ABSTRACT

Title of Thesis:	NUTRIENT LEACHING FROM BIORETENTION AMENDED WITH SOURCE – SEPARATED COMPOST
	Dylan Casey Owen, Master of Science, 2016
Thesis Directed By:	Dr. Allen P. Davis, Department of Civil and Environmental Engineering

Bioretention has been noted to be an effective stormwater control measure (SCM). Compost addition to bioretention could be beneficial, but could also act as a source for excess nutrients. This project analyzed possible nitrogen (N) and phosphorus (P) leaching from bioretention soil media (BSM) amended with source-separated compost. Columns were mixed with compost and BSM at volumes of 30%, and 15%. A final column had 15% compost and an additional 4% water treatment residual (WTR). Synthetic stormwater was applied to each column and the effluent was analyzed for N and P. The 30% column increased the mass exported for both nutrients. Both 15% columns had a net zero effect on nitrogen, but the 15%+WTR column reduced the exported phosphorus load. All compost columns discharged more nutrients than standard BSM. Compost addition should be minimized in bioretention, less than 15% by volume, and WTR should be added to control phosphorus leaching.

NUTRIENT LEACHING FROM BIORETENTION AMENDED WITH
SOURCE – SEPARATED COMPOST

by

Dylan Casey Owen

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2016

Advisory Committee:
 Dr. Allen P. Davis, Chair
 Dr. Birthe Kjellerup
 Dr. Kaye L. Brubaker

DEDICATION

To my brother and my family. I hope everyone continues to be happy and healthy.

Thank you to the Maryland State Highway Administration for their financial support.

Special thank you to my committee members, Dr. Kjellerup and Dr. Brubaker, for taking the time out to read and participate in my thesis process. Thank you to all the undergraduates and graduate students that helped me at various times throughout this research project.

Finally, and most importantly, I would like to thank Dr. Davis and my friends Kyle and Colleen who continued to motivate and challenge me throughout this entire process.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

Urban Runoff Quality

Stormwater runoff from urban sites is affected by a number of different factors including: local imperviousness, land slopes, soil types, rainfall intensity and durations, and antecedent dry days, along with any site specific land uses and human activity (Parka et al., 2009). Depending on the location and the design and purpose of the urban area, runoff could be dominated by a number of different heavy metals, organic pollutants, suspended solids, or nutrient loads. With increased development, a reduction in the ability for water to be stored in natural ponds or pools or infiltrate for plants and groundwater recharge occurs.

Since the implementation of the Clean Water Act, the United States Environmental Protection Agency (U.S. EPA) has been measuring, regulating, and later, managing water runoff across the nation. This act has led to the creation of total maximum daily loads (TMDLs) for various nutrients, metals, and chemicals in an effort to protect natural waterways. These pollutants can be either point source or non-point source, both of which exist in an urban environment. Point source pollutants come from wastewater treatment, storm sewer, or industrial discharge of water into streams and river ways. Non-point source pollutants refers to the debris and nutrients washed from impervious surfaces,

agricultural fields, and other land use areas into natural waterways. With these impervious lands comes an incredible burden on natural waterways. This stress leads to wide scale erosion, massive nutrient loading, eutrophication, dead zones, and a surge in toxic chemical concentrations (U.S. EPA, 1983, 2000; Davis and McCuen, 2005; LeFevre, 2015). Point source pollution primarily comes from wastewater treatment plants and industrial discharges.

Research has shown that heavy metals like copper, lead, and zinc are prevalent in urban stormwater along with increased nutrients, coliform bacteria, nitrogen and phosphorus species, and total suspended solids (U.S. EPA, 1983; Maestre and Pitt, 1995, 2005; Kim et al., 2007). U.S. EPA presented values of 93 µg-Cu/L, 350 µg-Pb/L, and 500 µg-Zn/L for heavy metals in over 90 percent of urban runoff values. Total phosphorus (TP) values were presented at 0.33 mg/L, of which 0.12 mg/L was soluble phosphorus (SP). Just over a third of the phosphorus measured was soluble. Nitrogen values were 1.5 mg/L for total Kjeldahl nitrogen (TKN) and nitrate and nitrite combined were 0.68 mg/L. Phosphorus and nitrogen values were presented as event mean concentrations on an annual average load basis (U.S. EPA, 1983). Kim et al. (2007) researched runoff specifically collected from a parking lot in Kongju, Korea and found event mean concentration (EMC) values averaging at 1.67 mg/L for total nitrogen (TN) of which 1.46 mg/L was TKN, a combined organic N and ammonium of 88%. Phosphorus values averaged 0.22 mg/L TP and 0.004 mg/L phosphate; 98% of the

TP was organic or particulate phosphorus. Values in the Kim et al. study came from a five month study that spanned the late spring, summer, and fall. During the summer months all values dropped.

Table 1.1 shows the EMC average values collected in the two studies presented above and the National Stormwater Quality Database (NSQD) (International Stormwater BMP Database (ISBD), 2015). The NSQD values are averaged from Prince George County, MD values.

Table 1.1: Table comparing different EMC pollutant values for phosphorus, nitrogen, and some heavy metals, the U.S. national averages (U.S. EPA, 1983), averages found in Kongju, Korea (Kim et al., 2005) and averages from Prince George County, MD (ISBD, 2015)

Pollutant	U.S. EPA (1983)	Kim (2005)	ISBD (2015)
Phosphorus	0.33 mg-P/L TP 0.12 mg-P/L SP	0.22 mg-P/L TP 0.004 mg-P/L PO_4	0.24 mg-P/L TP
Nitrogen	1.5 mg-N/L TKN 0.68 mg-N/L NO_X	1.67 mg-N/L TN 1.46 mg-N/L TKN	1.77 mg-N/L TKN 0.60 mg-N/L NO_X
Heavy Metals	93 µg/L Cu 350 µg/L Pb 500 µg/L Zn	Not Measured	27 µg/L Cu 43 µg/L Pb 185 µg/L Zn

Bioretention

In an effort to mitigate the increased volume of water and reduce the excess nutrients, metals, and other pollutants in stormwater runoff, many different best management practices (BPMs), also known as stormwater control measures (SCMs), have been designed. Over the last few decades bioretention has become

one of the most popular due to its simplicity, small design, effectiveness, and economic cost (Davis and McCuen, 2005). The need for the use of these retention sites has increased over the years as the area of impervious land has also increased. Parking lots, roadways, homes, and office buildings scatter over previously un-developed land. By incorporating well-designed and engineered SCMs much of the strain placed on natural waterways can be mitigated.

