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BIORETENTION IN A MIXED-USE AGRICULTURAL LANDSCAPE: LESSONS LEARNED FROM THE APPLICATION OF LOW-PHOSPHORUS COMPOST AND *PANICUM VIRGATUM*

A Thesis Presented

by

Jason M. Kokkinos

to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
For the degree of Master of Science
Specializing in Plant and Soil Science

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Thesis Examination Committee:

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Abstract

Bioretention cells are a stormwater treatment technology that uses soil and vegetation to remove pollutants from runoff and improve downstream water quality. While bioretention has been shown to be effective at removing certain stormwater pollutants such as sediment and heavy metals, removal of nutrients has been more variable. Design components of bioretention such as vegetation and soil media amendments can influence pollutant removal performance. In my experiment, I isolate the effects of low-phosphorus compost and a Switchgrass (*Panicum virgatum*) monoculture on bioretention performance. In fall 2016, three bioretention cells were installed at the University of Vermont Miller Research Complex, a mixed-use research and agricultural production facility located in South Burlington, VT. Each bioretention cell had a unique experimental treatment that allowed for the comparison of the presence of the following design components: (1) compost with planted vegetation, (2) no compost and vegetation, and (3) no compost or vegetation. Results suggest that the presence of a low-P compost layer had a small deleterious effect on nutrient removal performance, as the bioretention cell with an added compost layer exported higher concentrations of phosphorus and nitrogen and exhibited a higher concentration of water extractable phosphorus in the bioretention media. The bioretention cell with vegetation and no compost was the only treatment to significantly reduce total nitrogen and phosphorus concentrations; however, there was no effect on media phosphorus concentration. The presence of low-P compost significantly increased the above-ground biomass growth of Switchgrass, but had no effect on the total number of plants surviving in the first year. Switchgrass proved to be a durable plant, capable of surviving in bioretention media without compost, but was slow to grow and required additional watering through droughty conditions.

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Table of Contents

Page

List of Figures

Page

List of Tables

Page

List of Equations

Page

Chapter One: Thesis Overview

Alteration of landscapes through urbanization and agriculture can have a significant impact on local hydrology and biogeochemistry, with negative implications for downstream water quality (Booth and Jackson 1997). The proliferation of impervious area and loss of the ability for landscapes to retain stormwater can dramatically increase runoff volume and flow (Dunne and Leopold 1978). This stormwater can carry excessively high pollutant loads, including nutrients and sediment, which can accelerate eutrophication and degrade aquatic habitat (House et al. 1993, Boogard et al. 2014). A recent survey of national water quality found that non-point source loading of pollutants via stormwater runoff has been determined to be the primary cause for estuary impairment and third leading cause of lake impairment in the United States (US EPA 2009).

Bioretention is one stormwater treatment solution that attempts to restore landscapes to their predevelopment hydrological conditions and treat runoff of pollutants using natural processes (Debusk and Wynn 2011). Bioretention consists of a depression in the ground, filled with high permeability soil and planted with herbaceous vegetation (Roy-Poirier et al. 2010). In these units, stormwater is captured and retained, thereby being treated by interaction with the plants, soil, and microbial community, and mimicking ecosystems services that may have been lost by development. In addition to the removal of stormwater pollutants and attenuation of flow, bioretention cells can have ancillary recreational, educational, and aesthetic benefits (Jones and Jha 2009).

Bioretention also provides flexibility in its design; specific components, such as the soil media or vegetation palette, can be altered based on the specific needs of the landscape or pollutants targeted for removal. While this technology has been demonstrated as consistently effective at treating stormwater of sediment (Hsieh and Davis 2005), metals (Sun and Davis 2007), and pathogenic organisms (Rusciano and Obropta 2007), removal of nutrients has been more variable (Dietz and Clausen 2005, Hunt et al. 2006, Manka et al. 2016). In order to meet water quality goals, bioretention designers will require a greater understanding of the factors that influence nutrient removal performance.

One component of bioretention design that can influence nutrient removal is the presence of organic matter in the soil media. Compost is often recommended in bioretention cells to improve plant establishment; however, excess nutrient leaching has been observed in previous bioretention projects leading to lower nutrient removal rates or at times a net export (Paus et al. 2014, Mullane et al. 2015). Also, the presence and type of vegetation planted in bioretention cells may influence nutrient retention. The impact of vegetation on nutrient removal in bioretention cells has been shown to range from significantly positive to no effect (Lucas and Greenway 2008, Read et al. 2008).

In this thesis, I report on the effects of low-phosphorus (low-P) compost and *Panicum virgatum* on bioretention performance in a mixed use agricultural landscape. My intention is to detail the benefits and drawbacks to using these specific design components in the context of nutrient treatment, as well as other important factors such as vegetation establishment and soil media sorption potential. I expect my results to better

equip bioretention designers when making decisions on organic soil media amendments and vegetation selection.

Chapter Two of this thesis consists of a comprehensive literature review detailing the impacts of runoff from urban and agricultural landscapes, an overview of bioretention cells' potential to improve water quality including soil media phosphorus sorption, and the documented impacts of compost and vegetation on bioretention performance. Chapter Three reports on the first year of sampling from the University of Vermont Miller Research Complex Bioretention Cells and impacts of low-phosphorus compost and *Panicum virgatum* on performance; this chapter is formatted and intended for publication in a peer vreivewed scientific journal. Chapter Four is a brief analysis of the hydrological conditions of the Miller Research Complex Bioretention Cells and suggestions to improve future sampling. Chapter Five lists methods and results of additional media, vegetation, and water quality analyses performed in this research, but did not meet the scope of the intended article publication.

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Chapter Two: Comprehensive Literature Review

2.1 Runoff in a Changing Landscape

Development and proliferation of impervious area decreases a landscape's ability to naturally retain water, leading to increased runoff volumes and velocity, and subsequently affecting downstream hydrological patterns (Dunne and Leopold 1978). Traditionally, the goal of stormwater management has been to transport runoff away from a site as quickly as possible through drainage and conveyance systems. However, as impervious area increases, this practice has negative implications for the pattern and quality of flow for receiving water bodies (Booth et al. 2002). For example, the percent impervious cover of watersheds has been shown to be directly correlated with stream channel flow and bank erosion (Paul and Meyer 2001, Pappas et al. 2008). A survey of land cover and hydrological regimes in the Puget Sound watershed found that discharge rates of urban watersheds with high impervious area (48-71%) resulted in a two-fold increase in peak flow rate for storms of higher intensity (2-year to 25-year interval storms) when compared to forested watersheds or modeled predevelopment conditions (Wissmar et al. 2004). A comparison of 26 paired watersheds in the Mid-Atlantic region found that urbanized watersheds with high impervious cover had significantly wider stream beds compared with forested watersheds, likely due to the erosion of stream bends and curves (Hession et al. 2002). These effects, in turn, negatively impact the quality of fish habitat (Wang et al. 2001), condition of riparian vegetation (White and Greer 2006), and macroinvertebrate community integrity (Stepenuck et al. 2002). A threshold of approximately 10% impervious area in a watershed has been recognized as the point in

which stream quality begins to be significantly degraded by altered hydrological conditions (Booth and Jackson 1997, Booth et al. 2002).

The volumes of stormwater generated by impervious areas also results in large quantities of pollutants being delivered downstream (Brezonik and Stadelman 2002). Additionally, the greater velocity of runoff allows more particulate pollutants to be carried by the flow (Krishnappan and Marsalek 2002). Pollutants of concern that can be delivered via stormwater runoff include biodegradable organic matter (BOD), nutrients (nitrogen and phosphorus), heavy metals, organic micro-pollutants, solids, and pathogenic organisms (Chiew et al. 1997). An overloading of these pollutants into downstream water bodies can have negative consequences such as physical habitat degradation, dissolved oxygen depletion, accelerated eutrophication, public health risk, and aesthetic deterioration (Carpenter et al. 1998, Gaffield et al. 2003). While its impact has been known since the early 1970's, stormwater pollution continues to be a leading cause for water body impairment in the United States (US EPA 2009).

Accelerated eutrophication, or an excessive richness of nutrients being delivered downstream, is one of the most concerning impacts of stormwater pollutant loading (Ryden et al. 1974, Ghane et al. 2016). Since the industrial revolution, humans have significantly altered the way N and P are delivered to and transported through waterways (Bouwman et al. 2013). The advent of the Haber - Bosch process (for industrial production of ammonia), discharge of human sewage, and utilization of manure and fertilizers at an industrial scale has led to N being readily delivered to waterbodies in excessive quantity (Kim et al. 2014). P is actively mined to the point in which it is becoming a scare resource and approaching its peak availability globally; its fate after use

in agriculture and industry is also a significant concern for water quality (Sharpley et al. 2013, Roy 2017). Excessive loading of either of these nutrients can have negative implications for water quality and human use including reduced water clarity and aesthetics, taste and odor issues, and shifts in fish populations to less desirable species (Carpenter et al. 1998, Smith et al. 1999). Also, N and P are typically the limiting nutrients for primary productivity for marine and freshwater bodies, respectively, and excessive loading can lead to sustained plant and algae growth (Hecky and Kilham 1988, Elser et al. 1977) and/or a shift in the dominant microbial community (Levich 1996). Eutrophication has been linked to harmful algae blooms that release toxins into water (Hallegraeff 1993, Anderson et al. 2002, Heisler et al. 2008, Watson et al. 2016) and to lowering dissolved oxygen levels in waterbodies as heterotrophic bacteria consume biomass and deplete the available oxygen (Miranda et al. 2001). Eutrophication from stormwater continues to pose a challenge for water quality nationwide; there is a present need to identify and mitigate its loading from different landscapes.

2.2 Urban and Agricultural Stormwater

The impact of anthropogenic development on stormwater hydrology and biogeochemical cycling will depend largely on the use and cover of a landscape (Carpenter et al. 1998, Goonetilleke 2005, Mallin et al. 2009). Both urban centers and agricultural landscapes can have significant deleterious effects on water quality (Howarth et al. 2000); however, both categories pose their own unique challenges. While every landscape has a different impact on stormwater, certain similar patterns may exist within the context of land use. In order to address downstream water quality concerns, practitioners will require a greater understanding of stormwater behavior and characteristics in these landscapes.

2.2.1 Urban Watersheds

The term "urban" is often used loosely, but has been defined by the U.S. Census Bureau as an area with greater than 600 residents per square mile (U.S. Census Bureau 2010). This relatively high population density and accompanying infrastructure can have a significant impact on the local hydrology and stormwater flow characteristics (Dunne and Leopold 1978). Generally, urban areas experience amplified stormwater flow due to insufficient area for infiltration into soil and a loss of vegetations' volume attenuation (Booth and Jackson 1997). A survey of a typical American city (i.e. Indianapolis, IN) found that areas defined as "light urban" have an approximate impervious area of 30%, while "dense urban" can have 60% or greater; both classifications are far beyond the less than 10% impervious threshold suggested to maintain stream integrity (Lu and Weng 1996). Streams within watersheds with greater than 60% impervious cover have been

classified as “non-supporting”, or degraded to the point at which it would be exceedingly difficult or impossible to ever restore predevelopment integrity and ecological function (Schueler et al. 2009). The high impervious cover of urban watersheds also results in diminishing groundwater recharge and the accompanying slow, sub-surface feeding of streams (Harbor 1994).

Stormwater loading of pollutants from urban areas has a major effect on downstream water quality, and is estimated to be the reason for the impairment of 5,000 square miles of estuaries, 1.4 million acres of lakes, and 30,000 miles of rivers in the United States (US EPA 2009). A list of stormwater pollutant sources in urban areas includes, but is not limited to: leaf and garden waste, lawn fertilizer, pet waste, herbicides and pesticides, vehicle and industrial emissions, wear from vehicles or machinery, erosion from construction activity, and litter from various sources (Chiew et al. 1997). Given the varying uses of land in urban areas, a clear characterization of urban runoff is difficult and surveys have reported a wide range of pollutant concentrations in runoff (Torno et al. 2013). For example, stormwater sampling of parking lots and bridges found a high and persistent loading of solids, heavy metals, and grease, but relatively low nutrient concentrations (Kim et al. 2007). Conversely, nutrient loading from urban centers can be quite high in areas with exposed human sewage (Nyenje et al. 2010) and urban farming (Niemczynowicz, 1999, Moore et al. 2003). In general, stormwater nutrient concentrations are lower in urban watersheds than the concentrations in runoff from agricultural or forested land uses (Beaulac and Reckhow 1982), as well as lower than wastewater concentrations (Carey and Migliaccio 2009).Further, expected concentrations of pollutants in urban runoff vary depending on factors such as

impervious cover (Konrad et al. 1978, Arnold et al. 1996, Walsh 2004), land use (Mander et al. 2000, Goonetilleke et al. 2005), and population density (Hatt et al. 2004). A brief list of nitrogen and phosphorus concentrations in urban stormwater with a description of accompanying land use is listed in Table 1.

Table 1 – List of average Total Nitrogen (TN) and Total Phosphorus (TP) runoff concentrations or EMCs, with corresponding urban land use.

Study	Avg. Concentration/ EMC		Land Use Description
	TN (mg/L)	TP (mg/L)	
Brezonik and Stadelmann 2002	3.08	0.58	Mixed Urban and Suburban - MN, USA
Carleton et al. 2000	2.18	0.33	Townhouses and Apt. Complex - VA, USA
Hongbing et al. 2009	3.73	2.32	Villages and Asphalt Roads - China
Passeport and Hunt 2009	1.83	0.20	Asphalt Parking Lots - NC, USA
Schueler 2003	2.00	0.26	Suburban Homes and Yards - MD, USA
Taebi and Drost 2004	6.75	2.98	Shops and Residences - Iran

2.2.2 Agricultural Watersheds

Stormwater from agricultural watersheds also poses significant challenges for downstream water quality (Daniel et al. 1998). The amount of area dedicated to agricultural production is vast; it is estimated that over 44.6% of the United States' land area is either traditional row crops or pasture (United Nations Food and Agriculture Organization 2017). While the impervious area of agricultural landscapes is generally less than that of urban watersheds (Brabec 2009), there are a number of factors that can have a similar effect on local hydrology including decreasing evapotransipiration rates (Li et al. 2009), soil compaction (Fullen 1985), and tile draining or loss of wetlands

(Schilling and Helmers 2008). Runoff infiltration could even be higher than predevelopment conditions, causing issues for baseflow and groundwater recharge; baseflow into streams and rivers can increase substantially in spring months when land has been recently plowed or are fallow, leading to negative consequences for stream flow regimes and aquatic habitat (Schilling and Zhang 2004). Finally, farm fields and pastures are not the only components of the agricultural sector with an effect on local hydrology; as farming operations become more industrialized and Concentrated Animal Feeding Operations become more common, water quality managers will need to consider how to regulate and mitigate runoff from landscapes with higher impervious area (parking lots, rooftops, etc.), but have stormwater pollutants similar to that of production fields (i.e. high nutrient and sediment loading) (Donham et al. 2007, Faulkner et al. 2011).

Nonpoint source loading of pollutants from agricultural landscapes has long been recognized as a major impediment to the quality of nearby lakes, rivers, and estuaries (Osborne and Wiley 1988, Howarth et al. 2006). Two of the most common water pollutants from agricultural landscapes are sediments and nutrients (Jordan et al. 2003, Matthaei et al. 2010); however, depending on the type of operation, pesticides (Wauchope 1978) and pathogenic organisms (Harmel et al. 2010) can also be of concern. Erosion of soil due to unsustainable farming practices like over-tilling and exposing bare soil exposed is a common problem in agricultural landscapes (Montgomery 2007). A comparison of soil management practices in olive groves found that the use of cover crops significantly reduced erosion rates compared to conventional tilling (Gomez et al. 2009). The loss of native ecosystem services also influences the rate of erosion from farm fields; an experiment in Georgia showed that root establishment improves soil retention,

as plots planted with a mix of sweet gum and fescue significantly reduced soil loss compared to row crop corn (Nyakatawa et al. 2006).

Soil erosion is one contributing factor to the excessive nutrient export observed from many agricultural landscapes (Ekholm and Lehtoranta 2012). Other factors that lead to sustained nitrogen and phosphors loss, including increasing fertilizer application (McIsaac et al. 2001) and concentration of livestock waste (Mallin et al. 2003). One challenge is in determining the optimum timing and rate of application of livestock manure or fertilizer for crop growth (Hart et al. 2004). If these are applied too soon after rainfall (Smith et al. 2007) or in excessively high concentrations (Beman et al. 2005), nitrogen and phosphorus can be exported off site via runoff in large quantities. The export loading of nitrogen and phosphorus will also depend largely on the volume of runoff produced on site, emphasizing the importance of stormwater volume attenuation (Lowrance et al. 1984, Kang et al. 2001). This further underscores the challenge facing agricultural production facilities that have high impervious area, but are undergoing farming operations with potential for high nutrient loading (i.e. movement and storage of grains, silage, manures, and fertilizers) (Faulkner et al. 2011). A brief list of nitrogen and phosphorus concentrations in agricultural stormwater with a description of accompanying land use is listed in Table 2.

Table 2 – List of average Total Nitrogen (TN) and Total Phosphorus (TP) runoff concentrations and EMCs, with corresponding agricultural land use.

Study	Avg. Concentration/ EMC TN (mg/L)	TP (mg/L)	Land Use Description
Gilley et al. 2007	5.83	2.00	Fallow Land Tilled w/ Cattle Manure - NE, USA
Huett et al. 2005	10.10	0.58	Ornamental Plant Nursery - Australia
Kato et al. 2009	18.41	2.33	Rice Paddies, Vegetable Fields, Pig Barns - Japan
Kim et al. 2006	2.94	0.11	Rice Paddies (Runoff Flow Return Water) - Korea
Liu et al. 2014	6.30	0.49	Cattle Grazing Pasture and Grain Production - China
Packett et al. 2009	4.10	0.63	Active Cattle Grazing Pasture - Australia
Young et al. 1980	49.40	23.10	Active Livestock Feedlot - MN, USA

2.2.3 Eutrophication of Lake Champlain Basin: A Mixed Urban and Agricultural Watershed

In the past several decades, there has been increasing effort in the Lake Champlain Basin (LCB), to identify and mitigate sources of elevated nutrient loads. The LCB is a total of 21,326 km^2, shared by the states of New York and Vermont, on the West and East, respectively, and the territory of Quebec to the North. The LCB can be considered a mixed-use water shed with agricultural and urban land covering a significant fraction of the total land area (16% and 6%, respectively) (US EPA 2016). Phosphorus has been the primary nutrient of concern because of degrading freshwater quality and perennial outbreaks of cyanobacteria blooms (LCBP 2015). While there are a variety of land uses in the basin, models have shown agricultural land to be the greatest overall contributor of phosphorus to Lake Champlain and its tributaries; agriculture covers only about one sixth of the total land area of the basin, but accounts for 28%, or 262 MT Yr^{-1}, of total phosphorus loading (US EPA 2016). Some portions of the watershed have a

substantial proportion of agricultural loading, such as Missisquoi Bay which contributes upwards of 42.3% of its phosphorus load through farming activities. There are also several urban areas within the Lake Champlain Basin that are significant contributors of phosphorus. It is estimated that urban land contributes four times as much phosphorus per unit land area as agricultural land in the Lake Champlain Basin and seven times as much as forested or natural areas, totaling 147 MT Yr-1 (US EPA 2016). Land use is continuing to change in Vermont with expanding urban area yet decreasing total agricultural area, leading to both new challenges and opportunities for water quality management (USDA Economic Research Service 2012).

