647	1.05595386
FL_A	140911_FL_A_Roots_01	6.40	3266.33	0.104105154	1.62664303
	140911_FL_A_Roots_02	5.90	3150.99	0.099500579	1.686450489
	140911_FL_A_Roots_03	5.70	2902.99	0.089599984	1.571929544
FL_B	140911_FL_B_Roots_01	6.10	2969.16	0.092241606	1.512157483
	140911_FL_B_Roots_02	5.50	2817.61	0.086191465	1.567117541
	140911_FL_B_Roots_03	5.00	2800.94	0.085525969	1.710519382
SC_A	140701_SC_A_#1_Leaves_01	5.00	4381.24	0.148614316	2.972286319
	140701_SC_A_#1_Leaves_02	5.00	3877.69	0.128511717	2.570234341
	140701_SC_A_#1_Leaves_03	5.10	4292.92	0.145088427	2.844871111
	140701_SC_A_#2_Leaves_01	5.10	4379.17	0.148531678	2.912385841
	140701_SC_A_#2_Leaves_02	5.00	4798.97	0.16529083	3.305816599
	140701_SC_A_#2_Leaves_03	5.00	4329.11	0.146533195	2.930663899
	140630_SC_A_#1_Stem_01	5.10	2026.45	0.05460697	1.070724909
	140630_SC_A_#1_Stem_02	5.10	1705.6	0.041798076	0.819570113
	140630_SC_A_#1_Stem_03	5.00	1991.94	0.053229271	1.064585413
	140908_SC_A_#1_Stem_04	5.80	2372.78	0.068433071	1.179880538
	140630_SC_A_#2_Stem_01	5.00	3243.78	0.103204918	2.064098367
	140630_SC_A_#2_Stem_02	5.00	2732.72	0.082802507	1.656050142
	140630_SC_A_#2_Stem_03	5.10	3260.64	0.103877999	2.036823512
	140908_SC_A_#2_Stem_04	7.40	3858.63	0.127750808	1.726362276
	140908_SC_A_#2_Stem_05	4.90	2892.87	0.089195976	1.820326039
	140910_SC_A_#3_Stem_01	5.80	2754.95	0.083689968	1.442930477
	140910_SC_A_#3_Stem_02	5.00	2713.07	0.082018045	1.640360893
	140910_SC_A_#3_Stem_03	4.80	2394.41	0.069296579	1.443678723
SC_B	140630_SC_B_#1_Leaves_01	5.10	4654.32	0.159516148	3.127767615
	140630_SC_B_#1_Leaves_02	5.10	4683.34	0.160674678	3.150483875
	140630_SC_B_#1_Leaves_03	5.00	4373.65	0.14831131	2.966226197
	140701_SC_B_#2_Leaves_01	5.10	3715.74	0.122046389	2.393066452
	140701_SC_B_#2_Leaves_02	5.10	4127.55	0.138486566	2.715422869
	140701_SC_B_#2_Leaves_03	5.00	3787.67	0.124917961	2.498359216
	140911_SC_B_#3_Leaves_01	5.40	4381.03	0.148605932	2.751961711
	140911_SC_B_#3_Leaves_02	6.80	5169.18	0.180070262	2.648092092

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Table B.4: Baseline TN 3000 data for SC, SP, and EH species