Bioretention is a SCM that incorporates high flow media, sand or gravel (Hunt et al., 2012), with top soil, clays, and organic matter (Figure 1.1). A goal is to reduce the flow rate and volume of water that enters waterways from impervious surfaces. By incorporating the high flow media, like sand and gravel, and depressing the retention area below that of the surrounding surface, water is allowed to pool over the bioretention site and filter as it passes through. Bioretention incorporates basic components of water management unit processes including chemical adsorption and complexation, physical precipitation, and biological conversion of chemical nutrients. These processes will ideally remove most pollutants carried from the surrounding non-point sources and reduce the rate of flow and volume of water.
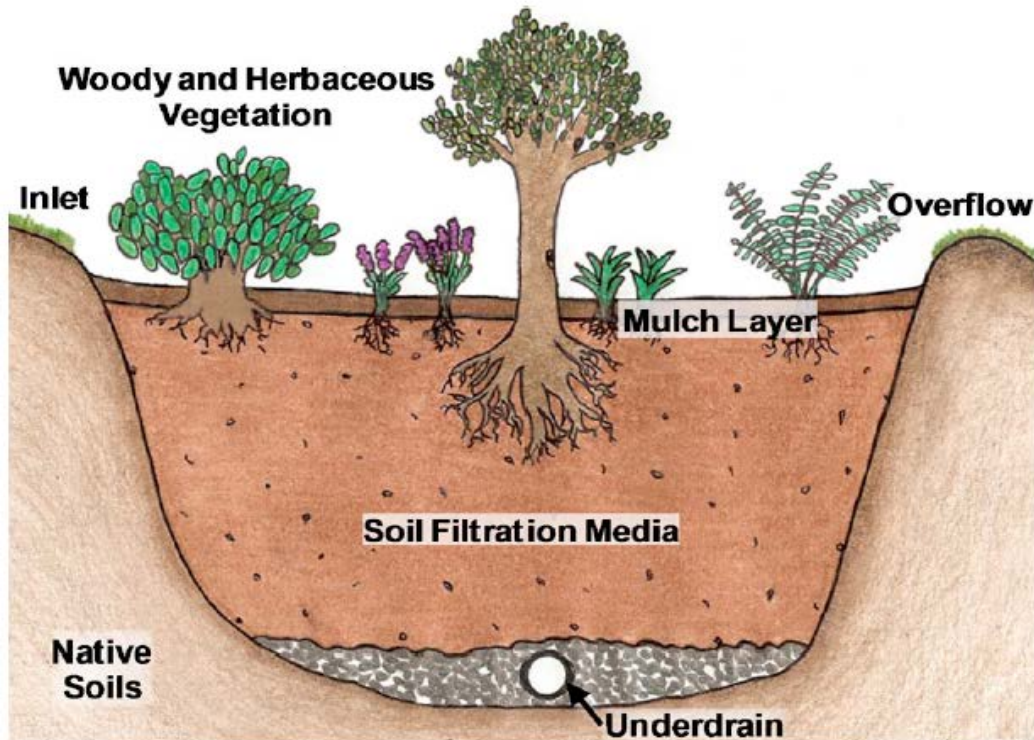
Figure 1.1: Schematic of a typical bioretention system (Roy-Poirier, 2010)

From laboratory and field studies performed throughout the early 2000's, bioretention sites have proven to be extremely effective in metal uptake and suspended solids removal (Davis et al., 2001, 2003; Glass and Bissouma, 2005; Roseen et al., 2006; Hunt et al., 2006; Li and Davis, 2008). Sun and Davis (2007) also studied the impact of bioretention plant life on heavy metal uptake and found that, while limited, a percentage of heavy metals is taken into the plant mass as the biomass is increased.

Bioretention has also shown reduction in TN and ammonium, but has had limited effectiveness in retaining nitrates and nitrites (Hunt et al., 2006; Davis et al., 2001, 2003, 2006; Dietz and Clausen, 2006). Observations for wetting and drying cycles by Hatt et al. (2007) showed an increase in initial nitrogen levels after longer periods of drying, but removal rates for heavy metals and phosphorus were seemingly unaffected.

Phosphorus removal has been far less consistent. Studies by Hunt et al. (2006) showed both a removal of phosphorus of 65% and an outflow increase of 240%, while Davis (2007) showed consistently high, 77-79%, removal. Dietz and Clausen (2006) also showed phosphorus leaching in raingardens, 98% to 117% increase in the effluent. The retention of phosphorus is highly dependent on the adsorption characteristics of the media (Lucas and Greenway, 2008, 2011). This and the variability of phosphorus partitioning (particulate vis-à-vis soluble) in runoff, could account for many of the differences in removal values. Since bioretention media has a variable organic component in the top soil mix, there is a large variety in initial concentrations of soluble and organic P available.

Compost

In May of 2014 the Maryland General Assembly passed House Bill 878 to stimulate reused, recycled, and reclaimed materials in state-funded projects. After

this decision, the Maryland State Highway Administration (SHA) began to take steps to implement the use of locally composted materials in many of their large scale roadway construction plans. Maryland is following a growing trend that has been seen in Washington, Florida, Texas, and other states around the nation who have all begun research into using compost in state-funded projects (Kirchoff, 2003; Herrera, 2012). These efforts have all been designed to reduce the effects of highway runoff, increase the use of recycled materials, and use more locally sourced, reclaimed materials.