2.3 Bioretention for Stormwater Treatment: Performance and Limitations

Bioretention is one form landscape design and stormwater treatment technology that attempts to restore a site's predevelopment hydrology and biogeochemistry using natural plant, soil, and microbial processes. Bioretention cells consist of a depression in the ground, filled with high permeability soil and planted with herbaceous or woody vegetation (Roy-Poirier et al. 2010). In these systems, runoff is captured and channeled into the cell, where it collects on the surface and infiltrates through the permeable soil media, typically within 24 hours of the rain event (Davis et al. 2009). In sites where the surrounding soil is mostly clay, urban fill, or infiltration is not desirable for other reasons, bioretention cells can also be designed with an impermeable fabric and/or discharge into an underdrain pipe that is connected to a stormwater drainage system. Bioretention has been shown to mitigate hydrological conditions like elevated stormwater flow or volume (Davis 2008) and lower pollutant loading from developed areas (Cording 2016). While bioretention cells have traditionally been relegated to urban and suburban areas (Davis 2001, Liu et al. 2014), they may also be beneficial for capturing runoff from agricultural landscapes (Ergas et al. 2010, Dietz 2016).

2.3.1 Bioretention Treatment: Hydrology, Filtration, and Sorption

A primary benefit of bioretention cells is their ability to mimic predevelopment hydrological conditions of a site (Debusk et al. 2010). This is achieved through the attenuation of stormwater volume and mitigation of peak flow (Davis 2008). Several studies have observed bioretention cells to fully retain influent stormwater during small storms, resulting in zero effluent volume (Davis 2008). A survey of two bioretention cells

with impermeable liners in Maryland found that approximately one out of every five storm events were fully retained. Peak stormwater flow rates are effectively reduced by bioretention cells; Hatt et al. (2009) observed an average of 80% peak flow reduction in a bioretention cell treating parking lot runoff, though efficiency changed with the intensity of storms. Though generally thought to be effective in this role, the hydrological performance of bioretention cells can be influenced by a number of factors including the soil media's hydraulic conductivity (Le Coustumer et al. 2009) and depth (Brown and Hunt 2010), local temperature and season (Braga et al. 2007), and vegetation evapotranspiration (Wadzuk et al. 2014).

Bioretention cells use a suite of vegetative, soil, and microbial processes to remove stormwater pollutants (Davis et al. 2009, Roy-Poirier et al. 2010). Modeling of a spectrum of planning scenarios has shown that sufficient bioretention cells properly placed in an urban watershed could significantly reduce pollutant loading to nearby waterways, while also providing ancillary landscape benefits such open space and aesthetics (Hurley and Forman 2011). One of the most efficient treatment mechanisms of bioretention cells is physical filtration (Li and Davis 2008). When stormwater passes through the bioretention soil media, particulate pollutants and filterable materials are effectively removed resulting in high mass reductions for sediment (Hsieh and Davis 2005, Li and Davis 2008), heavy metals (Sun and Davis 2007, Muthanna et al. 2007), pathogenic organisms (Rusciano and Obropta 2007), oils and grease (Hong et al. 2006), and particulate/organic nutrients (Hsieh et al. 2007). Another likely mechanism for TSS retention in vegetated bioretention cells is increased hydraulic retention time; the longer time that water is kept within the cells may result in higher sediment sorption and settling

(Hunt et al. 2006). Analysis of bioretention media has shown that capture of these pollutants primarily occurs in the top 15 cm of the soil media (Komlos and Traver 2012, Muerdter et al. 2015) or in an overlying mulch layer, if mulch is present (Hsieh et al. 2007); this may pose a challenge for practitioners as clogging in the upper media has been observed and material may need to be replaced over time to maintain proper drainage (Li and Davis 2008).

Chemical sorption of pollutants to the bioretention media is also an important factor of their treatment performance, especially with regards to phosphorus removal (Henderson et al. 2007). Sand is often used as the soil media in bioretention cells for its high hydraulic conductivity (Le Coustumer et al. 2007); however, the low iron, aluminum, and calcium contents may make it unsuitable for sorption of phosphorus (Del Bubba et al. 2003). This low sorption potential may mean that the treatment capacity of bioretention cells may become exhausted in only a few years after installation (Hsieh et al. 2007). To overcome this challenge, the use of higher sorbing materials have been recommended as additives to sandy soils including drinking water treatment residuals (Lucas and Greenway 2011), engineered Sorbitive Media (™) (UVM Bioretention Laboratory 2015, Cording 2016), "red mud" (Snars et al. 2003), and clay (Khalid et al. 1977). Each of these treatment options has been shown to significantly improve phosphorus removal in bioretention cells; however they pose unique challenges themselves such as cost, availability, and decreased hydraulic conductivity. The presence of vegetation may also improve the total mass retention of phosphorus upwards of 20% compared to nonvegetated cells by means of uptake and biomass growth (Lucas and

Greenway 2008). There is a present need to understand the limitations of phosphorus removal in bioretention cells and improve treatment efficiency.

2.3.2 Uncertainty and Limitations to Bioretention Performance

One limitation of bioretention cells is their apparent variation in treatment efficiency across sites. For example, some studies have observed relatively high concentration reduction and mass removal of nutrients (Davis 2001, Bratieres et al. 2008), while others have noted low removal efficiency or even a net export (Dietz and Clausen 2005, Hunt et al. 2006). Part of this is due to the nature of the landscape in the drainage area and its associated pollutant loading. It is easier to remove a high percentage of pollutants from a landscape with high loads, but if a landscape is already relatively "clean," treatment by vegetative, soil, and microbial processes may be insufficient to reduce loads by that same percentage(Barrett 2008, McNett et al. 2011). It is for this reason that some practitioners have been critical of the percent pollutant load reductions prescribed in stormwater manuals (Strecker et al. 2001). Practitioners would benefit from a wider survey of bioretention treatment efficiency across sites with various pollutant loading levels. A selection of pollutant loads ascribed to being removed by bioretention processes is presented in Table 3.

Table 3 – Average bioretention mass removal rates Total Nitrogen (TN) and Total Phosphorus (TP) with corresponding runoff or site description. Negative values indicate a net export of nutrient mass.

	Mass Reduction		
Study	TN (%)	TP (%)	Runoff/Site Description
Davis 2007	--	78	Parking Lot
Debusk and Wynn 2011	99	99	Parking Lot
Dietz and Clausen 2005	32.00	-110	Shingled Roof
Egas et al. 2010	66	65	Dairy Farm
Hunt et al. 2006	40	-240	Parking Lot/ Sidewalk
Li and Davis 2014	41	--	Parking Lot
Lucas and Greenway 2008	76	92	Synthetic Urban Stormwater

Another reason for the often highly variable pollutant removal of bioretention cells is the flexibility available in their design. Designers of bioretention cells have the ability to alter many components to fit a site's needs including hydraulics, media configuration, and plant palette. While this is a benefit in many ways, it has also resulted in a wide variation in treatment performance across designs. Two components of bioretention design that can have a significant impact on nutrient retention/removal performance are compost amendments and choice of vegetation planted.

2.4 Effects of Compost and Vegetation on Bioretention Performance

2.4.1 Compost in Bioretention Cells

It is often recommended that the media of bioretention cells be amended with organic matter, usually compost (VT Stormwater Manual 2002, Clark and Pitt 2009, Davis et al. 2009, NJ DEP 2014). While compost has several properties that can be considered beneficial to bioretention including improved plant establishment, greater retention of water, and ability to complex with metal cations, it has can also be detrimental to nutrient treatment (Paus et al. 2014). Excess N and P that are not taken up by vegetation have a tendency to either leach out with the effluent stormwater or complex onto sorption sites within the media, lowering or countermanding the nutrient removal goals of bioretention (Hurley et al. 2017).

The contribution of nutrients to bioretention effluent can be substantial. In a bioretention column experiment with 40:60 compost to sand fraction, Chahal et al. (2015) observed nutrient export up to three times the concentration of synthetic urban stormwater. In another bioretention column experiment, Mullane et al. (2015) noted that nutrients were exported in "pulses" following simulated rain events. Interestingly, the authors noted that the compost aged 6-month leached significantly less pollutant mass than the 24-month-aged compost, suggesting the maturity of the compost may have less to do with leaching dynamics than the amount of nutrients previously leached. Paus et al. (2014) noted the trade-offs that may come with the application of compost to bioretention cells; in a column study, the authors found that while increasing the volume fraction of compost in the soil media improved metal retention, it also significantly decreased hydraulic conductivity and exported P. It should be noted, however, that "all composts

are not created equal" (Hurley et al. 2017). Hurley et al. (2017) tested the leaching potential of several composts and compost-amended bioretention media blends and found that a low-phosphorus, leaf mix blend leached lower nutrient concentrations than a vermicompost or manure based compost. These authors also made note of the greater release of phosphates from composts under longer saturated times; this raises another tradeoff in bioretention in that longer saturation may improve denitirification in bioretention cells and lower effluent nitrate loads but at the cost of higher phosphate desorption. However, while leaf based and low-phosphorus composts leach less than composts derived from other feedstocks, they still may leach nutrients (Bratieres et al. 2008, Hurley et al. 2017). In a column experiment testing various bioretention media and vegetation configurations, Bratieres et al. (2008) observed that the addition of a leaf-based compost and mulch to sandy load exported phosphate. This net export may likely be due to the low levels of nutrients already within the simulated influent stormwater, further emphasizing the nutrient removal performance of bioretention cells will often be due to the characteristics of influent stormwater and the nature of the land use(s) being treated (McNett et al. 2011).

2.4.2 Vegetation in Bioretention Cells

Bioretention designers have a wide flexibility in their choice of vegetation, allowing them to achieve a variety of goals including aesthetics, pollinator and wildlife habitat, or minimal upkeep and maintenance. The choice of vegetation may also influence sediment retention of bioretention cells. Hsieh and Davis (2005) noted in a survey of six vegetated bioretention cells that TSS removal was lowest in the two newest cells, leading

to the hypothesis that increasing root structure could provided stabilization to the media and prevented any flushing of loose fines. Read et al. (2008) observed a 2-4 fold difference in the TSS removal of different species used in bioretention columns; however, the authors also noted high variability among species used, and no statistical difference could be detected when the average performance of all vegetated columns was compared with soil-only columns.

Vegetation could also influence bioretention nutrient treatment. Bratieres et al. (2008) reported a significantly higher removal rate of NO_X and TN for vegetated cells than unvegetated cells. Of the vegetated cells, *Carex* was shown to have an immediate effect, *Melaleuca* a growing effect with time, and no effect was shown for the other three species studied (*Microleana, Dianella,* and *Leucophyta*), highlighting the importance of choice of species in bioretention planting plans. Gautam et al. 2014 studied the nutrient uptake of five different plant species in bioretention cells and found the plants with higher growth rate and biomass retained a higher amount of nutrients in roots, stem and leaves. This suggests nutrient uptake by plants could be a primary mechanism of pollutant removal would encourage the use of fast growing species, followed by end-of season harvest (as a means of removing nutrients from the system before plant senescense). However, Lucas and Greenway (2008) found that quantity of nutrients removed by vegetation exceeded what was possible for simple plant uptake and growth in a bioretention column experiment. They attributed the extra nutrient removal to the soil rhizosphere providing a proper chemical environment for P adsorption and a longer saturated retention time for denitrification processes (Lucas and Greenway 2008). A study of 20 Australian plant species used in bioretention columns found similar results

with increased nutrient removal in vegetated versus unvegetated cells, but also noted a significant decrease in TP concentration between influent and effluent water, regardless of the presence of vegetation; this suggests that soil processes alone may be sufficient to treat nutrient loading (Read et al. 2008).

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Chapter Three: Bioretention in a Mixed-Use Agricultural Landscape: Lessons Learned from Use of Low-Phosphorus Compost and *Panicum virgatum*

Jason M. Kokkinos

Keywords: Stormwater, Bioretention, Agriculture, Water Quality, Compost, Vegetation

Abstract

Bioretention cells are a stormwater treatment technology that uses soil and vegetation to remove pollutants from runoff and improve downstream water quality. While bioretention has been shown to be effective at removing certain stormwater pollutants such as sediment and heavy metals, removal of nutrients has been more variable. Design components of bioretention such as vegetation and soil media amendments can influence pollutant removal performance. In my experiment, I isolate the effects of low-phosphorus compost and a Switchgrass (*Panicum virgatum*) monoculture on bioretention performance. In fall 2016, three bioretention cells were installed at the University of Vermont Miller Research Complex, a mixed-use research and agricultural production facility located in South Burlington, VT. Each bioretention cell had a unique experimental treatment that allowed for the comparison of the presence of the following design components: (1) compost with planted vegetation, (2) no compost and vegetation, and (3) no compost or vegetation. Results suggest that the presence of a low-P compost layer had a small deleterious effect on nutrient removal performance, as the bioretention cell with an added compost layer exported higher concentrations of phosphorus and nitrogen and exhibited a higher concentration of water extractable phosphorus in the bioretention media. The bioretention cell with vegetation and no compost was the only treatment to significantly reduce total nitrogen and phosphorus concentrations; however, there was no effect on media phosphorus concentration. The presence of low-P compost significantly increased the above-ground biomass growth of Switchgrass, but had no effect on the total number of plants surviving in the first year. Switchgrass proved to be a durable plant, capable of surviving in bioretention media without compost, but was slow to grow and required additional watering through droughty conditions.

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3.1 Introduction

3.1.1 Runoff in the Landscape

Proliferation of urbanization and agriculture has had significant impacts on local hydrology and surface water quality. Consequences of landscape alteration, such as soil compaction, increased impervious area, and loss of functional plant diversity, decrease the chances for infiltration and groundwater recharge (Booth and Jackson 1998). These changes lead to increased surface runoff volumes and velocities, resulting in more frequent "flash flood" conditions and allowing a greater quantity of pollutants to move across the landscape and into downstream water bodies (Davis 2008). This nonpoint source loading of pollutants can have a detrimental effect on downstream aquatic habitat (Line and White 2007, Lin et al. 2009) and is effectively responsible for the impairment of 40% of all water bodies, nationally (US EPA 2009).

Nutrient loads are major pollutants of concern in stormwater. High concentrations of nitrogen (N) and phosphorus (P) delivered via runoff into receiving water bodies can disrupt biogeochemical cycling and degrade the local aquatic ecosystem (Smith et al. 2014). N and P are typically considered to be the limiting nutrients for primary productivity in marine and freshwater environments, respectively, and any addition to water bodies can lead to sustained plant and algal growth. Reduced water quality from eutrophication has significant societal and economic implications including high drinking water treatment costs, loss of tourism and recreation, and degraded fishing waters (Dodds et al. 2008). With over 17% of rivers and 28% of lakes classified as impaired by either N or P, nationally, it is clear that a mitigation of nutrient loads will remain a primary component of water quality management (US EPA 2009).

Another stormwater pollutant of concern in is Total Suspended Solids (TSS). TSS consist of any particles greater than 2 micrometers suspended within water (i.e., anything less than this size is considered dissolved) (APHA 2011). TSS are a primary reason for water turbidity, and concentrations are often used as general indicator of water quality (Ramakrishnadas 2011). Nonpoint source loading of TSS can be problematic in developed areas as the relatively higher runoff velocities associated with high impervious area allow a greater amount of sediments to remain suspended and be transported during storm events (Booth and Jackson 1998, Chen et al. 2015).

One type of land use that poses unique challenges for runoff water quality is agricultural production facilities. Many feedlots and dairy operations have a relatively high percent of impervious area, and can resemble urban centers in the volume of runoff produced during rainfall events (Miller et al. 2004). However, while the local hydrology of these sites can resemble urban areas, farming related activities such as manure handling and feed transport can contribute significantly higher concentrations of nutrients and sediment than observed in city stormwater (Young and Hunt 1980). If left unmanaged, the runoff from agricultural production facilities can contribute significantly to the accelerated eutrophication of nearby water bodies (Howarth et al. 2002). As livestock farming operations increase in scale and Concentrated Animal Feeding Operations become more common, water quality managers will need to consider how to mitigate runoff volumes and reduce elevated pollutant loading (Faulkner et al. 2011).

3.1.2 Bioretention Cells

Bioretention cells consist of a depression in the ground, filled with high permeability soil media, and planted with herbaceous vegetation or shrubs (Roy-Porier 2010). Bioretention cells use vegetation, soil, and microbial processes to filter pollutants from runoff and attenuate storm flows. In these systems, runoff is captured and channeled into the cell, where it collects on the surface and infiltrates through the permeable media within 24 hours of the rain event (Davis et al. 2009). At sites where the surrounding soil is mostly clay, urban fill, or deep seepage is not desirable for other reasons, bioretention cells can also be designed with an impermeable liner and/or discharge into an underdrain pipe that is connected to a stormwater drainage system.

Bioretention cell designs may be required to meet certain drainage and water quality standards (PGCo Bioretention Manual 2014). Specific requirements will depend on the site location, characteristics of stormwater pollutants, and set pollution reduction standards. A benefit of bioretention is the flexibility that designers have to meet these goals by altering hydrology, media composition, and vegetation (Davis et al. 2009). However, there is a lack of tested, regionally-specific recommendations for bioretention design, and in particular data on bioretention performance in agricultural production facility settings is lacking. Therefore, there is a growing need for quantitative assessment of bioretention design parameters and pollutant removal efficiency in this land use category.

3.1.3 Influences of Compost and Vegetation on Bioretention Nutrient Removal Performance

Previous research has shown bioretention cells and rain gardens to have mixed success in removing nutrients from stormwater. While some studies have shown high overall removal (Davis 2001, Davis 2006), others have a reported low removal efficiency and sometimes even a net export (Hunt et al. 2006). The addition of compost, mulch, or organic matter to bioretention cells may lower their nutrient removal efficiency by contributing excess N and P to the effluent (Hurley et al. 2017). In a rain garden experiment, Dietz and Clausen (2005) noted a low removal rate of all nitrogen species (with the exception of NH4-N, and a net export of TP. The authors attributed this flux to a release of nutrients from physical disturbance of the native soil and a leaching from the top mulch layer. A field study of three different bioretention sites in North Carolina compared nutrient removal rates and found an increase in the outflow mass of phosphorus of the one cell planted with a high P-Index topsoil (86-100; Mehlich-3), leading the authors to hypothesize that the media had become phosphorus saturated (Hunt et al. 2006). At the laboratory scale, Bratieres et al. (2008) showed that columns with a standard sandy loam media performed significantly better at nitrogen removal than columns with added organic matter. In a column study isolating the effects of compost on bioretention effluent, nutrients from mature and freshly applied compost were shown to export in "pulses" following storm events (Mullane et al. 2015). Alternatives to typical composts, such as those with low-phosphorus (low-P) concentrations, are important to consider in bioretention design. However, these have not been extensively studied.