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)
	140911_SC_B_#3_Leaves_03	6.10	4947.87	0.171235179	2.807134083
	140630_SC_B_#1_Stem_01	5.00	2740.48	0.0831123	1.662245998
	140630_SC_B_#1_Stem_02	5.10	2283.97	0.06488762	1.27230628
	140630_SC_B_#1_Stem_03	5.00	2480.66	0.07273983	1.454796599
	140908_SC_B_#1_Stem_04	5.10	2461.72	0.071983712	1.411445332
	140701_SC_B_#2_Stem_01	5.10	3361.13	0.107889736	2.115485022
	140701_SC_B_#2_Stem_02	5.10	3119.17	0.098230269	1.926083699
	140701_SC_B_#2_Stem_03	5.10	3331.49	0.106706455	2.092283438
	140910_SC_B_#3_Stem_01	5.20	3069.33	0.096240568	1.850780163
	140910_SC_B_#3_Stem_02	5.50	3391.54	0.109103757	1.983704666
	140910_SC_B_#3_Stem_03	4.80	2979.9	0.092670366	1.930632627
SC_A	140702_SC_A_#2_REP_01	5.00	4032.25	0.134682023	2.693640465
	140702_SC_A_#2_REP_02	5.00	4362.03	0.147847419	2.956948381
	140702_SC_A_#2_REP_03	5.00	4419.4	0.15013773	3.002754601
SP_A	140620_SP_A_#1_Stems_01	5.10	1779.61	0.044752685	0.877503622
	140620_SP_A_#1_Stems_02	5.10	1647.23	0.039467843	0.773879275
	140620_SP_A_#1_Stems_03	5.10	1469.98	0.032391712	0.635131613
	140908_SP_A_#1_Stems_04	5.20	1063.95	0.016182283	0.311197745
	140908_SP_A_#1_Stems_05	8.80	2068.52	0.056286479	0.639619074
	140908_SP_A_#1_Stems_06	6.20	1681.52	0.04083676	0.658657419
	140620_SP_A_#2_Stems_01	5.00	1685.67	0.041002435	0.820048705
	140620_SP_A_#2_Stems_02	5.10	1685.61	0.04100004	0.803922351
	140620_SP_A_#2_Stems_03	5.10	1324.34	0.026577508	0.521127609
	140908_SP_A_#2_Stems_04	5.80	1788.61	0.045111981	0.777792768
	140911_SP_A_#3_Stems_01	6.00	1699.85	0.041568526	0.692808761
	140911_SP_A_#3_Stems_02	7.20	1905.07	0.049761268	0.691128721
	140911_SP_A_#3_Stems_03	4.90	1551.57	0.035648928	0.727529145
SP_B	140620_SP_B_#1_Stems_01	5.10	1656.68	0.039845104	0.781276541
	140620_SP_B_#1_Stems_02	5.00	1541.55	0.035248912	0.704978243
	140620_SP_B_#1_Stems_03	5.00	1501.99	0.033669608	0.673392151
	140623_SP_B_#2_Stems_01	5.00	1747.36	0.043465208	0.869304164
	140623_SP_B_#2_Stems_02	5.10	1628.26	0.038710527	0.759029948
	140623_SP_B_#2_Stems_03	5.00	1654.6	0.039762066	0.795241327
SP_A	140911_SP_A_Roots_01	4.80	1628.26	0.038710527	0.80646932
	140911_SP_A_Roots_02	5.50	1472.09	0.032475947	0.590471766
	140911_SP_A_Roots_03	5.30	1641.72	0.039247874	0.740525928
SP_B	140911_SP_B_Roots_01	5.00	1736.54	0.043033255	0.860665096
	140911_SP_B_Roots_02	5.10	1729.88	0.042767376	0.838575999
	140911_SP_B_Roots_03	6.20	1945.78	0.051386482	0.828814234
EH_A	140618_EH_A_#1_Stems_01	5.10	3124.3	0.098435067	1.930099358
	140618_EH_A_#1_Stems_02	5.00	2948.78	0.091428001	1.828560022
	140618_EH_A_#1_Stems_03	5.00	3264.27	0.104022915	2.080458302
	140618_EH_A_#2_Stems_01	5.10	1924.98	0.05055611	0.991296275
	140618_EH_A_#2_Stems_02	5.10	2090.32	0.057156773	1.120721034
	140618_EH_A_#2_Stems_03	5.10	2683.06	0.080819993	1.584705741
	140908_EH_A_#2_Stems_04	5.80	2762.62	0.083996168	1.448209785
	140908_EH_A_#2_Stems_05	6.50	2871.28	0.088334065	1.358985619
	140910_EH_A_#3_Stems_01	5.30	2720.25	0.082304683	1.552918544
	140910_EH_A_#3_Stems_02	5.40	2773.58	0.08443371	1.563587221
	140910_EH_A_#3_Stems_03	5.10	2437.16	0.071003234	1.392220268
EH_B	140618_EH_B_#1_Stems_01	5.00	2496.7	0.073380175	1.467603497
	140618_EH_B_#1_Stems_02	5.00	2508.38	0.073846461	1.476929219
	140618_EH_B_#1_Stems_03	5.10	2518.24	0.074240089	1.455688028
	140618_EH_B_#2_Stems_01	5.00	2146.69	0.059407162	1.188143239
	140618_EH_B_#2_Stems_02	5.00	2292.66	0.06523454	1.304690806
	140618_EH_B_#2_Stems_03	5.10	2283.25	0.064858877	1.271742678
	140910_EH_B_#3_Stems_01	4.80	1990.37	0.053166593	1.107637364
	140910_EH_B_#3_Stems_02	4.80	1914.37	0.05013254	1.044427921
	140910_EH_B_#3_Stems_03	6.00	2303.3	0.065659308	1.094321796
EH_A	140911_EH_A_Roots_01	7.40	2561.26	0.075957523	1.026453017
	140911_EH_A_Roots_02	7.70	2817.75	0.086197054	1.119442257

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Table B.5: Baseline TN 3000 data for EH, CL, and SA species