As described by the Maryland SHA, composted material are classified into two classes: biosolids and source-separated compost. Compost in Maryland is defined as:

> "A stabilized organic product produced by the controlled aerobic decomposition process in such a manner that the product may be handled, stored, and applied to the land or used as a soil conditioner in an environmentally acceptable manner without adversely affecting plant growth" – (COMAR 15.18.04.01).

The SHA categorizes these composts by stability, pH, soluble salts, moisture content, particle size and grading, and the feedstock used to create the final product (SHA spec. 920.02.05, Appendix A). Biosolids-derived composts are created from the residual material remaining after wastewater treatment.

Source-separated compost is derived from any material that is not wastewater residual. This form of compost can be made from yard trimmings, grass clippings, food waste, animal manure, and more. This category of compost is the focus of this project.

Ultimately, compost is the biological decomposition of any organic material through the efforts of bacteria, fungi, worms, and other organisms (De Bertoldi, 2007). The process of composting is simple in its most basic form. Each feedstock contains a unique blend of macronutrients: carbon, nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, and micronutrients: copper, zinc, iron, boron, and manganese (Diaz et al., 2007). These feedstocks are broken down by bacteria, fungi and other organisms over time to create an earthy humic material rich in nutrients. The combination of different feedstocks helps determine the quality of the final composted product, i.e., feedstocks high in nitrogen will lead to a final compost that likely has a large amount of nitrogen. Feedstocks also help to determine how effective the composting project will be. Optimal composting occurs with a C:N ratio around 30:1 (Diaz et al., 2007; Rynk, 2008); this offers bacteria and fungi enough food to properly break down the material. If the feedstocks have a ratio much higher than 30:1 organisms might immobilize the nitrogen (Diaz et al., 2007). Other essential elements to a quick and complete composting process are oxygen, heat, and moisture. Examples of different feedstocks and their C:N ratios are presented in Table 1.2.

Table 1.2: Compost feedstocks and their carbon: nitrogen ratios ("Carbon-to-Nitrogen Ratios"; Rynk, 2008)

FEEDSTOCK	CARBON: NITROGEN
Leaves	60:1
Manure	15:1
Weeds	30:1
Wood chips	400:1
Grass clippings	20:1

Composting is done under either aerobic or anaerobic conditions. In the aerobic process mesophilic, thermophilic, secondary mesophilic, and maturation phases are used to accomplish the final product. In an anaerobic process, completely different bacteria create a highly acidic environment that accomplishes the same goal, but requires a substantially longer time to completely break down feedstocks (Diaz, 2007; Dunne, 2013). This process also releases a pungent odor full of sulfides and nitrous oxides, but requires no maintenance and very little space. This project focused on aerobically-produced compost due to its availability and reduced impact on the environment.

The aerobic process incorporates a variety of different organisms that thrive in the moisture surrounding organic materials. In the initial mesophilic phase, large primary decomposers, such as fungi and other macro organisms, break down easy compounds, sugars, oligosaccharides and proteins. This phase begins to produce a large amount of heat that exceeds the threshold for mesophilic

organisms which are replaced by thermophilic species. In the second phase, the

thermophilic phase, organisms superheat the compost and kill off harmful

bacteria, weeds, and insect larvae. As the feedstock for this phase diminishes, the

heat also reduces and a secondary mesophilic phase begins where recolonization

of bacteria and fungi leads to the breakdown of harder to reduce starches and

cellulose (Figure 1.2).
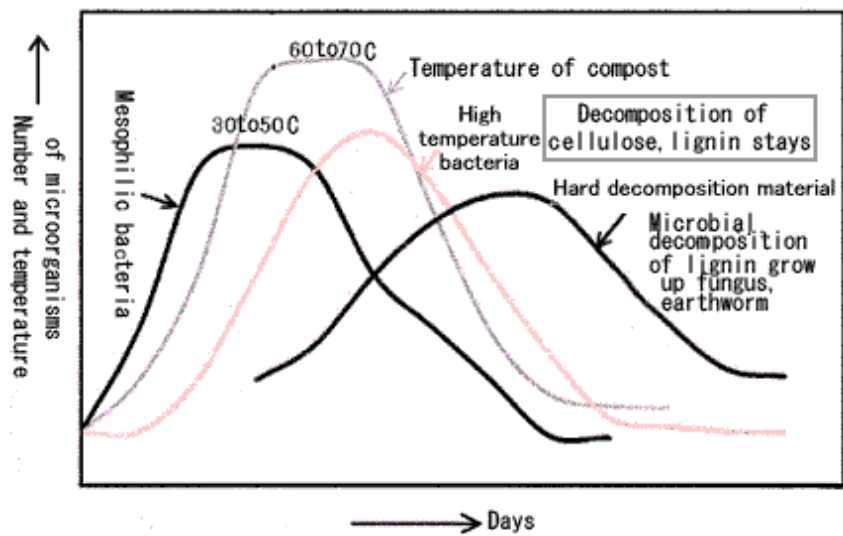
Figure 1.2: Example of the decomposition process occurring within the compost. The black lines represent the mesophilic bacteria and the red line represents thermophilic bacteria. Both of these are overlaid onto the gray line that shows the temperature of compost throughout the process (Chubu Ecotec Co., 1994).

In the final maturation phase, non-degradable compounds are formed and

become predominant. Determination of a completed compost is largely measured

by temperature and appearance. The material will shrink significantly, up to one-half its original volume, the original organic materials are no longer recognizable, the pile will no longer generate a significant amount of heat, and the material remaining will have a dark crumbly appearance with an earthy odor ("The Finished Product"; Diaz, 2007; Dunne, 2013). Final maturation of compost is also determined by the oxygen uptake of the stack, seed germination efficiency and vigor, and C:N ratio. Each of these results are defined differently by each state, organization, county, or other governing body.