The presence and type of vegetation in bioretention cells can also play a large role in nutrient removal. Bratieres et al. (2008) reported a significantly higher removal rate of NO_X and TN by vegetated cells compared to nonvegetated cells, though with variation across species in terms of the near-term and long-term N removal performance. Lucas and Greenway (2008) also compared the nutrient removal rate of vegetated and nonvegetated bioretention mesocosms, and found that nutrients were removed by both vegetative uptake and increased microbial activity in the root system.

3.1.4 Bioretention Media Phosphorus

While influent and effluent of bioretention cells have been relatively well studied, there are few experiments focused on the accumulation and movement of nutrients through bioretention media. Laboratory analysis and modeling have shown that the majority of incoming particles (including sediment-bound nutrients) adhere to the top layer of bioretention cells (Hsieh and Davis 2005, Li and Davis 2008). In a field study, Komlos and Traver (2012) confirmed this by using simple acid extraction to determine the concentration of phosphate that had sorbed to bioretention soil nine years after installation. Muerdter et al. (2015) reported similar results with soil P concentration decreasing with depth in a seven year old bioretention cell using a Mehlich-3 extraction. These field studies support the hypothesis that nutrients accumulate in top layer of bioretention soil media; however, there have been no studies to my knowledge that explore the separate effects of vegetation and low-P compost on this phenomenon.

3.1.5 Influences of Compost and Vegetation on Bioretention TSS Removal Performance

Bioretention has been shown to be capable of high TSS removal in both field and laboratory experiments. The primary mechanisms for TSS removal in bioretention cells are physical filtration and adsorption to soil particles (Roy-Poirtier et al. 2010). In a field study, Trowsdale and Simcock (2011) noted that even with high and variable loading of sediment, a bioretention cell receiving parking lot runoff consistently removed TSS mass by an average of 95% over 10 storm events. Hatt et al. (2009) used synthetic stormwater to test pollutant removal in a field bioretention study finding high (93%) TSS removal rates. Similar results have been obtained in laboratory settings; Hsieh and Davis (2005) observed that 90% of TSS from synthetic stormwater was retained within a bioretention column.

The removal of TSS may be influenced by compost amendments to bioretention media. Carpenter and Hallam (2009) found bioretention columns with 80% compost by volume reduced TSS concentration of synthetic stormwater significantly more than columns with 20% compost by volume. The position of the compost or media amendment may also influence removal. Studies have observed that the majority of incoming sediments settle in the top layer of bioretention media (Li and Davis 2008), and an overlaying organic media amendment may provide additional opportunity for particle capture and adsorption (Hsieh and Davis 2005).

The presence of vegetation and a root zone has been show to increase hydraulic retention time of bioretention cells, subsequently increasing chances for sediment absorption (Hunt et al. 2006, Read et al. 2008). Read et al. (2008) found a 2-4 fold difference in the TSS effluent concentration of bioretention columns planted with

different species. Analysis of the species used found that there was a correlation between total root mass and TSS removal (Read et al. 2008). Complex root architecture can increase absorptive surfaces, physiological uptake, and growth rate of the plant while also affecting soil physiochemistry and microbial communities (Skene 2003). However, Read et al. (2008) also noted a high amount of variation between species used, and no statistical difference could be detected when the average removal of all vegetated columns was compared with soil-only columns.

3.2 Objectives

This study aims to isolate the effects of compost and vegetation on the treatment of nutrients and TSS from stormwater in a mixed use agricultural landscape. The site studied is the production area of a dairy farm and research center located in South Burlington, VT. The landscape has a high percentage of impervious area and uses that could contribute high nutrient and sediment loads. The drainage area that is directed to the bioretention cells is similar to that studied by Dietz (2016), both being agricultural production/storage facilities in New England with uses typical of agricultural operations, but no pasture or row crops.

Through a factorial design bioretention field experiment, I compare how the presence of a leaf-based, low-P compost or a planted Switchgrass (*Panicum virgatum*) monoculture individually impact the performance of bioretention with respect to stormwater nutrient and TSS removal and sand-based media P concentration. I also quantify the impact of the low-P compost on Switchgrass survivorship and biomass accumulation. Switchgrass was chosen for this study because of its hardiness and suitability for sandy, well drained soils, while low-P compost was chosen for the assumption that it may be less susceptible to nutrient leaching observed in previous bioretention experiments using more enrich composts. The results have the potential to aid designers and water quality managers in selection of vegetation and soil media amendments for bioretention in landscapes with high potential for nutrient loading.

Objectives were to:

1) Determine the effect of low-P compost and Switchgrass (P*anicum virgatum*) in the first year of installation on bioretention cell:

A) Concentration reduction of stormwater nutrients (N and P) and total suspended solids (TSS).

B) Sand-based media P concentration

2) Quantify the impact of low-P compost on plant survivorship and biomass accumulation.

3.3 Methods

3.3.1 Study Site

Construction of three bioretention cells was completed in fall 2016 at the University of Vermont Paul R. Miller Research Complex (MRC), a dairy and equestrian teaching and research facility located in South Burlington, VT (44° 27' 33.411" N, 73° 11' 21.9696"). South Burlington has average high and low temperatures of 12.9 and 2.33 °C, respectively, average annual rainfall of 93.4 cm, and precipitation 151 days of the year (U.S. Climate Data 1981-2010). The bioretention cells treat runoff from buildings, rooftops, grassy lawns, paved and dirt parking and driving lanes, and some areas where dairy cows and farm equipment cross paths between paddocks and the barns. The entire drainage area is 12,974 m^2 with four dominant land cover types: pavement, rooftop, grass, and dirt/gravel roads (Figure 1). The complex can be considered as a unique stormwater runoff landscape with uses resembling both that of a typical suburban/ institutional area and an agricultural production facility. The landscape is within the Potash Brook Watershed (HUC-8, 01100002), a tributary to Lake Champlain.

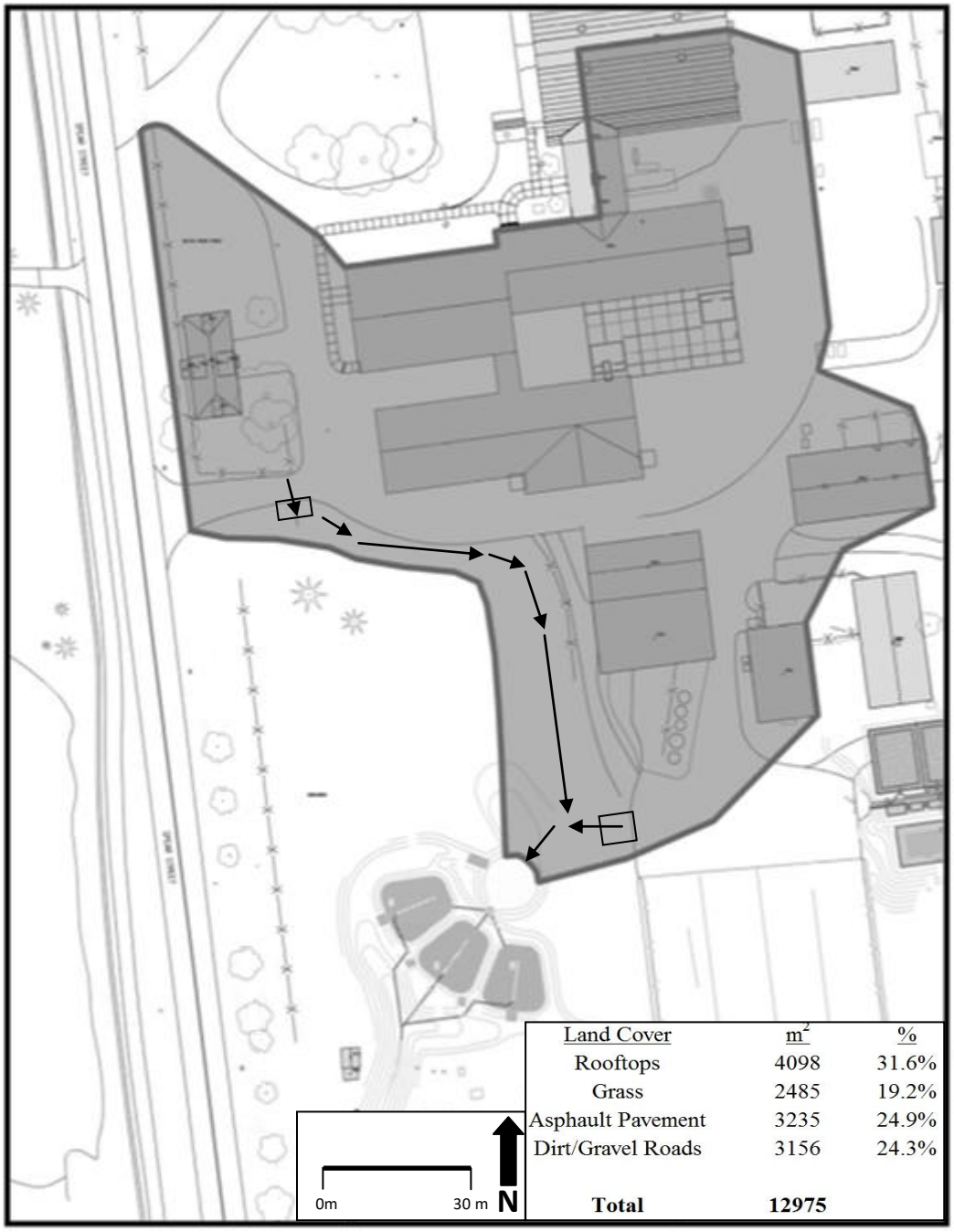


Figure 1 – Watershed drainage area of MRC Bioretention Cells. Runoff from the southwest (institutional) and southeast (agricultural production facility) ends of the complex is channeled into the forebay of the bioretention cells via two grass lined swales (the location and direction of flow is conceptually depicted by arrows). The four main land cover classifications of this watershed are described in text, along with their area and percent of total watershed.

The bioretention cells' surfaces are trapezoidal and have an approximate total area of 249.3 m^2, 3 x 83.1 m^2 cells, together representing ~1.9% of the total drainage area. The vertical profile of the cells from top to bottom includes a 7.6-cm layer of pea-stone, a 76-cm layer of sand-based bioretention media, a second 15.2-cm layer of peastone, and a 30.5-cm layer of roughly 2.2-cm diameter gravel (Figure 2). The sand-based bioretention media is 90% silica sand, 8% fine gravel, and 2% silt and clay, with an average porosity of 0.25. Each bioretention cell has a maximum ponding depth of 30.5 cm, resulting in a total of 53 m^3 of storage capacity per cell (excluding the volume of the media). The cells are unlined; surrounding soils range from dense clay to dense sandy loam, with intermittent pockets of loose gravel and urban fill. A perforated 10.2-cm diameter PVC underdrain pipe runs along the longitudinal center of each cell within the gravel layer, conveying water that does not seep into the subgrade, into three separate outflow structures, one per bioretention cell.

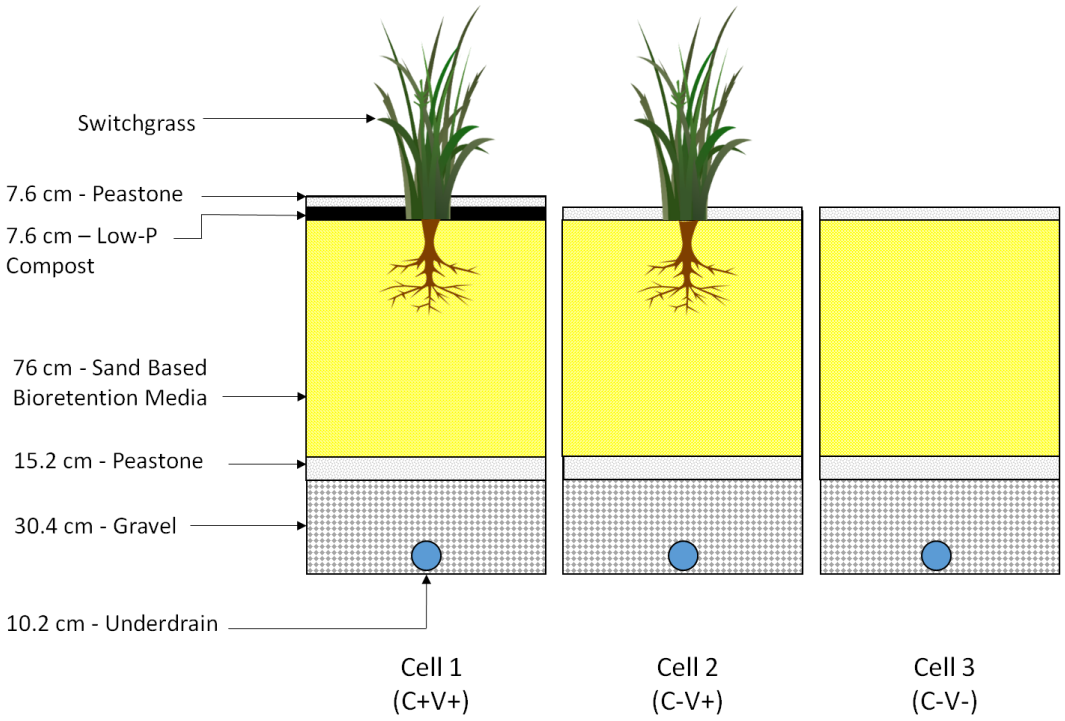


Figure 2 – Vertical section of the Miller Research Complex Bioretention Cells, showing material composition, depths of media samples taken, and individual media and vegetation treatments including Compost with Vegetation (C+V+), No Compost and Vegetation (C-V+), and No Compost or Vegetation (C-V-).

3.3.2 Compost and Vegetation Treatments of Bioretention Cells

Each bioretention cell has a unique treatment that allowed for experimental comparison (Figure 2). Cell 1 (C+V+) was installed with a layer of low-P compost and planted with Switchgrass (*Panicum virgatum*), Cell 2 (C-V+) had no compost and was planted with Switchgrass, and Cell 3 (C-V-) had neither compost nor vegetation. Low-P compost was defined as being entirely composed of leaves and plant material and excluding manures and foodscraps, with less than 0.2% total phosphorus by dry weight. In Cell 1, a 7.6-cm layer of compost was added between the sand-based bioretention media layer and upper peastone layer (Figure 2). In the two planted cells, Cell 1 and Cell 2, 300

Switchgrass plants were installed from 10.2-cm pots at an approximate density of one plant per 0.25 m^2. Plants were rooted in the low-P compost in Cell 1 and sand-based bioretention media in Cell 2, with the base of the plants in both Cells 1 and 2 surrounded by peastone (as a mulch alternative). Plants were installed between June 1 and June 8, 2016 and for the first six weeks after installation were watered with an oscillating sprinkler for approximately two hours, three to five times per week. All cells, including the non-vegetated Cell 3, were watered equally to maintain consistency.

3.3.3 Stormwater Flow

Figure 3 illustrates the flow of stormwater through the bioretention cells and sampling infrastructure. During storm events, runoff is collected and channeled by two grass lined swales into a 0.75-m deep by 15-m diameter circular sediment forebay, meant for settling large incoming solids. Stormwater exits the forebay via a 10.2-cm diameter PVC upturned elbow pipe. The bioretention inflow consists of a three-way splitting structure designed to direct approximately equal volumes into each of the bioretention cells via three separate 15.2-cm diameter upturned elbow pipes that were leveled and placed at the same elevation using a laser transit level. Stormwater from the splitting structure enters the bioretention cells through a 10.2-cm diameter PVC inlet pipe, and spreads across the surface of each cell before percolating through the media. Water that is not lost via seepage into the surrounding soil is collected by the 10.2-cm-diameter perforated PVC underdrain (Figure 2) and channeled into a 76-cm diameter outflow sampling structure, one per bioretention cell. When the outflow sampling structure fills, stormwater will overflow into another 15.2-cm diameter upturned elbow pipes that

discharges to a grassy swale and eventually into Potash Brook. In extreme rainfall events (T ≥ 25 Years, 8.8-cm/24 hours), excess stormwater will bypass the system via emergency spillways in the bioretention cells and forebay that conveys runoff directly to the discharge swale (not shown in Figure 3).

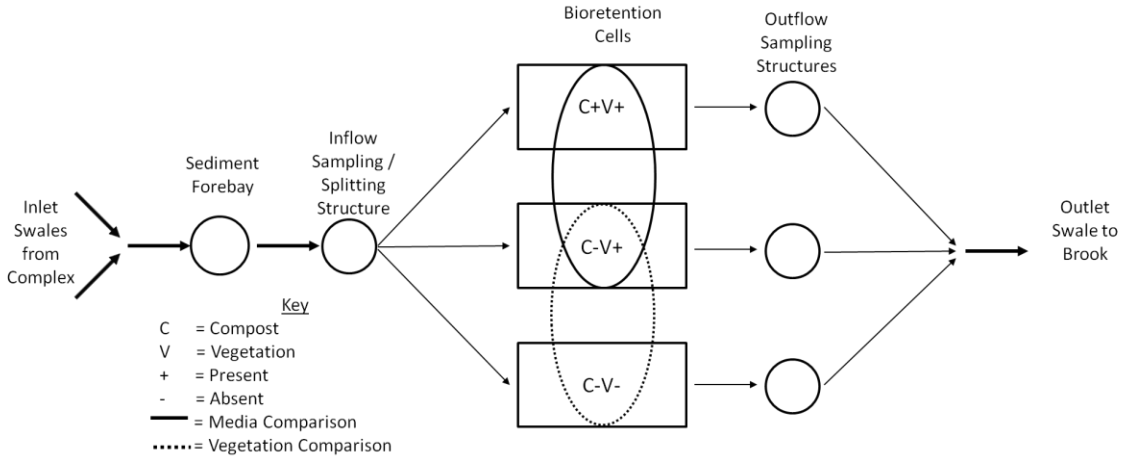


Figure 3 – Conceptual diagram of stormwater collection and experimental treatments of the Miller Research Complex Bioretention Cells. Solid line represents experimental comparison of presence of low-P compost and dashed line represents comparison of presence of vegetation (*Panicum virgatum*).

3.3.4 Runoff Sampling

Runoff samples were collected during storm events using a flow-based sampling protocol (Leecaster et al. 2002). For the flow calculation, the upturned 15.2-cm diameter PVC elbow pipes in the inflow splitting structure and three outflow sampling structures were treated as rectangular sharp-crested weirs without end contractions. Before storm events, the sampling structures were filled with tap water to overflow the weirs and calibrate a pressure transducer level sensor (Teledyne ISCO 720 Module, Lincoln, NE) to zero (0.00 m). During storm events, the water height above the weirs was measured by a pressure transducer and converted to flow via the equation:

[1] $Q = 3.33LH^{3/2}$

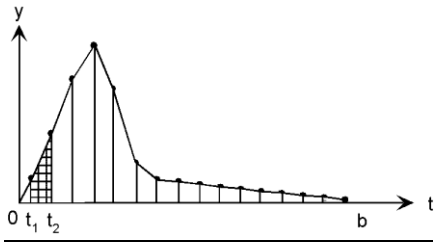
where Q is the flow (m^3/s), L is the length of the weir (m), and H is the measured height of the water above the weir crest (m) (U.S. Dept. of the Interior Bureau of Reclamation 2001).