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)
	140911_EH_A_Roots_03	8.30	2070.66	0.056371911	0.679179651
	140911_EH_A_Roots_04	5.60	2785.85	0.08492355	1.516491961
	140911_EH_A_Roots_05	7.10	2636.88	0.078976406	1.11234375
EH_B	140911_EH_B_Roots_01	7.10	2278.33	0.064662462	0.910738895
	140911_EH_B_Roots_02	6.30	2110.12	0.057947223	0.919797197
	140911_EH_B_Roots_03	6.80	2051.06	0.055589445	0.817491834
CL_A	140704_CL_A_#1_Leaves_01	5.20	3795.82	0.125243323	2.408525444
	140704_CL_A_#1_Leaves_02	5.00	3629.51	0.118603936	2.372078726
	140704_CL_A_#1_Leaves_03	5.00	3607.65	0.117731247	2.354624935
	140701_CL_A_#2_Leaves_01	5.10	3779.81	0.124604176	2.443219134
	140701_CL_A_#2_Leaves_02	5.00	4126.19	0.138432273	2.768645455
	140701_CL_A_#2_Leaves_03	5.10	3748.61	0.123358617	2.418796414
	140701_CL_A_#1_Stem_01	5.10	2415.26	0.070128947	1.375077397
	140701_CL_A_#1_Stem_02	5.00	2334.32	0.066897681	1.337953611
	140701_CL_A_#1_Stem_03	5.10	2277.98	0.064648489	1.267617431
	140701_CL_A_#2_Stem_01	5.10	2763.4	0.084027306	1.647594245
	140701_CL_A_#2_Stem_02	5.10	2037.24	0.055037726	1.079171099
	140701_CL_A_#2_Stem_03	5.10	2568.54	0.076248154	1.495061836
	140908_CL_A_#2_Stem_04	6.60	2886.66	0.088948062	1.347697906
	140908_CL_A_#2_Stem_05	5.10	2560.96	0.075945547	1.489128367
CL_B	140701_CL_B_#1_Leaves_01	5.10	4059.92	0.135786658	2.662483493
	140701_CL_B_#1_Leaves_02	5.10	3609.01	0.11778554	2.309520399
	140701_CL_B_#1_Leaves_03	4.90	3716.9	0.122092698	2.491687721
	140701_CL_B_#2_Leaves_01	5.10	3753.12	0.123538664	2.422326749
	140701_CL_B_#2_Leaves_02	5.00	4294.2	0.145139527	2.902790531
	140701_CL_B_#2_Leaves_03	5.10	4081.36	0.136642581	2.679266285
	140701_CL_B_#1_Stem_01	5.10	2570.16	0.076312827	1.496329938
	140701_CL_B_#1_Stem_02	5.00	2667.45	0.080196814	1.603936285
	140701_CL_B_#1_Stem_03	5.00	2617.84	0.078216296	1.564325921
	140701_CL_B_#2_Stem_01	5.00	2006.03	0.053791768	1.075835363
	140701_CL_B_#2_Stem_02	5.10	1895.75	0.049389197	0.968415631
	140701_CL_B_#2_Stem_03	5.00	1961.29	0.052005669	1.040113378
	140911_CL_B_#3_Stem_01	7.70	2685.32	0.080910216	1.050782026
	140911_CL_B_#3_Stem_02	4.60	2040.06	0.055150305	1.198919683
	140911_CL_B_#3_Stem_03	5.20	1949.54	0.051536588	0.991088236
CL_A	140701_CL_A_#1_REP_01	5.10	4192.11	0.141063915	2.765959112
	140701_CL_A_#1_REP_02	5.10	3860.26	0.127815881	2.506193743
	140701_CL_A_#1_REP_03	5.00	4016.12	0.134038085	2.680761707
CL_B	140702_CL_B_#1_REP_01	5.10	4321.08	0.146212623	2.866914182
	140702_CL_B_#1_REP_02	5.00	4195.7	0.141207234	2.824144676
	140702_CL_B_#1_REP_03	5.00	4081.95	0.136666134	2.733322688
CL_A	141002_CL_A_Roots_01	5.60	1767.52	0.044270031	0.790536263
	141002_CL_A_Roots_02	6.10	1804.92	0.045763104	0.750214825
	141002_CL_A_Roots_03	5.70	1746.26	0.043421294	0.761777092
CL_B	141002_CL_B_Roots_01	5.50	1883.04	0.048881792	0.888759849
	141002_CL_B_Roots_02	6.30	1161.93	0.020093816	0.318949462
	141002_CL_B_Roots_03	6.60	1737.64	0.043077169	0.652684375
	141002_CL_B_Roots_04	6.20	2122.38	0.058436664	0.942526841
	141002_CL_B_Roots_05	4.90	1718.76	0.042323446	0.863743797
SA_A	140704_SA_A_#0_ALL_01	5.10	3077.9	0.096582698	1.89377839
	140704_SA_A_#0_ALL_02	5.10	2939.31	0.091049942	1.785292983
	140704_SA_A_#0_ALL_03	5.00	2781.79	0.084761468	1.69522935
SA_B	140704_SA_B_#1_Leaves_01	5.00	2982.89	0.092789732	1.855794643
	140704_SA_B_#1_Leaves_02	5.10	2969.21	0.092243603	1.808698089
	140704_SA_B_#1_Leaves_03	5.00	2922.45	0.090376861	1.807537227
	140704_SA_B_#0_ALL_01	5.00	2596.97	0.077383129	1.547662581
	140704_SA_B_#0_ALL_02	5.00	2763	0.084011338	1.680226756
	140704_SA_B_#0_ALL_03	5.10	2872.88	0.08839794	1.733292942
SA_A	141002_SA_A_Roots_01	4.40	1604.47	0.037760789	0.858199747
	141002_SA_A_Roots_02	6.90	2012.21	0.054038485	0.783166443
	141002_SA_A_Roots_03	6.70	2051.73	0.055616192	0.830092422

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Table B.6: Baseline TN 3000 data for SA, IV, and SF species