Water Treatment Residual

Previous studies have shown a major reduction in the mass of phosphorus exported from bioretention sites through the addition of water treatment residual (WTR) (O'Neill, 2012; Liu, 2013). This byproduct of the drinking water treatment process has a large concentration of aluminum and/or iron, in the form of precipitated (hydr)oxides. These (hydr)oxides readily adsorb phosphorus, largely in the form of phosphates, due to their positive charge and large amorphous structure with a large surface area (O'Neill, 2012).

The essential processes of adsorption to aluminum hydride is presented in Figure 1.2 (Hubbard, 2002). The first adsorption process to likely occur in a WTR-amended soil media is the outer sphere electrostatic ion-exchange reaction

that occurs rapidly between the phosphate and the surface of the hydrated

aluminum. This complex is highly reversible, however. From longer term

interactions, less reversible inner-sphere surface complexes can form to create a

bidentate bond. Organic matter has the ability to complex with phosphates or

block phosphate adsorption sites on WTR and has been seen to reduce the

effectiveness of P sorption (Kang et al., 2009). This is likely to occur with short

term interactions as the organic matter (OM) will react more readily with the

aluminum charge, but as time is allowed P will exchange with the OM (Borggaard

et al., 2005).
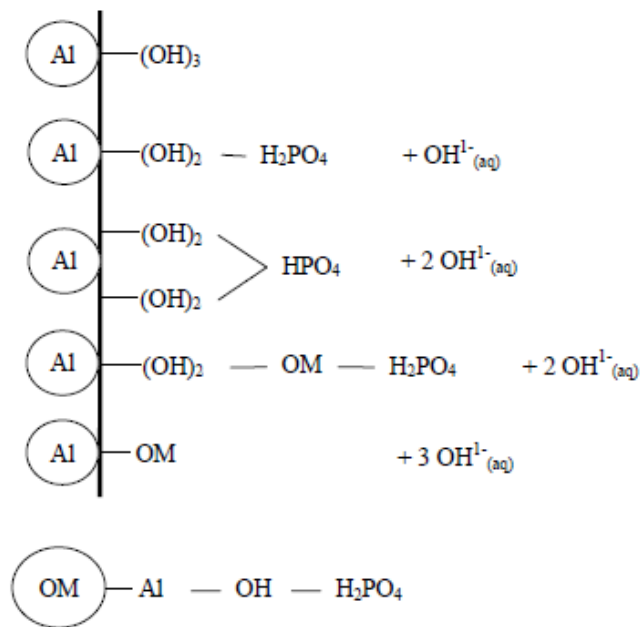
Figure 1.3: Potential interactions between the Al-WTR surface and inorganic P species in solution. Additionally, interactions may also potentially occur on the surface of OM (O'Niell, 2010).

Research Objectives and Goals

Compost has the potential to greatly improve the effectiveness of a SCM. With the addition of compost, there is an increase in organic matter (OM) content, which has the potential to increase heavy metal pollutant uptake through organic complexation. Compost has been shown to improve soil porosity and decrease soil bulk density, leading to greater water holding capacity, at both the field capacity and the wilting point. Soil stabilization and aggregation properties as well as its buffering capacity are also improved with the addition of compost (He et al., 1992; Mitchell, 1997; Weng et. al., 2002; Kirchoff, 2003; Paus et al., 2014). Compost is currently used as a soil amendment for improved plant growth, and OM has been shown to potentially precipitate soluble phosphates, which would decrease phosphorus leaching (Kang et al., 2009).

The potentially beneficial implications to compost addition are also accompanied by a variety of concerns. Compost has a high concentration of nutrients, specifically nitrogen and phosphorus. When these nutrients are introduced into the environment in excessive levels, unwanted and damaging effects can result, including eutrophication and dead zones. By adding compost to bioretention media, a design established to filter large volumes of water quickly, high leachate levels of phosphorus and nitrogen may occur. This uncertainty led to the design of this project.

To investigate possible benefits and consequences of the addition of compost to bioretention soil media, the following objectives were developed:

1. Determine the concentrations and masses of nitrogen and phosphorus captured or released from bioretention soil media amended with source-separated compost;

2. Categorize the dominant species of nitrogen and phosphorus found in synthetic stormwater leachate;

3. Compare nutrient leaching performance of different compost/BSM (bioretention soil media) mixtures

4. Introduce a possible solution to nutrient leaching issues found from the addition of compost to the BSM.

These objectives were met through a series of large column studies and concurrent lab analysis of leachate from the synthetic storm water that was applied to these columns. Three columns were created using 30% compost, 15% compost, and 15% compost with 4% WTR, and compared to a column of BSM only. Each was created with the same media depth. Synthetic storms were created and infiltrated through each media to obtain an effluent that was analyzed for total phosphorus and nitrogen as well as the species of each.

Source Materials

In a preliminary study (Davis et al., 2016) three source separated composts were collected based on their dominant feedstock source. The three compost feedstocks were:

1. Major nutrient source tree trimmings. Pogo Tree Experts in Olney, MD

2. Major nutrient source leaf debris and grass clippings; minor source tree trimmings. Dickerson Compost Facility in Dickerson, MD

3. Major nutrient source a mixture of chicken and cow manure; minor source farm debris. United States Department of Agriculture (USDA) in Beltsville, MD

Each of these composts were measured for KCl extractable nitrogen, Mehlich-3 extractable phosphorus, and $CaCl_2$ extractable phosphorus in a previous study (Davis et al., 2016). Then, a series of small column studies were used to simulate and measure possible leaching of total nitrogen and phosphorus as well as dominant species of N and P.

The first two composts were SHA approved based on SHA specification 920.02.05 (Appendix A.1). The USDA compost is not certified by the SHA

specification and was chosen to analyze the effects of manure, as a feedstock, on nutrient leaching. From the previous research, compost from Dickerson, MD was chosen and used for all projects in this research.