Height was recorded and flow was calculated every minute and converted to a measure of volume (V, m^3) via the equation:

[2] $V = \int Q(t)\, \partial t$

The trapezoidal method of numeric integration was used to estimate the area under the hydrograph (i.e. volume) based on discrete sampling points along the curve. Trapezoidal integration as a general function of estimating area under a curve (i.e. volume of the hydrograph) is illustrated by:

[3] $A = \Sigma\, (t_2-t_1) * [(f)t_2-(f)t_1]/2$



where A is the area under the curve, t_1 and t_2 are time points (i.e. minutes), and $(f)t_1$ and $(f)t_2$ are the flow rates at t_1 and t_2, respectively.

A 900-mL sample of runoff was taken for every set amount of volume that was calculated to have passed through the sampling structure with a maximum total of 24 bottles that could be filled by the auto samplers (Teledyne ISCO ISCO 6712, Lincoln, NE). The volume between samples was pre-determined in order to best capture the entire duration of a predicted storm, and varied from one storm event to the next. Inflow volume between samples was determined by using the forecasted rainfall depth in the Curve Number Equation (Akan 1993), and dividing by 24. Outflow volume between samples for each cell was estimated as one third the inflow volume. A total of thirteen storms were sampled between June 22nd to November 3rd, 2016 (Appendix A).

3.3.5 Water Quality Analysis

Nutrient Concentration

Stormwater samples were analyzed for concentrations of Total Nitrogen (TN), combined Nitrate and Nitrite (NOx-N), Ammonium (NH4-N), Total Phosphorus (TP), and Soluble Reactive Phosphate (SRP). Concentrations were measured for every sample bottle taken during a storm event. Soluble nutrient species (NOx-N, NH4-N, and SRP) were prepared for analysis by filtration through a 0.45μm pore nylon mesh filter. Total nutrient species (TN and TP) were prepared for analysis via persulfate digestion of an unfiltered sample, which oxidized all forms of nitrogen and phosphorus into NOx-N and SRP, respectively. All preparations for nutrient analysis were done within 48 hours of the sampled storm event.

Nutrient concentrations were determined via flow injection analysis and automated colorimetry (Lachat Instruments QuickChem8000 AE, Hach Inc., Loveland,

CO). In this procedure, the concentration of solute is directly proportional to its color and the absorbance read at 520 nm for NOx-N (magenta), 660 nm for NH4-N (emerald green), and 880 nm for SRP (blue) (APHA 2010 – 4500 P-B). Each analysis was calibrated with 12 standards of NOx-N, NH4-N, and SRP in deionized water ranging in concentration from 0.005-10.0 mg/L along with two Quality Control Checks in a similar range. The instrument was recalibrated or samples were reanalyzed with new standards if Quality Controls deviated by greater than 10% of their expected value. If preliminary results showed a wide range in concentration values, results were calibrated along two different curves. When concentrations were less than 0.1 mg/L for either nitrogen or phosphorus from the full calibration curve, a low calibration curve was used instead, ranging from 0.005-0.2 mg/L.

TSS Concentration

Total suspended solids (TSS) concentration was measured by taking a 400-mL subsample from each bottle (APHA 2010 – 2540D). Deionized water was first passed over a Whatman 47-mm standard glass fiber filter and dried at 100 ^{o}C overnight. Filters were then weighed and had a subsample applied to them over a vacuum filter from a vigorously shaken bottle. The subsample of 400 mL was used for analysis, unless clogging of the filter was observed, in which case a smaller sample of 100 mL was used. Once the entire subsample has passed through the filter, it was dried again overnight at the same temperature and its final weight recorded. Final TSS concentrations were calculated as the difference between filter weights divided by the subsample volume.

Mass Removal

Mass was calculated using stormwater volume and pollutant concentrations of twelve storms for nitrogen (TN, NOx-N, NH4-N) and TSS, and of eleven storms for phosphorus (TP, SRP). Several storm events were missing either flow or water quality data due to instrument error, and were therefore left out of analysis (Appendix A). Mass of nutrients and TSS that passed through the sampling structures during a storm event were calculated via the equation:

$$[4]\ M = \Sigma(VC)$$

where M is mass, V is volume of stormwater passing through the sampling structure during a sampling interval, and C is the concentration of the stormwater pollutant (i.e. nutrients, TSS) during the same interval. Concentration in the sample bottle was multiplied by the preceding volume, and, in the last sample taken, by the final volume that did not result in a bottle being filled. If the event had no volume measured from its outflow structure, mass was assumed to be either fully retained by the bioretention cell or to have seeped into the surrounding soil. All mass was reported in kilograms (kg).

The mass of stormwater pollutants removed by the bioretention cell per storm (excluding seepage) was estimated via the equation:

$$[5]\ M_R = M_I - (M_O + M_S)$$

where M_R is the mass removed by the cell, M_I is the mass into the cell via the inflow structure, M_O is the mass out of the cell via the outflow structure, and M_S is the mass out of the cell via seepage to the surrounding soil media. M_S was calculated as the EMC of the outflow event for an event multiplied by the estimated volume of seepage from the cell. The estimated volume of seepage per cell for a storm event was calculated via the equation:

$$[6]\ V_S = (V_P + V_I) - V_O$$

where V_S is the volume of seepage from a cell, V_P is the volume of precipitation fallen on a cell during a storm event (i.e. cm x m^2), V_I is the volume of stormwater entering the cell (i.e. 1/3 of total inflow volume for an event), and V_O is the volume of stormwater exiting through the outflow structure. For the purpose of this estimation, I assumed the media was at field capacity and there was no storage during a storm event. Equal influent volume between the cells could not be assumed before the installation of the baffle in the inflow structure, and therefore the mass retention of each bioretention cell was only calculated for two storms after this date (October 22 and 28). Evapotranspiration was assumed to be negligible in this model due to high frequency of rainfall between these dates and relatively cooler ambient temperatures.

3.3.6 Bioretention Media Water Extractable Phosphorus (WEP)

Samples of the sand-based bioretention media were taken using a 2.54-cm soil core on June 8 and again on November 7, 2016 using methods similar to that of Muerdter et el. (2015). The dates of sampling represent the first day of installation of the bioretention cells and one week after the final water quality sampling date, respectively. Three equidistant points (2.74 m) along the center transect of each bioretention cell were marked with flags for sampling locations (Figure 4). At each of these locations, two separate cores were taken 10 cm perpendicular to center transect line for each sampling date; to the left in June and the right in November. Peastone mulch, and compost in Cell 1, was cleared away from the sampling locations so that cores were taken from the top of the sand-based bioretention media in all three cells. Media was extracted to a depth of 40 cm and divided into five separate segments of 0-5 cm, 5-10 cm, 10-15 cm, 25-30 cm, and 35-40 cm (lowest sampling depths chosen to represent the full extent of the soil core). Similar depth segments of the two cores samples taken at each location per time point were composited and evenly mixed. This resulted in a total of 15 media samples per cell per sampling time (5 depths x 3 sampling points). Media samples were allowed to air dry for one week in paper envelopes before weighing and analysis.

A measure of Water Extractable Phosphorus (WEP) concentration was obtained for both sample dates. Three grams of soil were combined with 30 mL of deionized water and shaken for 1 hour. Samples were then centrifuged for 10 minutes at 5000 RPM, and the supernatant liquid was extracted using a polypropylene syringe and filtered through a 0.45μm pore nylon mesh filter. This solution was then analyzed for SRP using automated

molybdate blue colorimetry. WEP concentration was reported in mg P/kg Media (dry weight).

3.3.7 Vegetation Harvest and Sampling

A total count of surviving Switchgrass was done on October 22, 2016; survival was defined in this experiment as a plant being alive at the end of the growing season, and does not include a count after overwintering. A plant was considered to have survived if it could be positively identified at the time of counting. Surviving plants were divided by the total originally planted (i.e. 300), to obtain a measure of plant survivorship in each cell.

On November 7, 2016, a representative subsample of Switchgrass above-ground biomass was harvested from each of the two planted cells. One m^2 PVC quadrats were placed along a systematic grid within the two cells in nine locations (Figure 4), and all Switchgrass plant material within these areas was harvested at 2.54 cm above the peastone layer. The harvested contents of each quadrat were placed in separate paper bags and dried at 100 ^{o}C for 24 hours. Total biomass (sans paper bag) was weighed immediately after drying. The average biomass per harvested quadrat was assumed to be representative of the entire cell and was multiplied by the total area to obtain an estimate of total biomass.

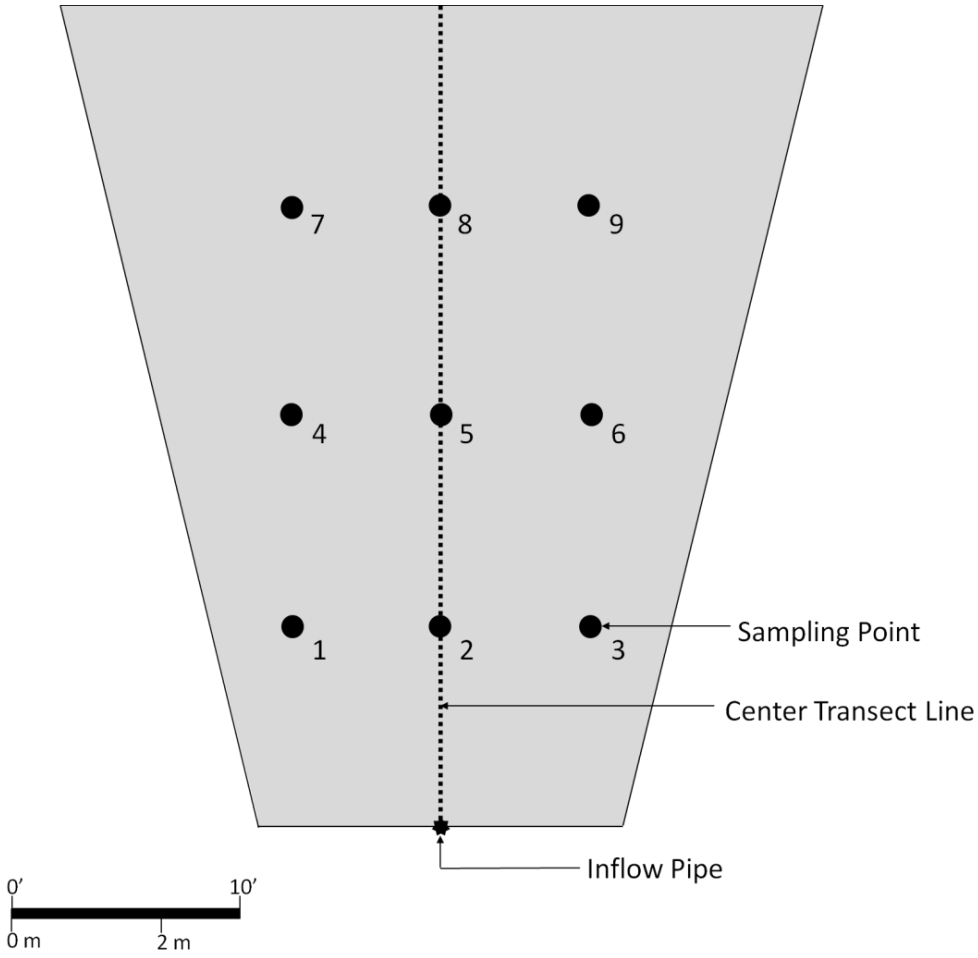


Figure 4 – Surface area of bioretention cells including locations for quadrat sampling points for vegetation cover, media cores (#2, #5, and #8), and vegetation harvest points (#1 - #9).

3.3.8 Statistical Analysis

Nutrient and TSS concentration reduction was compared across the three treatments using Analysis of Covariance (ANCOVA), in which the average outflow concentrations of individual storm events from separate treatments were the tested dependent variables and the inflow concentration was the independent covariate. In this model, a main effect of inflow concentration upon treatment outflow concentration was tested, and if no significant effect was found, a test of interaction between the treatments

was performed. In the event that influent concentration was to have a significant effect on treatment effluent concentration, a one-way ANOVA with Least Squares Difference analysis was used to test for a significant difference across treatments.

Individual treatment reduction of stormwater pollutant concentration was analyzed by comparing influent concentrations of storm events with the individual treatment effluent concentrations in a paired samples t-test.

A four-way Analysis of Variance (ANOVA) with two-way interaction was used to compare WEP concentration in the bioretention media, testing for a significant effect and interaction on treatment, time, media depth, and distance from cell inlet.

Switchgrass biomass was compared across the planted bioretention cells, Cell 1 (C+V+) and Cell 2 (C-V+) using independent samples *t*-test.

A threshold of $p<0.05$ was used as an indicator of significance in all tests. Values between 0.05 and 0.1 were considered “marginally significant”. Statistical models were run on IBM SPSS, Version 23.

3.4 Results

3.4.1 Nutrient and TSS Removal Performance

3.4.1.1 Concentration Reduction

Nitrogen – The average influent concentration of TN per storm measured from twelve events was 4.00 (± 1.87) mg/L, ranging from a low of 1.47 mg/L to a high of 14.2 mg/L (Figure 5). The average effluent TN concentration of Cell 1 (C+V+) was 3.31 (± 1.12) mg/L, a 17.1% reduction from seven events; Cell 2 (C-V+) was 2.46 (± 0.68) mg/L, 38.5% reduction from eight events; Cell 3 (C-V-) was 2.65 (±1.04) mg/L, a 33.8% reduction from four events. Only Cell 2 significantly reduced TN concentration via a paired samples t-test with influent concentrations ($p = 0.019$). Influent TN concentration did not significantly affect the difference in treatment performance ($p = 0.984$), nor was there a statistically significant difference in effluent TN concentration across treatments ($p = 0.984$).

The average influent concentration of NH4-N per storm measured from thirteen events was 0.369 (± 0.212) mg/L, ranging from a low of 0.027 mg/L to a high of 1.52 mg/L. The average effluent NH4-N concentration of Cell1 was 0.060± (0.023) mg/L, an 83.7% reduction from seven events; Cell 2 was 0.023 ± (0.012) mg/L, a 93.8% reduction from nine events; Cell 3 was 0.020 ± (0.008) mg/L, a 94.6% reduction from five events. Influent concentration of NH4-N had a significant effect on the difference in treatment performance ($p = 0.016$), such that higher influent concentrations were correlated with higher effluent concentrations in Cell 1. Effluent from Cell 1 and was significantly greater than that of Cell 2 and 3 ($p < 0.001$). Reductions of concentration from the

influent were statistically significant via paired samples t-test for Cell 2 ($p = 0.024$) and Cell 3 ($p = 0.008$), and marginally significant for Cell 1 ($p = 0.054$)

The average influent concentration of NOx-N per storm measured from thirteen events was 0.230 (± 0.188) mg/L, ranging from a low of 0.027 mg/L to a high of 1.34 mg/L. The average effluent NOx-N concentration of Cell1 was 2.23 (± 0.41) mg/L, a 970% increase from seven events; Cell 2 was 1.70 (± 0.63) mg/L, a 739% increase from nine events; Cell 3 was 1.75 (± 0.76) mg/L, a 761% increase from five events. All treatments significantly increased concentration compared to influent in a paired samples t-test ($p <0.001$). Influent NOx-N concentration did not significantly affect the difference in treatment performance ($p = 0.465$), nor was there a statistically significant difference of NOx-N effluent concentration between treatments ($p = 0.294$).

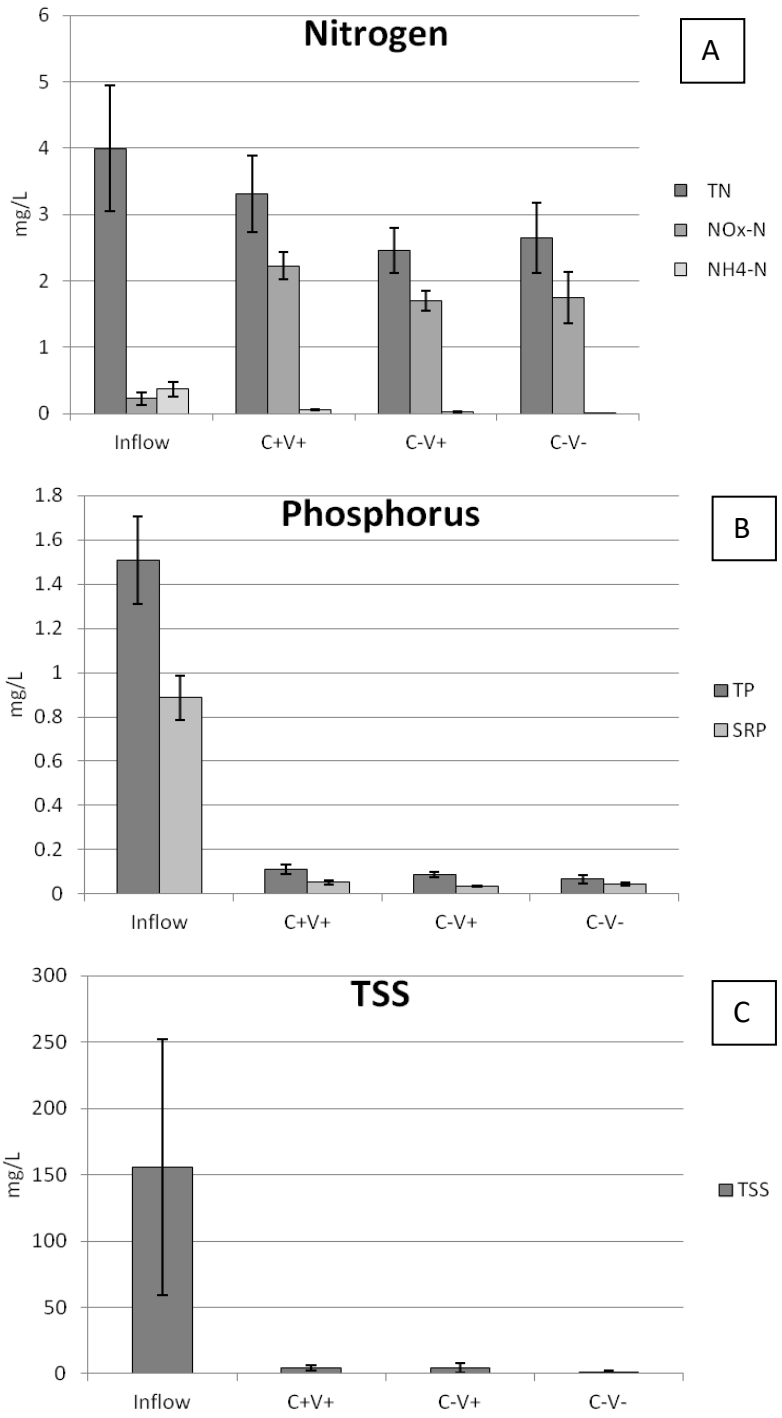


Figure 5 – Average storm event concentrations of (A) Nitrogen, (B) Phosphorus, and (C) Total Suspended Solids (TSS) from Miller Complex Center Bioretention Cells' influent and effluent of separate treatments (Cell 1 - Compost and Vegetation (C+V+), Cell 2 - Vegetation with No Compost (C-V+), and Cell 3 - No Compost or Vegetation (C-V-).