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)
SA_B	141002_SA_B_Roots_01	6.50	1876.16	0.04860713	0.747802
	141002_SA_B_Roots_02	5.50	1433.86	0.030949739	0.562722518
	141002_SA_B_Roots_03	5.40	1492.57	0.033293545	0.616547123
	141002_SA_B_Roots_04	4.60	1667.6	0.040281049	0.875674981
	141002_SA_B_Roots_05	6.40	1831.54	0.046825821	0.731653459
IV_A	140704_IV_A_#1_Leaves_01	5.00	3564.52	0.116009422	2.320188431
	140704_IV_A_#1_Leaves_02	5.00	3281.57	0.104713561	2.094271228
	140704_IV_A_#1_Leaves_03	5.10	3676.47	0.120478662	2.362326702
	140704_IV_A_#2_Leaves_01	5.10	3342.44	0.107143599	2.100854873
	140704_IV_A_#2_Leaves_02	5.20	3733.08	0.122738632	2.360358313
	140704_IV_A_#2_Leaves_03	5.10	3569.7	0.116216216	2.278749338
IV_B	140704_IV_B_#1_Leaves_01	5.10	3830.43	0.126625015	2.482843431
	140704_IV_B_#1_Leaves_02	5.00	3720.24	0.122226037	2.444520739
	140704_IV_B_#1_Leaves_03	5.10	4035.26	0.134802188	2.643180151
IV_A	141002_IV_A_Roots_01	6.30	2773.56	0.084432911	1.340204944
	141002_IV_A_Roots_03	7.40	2605.22	0.077712484	1.050168696
IV_B	141002_IV_B_Roots_01	7.70	1936.36	0.05101042	0.662472982
	141002_IV_B_Roots_02	5.60	1759.6	0.04395385	0.784890187
SF_A	140704_SF_A_#1_Leaves_01	5.00	2442.38	0.071211625	1.424232504
	140704_SF_A_#1_Leaves_02	5.00	2996.29	0.093324684	1.866493672
	140704_SF_A_#1_Leaves_03	4.90	2888.43	0.089018723	1.816708639
	140908_SF_A_#1_Leaves_04	6.00	3470.92	0.112272745	1.871212424
	140630_SF_A_#2_Leaves_01	5.00	2862.02	0.08796439	1.759287796
	140630_SF_A_#2_Leaves_02	5.10	3121.77	0.098334065	1.928118926
	140630_SF_A_#2_Leaves_03	5.10	3015.76	0.09410196	1.845136474
	140704_SF_A_#1_Stem_01	4.90	1977.68	0.052659986	1.074693601
	140704_SF_A_#1_Stem_02	5.10	2186.46	0.06099485	1.195977453
	140704_SF_A_#1_Stem_03	5.00	1868.09	0.048284961	0.96569923
	140908_SF_A_#1_Stem_04	5.90	2297.86	0.065442133	1.109188702
	140704_SF_A_#2_Stem_01	5.10	2046.82	0.055420176	1.086670127
	140704_SF_A_#2_Stem_02	5.10	1940.61	0.051180087	1.003531118
	140704_SF_A_#2_Stem_03	5.00	1679.81	0.040768494	0.815369875
	140908_SF_A_#2_Stem_04	5.30	2116.22	0.058190746	1.097938606
SF_B	140630_SF_B_#1_Leaves_01	5.00	2806.35	0.085741946	1.714838916
	140630_SF_B_#1_Leaves_02	5.00	3231.98	0.102733842	2.054676833
	140630_SF_B_#1_Leaves_03	5.10	3408.81	0.109793205	2.152807947
	140908_SF_B_#1_Leaves_04	6.10	3789.98	0.12501018	2.049347214
	140630_SF_B_#2_Leaves_01	5.00	3518.81	0.114184598	2.283691964
	140630_SF_B_#2_Leaves_02	5.00	3240.69	0.10308156	2.061631203
	140630_SF_B_#2_Leaves_03	5.10	3144.82	0.099254262	1.946161993
	140704_SF_B_#1_Stem_01	5.20	1760.45	0.043987784	0.845918922
	140704_SF_B_#1_Stem_02	5.20	1748.41	0.043507126	0.836675501
	140704_SF_B_#1_Stem_03	5.20	2125.13	0.058546449	1.125893249
	140704_SF_B_#2_Stem_01	5.20	2206.44	0.061792487	1.188317052
	140704_SF_B_#2_Stem_02	5.10	1875.98	0.048599944	0.952940081
	140704_SF_B_#2_Stem_03	5.10	2573.02	0.076427003	1.498568688
	140908_SF_B_#2_Stem_04	5.40	2489.94	0.073110304	1.353894515
	140908_SF_B_#2_Stem_05	4.90	2258.85	0.063884786	1.303771139
	1400911_SF_B_#3_Stem_01	5.50	2915.43	0.090096611	1.638120194
	1400911_SF_B_#3_Stem_02	5.40	2693.47	0.081235578	1.50436256
	1400911_SF_B_#3_Stem_03	7.10	3291.76	0.105120364	1.480568508
SF_A	140630_SF_A_#1_Roots_01	5.00	2369.7	0.068310112	1.366202244
	140630_SF_A_#1_Roots_02	5.20	2255.1	0.063735079	1.225674601
	140630_SF_A_#1_Roots_03	5.10	2544.41	0.075284842	1.476173367
	140630_SF_A_#2_Roots_01	5.10	2369.7	0.068310112	1.339413964
	140630_SF_A_#2_Roots_02	4.90	2308.25	0.06585692	1.344018784
	140630_SF_A_#2_Roots_03	5.00	2298.58	0.065470877	1.309417542
SF_B	140630_SF_B_#1_Roots_01	5.10	2788.02	0.08501018	1.666866275
	140630_SF_B_#1_Roots_02	5.10	2736.2	0.082941435	1.626302643
	140630_SF_B_#1_Roots_03	5.10	2902.25	0.089570442	1.756283175
	140630_SF_B_#2_Roots_01	5.10	2637.57	0.079003952	1.549097103
	140630_SF_B_#2_Roots_02	5.10	2973.93	0.092432033	1.812392808
	140630_SF_B_#2_Roots_03	5.10	2562	0.075987065	1.489942458

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Table B.7: Baseline TN 3000 data for HL and TD species