Bioretention soil media (BSM) was provided by Stancill's Inc. in Waldorf, MD and met the specifications presented in SHA specification 920.01.05 (Appendix A.2). Paver sand and #7 gravel were provided by Stancill's Inc. as well. To ensure no suspended particulate matter would contaminate samples, both gravel and sand were rinsed and mixed with water until the water ran clear, then allowed to dry before use. Aluminum-based water treatment residual (WTR) was provided by the Dalecarlia Drinking Water Treatment facility in Washington DC. All compost, sand, WTR, and BSM were sieved with a 1 cm sieve prior to column setup. Due to the clay like structure of WTR, after sieving, the material was allowed to air dry for two days.

Acrylic columns were purchased from Piedmont Plastics located in Elkridge, MD. Each column has an inner diameter of 19.1 cm and is 122 cm long. In addition, to prevent pooling, there is a small solid wedge of acrylic with a 14.7 degree slope at the bottom of each column that leads to a 3.8 cm sampling port. Columns were placed on top of 20 cm concrete blocks to aid with sampling. Taps were inserted into the sides of the column for possible sampling, but they were not utilized in this project.

Column Setup

Three large compost amended column studies and one control were conducted over the course of one year in a controlled greenhouse environment. The greenhouse was maintained at a relatively constant temperature of 20 $^{\circ}$C with no additional lighting or watering. All lighting to the space was natural and the watering was exclusively synthetic stormwater used throughout the research.

Four columns were constructed, three experimental designs and one control. The control column was made of 100% BSM. The compost amended columns were mixed and filled based on volume and mass measurements at 15% compost/85% BSM, 30% compost/70% BSM, and 15% compost/3.75% WTR/81.25% BSM. Each mixture was created in a large plastic trash can; this material was then rotated and physically mixed with a shovel until the contents were consistent. Between every synthetic storm event application the columns, buckets, and trash cans were washed and rinsed with tap water and Alconox soap.

Each column was packed the same way with an initial 7 cm layer of # 7 gravel separated by a 1 mm^2 screen mesh, purchased at Home Depot in College Park, MD, and a 7 cm layer of sand to eliminate media loss from the column, followed by 77-80 cm of media (Figure 2.1). Columns were wrapped in foil to limit sunlight exposure to the soil profile, and tall fescue grass from Behnke

Nursery in Beltsville, MD was planted on top of the media. Layers were loosely packed by the weight of the next layer along with light shaking. After the first synthetic storm event was applied to the column, additional media was added to return the media height to between 77 and 80 cm.

Some columns received grass or foil after the initial synthetic storm event. In the 30% compost column, foil was added before the fourth synthetic storm event and grass was planted before the seventh synthetic storm event. The 15% compost column received foil and dead grass before the first synthetic storm event. The 15%+WTR column was wrapped in foil before trials began and received grass before the third synthetic storm event. The control column had foil and dead grass before the first synthetic storm event. It is unknown whether these differences affected the final results.

Column Diagram	Column Unfilled	Column Filled	Completed Column

Figure 2.1: Large bioretention column setups for experimental trials.

Stormwater Preparation

Synthetic stormwater was prepared using a composition based on research in urban runoff quality and bioretention loading; these values are presented in Table 2.1 (U.S. EPA, 1983; Kim et al., 2005; O'Neill et al., 2012; Li et al., 2013; ISBD, 2015).

Table 2.1: Synthetic stormwater composition for use in large column trials.

Component	Value	Source
Inorganic nitrogen: NO_3^-	1 mg/L as N	$NaNO_3$ (JT Baker)
Organic nitrogen	2 mg/L as N	Glycine (Alfa Aesar)
Copper	0.06 mg/L	$CuCl_2$ (Acros Organics)
Zinc	0.5 mg/L	$ZnCl_2$ (Fisher Chemical)
Dissolved Solids	80 mg/L	$CaCl_2$ (JT Baker)
Dissolved Solids (Salts)	100 mg/L	NaCl (Sigma)

Neither HCl nor NaOH were necessary since the influent water remained neutral. Because the phosphorus concentration of the tap water exceeded 0.20 mg-P/L, phosphorus was not added to the synthetic stormwater. The N and P concentrations found in the tap water were 0.025 mg-N/L and 0.36 mg-P/L, respectively. To neutralize the chlorine found in tap water, 2.2 mg/L of sodium bisulfate (JT Baker) was also added. A concentrated stormwater solution was prepared from the above materials and added to 50 L of tap water to create the above synthetic stormwater concentrations.

Stormwater Sampling

The 15% and 15%+WTR columns were run for 8 storm events. The 30% column and control column received 45 and 9 total storm events, respectively. The 30% column ran an additional 37 storm events to interpret long term cell performance and the control was run to

have one additional 15 cm/hr storm event after the increased flow storm. The 'normal' synthetic storm applied in this project lasted for 6 hours at a rate of 15 cm/hr. This is the equivalent of 0.8 cm/hr of rainfall over the entire catchment area (20-times the bioretention surface area, Environmental Services Division et al., 2007) and ultimately yields a storm event depth of 4.5 cm.

Storms 1, 2, 3, 4, 7, and 8 had an influent velocity of 15 cm/hr (72 mL/min) for all compost-amended columns. At storm 5 and storm 6 the flow rate was changed to examine performance with increased and decreased influent flow rates. The flow was halved to 7.6 cm/hr (36 mL/min) during storm 5 and increased to 30 cm/hr (144.68 mL/min) for storm 6. The control column had a slightly altered storm schedule: 15 cm/hr storms for storms 1, 2, 3, 4, 5, 8, and 9, reduced flow for storm 6, and increased flow for storm 7. The 37 additional storm events (9 through 45) for the 30% column were all 15 cm/hr storm events. Only two of those storm events (26 and 45) received the synthetic stormwater, the others received tap water. The 30% column ended with 45 total storm events after 313 days, the 15% column ended with 8 total storm events after 55 days, the 15%+WTR column ended with 8 total storm events after 57 days, and the control column ran for 9 storm events after 67 days.