Phosphorus - The average influent concentration of TP per storm measured from eleven events was 1.50 (± 0.362) mg/L, ranging from a low of 0.558 mg/L to a high of 3.08 mg/L. The average effluent TP concentration of Cell 1 was 0.112 (± 0.042) mg/L, a 92.5% reduction from six outflow events; Cell 2 was 0.088 (± 0.024) mg/L, a 94.1% reduction from seven events ; Cell 3 was 0.066 (± 0.037) mg/L, a 95.6% reduction from three events. Both Cells 1 and 2 were found to significantly reduce influent concentrations via paired samples t-test ($p = 0.001$ and $p < 0.001$, respectively), and Cell 3 was found to have a marginally significant effect ($p = 0.054$). Influent TP concentration did not significantly affect the difference in treatment performance ($p = 0.197$). Treatments' effluent concentrations were not found to be significantly different from each other ($p = 0.194$); however, effluent concentration from Cell 1 was marginally significantly greater than Cell 3 ($p = 0.080$).

The average influent SRP concentration per storm measured from twelve events was 0.887 (± 0.196) mg/L, ranging from a low of 0.258 mg/L to a high of 3.08 mg/L. The average effluent SRP concentration of Cell 1 was 0.052 (± 0.019) mg/L, a 94.1% reduction from six outflow events; Cell 2 was 0.035 (± 0.007) mg/L, a 96.1% reduction from eight outflow events; Cell 3 was 0.046 (± 0.013) mg/L a 94.8% reduction from four outflow events. All treatments were found to significantly reduce influent SRP concentration via paired samples t-test ($p < 0.001$). Influent SRP concentration did not significantly affect the difference in treatment performance ($p = 0.747$), nor was there a statistically significant difference in effluent concentration between treatments ($p =$

0.226), however, effluent concentration from Cell 1 was marginally significantly greater than Cell 2 ($p = 0.100$).

TSS – The average influent TSS concentration per storm measured from twelve events was 155.7 (± 197.0) mg/L, ranging from a low of 9.2 mg/L to a high of 1137.8 mg/L. The average effluent TSS concentration of Cell 1 was 4.1 (± 4.2) mg/L, a 97.4% reduction from eight events; Cell 2 was 4.4 (± 6.3) mg/L, a 97.2% reduction from eight outflow events; Cell 3 was 1.5 (± 1.9) mg/L, a 99.0% reduction from four events. All treatments had a marginally significant reduction of TSS concentration via paired sample t-test (Cell 1 - $p = 0.077$; Cell 2 - $p = 0.057$; Cell 3 - $p = 0.051$). Influent TSS concentration did not significantly affect the difference in treatment performance ($p = 0.835$), nor was there a statistically significant difference in effluent concentration across treatments ($p = 0.812$).

3.4.1.2 Mass Removal

Table 4 reports the estimated mass of stormwater pollutants retained by the bioretention cell media during the two sampled storms that occurred after modifications to the inflow splitting structure to equalize volume of all three bioretention cells' inflow. The storms occurred on October 22 and 28 and rainfall depth recorded was 2.78cm and 1.02 cm, respectively. Rainfall was sparse in the weeks prior to the October 22, with inflow being last observed 33 days prior.

This limited data set suggests a possible effect of treatment on bioretention TSS and nutrient mass retention. The general trend was Cell 2 had a greater retention of nutrient and sediments than Cell 1 and Cell 3. This pattern is similar for TN, NH4-N, TP,

and TSS. The difference between treatments is shown most notably by a low, but positive retention of TN by Cell 2 (2.17%), but a net export by Cell 1 (-51.89%) and Cell 3 (-12.70%). NOx-N was an exception to the pattern with mass exported at notably higher levels in Cell 3 (-1919%) than Cell 1 (-1440%), but both still greater than Cell 2 (-1161%).

Table 4 – Average stormwater pollutant mass retention of MRC Bioretention Cells for October 22nd and 28th Storms. These events were sampled after the installation of the inflow baffle, and can therefore be assumed to have equal volume directed to all three cells.

	Cell 1 (C+V+)		Cell 2 (C-V+)		Cell 3 (C-V-)	
	$M_{R\_\%}$	M_R (kg)	$M_{R\_\%}$	M_R (kg)	$M_{R\_\%}$	M_R (kg)
TSS	85.73%	1.286	96.47%	1.233	83.21%	1.406
TN	-51.89%	-0.030	2.17%	0.004	-12.70%	-0.019
NOx-N	-1440.11%	-0.050	-1161.24%	-0.039	-1919.71%	-0.065
NH4-N	67.95%	0.003	86.37%	0.003	80.09%	0.003
TP	80.44%	0.022	92.45%	0.023	79.68%	0.020
SRP	91.37%	0.016	94.70%	0.016	96.46%	0.017

3.4.2 Media Water Extractable Phosphorus (WEP) Concentration

The average concentration of Water Extractable Phosphorus (WEP) in the bioretention media at different soil core depths is shown in Figure 6 for both June and November sampling. The average WEP concentration across all depths in Cell 1 decreased between June and November, from 1.53 (± 1.22) mg P/kg Media to1.15 (± 0.34) mg P/kg Media, due primarily to the significant lowering in the shallow layer. The four deeper layers of Cell 1 have an average increase in concentration over time. Both Cell 2 and3 showed a net increase in average WEP concentration over time from 0.317 (±

0.046) mg P/kg Media to 0.700 (± 0.248) mg P/kg Media and from 0.368 (± 0.106) mg P/kg Media to 0.706 (± 0.279) mg P/kg Media, respectively.

There was a statistically significant effect of treatment on WEP concentration ($p = 0.001$), with Cell 1 significantly greater than Cell 2 ($p = 0.003$) and Cell 3 ($p = 0.004$). There was also an effect of depth ($p < 0.001$) and interaction of depth and treatment ($p = 0.016$) on WEP concentration. These results suggest greater WEP concentrations in the shallow depths of the bioretention media, and that Cell 1 had higher concentrations in its shallow depth than either Cell 2 or Cell 3. There was no statistically significant effect of time or distance from inlet on WEP concentration.

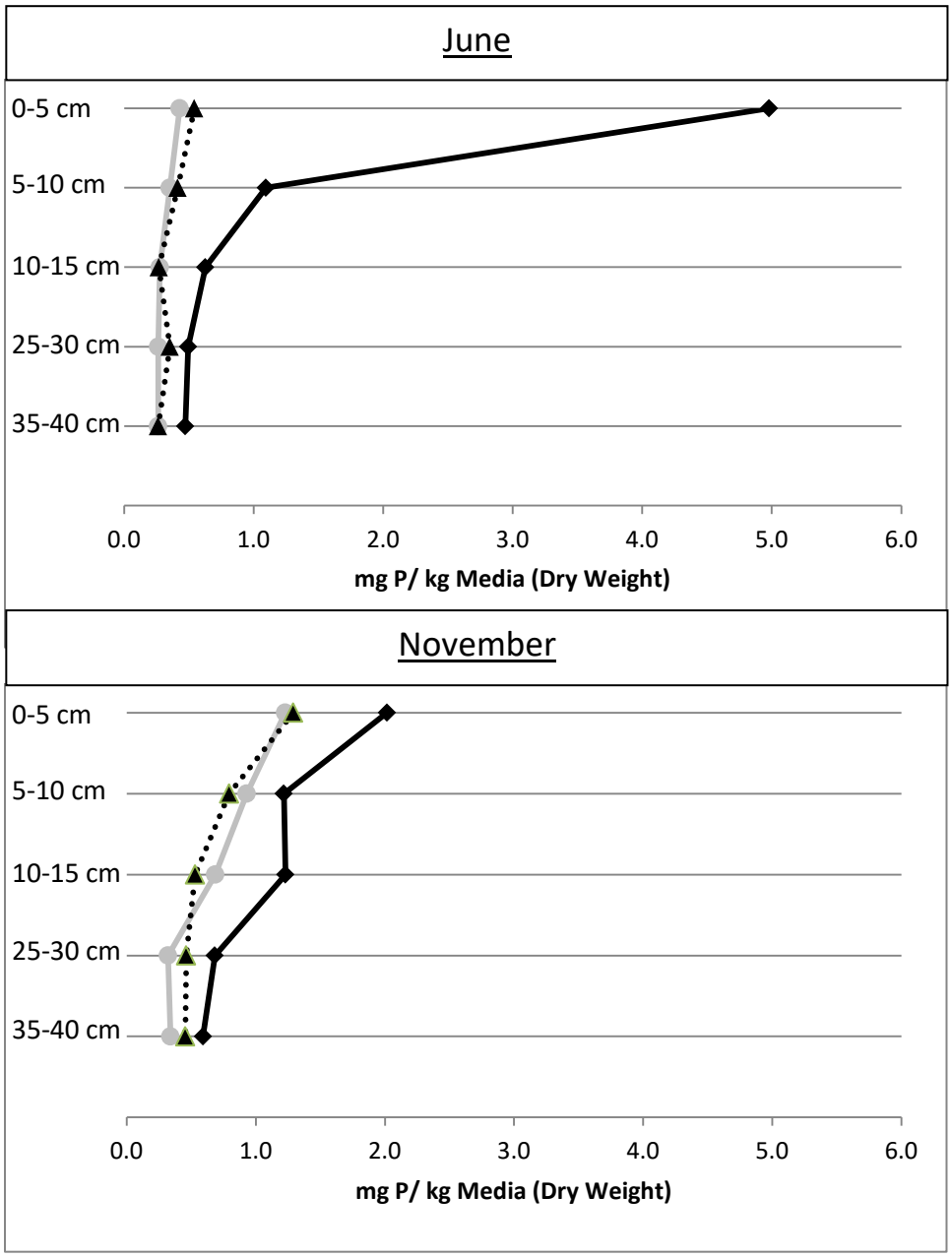


Figure 6 – Average Water Extractable Phosphorus (WEP) concentrations of sand-based bioretention media at different depths from June and November sampling for Cell 1 (Compost and Vegetation, C+V+), Cell 2 (No Compost and Vegetation, C-V+), and Cell 3 (No Compost and No Vegetation, C-V-).

3.4.3 Vegetation Survivorship and Biomass

The survivorship of the planted species, Switchgrass (*Panicum virgatum*), was similar between the two vegetated bioretention cells with a total count of 252 for Cell 1 (C+V+) and 238 for Cell 2 (C-V+), on October 22nd (136 days since planting). Out of the initial 300 per cell planted on June 8, this is a relative survivorship of 84% and 79.3%, respectively.

The above-ground biomass accumulation of the cells was significantly different via independent samples t-test, with Cell 1 yielding an average of 0.346 (± 0.103) kg/m^2 and Cell 2 yielding an average of 0.037 (± 0.013) kg/m^2 ($p < 0.001$) (Figure 7). Factoring this measure of biomass by the total planted area of the cells (i.e. 83.1 m^2) yields total above-ground biomass measurements of 28.75 kg for Cell 1 (C+V+) 3.07 kg for Cell 2 (C-V+), 936% more biomass in the cell with low-P compost.

Cell 1 (C+V+) Cell 2 (C-V+)

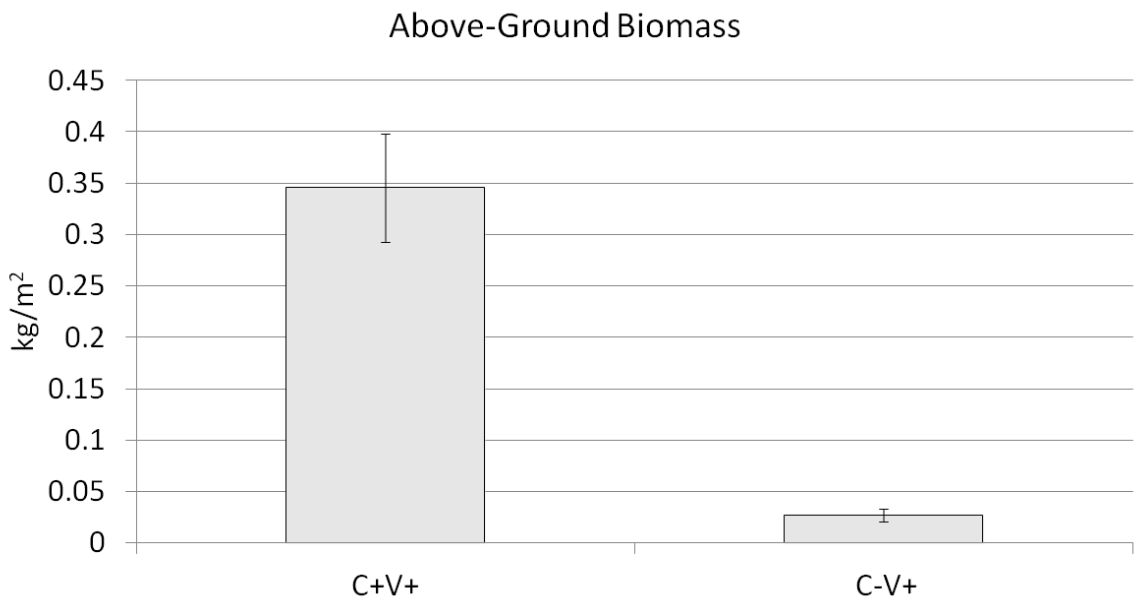


Figure 7 – Top:) Photos taken September 29th, 113 days after planting, of Cell 1, bioretention cell with layer of low-P compost (left) and Cell 2 without compost (right). Bottom:) Average measured above-ground biomass of bioretention cells with layer of low-P compost (C+V+) and without (C-V+). Measures taken from nine equidistant m^2 quadrats within planted cells.

3.5 Discussion

3.5.1 Nutrients and TSS Removal Performance

3.5.1.1 Low-P compost effects on water quality: Cell 1 (C+) vs. Cell 2 (C-)

Overall, the presence of compost had no effect on TSS concentration reduction and only a marginal effect on nutrient concentration reduction. This effect can be seen by Cell 1 (C+V+) having effluent TP concentrations marginally higher than Cell 2 (C-V+) though both bioretention treatments significantly reduced concentrations from the influent. This may suggest a potential for the low-P compost to leach some phosphorus, but not to an extent that it severely depresses concentration reduction potential of bioretention cells treating this type of mixed institutional and agricultural runoff. Compost and native soils with high P fractions have been shown to decrease concentration reduction in bioretention cells, and at times even lead to a net increase of P (Hunt et al. 2006, Bratieres et al. 2008, Paus et al. 2014, Chahal et al. 2016). This study contributes to the available literature which reports this range in potential for excess phosphorus leaching from bioretention, and underscores the importance of soil media specification and design.

Also, related to the presence of compost, the effluent NH4-N concentration of Cell 1 was found to be significantly affected by influent concentration and significantly greater than Cell 2's effluent concentrations. This suggests that NH4-N removal performance was poorer in the presence of compost and especially during storms where NH4-N influent loading was high. One possible cause of this could have been a relation between storm intensity and observed effluent. It is possible that heavy, intense rainstorms that carried higher concentration of influent NH4-N to the cells from the

watershed also caused greater leaching of NH4-N from the compost in Cell 1. Li et al. (2006) noted a significant correlation between maximum rainfall intensity and the concentration of stormwater pollutants. Also, simulated high intensity or high volume rain events have been shown to increase effluent pollutant concentration of bioretention mesocosms (Yang et al. 2013). However, the sample size of storms for this study was small, and available rainfall data did not explicitly point to any patterns related to storm intensity and NH4-N concentrations. Future study of these cells should take the intensity of rainfall into consideration to further explore this hypothesis.

Of the pair, only Cell 2 was found to significantly reduce TN concentration from influent levels, though effluent concentration was not significantly different between treatments. The lower reduction of TN and NOx-N concentration may be indicative of leaching of compost by the Cell 1, a phenomenon seen in several previous studies that have used organic soil amendments in bioretention (Davis et al. 2001, Hsieh and Davis 2005, Mullane et al. 2015, Hurley et al. 2017). Here I make note that the treatment of a vegetated bioretention cell without added compost was the only configuration tested to significantly reduce both Total Nitrogen and Total Phosphorus. This finding is noteworthy, and raises questions about whether compost is necessary or advisable to achieve nutrient-related water quality goals for stormwater.

An analysis of the mass retention by the different treatments from two storms in which equal flow between the cells could be assumed (Table 4) also suggested that the presence of low-P compost has a marginal negative effect on bioretention pollutant mass removal. Mullane et al. (2015) noted a similar contribution of nutrients from compost to the effluent of bioretention mesocosms, but observed a decreasing effect over time as

nutrients washed out of the system. The estimations of mass retention by the MRC bioretention cells are from a very limited data set taken in the first year of operation; it is possible that the nutrient leaching may decrease over time.

3.5.1.2 *Panicum virgatum* effects on water quality: Cell 2 (V+) vs. Cell 3 (V-)

The presence of vegetation had no effect on TSS concentration reduction and only a small effect on nutrient concentration reduction. The only detectable difference between treatments, was that TN influent concentration was significantly reduced by Cell 2 but not Cell 3. This has been seen in previous studies, with a positive effect of vegetative uptake of nitrogen (Bratieres et al. 2008, Lucas and Greenway 2008), but little to no effect on phosphorus concentration (Read et al. 2008). I should note, however, that bioretention vegetation's capacity for nutrient uptake has been reported to change over the course of vegetation establishment (Houdeshel et al. 2015). This bioretention system was still in its first year of installation at the time of this study, and it is possible that a greater difference between treatments will be seen in subsequent years.

3.5.2 Media Water Extractable Phosphorus (WEP) Concentration

As expected, the WEP concentration of all treatments significantly decreased with depth, suggesting phosphorus sorption by the media in a top-down fashion. Over time, however, there was an increase in the concentration of the shallowest 15 cm of all treatments, with the exception of the first 5 cm of Cell 1. This was similar to results found by Muerdter et al. (2015), who noted a loading in shallow depths, but no significant increase in Mehlich-3 phosphorus concentration beyond media background

levels past a depth of 12 cm in a seven year old bioretention cell. Together these studies underpin the importance of the first 10-15 cm of bioretention media for phosphorus removal, a sentiment echoed by other bioretention studies focused on other stormwater pollutants such as sediment (Hsieh and Davis 2005), heavy metals (Sun and Davis 2007), and pathogenic organisms (Rusciano and Obropta 2009).

Compost had an immediate and significant effect on media WEP concentration. The highest concentrations of WEP measured in the shallow layers of Cell 1 in June, suggest the low-P compost leached loose, labile forms of phosphorus immediately after placement. The effect persisted into November; however, there was a convergence of average concentration across treatments, possibly due to of some initially leached phosphorus migrating to the lower media or discharging with the effluent. A contribution of phosphorus to bioretention media by compost is expected, and in many ways the goal of organic amendment, but long term loading onto media that has low sorption capacity could result in rapid saturation and decreased P removal. This finding provides a greater understanding of the mechanism by which leaching occurs when a layer of compost is added atop of the bioretention media, as opposed to mixed throughout.