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)
HL_A	140705_HL_A_#1_Leaves_01	5.10	3560.81	0.115861312	2.271790428
	140705_HL_A_#1_Leaves_02	5.10	3711.13	0.12186235	2.389457839
	140705_HL_A_#1_Leaves_03	5.10	3460.3	0.111848776	2.193113263
	140705_HL_A_#2_Leaves_01	5.10	3494.98	0.113233263	2.220260055
	140705_HL_A_#2_Leaves_02	5.10	3385.86	0.108877001	2.134843158
	140705_HL_A_#2_Leaves_03	5.10	3346.38	0.10730089	2.103939025
HL_B	140705_HL_B_#1_Leaves_01	5.10	3874.82	0.128397142	2.517591012
	140705_HL_B_#1_Leaves_02	5.10	3634.42	0.118799952	2.329410825
	140705_HL_B_#1_Leaves_03	5.10	3808.41	0.125745938	2.465606627
	140705_HL_B_#2_Leaves_01	5.00	3590.92	0.117063356	2.341267116
	140705_HL_B_#2_Leaves_02	5.00	3375.35	0.108457423	2.169148469
	140705_HL_B_#2_Leaves_03	5.10	3303.69	0.105596631	2.070522169
HL_A	140705_HL_A_Bulbs_01	5.10	1917.5	0.050257495	0.985441084
	140705_HL_A_Bulbs_02	5.10	1778.67	0.044715158	0.87676781
	140705_HL_A_Bulbs_03	5.10	1651.2	0.039626332	0.77698691
HL_B	140705_HL_B_Bulbs_01	5.10	1360.81	0.028033454	0.549675577
	140705_HL_B_Bulbs_02	5.10	1544.37	0.035361491	0.693362578
	140705_HL_B_Bulbs_03	5.00	1363.24	0.028130464	0.562609286
HL_A	140705_HL_A_Roots_01	5.10	2441.32	0.071169308	1.395476631
	140705_HL_A_Roots_02	5.10	2458.93	0.07187233	1.409261377
	140705_HL_A_Roots_03	5.10	2102.23	0.057632241	1.130043937
HL_B	140705_HL_B_Roots_01	5.00	2225.73	0.062562577	1.251251547
	140705_HL_B_Roots_02	5.10	2202.83	0.061648369	1.208791553
	140705_HL_B_Roots_03	5.00	2285.78	0.064959879	1.299197573
TD_A	140623_TD_A_#1_Leaves_01	5.20	3672.47	0.120318975	2.313826439
	140623_TD_A_#1_Leaves_02	5.10	3234.64	0.102840034	2.016471246
	140623_TD_A_#1_Leaves_03	5.10	3596.37	0.117280929	2.299626066
	140623_TD_A_#2_Leaves_01	5.00	3329.92	0.106643778	2.132875564
	140623_TD_A_#2_Leaves_02	5.00	3785.35	0.124825342	2.496506847
	140623_TD_A_#2_Leaves_03	5.00	3449.19	0.111405246	2.228104914
	140623_TD_A_#1_Stem_01	5.10	2634.68	0.078888578	1.54683487
	140623_TD_A_#1_Stem_02	5.00	2463.71	0.072063156	1.441263124
	140623_TD_A_#1_Stem_03	5.20	2423.48	0.070457104	1.354944309
	140626_TD_A_#2_Stem_01	5.10	2738.56	0.08303565	1.628150002
	140626_TD_A_#2_Stem_02	5.10	2717.98	0.08221406	1.612040401
	140626_TD_A_#2_Stem_03	5.10	2472.18	0.072401293	1.419633205
TD_B	140626_TD_B_#1_Leaves_01	5.10	3741.87	0.123089544	2.41352048
	140626_TD_B_#1_Leaves_02	5.00	4192.43	0.14107669	2.821533794
	140626_TD_B_#1_Leaves_03	5.10	3770.1	0.124216536	2.435618345
	140626_TD_B_#2_Leaves_01	5.00	3712.42	0.121913849	2.438276977
	140626_TD_B_#2_Leaves_02	5.10	3813.63	0.12595433	2.469692736
	140626_TD_B_#2_Leaves_03	5.10	4165.38	0.139996806	2.745035417
	140623_TD_B_#1_Stem_01	5.10	2965.67	0.09210228	1.80592705
	140623_TD_B_#1_Stem_02	5.20	3164.69	0.100047507	1.923990517
	140623_TD_B_#1_Stem_03	5.10	2973.71	0.09242325	1.812220597
	140623_TD_B_#2_Stem_01	5.00	3204.27	0.10162761	2.032552198
	140623_TD_B_#2_Stem_02	5.00	2863.91	0.088039842	1.760796838
	140623_TD_B_#2_Stem_03	5.00	2934.52	0.090858717	1.817174338
TD_A	141001_CL_A_Roots_01	6.10	3273.04	0.104373029	1.71103326
	141001_CL_A_Roots_02	5.40	2107.65	0.057848617	1.07127068
	141001_CL_A_Roots_03	7.10	1270.26	0.02441854	0.343923094
	141002_CL_A_Roots_04	5.10	2845.15	0.08729091	1.711586467
	141002_CL_A_Roots_05	5.60	2880.35	0.088696156	1.58385992
TD_B	141001_CL_B_Roots_01	7.20	2916.72	0.09014811	1.252057079
	141001_CL_B_Roots_02	5.40	2489.98	0.073111901	1.353924087
	141001_CL_B_Roots_03	6.30	3229.33	0.102628049	1.629016651
	141001_CL_B_Roots_04	6.60	3553.18	0.115556709	1.750859225
	141002_CL_B_Roots_05	6.30	3002.79	0.093584175	1.485463096

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Table B.8: Harvested above ground TN 3000 total nitrogen concentration data for CF, TO, FL, SC, SP, and EH species.