For all events, samples were taken every 30 minutes starting at the first drop of effluent for the first 2 hours of effluent, then at hour increments until the trial was over. Two additional samples were taken at the end of the 6 hour interval: one immediately after the influent flow had stopped and one 20 minutes after the influent flow had stopped, as shown in Figure (2.2). A total

of 9 to 11 samples were taken each storm event. All samples were frozen until analysis was

completed.
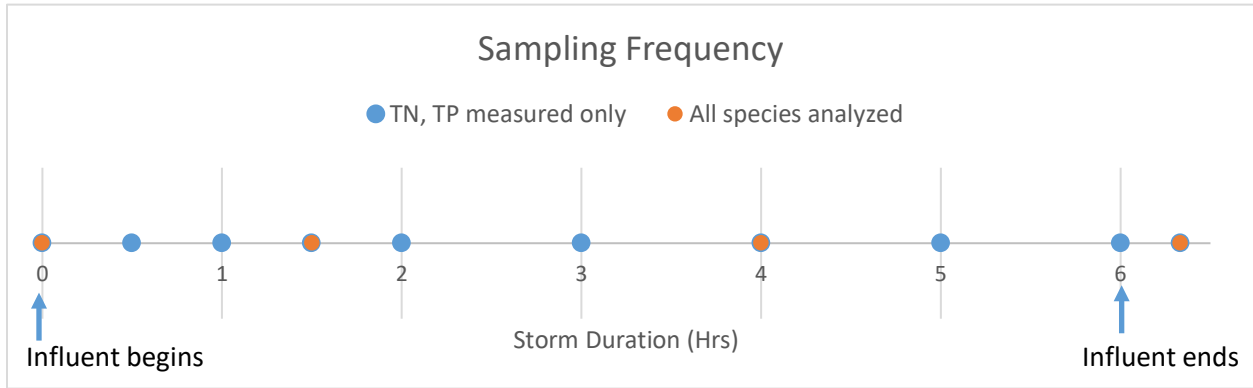
Figure 2.2: Sampling plan for large column trials. This figure assumes no delay between the initial inflow and the outflow. In reality there is an outflow delay that shifts the points between 0 and 5 hrs. to the right.

ANALYTIC PROCEDURES

      Complete analysis was conducted for samples 1, 4, 7, and the final sample: total nitrogen

(TN), total phosphorus (TP), ammonium, nitrate, nitrite, soluble reactive phosphorus (SRP), and

dissolved phosphorus (DP). All other samples were tested for TN and TP only.

Water-Soluble Phosphorus

      Extractions for water-soluble phosphorus were taken on mixtures of compost and WTR at

35%, 25%, and 15% WTR by volume. The standard method "Water- or Dilute Salt-Extractable

Phosphorus in Soil" (Moore and Joern 2009) was used in triplicate using a 0.01 M $CaCl_2$

solution. This method of phosphorus extraction was chosen due to its simple testing method and

well known correlation with SRP in stormwater runoff (Pote et. al 1996). Each of these solutions

was tested using the standard method for SRP using 25 mL of solution. Standards ranged from 0-

1 mg-P/L with a detection limit of 0.05 mg-P/L. The stock solution was made using Lab Chem Inc. 1000-ppm phosphate as phosphorus. Samples were analyzed using a Shimadzu UV160U UV Visible Recording Spectrophotometer.

Other Extractions

The KCl extractable test for nitrogen and the Mehlich-3 phosphorus extractable test were both used in Davis et al. (2016); some of these results are presented in the following sections. The nitrogen extraction followed the 2 M KCl method (Castle 2009) with a standard curve from 0-2 mg-N/L. Mehlich-3 extractions followed the soil extraction method by Pierzynski and Kovar (2009) with a standard curve from 0-1 mg-P/L.

Volume to Mass Relationships

Conversions from % volume to % mass were made after columns were set up in the 30% column and 15% column. Initial mixtures were made by volume then converted to kg dry mass. This was not necessary for 15% column as each addition of compost to the mixture and column were measured while the column was prepared. Each material, compost, BSM, and WTR, underwent its own volume to mass ratio calculation independently. The inverse of media density was used to calculate the volume to mass ratio. Four different volumes were measured between 50 mL and 250 mL with an additional 5 L measurement to ensure consistency at larger volumes. The measurements obtained were averaged and used to calculate the bulk densities of each material. These bulk densities were then used to determine the mass of compost and BSM in each column based on the volume of media.

To determine the dry mass of compost in each column, samples of WTR, compost, and BSM were weighed, then oven dried for 24 hours at 104°C and weighed again to determine the water mass in each sample; this process was done in triplicate. Samples were then allowed to sit in the oven for 7 additional days to remove any additional water, then weighed. No change occurred after the initial 24 hours. Water ratio results are presented in in Table 2.2. As a general trend, compost had the highest average water content; BSM and WTR had the lowest.

Table 2.2: Moisture content and volume to mass conversions. Not calculated (NC)

Sample	Dry/Wet (g/g)	Moisture Content (%)	Wet Bulk Density (kg-wet/m³-wet)	Dry Bulk Density (kg-dry/m³-dry)
Compost	0.43	57%	675	288
WTR	0.78	22%	626	487
BSM	0.91	9%	2131	1931
Sand	0.97	3%	NC	NC

Water Quality Parameters

All glassware was washed with tap water and Alconox soap, rinsed with deionized (DI) water then placed in an acid bath for a minimum of 4 hours before being rinsed with DI water and allowed to air dry.

All colorimetric measurements were taken on the Shimadzu UV 160U UV Visible Recording Spectrophotometer; this includes the TP, DP, SRP, nitrite, and ammonium tests. Any samples outside of the standards curve were diluted to fit within the range of standard values. This occurred largely at the beginning of each trial, especially for TP and TN.

Any measurements made below the detection limits set by the test were presented as half the stated detection limit. ("AMC Technical Brief" 2001).