Sands are often used as bioretention media due to their high rates of hydraulic conductivity and storage capacity (Fassman-Beck et al. 2015); however, their P sorption potential is typically low due to their relatively few Al and Fe complexion sites (Xu et al. 2006). This lower capacity could result in a decreased treatment lifespan of a bioretention cell receiving high loads of P, as complexion sites become saturated and begin desorption (Del Bubba et al. 2003). My study has shown that P loading onto sand-based bioretention media can be immediately apparent in the first year of installation, and exacerbated by

the presence of a low-P compost layer. Also, use of bioretention cells to treat agricultural production facilities is a relatively novel idea; P loading in this landscape is generally greater than the urban sites where bioretention has been most extensively studied. Future research should consider the long term implications of sand-based bioretention media accepting this level of P loading.

3.5.3 *Panicum virgatum* Survivorship and Biomass

Overall, Switchgrass proved to be a vigorous and hardy species, well suited for bioretention. When planted in compost, the Switchgrass grew rapidly and fully covered the area of the bioretention cell within the first few months. Even without compost, the plants were still able to survive an abnormally dry growing season and significantly reduce the concentration of nutrients in runoff. This fact leads us to recommend Switchgrass and other native C4 grasses capable of tolerating low nutrient environments in bioretention projects that abstain from compost amendment. Additionally, these types of plants may be well suited for bioretention in agricultural landscapes, where they can be readily harvested and utilized for other purposes such as biofuel or livestock bedding. One challenge of using Switchgrass was that it was a warm-season grass that took several months to establish after planted in spring and required frequent watering through early summer. Bioretention projects considering Switchgrass should be aware of its seasonality and plant accordingly to minimize extra management.

Low-P compost was found to have a significant effect on the total biomass growth of planted Switchgrass, but interestingly, little to no effect on the total survivorship. This suggests that low-P compost may aid in the initial growth of vegetation in bioretention

cells, but Switchgrass is able to survive and uptake a similar concentration of phosphorus when planted directly in sand-based media. Since there were detectably greater phosphorus concentrations Cell1's (C+V+) effluent and media, it can be assumed that the difference in biomass does not account for a total greater uptake of phosphorus. That is, the larger plants in this cell were not taking up enough phosphorus to overcome what was added by the compost in the first year. However, as plants mature and as nutrient leaching diminishes with time, vegetative uptake may be able to overcome the effect and result in a net phosphorus removal.

The role of these plants in bioretention phosphorus cycling should continue to be studied. Switchgrass biomass production has been shown to increase with age (Frank et al. 2004). By the time of the first season's harvest, the Switchgrass in Cell 1were at or close to their maximum size (1-1.5 m), but the Switchgrass in Cell 2 were significantly smaller, some near seedling size. The Switchgrass in Cell 2 (C-V+) are expected to continue to grow and eventually approach the same biomass as those planted in Cell 1. Plant uptake of phosphorus has been noted as a primary mechanism for removal in previous bioretention studies (Lucas and Greenway 2008); future bioretention studies should consider quantifying the change in nutrient water and media concentration as plants mature.

Several questions remain about the role of Switchgrass on bioretention performance that were not answered in this study. The Switchgrass used in this study were an open-pollinated variety with intended use for ecological restoration; it is possible that varieties bred for other purposes could have a different effect on bioretention performance. For example, varieties bred for biomass accumulation may have a more

pronounced affect on pollutant uptake (Reed et al. 1999) or varieties used for slope stabilization may influence soil media structure (Simon and Collison 2002). Also, different placement of Switchgrass in bioretention cells could be explored; Switchgrass in my studied were evenly spaced in rows, but grouping individuals could allow for natural benefits of intraspecific symbiosis such as shared mycorrhizal communities(Hart et al. 2003). Finally, a monoculture was studied in this experiment for the purpose of isolating the effects of a single species. Floristic diversity increases the productivity and chemical cycling of an ecosystem (Tilman et al. 1997); future studies could consider comparing how monocultures in bioretention compare in performance to communities with several species adapted to cohabitating with Switchgrass.

3.5.4 Uncertainty and Future Research on Bioretention Hydrology

Several issues limited my ability to study the cells' hydrology. One issue was the abnormally dry weather conditions of our sampling season; Vermont was in a Stage 2 drought during my sampling (NOAA National Centers for Environmental Information 2016). Runoff from low volume storms (< 13.5 m^3) can be fully retained by the forebay in this system; in an effort to increase flow through the cells such that bioretention performance could be better evaluated, including low-volume events, a shallow trench (8.8-cm deep, and approximately 1-m wide) was carved across the forebay from the inflow swales to the forebay outlet structure, which is the ihanflow to the bioretention cells. This trench channeled stormwater directly to the bioretention cells' inlet, minimizing forebay residence time and allowing the sampling of more low-volume storms. This feature is temporary, and the forebay will be restored at a later date. A

comprehensive water budget of the cells should be completed once the system is restored to its intended designed state and normal weather conditions can be assumed.

Another issue was that after the first half of the sampling season, it was observed that higher intensity storms delivered a greater volume to the center cell, Cell 2. As a modification, on October 15, a fiberglass baffle was installed in the splitting structure to dissipate flow, reduce turbulence, and more evenly distribute the influent volume across the three bioretention cells for all storm intensities. Equal inflow volume splitting to the three cells could not be assumed up to this point, and therefore a mass balance and measure of media retention could only be obtained for two storms (October 22 and 28). A more detailed mass and water balance model can be produced for these cells as more storm events are sampled with the assumed equal inflow splitting.

Finally, the effects of the experimental treatments on cell hydrology were not explored. The additional layer of compost in Cell 1 is expected to provide extra storage and the positive influence on growth may increase evapotranspiration rates compared to Cell 2. Similarly, the evapotranspiration of the Switchgrass present in Cell 2 could influence moisture content and storage compared to Cell 3. These may have a significant effect on the retention and pollutant removal of the bioretention cells overall, and should be considered in future years of sampling.

3.6 Conclusions

This study provides a better understanding of the benefits and drawbacks of using low-P compost in bioretention cells. On the one hand, the bioretention cell with the low-P compost had vigorous establishment of Switchgrass in the first year with only slightly higher effluent stormwater nutrient concentrations than the bioretention cell with no compost. However, on the other hand, the presence of this compost may shorten the treatment lifespan of a bioretention cell, as it was shown to significantly increase the concentration of labile phosphorus within media that may have low sorption potential. Also, while it was important for growth, the compost had no effect on the number of plants that survived, suggesting that at least some types of vegetation can successfully establish without added compost, low-P or otherwise.

Therefore, my recommendation of low-P compost for use in bioretention projects is dependent upon the situation. When fast plant establishment is required, I recommend its use over compost derived from manure or other enriched feedstocks which have been shown to have a greater leaching potential than leaf-based composts in other bioretention experiments (Hurley et al. 2017). However, I acknowledge that the presence of the low-P compost still had some deleterious effects upon stormwater nutrient treatment and encourage exploration of no-compost options whenever possible, especially in nutrient-sensitive watersheds.

At the time of this study, there was little to no effect of the presence of vegetation on either nutrient treatment or media phosphorus concentration in the Miller Research Complex Bioretention Cells. I note that my comparison took place after only five months, and it is possible that an effect could become apparent as the vegetation

grows. I encourage further research into species that can survive low nutrient bioretention media. Finally, continued testing of different Switchgrass varieties could increase choice among practitioners and encourage nutrient sensitive bioretention designs.

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Chapter 4: Hydrological Analysis of the Miller Research Complex Bioretention Cells

4.1 Introduction

The previous chapter of this thesis showed the Miller Research Complex Bioretention Cells had a significant positive reduction of nutrients and TSS concentration from stormwater in a mixed use agricultural landscape, with only marginal differences in performance between compost and vegetation treatments. While this is encouraging and supports the further use of this technology, pollutant concentrations are only one part of the story. The criteria for many stormwater manuals are based on mass load reduction, which factors both pollutant concentration and stormwater volume. The unknown fraction of volume that was distributed to each cell by the inflow structure before the installation of a baffle prevented a seasonal mass balance of individual treatments from being calculated, leaving only a limited dataset of two storms (Table 4). The individual treatment effluent mass calculated for the season is listed in Table 5 showing a general pattern of 1>2>3. I hypothesize that the large differences in treatment effluent pollutant mass were related to individual hydrological characteristics of the cells in addition to the affects of treatment. In this chapter, I explore some of these unique hydrological characteristics in greater detail for the purposes of better understanding mass removal performance and providing suggestions on improving future monitoring.

Table 5 – 2016 season total effluent mass and fraction of MRC Bioretention Cells

		Cell 1 (C+V+)		Cell 2 (C-V+)		Cell 3 (C-V-)	
	Storms	Mass (kg)	Outflow Fraction (%)	Mass (kg)	Outflow Fraction (%)	Mass (kg)	Outflow Fraction (%)
TSS	12	0.489	61.0%	0.265	33.0%	0.048	6.0%
TN	12	0.37	44.2%	0.341	40.7%	0.127	15.2%
NO_X-N	12	0.256	39.1%	0.282	43.1%	0.116	17.7%
NH4-N	12	0.009	69.2%	0.003	23.1%	0.001	7.7%
TP	11	0.01	47.6%	0.008	38.1%	0.003	14.3%
SRP	11	0.007	43.8%	0.006	37.5%	0.003	18.8%
Avg.			50.8%		35.9%		13.3%

4.2 Miller Research Complex Bioretention Cells Hydrology

Listed in Table 6 is a breakdown of certain important hydrological parameters for storms sampled at the MRC Bioretention Cells during the 2016 sampling season. A total of thirteen storms were sampled, however, the final storm of the season on November 3 was left out of analysis due to instrument error. Precipitation depth and time were measured using a tipping bucket rain gauge (HOBO Onset RG3, Bourne, MA), and precipitation intensity was calculated by dividing the former by the latter. Due to instrument (or user) error, the rain gauge did not record for the final two storms of the season, and these data are unavailable; in these cases the daily precipitation recorded by a local weather station were uses (KBTV South Burlington Airport). Inflow volume (of the system), inflow time, and individual cell outflow volumes were determined by the methods described in the Methods section of Chapter 3 of this thesis, and the fraction was calculated as the summed outflow volume of a storm from all three cells divided by the system inflow volume.

Twelve storms are considered in this analysis, four of which had zero outflow volume suggesting the influent stormwater was either fully retained by the cells or had seeped into the surrounding soil. The average fraction of outflow to system inflow for the season was 0.37, ranging from a low of 0.00 to 0.86. This is slightly lower than the 0.58-0.69 outflow fraction observed by Brown and Hunt (2012), who studied unlined bioretention cells in clay soils, suggesting the MRC Bioretention Cells had either greater ability for seepage into surrounding soil or more storage capacity. The average fraction of outflow volume per storm was highest for Cell 2 (55.9%), then Cell 1 (36.9%), and finally Cell 3 (7.2%). The fraction of outflow was generally higher for Cell 2 in the early

part of the season (6/22-7/23; Cell 2 = 68.1%), however in the latter half of the season, or post-baffle, Cell 1 has the greatest share of outflow volume (10/22-10/28; Cell 1 = 61.3%). Cell 3 consistently discharged the lowest fraction of effluent volume, with only four events greater than zero and one event, 8/16, greater than 30%.

One item to note is the abnormally dry conditions during this season. Vermont was under a Stage II drought in 2016, and the highest recorded precipitation event was 2.78 cm (1.09") on August 16. Interestingly, this date had the most even distribution of outflow volume between the cells at approximately 1/3 each and the second highest recorded total outflow fraction at 0.85. These bioretention cells were designed to meet the Vermont Stormwater Manual Water Quality Volume (WqV) of 0.9" (or 2.3 cm) over 24 hours, meaning that only on storm has been sampled at full capacity. We should take note of this in future years to determine if larger storms lead to more similar outflow volumes between the treatments.

Generally, we hypothesize that the difference in outflow fraction between the Bioretention Cells was due to issues in the inflow splitting structure and differences in the surrounding soil and seepage rates.

Table 6 – List of hydrological parameters for Miller Research Complex Bioretention Cells. Precipitation and time of rainfall was measured using tipping bucket rain gauge. Inflow or outflow volumes were measured as described in the Methods section of Chapter 3.

MRC Bioretention Cell Hydrology Table

Storm Date	Precip. Time (min)	Precip. Intensity (cm/min)	Precip. (cm)	Precip. Prior 3 Days (cm)	Inflow Time (min)	Inflow (m^3)	O1 (m^3)	O1 (%)	O2 (m^3)	O2 (%)	O3 (m^3)	O3 (%)	O Total (m^3)	O:I
22-Jun	67	0.0165	0.97	0.14	140	3.8								
1-Jul	39	0.0252	0.53	0.45	869	34.2	0.00	0.0%	3.59	100.0%	0.00	0.0%	3.59	0.11
10-Jul	69	0.023	0.91	0.67	1786	201.2	26.33	24.3%	68.26	63.0%	13.80	12.7%	108.39	0.54
14-Jul	45	0.0349	0.94	0.63	119	38.9	4.59	13.7%	24.95	74.4%	4.00	11.9%	33.54	0.86
18-Jul	58	0.0201	1.17	0	330	34.3	9.03	50.9%	8.7	49.1%	0.00	0.0%	17.73	0.52
23-Jul	210	0.0083	1.45	0.29	639	28.8	6.98	46.2%	8.13	53.8%	0.00	0.0%	15.11	0.53
1-Aug	44	0.0121	0.53	0	203	6.0								
13-Aug	118	0.0071	0.84	0	1088	72.2								
16-Aug	130	0.0148	1.93	0	976	104.8	33.58	37.5%	27.21	30.4%	28.65	32.0%	89.45	0.85
11-Sep	41	0.0271	0.99	0.12	187	31.8								
22-Oct	N/A	N/A	2.78	1.67	214	88.2	21.64	55.0%	17.26	43.9%	0.45	1.2%	39.36	0.45
28-Oct	N/A	N/A	1.02	0.14	744	34.4	12.59	67.6%	6.03	32.4%	0.00	0.0%	18.62	0.54
Avg	82.1	0.0189	1.17	0.34	607.92	56.55	14.34	36.9%	20.52	55.9%	5.86	7.2%	40.72	0.55
+/-	34.1	0.0055	0.36	0.27	289.16	31.00	8.09	15.7%	14.69	16.0%	7.18	7.9%	26.27	0.16

4.3 Flow Splitting

One issue that could have influenced the difference of volume discharged from individual cells was the fraction of influent volume each received. Put simply, if a cell received a greater volume compared to other cells, it follows that it could discharge a greater volume as well. The goal of this system design was to split equal volume between the three cells, however it was suspected that Cell 2 received a disproportionate fraction due to the position of its influent pipe directly across from the forebay inlet. Figure 8 visually shows the difference of inflow splitting during the storm with the highest intensity of the season (7/14) shows the difference in the fraction of outflow volume of the cells plotted against rainfall intensity before the installation of the baffle. Post-baffle analysis could not be performed due to errors with the rain gauge and the unknown rainfall intensity. An analysis of covariance (ANCOVA) comparing the fraction of outflow volume per storm between cells with precipitation intensity as a covariate found a Cell 2 significantly discharged a greater volume than Cell 1 in increasing intensity storms ($p = 0.012$). The effect was not significant between Cell 2 and Cell 3 ($p = 0.116$), due possibly to the low samples size of Cell 3; however, a similar trend can be seen as Cell 3's fraction of outflow decreases slightly with increased precipitation intensity.

This supports my theory of inflow splitting issues before the baffle, but goes counter to the mass discharge observed from each cell. That is, Cell 1 on average discharged a lesser volume but greater mass of pollutants over the season than Cell 2. One reason for this is likely due to the higher concentration of pollutants discharged from Cell 1 and its added compost layer. Another theory may be that a higher flow in Cell 2 in

one storm could have “flushed” pollutants from previous events such that the following storm discharged lower concentration and subsequently mass. This “flushing” phenomenon has been noted previously in bioretention projects (Jones and Davis 2012), and underscores the difficulty in determining loads based on only a few storm events.

In future years, I suggest monitoring the peak flow rate through each Cell’s inflow pipe to determine if the baffle is splitting flow equally. I also suggest taking note of effluent concentration changes between storms to determine if concentrations decrease following larger “flushing” storms. Also, now that equal inflow between the cells can be assumed, I suggest creating a water balance of every cell for each storm in the future that incorporates as many factors as possible including evapotransipiration, soil moisture, temperature, and storage capacity. Many of the means required to build a detailed water balance were unavailable in the first year of research, but further exploration of this topic would improve understanding of this systems and unlined bioretention cells in general.