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)	Total Sample Dry Weight (g)
CF	140730_CF_#1_AGB_01	5.00	2347.21	0.067412272	1.348245439	2.01
	140730_CF_#1_AGB_02	5.00	2426.55	0.070579664	1.411593277	
	140730_CF_#1_AGB_03	5.00	2261.05	0.063972614	1.279452274	
CF	140825_CF_#7_AGB_01	5.30	1953.62	0.051699469	0.97546168	1.08
	140825_CF_#7_AGB_02	5.20	2010.29	0.053961835	1.037727592	
	140825_CF_#7_AGB_03	4.90	1916.79	0.050229151	1.025084712	
	140825_CF_#2_AGB_01	5.20	2274.22	0.064498383	1.240353522	5.27
	140825_CF_#2_AGB_02	5.10	2186.87	0.061011218	1.196298392	
	140825_CF_#2_AGB_03	5.10	2149.32	0.059512156	1.166905023	
TO	140825_TO_#1_AGB_01	5.10	1755.36	0.043784582	0.85852122	5.17
	140825_TO_#1_AGB_02	5.20	1923.71	0.050505409	0.971257873	
	140825_TO_#1_AGB_03	5.50	1948.92	0.051511837	0.936578851	
	140825_TO_#4_AGB_01	5.40	2400.48	0.069538904	1.287757477	5.24
	140825_TO_#4_AGB_02	5.50	2478.15	0.072639626	1.320720479	
	140825_TO_#4_AGB_03	5.10	2124.34	0.058514911	1.147351192	
	140825_TO_#6_AGB_01	5.00	2625.69	0.078529682	1.570593636	1.86
	140825_TO_#6_AGB_02	5.30	2566.33	0.076159927	1.436979746	
	140825_TO_#6_AGB_03	5.30	2542.85	0.075222564	1.419293656	
FL	140825_FL_#2_AGB_01	5.30	2981.44	0.092731846	1.749657464	3.91
	140825_FL_#2_AGB_02	5.80	2974.9	0.092470757	1.594323402	
	140825_FL_#2_AGB_03	5.70	2575.98	0.076545171	1.342897745	
	140825_FL_#2_AGB_04	5.70	2469.12	0.072279133	1.268054963	
	140825_FL_#2_AGB_05	5.60	2789.88	0.085084435	1.519364902	
	140825_FL_#4_AGB_01	5.30	2735.99	0.082933051	1.564774551	2.08
	140825_FL_#4_AGB_02	5.10	2557.44	0.075805022	1.486372983	
	140825_FL_#4_AGB_03	5.30	2752.99	0.083611721	1.577579642	
	140825_FL_#5_AGB_01	5.30	2781.47	0.084748693	1.599031935	13.78
	140825_FL_#5_AGB_02	5.00	2587.61	0.077009461	1.540189229	
	140825_FL_#5_AGB_03	5.20	2447.97	0.071434788	1.37374592	
SC	140826_SC_#1_AGB_01	5.30	2348.99	0.067483333	1.273270428	34.11
	140826_SC_#1_AGB_02	5.50	2577.97	0.076624616	1.393174832	
	140826_SC_#1_AGB_03	5.30	2342.22	0.067213062	1.268170989	
	140826_SC_#6_AGB_01	5.30	2419.3	0.070290231	1.326230776	87.30
	140826_SC_#6_AGB_02	5.60	2391.11	0.069164837	1.235086374	
	140826_SC_#6_AGB_03	5.90	2294.99	0.065327558	1.107246746	
	140826_SC_#7_AGB_01	5.20	2232.74	0.062842429	1.208508247	59.48
	140826_SC_#7_AGB_02	5.20	2477.37	0.072608487	1.396317065	
	140826_SC_#7_AGB_03	5.10	2683.48	0.08083676	1.585034509	
	140826_SC_#7_AGB_04	4.70	2325.91	0.066561939	1.41621146	
SP	140826_SP_#2_AGB_01	5.20	1685.27	0.040986467	0.788201279	18.76
	140826_SP_#2_AGB_02	5.70	1759.47	0.043948661	0.771029134	
	140826_SP_#2_AGB_03	5.50	1635.23	0.038988782	0.708886945	
	140826_SP_#4_AGB_01	5.50	2179.42	0.060713801	1.10388729	11.14
	140826_SP_#4_AGB_02	4.90	1958.69	0.051901872	1.059221884	
	140826_SP_#4_AGB_03	5.70	2032.51	0.054848896	0.962261336	
	140826_SP_#11_AGB_01	5.40	1949.04	0.051516627	0.954011619	23.87
	140826_SP_#11_AGB_02	4.70	1736.25	0.043021678	0.915354841	
	140826_SP_#11_AGB_03	5.40	1961.59	0.052017645	0.96328973	
EH	140826_EH_#1_AGB_01	4.60	1331.24	0.026852968	0.583760178	2.61
	140826_EH_#1_AGB_02	6.10	1733.6	0.042915885	0.703539096	
	140826_EH_#1_AGB_03	4.80	1592.71	0.037291309	0.776902272	
	140826_EH_#1_AGB_04	5.50	1625.49	0.038599944	0.701817166	
	140826_EH_#2_AGB_01	5.00	2217.76	0.062244401	1.244888019	8.57
	140826_EH_#2_AGB_02	5.20	2247.61	0.063436065	1.219924333	
	140826_EH_#2_AGB_03	4.80	2072.03	0.056426604	1.175554247	
	140826_EH_#3_AGB_01	5.30	1738.63	0.043116691	0.813522477	6.77
	140826_EH_#3_AGB_02	4.70	1610.61	0.038005908	0.808636349	
	140826_EH_#3_AGB_03	5.50	1857.78	0.047873368	0.870424876	

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Table B.9: Harvested above ground TN 3000 total nitrogen concentration data for CL, SA, IV, and SF species.