Total Phosphorus and Speciation Measurements

Each sample from the large column trials was measured for total phosphorus using the persulfate oxidation method and the ascorbic acid method based on the Murphy and Riley (1977) colorimetric method. Standards ranged from 0-2 mg-P/L created from a stock solution of Lab Chem Inc. 1000-ppm phosphate as phosphorus (SKU: LC185901) with a detection limit of 0.05 mg-P/L or 0.02 mg-P/L depending on the trial and previous measurement results. With large phosphorus tests a standard check (sample of known concentration) was incorporated within the samples as a quality control measure. This was not done with every test.

SRP and DP were measured after samples were filtered through a 0.22 μm membrane to remove suspended particles. Both measurements then went through the Murphy and Riley (1977) colorimetric method. SRP was not digested since this method specifically checks for phosphates. Particulate P and DOP were calculated as:

$$Particulate\ P = TP - DP \qquad\qquad\qquad 2(a)$$

$$DOP = DP - SRP \qquad\qquad\qquad 2(b)$$

Total Nitrogen and Speciation Measurements

All samples were analyzed using a Shimadzu SSM-5000A with a total nitrogen measuring unit. Some samples were diluted to fit within the standard curve from 0-5 mg-N/L with a detection limit of 0.05 mg-N/L. Standards were created from a 5 mg-N/L diluted solution taken from Lab Chem Inc. 1000-ppm nitrogen as nitrate derived stock solution. Each test

included one standards check for every 10 samples tested. The first two weeks of samples for the 15% column were filtered through a coarse filter to remove sediment that had escaped the column into the sample. Samples 1, 4, 7, and the final sample were filtered through a 0.22 μm membrane to remove suspended particles before nitrate and nitrite were measured.

Nitrate was measured using a standard curve from 0-5 mg-N/L; some samples were diluted to fit within this curve. Each sample was measured using a Dionex ICS-1100 with ASRS 4 mm suppressor with a Dionex IonPac AS22 column. The eluent (4.5 mM Na_2CO_3 and 1.4 mM $NaHCO_3$, Fisher Scientific) flow through the instrument was set to 1.2 mL/min with a suppressing current of 34 mA. Each sample measuring time was set to a maximum of 12 minutes. Following sample analysis, peaks were checked at enlarged scales to check baseline measurements. The baseline was adjusted, if necessary, as shown in Figure 2.3. Measurements were then exported to Microsoft Excel to calculate the standard curve and apply the resulting linear equation to measured peaks of samples, achieving the amount of nitrate-N present in mg-N/L.
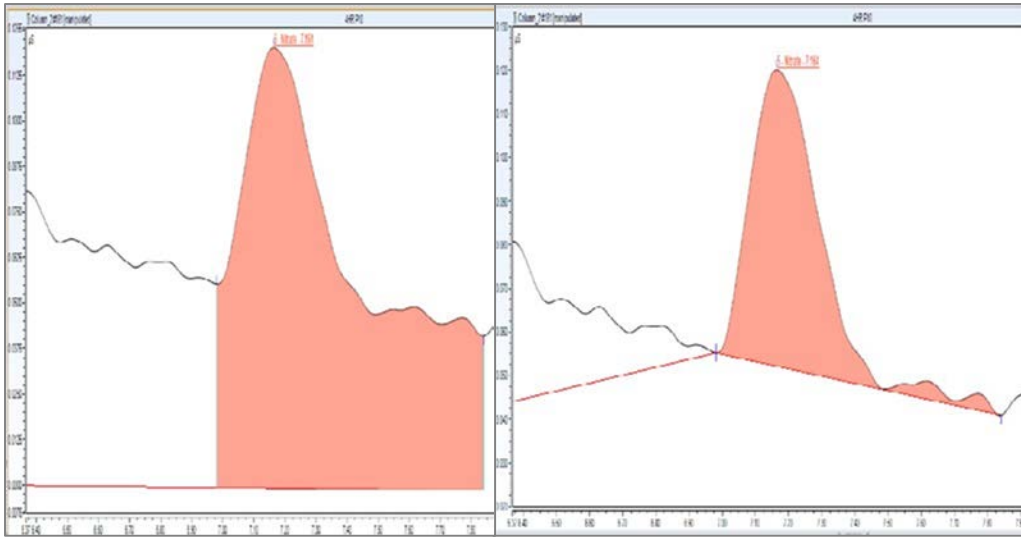
Figure 2.3: Nitrate baseline adjustment. The baseline was raised or lowered to remove any noise from the instrument or residual measurements.

Ammonium concentrations were measured using the 4500-NH_3 F Phenate method (Clesceri et al. 2005). Deviating from the method design, which calls for 25 mL of solution, only 10 mL of solution was used for both samples and standards. Standards ranged from 0-1 mg-NH_3/L with a detection limit of 0.05 mg-NH_3/L and were prepared from a 5 mg-NH_3/L solution prepared from a Fisher Scientific ammonium chloride (A649-500) stock solution.

Nitrite was measured using the 4500-NO_2-B Colorimetric Method (Clesceri et al. 2005). Similar to the ammonium, the method was changed to only use 10 mL of solution. Standards, created from a stock solution prepared from J.T. Baker Sodium nitrite, ranged from 0-0.2 with a detection limit of 0.01 mg-N/L.

Organic nitrogen was not measured, but was calculated based on the other nitrogen species measured as:

$$Org\ N = TN - ([NO_3^- - N] + [NO_2^- - N] + [NH_3 - N]) \qquad\qquad 2(c)$$

STATISTICAL ANALYSIS

Kendall Tau Test

The Kendall Tau test for trend was used to determine if there was any general trend in the phosphorus or nitrogen concentration data collected. This was done within the storm events and throughout the trial. The null hypothesis is that the sample contains no trend and all variables are identically distributed and random. The alternative hypothesis is that the distribution of variables are not identical and there is a decreasing trend in the data; a decline in concentration values (Daniel, 1990). The one-tailed test for the Kendall Tau was used to specifically indicate negative slopes.