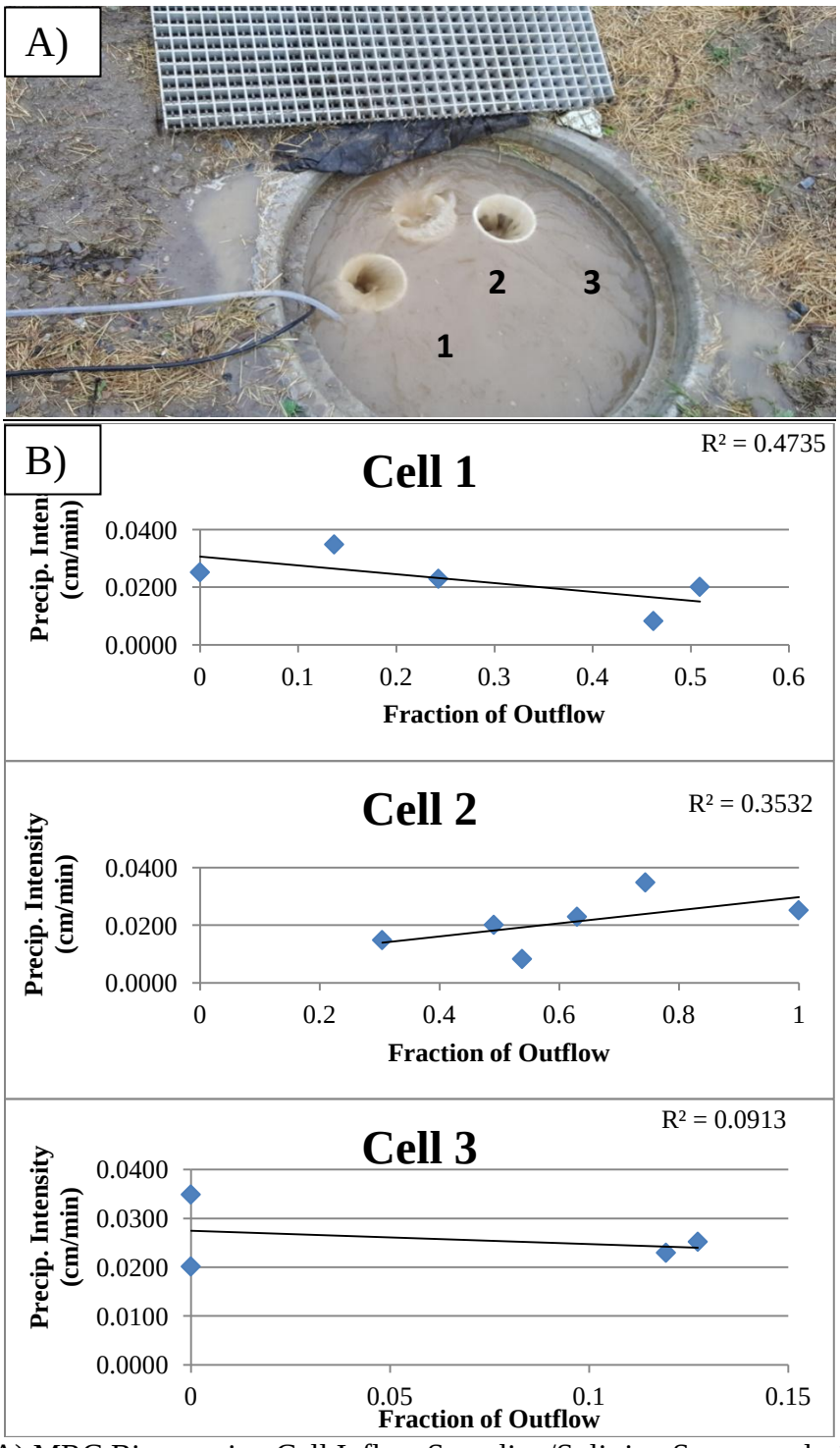


Figure 8 - A) MRC Bioretention Cell Inflow Sampling/Splitting Structure during 7/14/2016 Storm. B) Storm intensity plotted against fraction of total outflow volume for MRC Bioretention Cells before the installation of the inflow baffle

4.4 Surrounding Soil and Seepage

While issues with the inflow splitting structure may be the reason for the higher fraction of outflow exiting Cell 2, it does not account for such significant differences between Cell 1 and Cell 3 which should have received equal inflow volume even before the baffle. I hypothesized that the volume discharging through the outflow structures may have been due to differences in the Cells' surrounding soil and ability for seepage. In order to test this hypothesis, two tensiometers were installed at points equidistant between the outflow sampling structures of Cell 1 and Cell 2 (T12) and Cell 2 and Cell 3 (T23) on October 16 (Figure 8). A total of five tensiometers were placed in a vertical profile at intervals of 10", and the soil tension (kPa) was measured every 3-5 days for the latter half of the season (8 sampling times total). Additionally, a soil texture profile was performed on October 29th using the USDA Soils Texture Flow Chart (Appendix B) approximately 12" south of the tensiometers at similar interval depths.

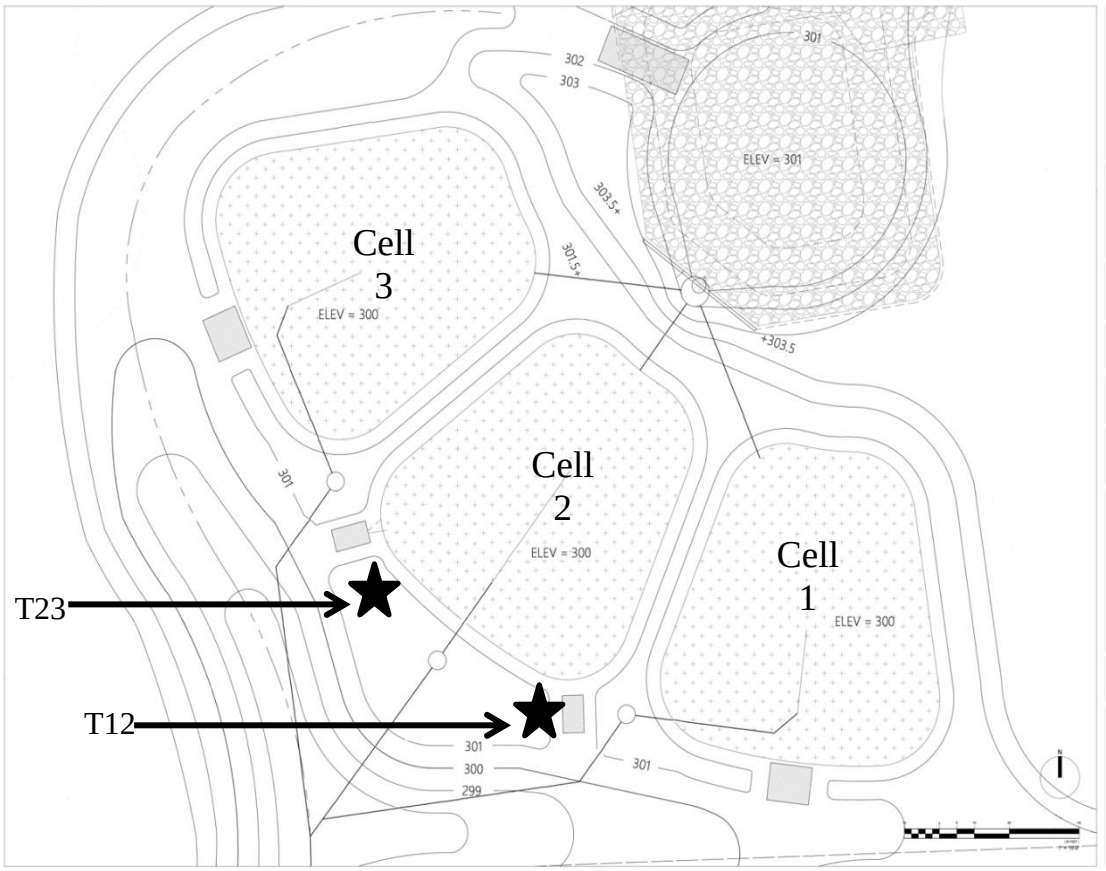
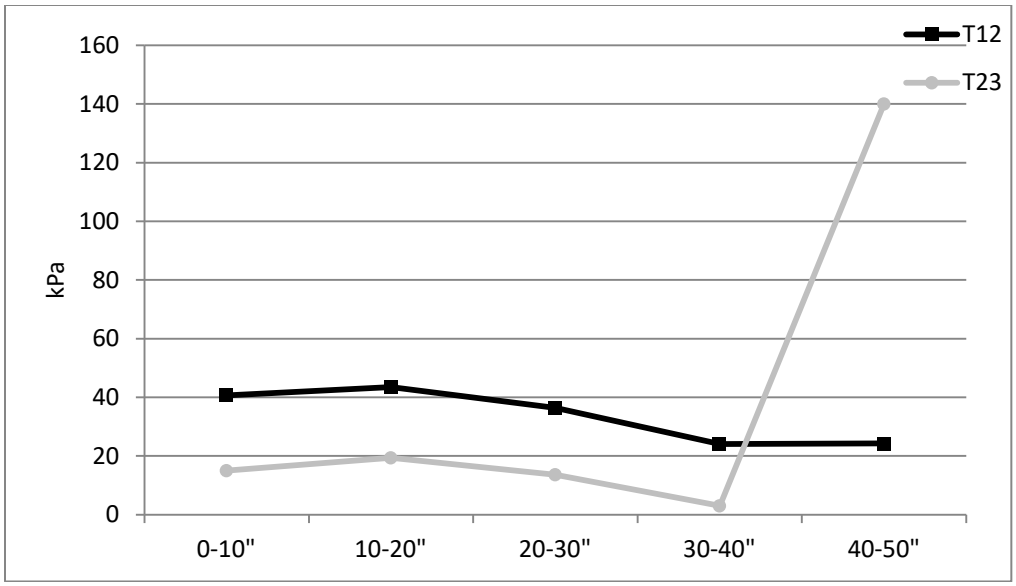


Figure 9 - Locations of tensiometer sampling locations equidistant between Cell 1 and Cell 2 (T12) and between Cell 2 and Cell 3 (T23). Tensiometers were placed at intervals of approximately 10" down to a dpeth of 50". Soil tension (kPa) was measured at each depth and eight times in the latter half of the season (beginning October 19).

Results of the tensiometers testing show a trend of decreasing soil tension with depth, with the exception of 40-50" in T23, which increased dramatically above the rest of the profile (Figure 10). The soil texture test found surrounding soil to range from sand to dense clay, however, in the 40-50" the soil removed by the auger was coarse gravel and urban fill. This suggests that in some areas of the surrounding soil the potential for seepage is much greater (Figure 10). This site has been used for several construction projects in the past including constructed wetlands and a horse racing track, which may

account for this heterogeneity. It may be that pockets of this gravel influence the soil tension around Cell 3and resulted in such greater seepage that there were fewer outflow events. In the case of the August 16 storm, where outflow was approximately equal between the cells, the surrounding media could have been saturated and all influent stormwater not retained by the cells was force to discharge through the outflow structures. However, because these sampling locations are splitting the difference between outflow structures, we cannot definitively say if there is an effect on one cell over another. In the future, I suggest placing vertical tensiometer sampling locations outside of all three cells so that the potential seepage of each can be better understood. Additionally, I suggest placing them deeper so that the entire vertical profile of the outside of the cells can be measured.



T12	Sand	Loamy Sand	Loamy Sand	Silty Loam	Silty Clay Loam
T23	Loamy Sand	Clay Loam	Clay Loam	Clay	Gravel/ Urban Fill

Figure 10 – Soil tension measured a tensiometers locations between Cell 1 and Cell 2 (T12 and between Cell 2 and Cell 3 (T23), as well as corresponding soil texture at similar depths.

4.5 Conclusion

This brief analysis has shown that there were some issues relating to the MRC Bioretention Cell hydrology which may have had a large impact on mass removal. Simply considering the mass being discharged from the outflow sampling structures is not sufficient for understanding their performance. This logic would lead to the assumption that Cell 3 was the best configuration for stormwater treatment, which is not likely. Rather, factors that affected the volume of influent stormwater and its ability to seep into surrounding soil may have had an overpowering affect. Here I pose some suggestions for improving monitoring including continued analysis of large storms, flow meters for individual cells, estimating detailed water balances for every storm, and monitoring of soil tension at each outflow sampling location. The issue of equal inflow splitting may have been resolved by the installation of the baffle, however, there is nothing that can be done to equalize the seepage rate between the cells. While this latter issue confounds the ability to measure effluent mass, I see this as a possible opportunity to further explore the performance of unlined bioretention cells. If it is found to be the case that Cell 3 has a significantly different capacity for seepage than Cell 1 from continued tensiometers testing, this could be one more variable to test. Cell 3 could be modified to have the same vegetation and soil treatment as Cell 1, and the performance of cells with similar design components but different surrounding soil infiltration rates could be compared. This type of study could aid designers in understanding the benefits and drawbacks of bioretention placement in native soils and the dynamics of stormwater infiltration in general.

References

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Chapter 5: Additional Water Quality, Media, and Vegetation Analyses of the Miller Research Complex Bioretention Cells

5.1 Introduction

Over the course of my research, several additional tests and analyses regarding water quality, media, and vegetation were performed on the Miller Research Complex Bioretention Cells. These include:

(1) Water Quality: An assessment of the average nutrient and TSS removal by all three cells, considering them as one "system".

(2) Media: A measure of the phosphorus concentration (TP and Modified Morgan) of the bioretention media and low-P compost. Tests of the media include a Phosphorus Sorption Index and measure of the Phosphorus Sorption Maxima.

(3) Vegetation: Visual area covers of Switchgrass and total micro- and macronutrient concentrations within the tissue)

While the information is valuable to the overall understanding of these cells, it falls outside of the scope of the target research objectives posed in Chapter 3. Each subsection of this chapter consists of each analysis' methods, results, and a brief discussion of findings.

5.2 Total System Nutrient and TSS Removal

5.2.1 Methods

The water quality data was the same as reported in Chapter 3, however, in this analysis, the data was averaged across treatments to obtain one effluent value per storm event. Effluent nutrient concentrations were averaged across all treatments where outflow was observed. Effluent mass was averaged across all three treatments for every storm event, even if no outflow was observed (i.e. 0 kg). Statistical significance was tested using a paired samples t-test with a significance level of $p \leq 0.05$.

5.2.2 Results

Average Concentration

TSS - The average influent concentration of TSS per storm, measured from twelve events, was 155.7 (± 197.0) mg/L. The average TSS influent concentrations were highly variable between storms, ranging from a low of 9.2 mg/L to a high of 1137.8 mg/L. Despite this range, the system was effective at reducing TSS concentration with the three outflow structures discharging an average concentration of 5.6 (± 6.3) mg/L from eight system outflow events, or a 96.8% average reduction. However, while the whole system reduction of TSS concentration was quite high, it was not found to be statistically significant by a paired samples t-test ($p = 0.207$).

Nitrogen - The average influent concentration of Total Nitrogen (TN) per storm, measured from twelve events, was 4.00 (± 1.87) mg/L, with a range between storms of

1.47 to 14.2 mg/L. The average measured effluent concentration of TN from all three outflows was 2.84 mg/L, a 29% reduction measured from eight system outflow events, but not statistically significant ($p = 0.358$).

The average storm influent concentrations of NOx-N and NH4-N from thirteen events were notably lower than influent TN concentration, at 0.230 (± 0.188) and 0.369 (±0.212) mg /L, respectively, suggesting a high fraction (85%) of the influent nitrogen was in particulate form (i.e. organic). Average NH4-N effluent concentration of all three outflows observed from nine system outflow events was 0.036 (± 0.010) mg/L, a 90.2% reduction and statistically significant ($p = 0.019$). Conversely, the average NOx-N system effluent concentration observed from a similar number of events was 1.87 (± 0.48) mg/L, a statistically significant increase of 813% ($p < 0.001$). Fractional breakdown of the average system effluent nitrogen was 32.9% organic (i.e. particulate) and 67.1% soluble.

Phosphorus - The average storm influent concentration of TP measured from eleven events into the system was 1.50 (± 0.362) mg/L. The range in storm concentration was 0.558 mg/L to 3.08 mg/L. The average storm effluent TP concentration of all three outflows observed from seven system outflow events was 0.109 (± 0.029) mg/L, a 92.7% reduction and statistically significant ($p <0.001$).

The average storm influent SRP concentration measured from twelve events was 0.887 (± 0.196) mg/L, leading to the conclusion that approximately one half (59.1%) of the phosphorus within the runoff of this watershed was in soluble form. The average effluent SRP concentration of all three outflows observed from eight system outflow

events was 0.042 (± 0.011) mg/L, a 95.3% reduction and statistically significant ($p < 0.001$). Fractional breakdown of effluent phosphorus was 52.3% particulate and 47.7% soluble.

EMC and Mass

The average stormwater pollutant EMC of the system influent and average of all three outflow effluent EMC's per storm event are listed in Table 7, along with the percent reduction ($R_{EMC\%}$). The difference in average EMC between system influent and effluent was found to be statistically significant for all stormwater pollutants, with the exception of TSS. The average EMC of TSS, however, was reduced by 96.6%, and lack of statistical significance is likely due to high variation in samples. All nutrient EMC's were significantly reduced, with the exception of NOx-N, which on average exported an increase of 469% from influent levels. Despite this increase, TN EMC was modestly reduced by the system to 62.3% of influent levels.

Table 7 – Average system influent and effluent Event Mean Concentrations of measured stormwater pollutants for the season, along with percent reduction and statistical significance of paired samples *t*-test.

	Influent (mg/L)	±	Effluent (mg/L)	±	$R_{EMC\%}$	Sig.	*p*
TSS	160.51	187.79	2.11	1.88	98.7%		0.112
TN	3.98	1.88	1.50	0.83	62.3%	*	0.027
NOx-N	0.23	0.19	1.08	0.55	-469%	*	0.009
NH4-N	0.36	0.21	0.02	0.01	94.4%	*	0.004
TP	1.51	0.39	0.05	0.03	96.7%	*	<0.001
SRP	0.89	0.20	0.03	0.01	96.7%	*	<0.001

The system average storm influent and summed effluent mass of stormwater pollutants is listed in Table 8, along with total percent considered removed via either retention or seepage ($R_{M\%}$). Results suggest an effective removal of suspended solids and phosphorus by the system, each with greater than 90% removal. Nitrogen removal was less effective and had higher variability between storms, on several occasions exporting greater mass than the influent, leading to a relatively low average mass removal for the season (15.2%).

Table 8 – Average event mass (kg) for system influent and the total summed mass of the effluent, along with percent removed and statistical significance of paired samples *t*-test. $R_{M\%}$ represents the total percent of mass removed by the entire system per storm, either retained in the system or lost to seepage into the surrounding soil.

	Influent (kg/Storm)	±	Effluent (kg/Storm)	±	$R_{M\%}$	Sig.	*p*
TSS	86.6	169.8	5.6	10.97	93.5%		0.059
TN	3.35	0.452	2.84	5.56	15.2%		0.234
NOx-N	0.146	0.286	1.874	3.67	-1183.6%	*	<0.001
NH4-N	0.201	0.394	0.036	0.07	82.1%	*	0.009
TP	1.44	2.817	0.109	0.21	92.4%	*	<0.001
SRP	0.837	1.640	0.042	0.08	95.0%	*	<0.001

5.2.3 Discussion

TSS - The results of this study show that in their first year of operation, the Miller Research Complex Bioretention Cells considered as one system were highly effective at reducing suspended solids concentration from stormwater runoff in a mixed use agricultural setting. While the high variation of influent TSS concentrations and limits of detection of very low effluent concentrations prevented detection of statistical significance, the average concentration reduction and mass removal of TSS by the system

was 97% and 99%, respectively. These results were not surprising, as many studies have previously demonstrated bioretention as effective at TSS treatment (Hsieh and Davis 2005, Davis 2007, Hatt et al. 2009, Trowsdale and Simcock 2010, Le Coustumer et al. 2012).

Generally, physical filtration of solids by bioretention media is considered one of the most basic, yet important mechanisms for stormwater treatment (Roy-Poirier et al. 2010). The lifespan of solids removal for bioretention cells, however, is limited as stratification occurs over time and finer particles begin to clog the upper layers of the media (Li and Davis 2008, Kandra et al. 2014). The average influent TSS concentration of this system was similar to that of other urban and suburban bioretention studies (Hatt et al. 2009, Lucke and Nichols 2015) that observed this phenomenon, and it is possible that clogging could become an issue in the future. This system was also in its first year of installation with vegetation still establishing on the inflow swales and sediment forebay. This could have inflated influent TSS concentrations, and it is possible concentrations will drop in subsequent years as pretreatment vegetation cover increases. Therefore, while solids removal by this system is quite high continued stormwater monitoring and analysis of the bioretention media could point to issues related to clogging such as changing hydraulic conductivity.

Nitrogen - The system as a whole could not be reported as significantly reducing TN concentration, due primarily to the significant increase in NOx-N concentration. Dietz (2016) and Ergas et al. (2010) did note a significant reduction of TN concentration from bioretention cells treating watersheds with similar agricultural operation uses.