Plant ID	Sample Code	Sample Weight (mg)	Area	mg N	% (mgN/mg Sample)	Total Sample Dry Weight (g)
CL	140826_CL_#2_AGB_01	5.10	2328.18	0.066652561	1.30691296	7.33
	140826_CL_#2_AGB_02	4.70	2121.07	0.058384367	1.242220567	
	140826_CL_#2_AGB_03	5.50	2424.64	0.070503413	1.281880242	
	140826_CL_#4_AGB_01	5.50	2099.22	0.057512076	1.045674115	2.94
	140826_CL_#4_AGB_02	4.90	1890.1	0.049163639	1.003339577	
	140826_CL_#4_AGB_03	4.60	1841.01	0.04720388	1.026171313	
	140826_CL_#5_AGB_01	5.80	2374.34	0.068495349	1.180954295	6.90
	140826_CL_#5_AGB_02	4.70	2109.87	0.057937243	1.232707298	
	140826_CL_#5_AGB_03	5.40	2424.58	0.070501018	1.305574407	
SA	140827_SA_#4_AGB_01	4.70	2514.89	0.074106352	1.576730884	10.00
	140827_SA_#4_AGB_02	5.50	2752.32	0.083584973	1.51972679	
	140827_SA_#4_AGB_03	5.20	2458.79	0.071866741	1.382052715	
	140827_SA_#1_AGB_01	4.90	2577.5	0.076605853	1.563384745	5.50
	140827_SA_#1_AGB_02	4.60	2376.46	0.068579983	1.490869201	
	140827_SA_#1_AGB_03	5.40	2548.79	0.075459699	1.397401833	
	140827_SA_#2_AGB_01	5.20	2594.12	0.077269352	1.485949078	4.96
	140827_SA_#2_AGB_02	5.10	2510.51	0.073931494	1.449637143	
	140827_SA_#2_AGB_03	5.30	2596.42	0.077361172	1.459644757	
IV	140827_IV_#3_AGB_01	5.40	2179.4	0.060713003	1.124314861	15.75
	140827_IV_#3_AGB_02	5.60	2253.53	0.063672402	1.13700718	
	140827_IV_#3_AGB_03	5.50	2076.51	0.056605453	1.02919006	
	140827_IV_#4_AGB_01	5.50	2134.59	0.058924109	1.071347432	6.25
	140827_IV_#4_AGB_02	5.50	2070.59	0.056369117	1.024893028	
	140827_IV_#4_AGB_03	5.50	2108.83	0.057895724	1.052649534	
	140827_IV_#5_AGB_01	5.60	1898.69	0.049506567	0.884045842	6.00
	140827_IV_#5_AGB_02	5.60	1874	0.048520899	0.866444626	
	140827_IV_#5_AGB_03	5.10	1805.76	0.045796639	0.897973306	
SF	140827_SF_#2_AGB_01	5.40	2388.23	0.069049862	1.278701153	5.18
	140827_SF_#2_AGB_02	5.30	2590.57	0.07712763	1.455238299	
	140827_SF_#2_AGB_03	5.70	2571.87	0.076381093	1.340019176	
	140827_SF_#5_AGB_01	5.50	2634.62	0.078886183	1.434294238	14.45
	140827_SF_#5_AGB_02	5.00	2366.93	0.068199529	1.363990578	
	140827_SF_#5_AGB_03	5.80	2755	0.083691964	1.442964892	
	140827_SF_#8_AGB_01	4.70	2372.46	0.068420296	1.455750983	40.40
	140827_SF_#8_AGB_02	5.20	2543.34	0.075242125	1.446963951	
	140827_SF_#8_AGB_03	4.90	2621.85	0.078376382	1.599518006	

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Appendix C: List of Symbols and Acronyms

$\overline{TN}_{Acc}(x_i)$	Mean TN Concentration of Sample Plant Species (mg N/g biomass)
$\overline{\sigma}_{TN}$	Mean Total Nitrogen Density (mg N/m^2)
A	Annuals
A_C	Canopy Area (m^2)
AG	Above Ground
AG	Arachis glabrata
ANOVA	Analysis of Variance
APRC	Pollutant Removal Capacity (Acclimated)
ASCE	American Society of Civil Engineers
BAG	Baseline Above Ground Concentration
BBG	Baseline Below Ground Concentration
BG	Below Ground
BR 1	Bioretention 1
BR 2	Bioretention 2
BR 3	Bioretention 3
BR 4	Bioretention 4
BR 5	Bioretention 5
BR 6	Bioretention 6
BR 7	Bioretention 7
BR 8	Bioretention 8
BWL	Attracts Beneficial Wildlife
C	Coreopsis lanceolata

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C-1	Column 1
C-2	Column 2
CA	Callicarpa americano
CF	Canna flaccida
CH	Create Habitat
CL	Coreopsis leavenworthii
CN	Curve Number
D_B	Biomass Sample Dry Weight (g Biomass)
DCIA	Directly Connected Impervious Area, (%)
DoE	U.S. Department of Education
DTIB	Dynamic Theory of Island Biogeography
DW	Dry Weight
DW	A Terrestrial or Aquatic Species That Equally Tolerates Well Drained To Wet Soil Conditions
E	Establishment
EC	Evapotranspiration Capacity
EDP	Engineering Design Process
EH	Equisetum hyemale
EPA	Environmental Protection Agency
EPR	Establishment and Propagation Rate
ET	Evapotranspiration
f(x)	Function for Calculating the Quantitative Level Score
FL	Flaveria linearis

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FR	A Fine Root Biomass with Fibrous Root Structure
FT	A Mix of Fibrous and Tap Roots
GA	Graduate Assistant
GEC	Grand Engineering Challenges
GI	Green infrastructure
GSBL	Green Space Based Learning
GT	Glandularia tampensis
H	Harvestable
HA	Harvested Concentration
HA	Harvested Concentration
HCPS	Hillsborough County Public Schools
HD	Helianthus debilis
HH	Harvest Height
HL	Hymenocallis latifolia
HM	A Aquatic Species That May Be Classified As Submerged or Floating; or Emergent Vegetation That Will Not Readily Survive In Dry Conditions
HRT	Hydraulic Residence Time
HSE	Human, Social, and Economic Impacts
IMP	Impervious Surface, (%)
IPRC	Pollutant Removal Capacity (Initial)
IV	Iris virginica
IWS	Internal Water Storage
k	User Assigned Integer Ranking (k = 1,2,3… n)

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K-12	Kindergarten through 12th Grade
k_i	Function Parameter
LID	Low Impact Development
LLP	Long Lived Perennials
LLSS	A LLP That Reproduces Via Seed or Spores
LM	Limited Maintenance
LPR	LLP That Reproduces Via Rhizome Propagation
LPSP	A LLP That Reproduces via Seed and Rhizome Propagation at Equal Rates
MAE	Mean Actual Evapotranspiration
MC	Muhlenbergia capillaris
MD	Mean Density
ME	Mimics Environment
MF	Myrcianthus fragrans
MOIRL	Multiple Outcome Interdisciplinary Research and Learning
MP	Monardo punctate
MS	A Terrestrial or Aquatic Species That Prefers Moist Soil Conditions
MS	Mimosa strigillosa
MV	Medicinal Value, Including Reduced Mosquito Breeding
NAE	National Academy of Engineering
NF	A Root Network That Harbors Nitrogen Fixing Bacteria
NF	A Terrestrial Plant Species That Will Not Tolerate Fluctuations in Water Levels
NGR	Native to Geographical Region

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NGSS	Next Generation Science Standards
NH_3	Ammonia
NH_4^+	Ammonium
NIST	National Institute of Standards and Technology
NMI	Native Species with Minimal Impact from Pests and Disease.
NO_2^-	Nitrite
NO_3^-	Nitrate
NOAA	National Oceanic Atmospheric Association
NRC	National Research Council
NS	Native Species Free Of Pests and Disease
NS	Native Species Free Of Pests and Disease
NSF	National Science Foundation
OECD	Organization for Economic Cooperation and Development
ORG-N	Organic-N
P	Propagation
P3	People, Planet and Prosperity
PGC	Prince George County
PISA	Program for International Student Assessment
PL	Penta lanceolata
CH	Chamaecrista fasciculata
PSI	Plant Selection Utility Index
Q1	Annually
Q2	Semi-Annually

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Q_{DCIA}	Rainfall Excess for DCIA, (cm)
Q_{nDCIA}	Rainfall Excess for non-DCIA, (cm)
Q_R	Total rainfall excess, (cm)
R	Rainfall Event, (cm)
RET	Research Experience for Teachers
REU	Research Experience for Undergraduates
RF	Regionally Friendly Species Free Of Pests and Disease
RGR	Rapid Growth Rate
RMI	Regionally Friendly Species with Minimal Impact from Pests and Disease.
RN	Root Network
S	Soil Storage, (cm)
SA	Sisyrinchium angustifolium
SC	Salvia coccinea
SCS	Soil Conservation Service
SD	Stomata Density
SF	Solidago fistulosa
SI	Invasive Species
SJ	Stachytarpheta jamaicensis
SLP	Short Lived Perennials
SLSS	A SLP or A That Reproduces Via Seed or Spores
SP	Spartina patens
SPR	SLP or A That Reproduces via Rhizome Propagation

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SPSP	A SLP or A That Reproduces Via Seeds and Rhizome Propagation at Equal Rates
SR	Silphium asteriscus
SRE	Species Rich Ecosystem
SRM	Standard Reference Material
SV	Subsistence Value, Including Resale for More Bioretention Systems
SWFWMD	Southwest Florida Water Management District
TAN	Total Ammonia Nitrogen (TAN = NH_3 + NH_4^+)
TD	Tripsacum dactyloides
TIV	Textile or Industrial Value
TKN	Total Kjeldahl Nitrogen (TKN = org-N + TAN)
TN	Total Nitrogen
TO	Tradescantia ohiensis
TR	A Bulk Root Biomass with Tap Root Structure
TVI	Tampa Vocational Institute
$u(x)$	Additive Utility function (PSI score)
UH	Unable To Harvest Annually or Insignificant Harvest
USF	University of South Florida
USMCU	Urban Stormwater Management Curricular Unit
$v_i(x_i)$	Single Attribute Utility Function
WARE	Water Awareness Research and Education
WD	A Terrestrial or Aquatic Species That Prefers Well Drained Soil Conditions
WEF	Water Environment Federation

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w_i	User Defined Weighting Factor
XBWL	Does Not Attract Beneficial Wildlife
ZP	Samia puila
α	Post-hoc Confidence Factor
η	Porosity

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ABOUT THE AUTHOR

Ryan C. R. Locicero is a Graduate Assistance in Areas of National Need (GAANN) fellow at the University of South Florida Water-Energy-Materials-Human Nexus. He received his BS in Civil Engineering from the University of South Florida and Masters of Engineering in Environmental Engineering Sciences from the University of Florida. Between his BS and ME degree, Ryan worked for three years as an E.I.T for a private consultant, Stantec (formerly WilsonMiller Inc.). As a member of the public infrastructure group, Ryan was involved with several redevelopment projects for the City of Tampa (COT) and master planning for the (COT) Channel District. Ryan's dissertation is in partial fulfillment of his PhD in Environmental Engineering, focusing on transforming green spaces on school campuses and throughout the community into multi-use educational environments through the introduction of green infrastructure improvement projects. The goal of his research is to mainstream green infrastructure and stormwater management by focusing on education and outreach as a driving force for change in public and professional perception. In recognition of his academic achievements, Ryan was awarded the prestigious 2013/2014 Water Environment Federation Canham Graduate Studies Scholarship.

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