However, the observed influent concentrations of these studies were also approximately two and three times higher than that seen in the Miller Research Complex Bioretention System, respectively, which may have accounted for this difference in treatment performance; it is easier to reduce higher concentrations of stormwater pollutants than it is to "polish" runoff with already relatively low concentrations (Lenhart and Hunt 2010, McNett et al. 2010). The lower influent TN concentration observed at the Miller Research Complex also suggests the watershed may not be as typically agricultural as areas studied in similar bioretention projects. While much of the Complex was used for dairy and agricultural purposes, there was a significant area that included grassy lawns, rooftops, and parking lots. These relatively "cleaner" areas could have diluted influent TN concentration below that seen by Ergas et al. (2010) and Dietz (2016).

Solids concentration reduction by this system appeared to be related to the transformation of nitrogen species. There was a substantial movement of grain and silage in this watershed, both feeds known for their high concentration of nitrogen. The season average particulate component of nitrogen concentration (i.e. TN – (NOx-N + NH4-N)) decreased from 85.0% in the influent to 32.9% in the effluent. This decrease in particulate component, contrasted with the significant increase in NOx-N effluent concentration suggests a capturing of organic nitrogen, followed by subsequent aerobic metabolism, and nitrification of the ammonium by-product to nitrate (Verstraete and Focht 1977). Similarly, while the influent NH4-N concentration was significantly reduced, it is likely that a large fraction of the influent concentration was converted to nitrate, and not necessarily removed by the system.

Increases in nitrate concentration have been noted as a persistent issue in previous bioretention studies (Davis et al. 2006, Bratieres et al. 2008, Blecken et al. 2011). While an export of nitrate is quite often due to a leaching from bioretention media and organic matter amendments addition (DeBusk and Wynn 2011, Mullane et al. 2015), this study makes note of the potential for concentration increase due to changing forms of nitrogen. Bioretention design solutions centered on the promotion of denitirification, such as the use of a permanently saturated zone, should be further studied and considered in landscapes where high nitrogen loading from organic and particulate sources is a concern (Dietz and Clausen 2006, Gilchrist et al. 2014).

The mass removal of nitrogen by this system was inconsistent and generally low, with a season average removal per storm event of only 15.2%. This effluent mass of this system was quite variable, as there were several storm events in which 100% of the influent Total Nitrogen mass was either retained or seeped into surrounding media, but other instance in which the mass exported by the system was greater than the mass received by runoff. This suggests a loading of nitrogen in less intense events and subsequent "washout" in following larger events, a phenomenon seen in previous bioretention experiments (Hatt et al. 2009, Li and Davis 2011).

Phosphorus - The MRC bioretention system, as a whole, significantly reduced runoff phosphorus concentration and mass by greater than 95%. This is encouraging, as the ultimate fate of the treated stormwater is Lake Champlain currently under a phosphorus TMDL. At the Miller Research Complex, the influent concentration of TP and SRP was greater than that of typical urban or suburban watersheds, but lower than

that seen in runoff from typical farm fields (McFarland and Hauck 1999). Because urban watersheds are relatively "cleaner" with regards to their phosphorus loading, it may be difficult to achieve significant reductions through bioretention alone, possibly making them not worth the expenditure. Therefore, bioretention for phosphorus treatment appears to be a valuable tool for agricultural production facilities or other areas where impervious cover and nutrient loading are both high.

5.3 Bioretention Media Mineral Concentrations and Sorption Potential

5.3.1 Methods

TP and Modified Morgan Soil Test

A measure of total phosphorus (TP) for the bioretention media was obtained from the June sampling in Cell 1 and Cell 2. Approximately 0.25 g of media was placed in a Teflon reaction chamber with 10 mL of concentrated nitric acid. Chambers were sealed and placed in a microwave system (CEM MARS-5, Matthews, NC) and heated to 190 oC for 30 minutes. After cooling, the digested samples were diluted to 50 mL with nitric acid and analyzed on an ICP-OES (Optima 3000DV, Perkin Elmer Corp, Norwalk, CT). Two-point calibration was used for this instrument, along with a calibration blank. Concentrations of TP were reported in mg/kg.

The concentration of plant available micro- and macronutrients (including phosphorus) in unused low-P compost and sand based media, as well as composited samples of the sand-based media from the top layer of Cell 1 and 2 taken in November sampling, were analyzed via Modified Morgan extraction (USDA Cooperative State Research, Education and Extension Service 1995). Four grams of the compost or media sample was extracted with 20 mL of 0.62 N Ammonium Hydroxide with 1.25 N Acetic Acid and shaken 15 minutes. After filtering through Ahlstrom 642 paper, the extract was analyzed for SRP via molybdate blue colorimetry and for macro- and micronutrients via inductively coupled plasma spectroscopy (ICP-OES) (Perkin Elmer Corp, Norwalk, CT, USA).

Phosphorus Sorption Index and Maxima

A Phosphorus Sorption Index (PSI) was determined for all treatments in June media samples from all three treatments and five depths. Twenty mL of 50 mg/L phosphate solution in deionized water (i.e. SRP) was added to one gram of media and shaken for 24 hours. Samples were then centrifuged for 10 minutes at 5000 RPM, and the supernatant liquid was extracted using a polypropylene syringe and filtered through a 0.45μm pore nylon mesh filter. This solution was then analyzed for SRP using automated colorimetry. PSI was determined via the equation

[6] $PSI = q/\log CE$

where q is the amount of phosphorus sorbed (in mg/kg) and CE is the equilibrium solution phosphate concentration (Allen and Mallarino 2006). Statistical significance was tested using a two-way ANOVA, for an effect of treatment and depth on PSI ($p = 0.05$).

Phosphorus Sorption Maxima (PSM) were determined for six media samples which showed a range of PSI. Twenty mL of phosphate solution in deionized water at concentrations of 1.0, 5.0, 10.0, 20.0, and 50.0 mg/L were applied to 1 g of media samples and shaken for 18 hours. Samples were then centrifuged for 10 minutes at 5000 RPM, and the supernatant liquid was extracted using a polypropylene syringe and filtered through a 0.45μm pore nylon mesh filter. This solution was then analyzed for SRP using automated colorimetry. The PSM for these samples were determined from the Hanes-Woolf linearization of the Langmuir Equation as:

[7] $CE/(q) = (1/kqMax) + (CE/ qMax)$

where q is the amount of SRP sorbed per unit weight of media, CE is the concentration of P in the solution at equilibrium, qmax is the phosphorus sorption maximum, and k is a constant of enthalpy relating to the phosphorus sorption capacity of the media (Olsen and Watanabe 1957, Bolster and Hornberger 2007). Results were then compared against a nonlinearized Langmuir ($q = (qmax+k*CE)/(1+kCE)$ model using Microsoft Excel's Solver function to determine the relative fit and confidence in this measure.

5.2.3 Results

Total P and Modified Morgan Soil Test

The average Total Phosphorus (TP) concentration of the bioretention media measured from 27 samples taken in June was 516.0 (± 32.4) mg/kg. There was no pattern of TP concentration change observed across treatment, depth, or distance from inlet from this analysis, and, therefore, further laboratory tests of this measure were abandoned. The 15 samples analyzed from Cell 1(C+V+) had an average of 519.4 (± 35.9) mg/kg and the 12 samples from Cell 2 (C-V+) had an average of 511.7 (± 59.3) mg/kg. Treatments were not statistically significantly different via independent samples t-test ($p = 0.822$), suggesting that the addition of a compost layer above the media did not significantly increase its initial concentration of total phosphorus.

Table 9 shows the Modified Morgan concentration of phosphorus and other select available minerals in unused Low-P compost, unused sand-based bioretention media, and

composited bioretention media from samples taken in November, or five months into operation, from the top 5-cm layer of Cells 1 (C+V+) and 2 (C-V+). Available phosphorus concentration in the low-P compost was notably higher (120 mg/kg) than the sand-based bioretention media (1.62 mg/kg). Assuming the sand-based bioretention media had concentrations similar to that of the control at the beginning of the experiment (1.62 mg/kg), both treatments showed an increase of concentration over the season to 5.01 mg/kg in Cell 1 (309%) and 3.71 mg/kg in Cell 2 (229%). These results suggest a loading of available phosphorus onto the media to both treatments by the influent stormwater, but additional loading in Cell 1 presumably from the compost.

The available concentration of all minerals is also notably higher in the low-p compost than the sand-based bioretention media. The media samples taken from the cells at the end of the season have higher pH values than either the low-P compost or unused sand-based media, suggesting the stormwater loaded onto this system was alkaline.

Table 9 – Concentration (mg/kg) of plant available micro- and macronutrients (Modified Morgan Soil Test) and pH in low-P compost and sand-based bioretention media from unused material (Unused), and from top 5-cm layers of Cell 1 (C+V+) and Cell 2 (C-V+).

	Low-P Compost	Sand-Based BR Media (Unused)	Sand-Based BR Media (C+V+)	Sand-Based BR Media (C-V+)
P	120	1.62	5.01	3.71
Ca	5350	128.00	337.25	509.00
K	3001	17.80	71.55	44.63
Mg	1075	11.28	31.35	23.58
Na	550.60	4.85	9.70	5.47
Al	26.90	12.70	12.53	15.13
Fe	9.73	8.03	24.55	48.48
Mn	82.25	4.07	19.28	25.55
B	5.01	0.12	0.25	0.30
Cu	0.69	0.42	1.25	0.71
Zn	12.73	0.20	1.68	0.35
S	154.50	6.80	5.95	7.98
pH	7.07	6.94	7.80	7.79

Phosphorus Sorption Index and Maxima

The total average Phosphorus Sorption Index (PSI) of the bioretention media measured from June samples was 15.1 (± 3.35) L/kg. There was a statistically significant effect across treatments, with Cell 1's (C+V+) average PSI of 22.8 (± 5.92) L/kg significantly greater than Cell 2 (C-V+) (12.1 ± 5.0 L/kg) and Cell 3 (C-V-) (11.0 ± 5.13) L/kg (p = 0.001). There was, however, no statistically significant effect of PSI with depth (p = 0.263), nor interaction of depth with treatment (p = 0.396). The relative sorption of the media was quite low across all samples in this test, with a highest sorption observed of 88 mg/kg (i.e. 7.2% decrease in solution SRP concentration), and in some instances zero sorption or a small net export. This led to the assumption that the there is little

capacity for phosphorus sorption in this media, in general, and that values nearing zero are highly subject error.

An average measure of the Phosphorus Sorption Maximum (PSM) using a linear Langmuir model of six samples was calculated to be 44.32 (± 15.35). The data was poorly fit to the nonlinearized model, with R^2 values ranging from a low of 0.164 to a high of 0.455. Additionally, there was no relation of the six samples' PSI to their PSM (R^2 = 0.107). Similar to PSI, it is possible that sorption potential of this media was low enough that small errors in methods could have accounted for large variation.

5.2.4 Discussion

TP and Modified Morgan Soil Test

No statistically significant difference of the Total Phosphorus (TP) concentration within the sand-based bioretention media could be detected between the Cell 1 and Cell 2 from samples taken in June. This was not surprising, as these samples were taken only two weeks after the final completion of the cells and the methods used to determine TP concentration resulted in high variability between replicates. However, a measure of the plant available (Modified Morgan) phosphorus concentration taken from the first 5-cm media layer of these Cells' media from June sampling did detect some notable differences between the treatments. Assuming that the difference in Modified Morgan concentration between Cell 1 (5.01 mg/kg) and Cell 2 (3.71 mg/kg) was solely due to their treatments, it follows that the presence of compost increased the concentration of Modified Morgan P in the media by 1.3 mg/kg. I note that, due to issues with flow splitting, Cell 2 received a greater fraction of the influent than Cell 1 in the first half of

the season; it is likely that this increased loading of phosphorus onto Cell 2 lowered the difference in Modified Morgan P concentration between the cells.

A survey of agricultural topsoils found Modified Morgan P concentrations ranged from an average low of 5.7 mg/kg to a high of 18.7 mg/kg (Lumsdon et al. 2016). This suggests that after the first season of operation, available phosphorus contributed to the sand-based bioretention media by low-P compost is on the low end of what is required for sustained plant growth and establishment. The Switchgrass planted in Cell 1 were rooted directly in the low-P compost (120 mg/kg), which may explain their vigorous growth in the first season. Future bioretention projects that are installed with a compost layer above sand-based media should be aware of this possibility for P leaching into lower media depths, and whether plants rooted within the sand-based media will have sufficient surrounding available phosphorus to meet planting and establishment goals. Several bioretention projects have explored the effects of mixing compost with sand-based bioretention media (Hatt 2009, UVM Bioretention Laboratory 2015), however the design of Cell 1 with an added layer of compost above the sand-based media is relatively novel. I suggest continued monitoring of the bioretention media in all three cells to quantify the loading by the influent stormwater and the impact of compost leaching on plant available phosphorus.

Phosphorus Sorption Index and Maxima

While the presence of low-P compost did significantly increase the amount of phosphorus sorbed by Cell 1, sorption capacity of this media was quite low in general, and no practical benefit in long-term P sorption is expected from compost application in

this case. The addition of compost was expected to have a negative effect on P sorption, due to its contribution of labile P to the media; however, it is likely that physicochemical changes provided by compost such as organic matter loading may have increased the P sorption of this bioretention cell. While organic matter will often compete with phosphorus for sorption sites on soil, the iron and aluminum compounds of humic and fulvic acids can themselves sorb phosphorus (Levesque and Schnitzer 1967). However, this increase of sorption potential is only transient, as P is released from the OM over time and exhausts these additional sorption sites. I, therefore, suggest continued analysis of the phosphorus sorption of the sand-based bioretention media in all treatments to better understand the medium to long term effects.

The average PSM of the media of 44.3 mg/kg, derived by the linearized Langmuir equation, was within the low range of Danish sands used in constructed wetlands analyzed in a similar method (Del Bubba et al. 2003). The authors who studied this media made note of the low potential for sorption and limited lifespan for septic wastewater treatment. While influent concentrations are much lower at the Miller Research Complex than typical wastewater (Qin et al. 2015), phosphorus saturation within this media may be an issue in this media in the near future.

5.4 *Panicum virgatum* Visual Area Cover and Tissue Nutrient Concentration

5.3.1 Methods

Visual Area Cover

An area cover analysis of the planted bioretention cells was performed on October 22nd, using the Daubenmire class system (Bonham et al. 2004). A 1 m2 PVC quadrat was placed at three equidistant points along the center transect of the two planted bioretention cells, and values were assigned to represent vertical visual cover of the quadrat of Switchgrass, Bare Ground, and Weeds into numerical cover classes (1 = 0-5%, 2 = 5-25%, 3 = 25-50%, 4 = 50-75%, 5 = 75-95%, 6 = 95-100%). The midpoint of each range was used for analysis, and averaged across sampling points to obtain a cover estimate for the cell.

Tissue Nutrient Concentration

Concentrations of P, Ca, K, Mg, Na, Al, Fe, Mn, B, Cu, Zn, S, Co, Cr, Cd, Mo, Pb, and Ni were analyzed from a subsample of the harvested plant material in each 1-m2 quadrat. Approximately 0.25 g of finely ground biomass was placed in a Teflon reaction chamber with 10 mL of concentrated nitric acid. Chambers were sealed and placed in a microwave system (CEM MARS-5, Matthews, NC) and heated to 190 o C for 30 minutes. After cooling, the digested samples were diluted to 50 mL with nitric acid and analyzed on an ICP-OES (Optima 3000DV, Perkin Elmer Corp, Norwalk, CT). Two-point calibration was used for this instrument, along with a calibration blank. Concentrations were reported in mg/kg.

5.3.2 Results

Visual Area Cover

Visual area cover analysis yielded an average cover of Switchgrass of 85% for Cell1 (C+V+) and 15% for Cell 2 (C-V+). The visual cover of other tested groups was also different between treatments with average weed and bare ground cover of Cell 1(C+V+) was 12.5% and 2.5%, respectively, and was 2.5% and 12.5% for Cell 2 (C-V+). These results further support the suggestion that low-P compost significantly improved Switchgrass growth in the first year, but also that the compost may provide a more suitable habitat for weedy invasion.

Tissue Nutrient Concentration

Table 10 shows the average concentration of micro- and macronutrients, including phosphorus, within the above-ground tissue of harvested Switchgrass samples taken from Cell 1 and Cell 2. There was no statistically significant difference via independent samples t-test in phosphorus concentration between samples taken from Switchgrass planted in compost or the bioretention media, but significant differences in other nutrients, namely Calcium, Potassium, Iron, Manganese, Boron, Copper, Zinc, and Sulfur.

Table 10 – Concentration of micro and macronutrients in Switchgrass (*Panicum virgatum*) samples from cell with layer of low-P compost (C+V+) and without (C-V+) and measure of significance from independent samples t-test. BDL signals concentrations that were Below Detection Level.

	C+V+		C-V+		*p*	Sig.
	mg/kg	±	mg/kg	±		
P	1525.34	199.88	1340.17	273.73	0.300	
Ca	3282.07	360.92	7666.14	569.16	<0.001	*
K	5550.69	490.70	3598.41	315.49	<0.001	*
Mg	1703.76	222.44	2146.49	377.46	0.065	
Na	28.01	11.05	38.28	23.84	0.455	
Al	BDL		71.90	44.56		
Fe	1.33	7.44	105.60	45.69	<0.001	*
Mn	17.85	2.81	106.70	15.38	<0.001	*
B	22.34	5.88	10.52	2.38	0.002	*
Cu	11.76	1.83	5.94	1.84	<0.001	*
Zn	42.38	3.60	11.59	3.37	<0.001	*
S	774.77	54.49	957.19	104.76	0.008	*
Co	BDL		BDL			
Cr	BDL		3.27	0.47		
Cd	BDL		BDL			
Mo	BDL		BDL			
Pb	15.71	0.50	BDL			
Ni	BDL		BDL			

5.3.4 Discussion

The results of the area cover analysis further support the suggestion that low-P compost significantly improved Switchgrass growth in the first year, but also that the compost may provide a more suitable habitat for weedy invasion.

The concentration of micro and macronutrients within the Switchgrass of Cell 1 and Cell 2 were notably different, and related to the media they were initially planted. While this was not surprising, it does emphasize the potential of plant uptake as a primary mechanism for stormwater treatment in bioretention cells. Future bioretention projects

should take note of the nutrient concentrations within the media and incoming stormwater to better quantify the impact that plant uptake and harvest will have on the removal of pollutants from a landscape.

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Appendix A – List of Storms and Measured Water Quality Parameters

	TN	NH4-N	NOx-N	TP	SRP	TSS
6/22	X	X	X	X	X	X
7/1	X	X	X	X	X	X
7/10	X	X	X		X	X
7/14	X	X	X	X	X	X
7/18	X	X	X	X	X	X
7/23	X	X	X	X	X	X
8/1	X	X	X	X	X	X
8/13	X	X	X	X	X	X
8/16	X	X	X	X	X	X
9/11	X	X	X	X	X	X
10/22	X	X	X	X	X	X
10/28	X	X	X	X		X
11/3		X	X		X	

Appendix B – USDA Soil Texture Flow Chart