The statistic was calculated with a level of significance of 5% ($p<0.05$) and was calculated using the equations:

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sign(x_j - x_k) \qquad\qquad 2(d)$$

$$\xi = \begin{cases} \frac{S-1}{v^{0.5}}; for\ S > 0 \\ 0; for\ S = 0 \quad ; \xi\ is\ the\ normal\ distribution\ N(0,1) \\ \frac{S+1}{v^{0.5}}; for\ S < 0 \end{cases} \qquad\qquad 2(e)$$

$$v = \frac{n(n-1)(2n+5)-\sum_{i=1}^{g} t_i(t_i-1)(2t_i+5)}{18}; \begin{array}{l} g\ is\ the\ number\ of\ ties \\ t\ is\ the\ number\ of\ groups\ of\ ties \end{array} \qquad\qquad 2(f)$$

One-way ANOVA test

The ANOVA test was designed to test more than two samples taken from different treatments to determine if the samples are statistically similar or dissimilar by comparing the mean square for treatments (MSTr) and the mean square for the error (MSE). This one-tailed test uses the F distribution to determine acceptance or rejection of the hypothesis (Snedecor and Cochran, 1989).

This statistic was also calculated with a level of significance of 5% ($p<0.05$) and was calculated using the equations:

$$j = number\ of\ samples\ in\ a\ set;\ i = number\ of\ sets\ being\ tested;$$

$$\bar{X}_i\ is\ the\ mean\ of\ the\ i_{th}\ set;\ S_i\ is\ the\ standard\ deviation\ of\ the\ i_{th}set$$

$$MSTr = \frac{J}{I-1}\sum_{i=1}^{j}(\bar{X}_i - \bar{X}_{..})^2 \hspace{3cm} 2(g)$$

$$MSE = \frac{S_1^2 + \cdots + S_i^2}{i} \hspace{3cm} 2(h)$$

$$F = \frac{MSTr}{MSE} \hspace{3cm} 2(j)$$

Modified Thompson Tau Test

The modified Thompson tau test is an outlier test designed to test a single variable in a sample set with n measurements. This statistical method uses the τ-distribution which is a modified t-distribution with degrees of freedom equal to the number of data points minus 2. In the instance where there may be two or more outliers, only one outlier is tested at a time. The

largest deviation is tested then removed from the set to determine other suspected outliers. If the absolute value of the deviation from the mean of the sample is greater than the modified Thompson τ value then the value is determined to be an outlier (Cimbala, 2011).

This statistic was also calculated with a level of significance of 5% (p<0.05) and was calculated using the equations:

$n = number\ of\ points;\ \bar{x}_i = is\ the\ mean\ of\ the\ current\ set\ of\ points\ being\ tested$

$$\delta_i = |x_i - \bar{x}| \hspace{6cm} 2(k)$$

$$\tau = \frac{t_{\alpha/2}*(n-1)}{\sqrt{n}*\sqrt{n-2+t^2_{\alpha/2}}} \hspace{5cm} 2(l)$$

Effluent samples taken for each large column study using the source-separated Dickerson compost were dark brown in color which faded throughout the trials, ending with a relatively light colored effluent. This color change can be seen in Figure 3.1.
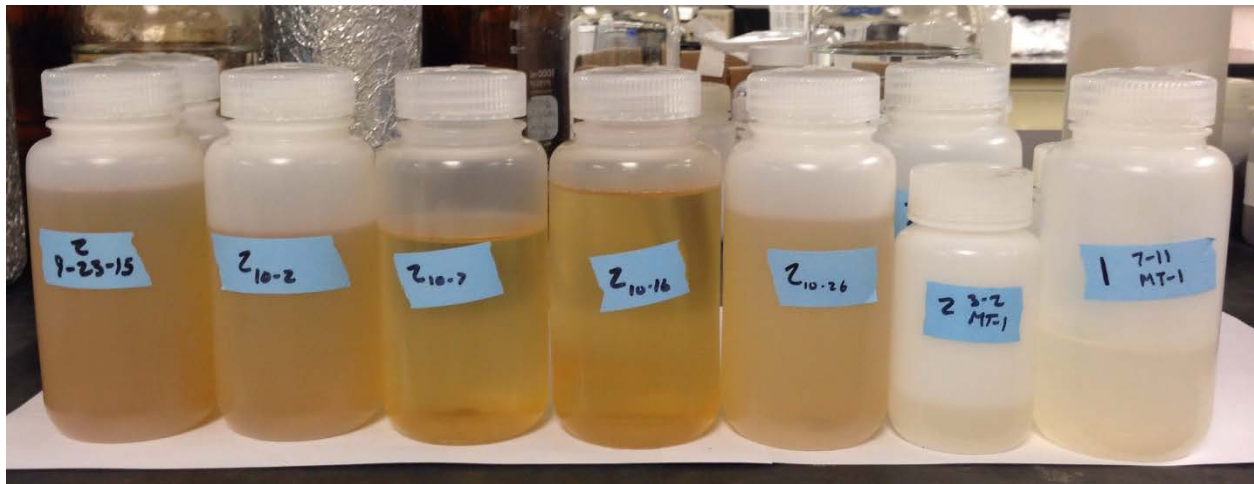
Figure 3.1: Sample bottles from different storm events for the 30% compost column. The leftmost sample is the earliest sample and the rightmost is the last sample taken. As the storms continue the color becomes less intense.

Columns with less or no compost, the 15%, 15%+WTR, and control columns, had much lighter coloring as a whole than that of the 30% column. All temporal values below are presented based on the cumulative depth of water applied to the column. In an average storm of 15 cm/hr, 90 cm of water was applied, corresponding to a total volume of 26 L per storm. Samples 1, 4, 7, and the final samples were ~ 250 mL each, 0.9% total storm volume, and the remaining samples were ~150 mL each, 0.5% total storm volume. Each sample is presented as a single point in the subsequent results due to their relative size to the total storm. High levels of particulate matter

were found in samples taken for the first three storms of each column, as was determined by the difficulty of the filtration process.

Nitrogen

Discrete nitrogen concentrations for total nitrogen can be seen in Figure 3.2 for all four large column trials. Specific to the compost-amended trials, a 'first flush' could be seen within the first 3 storm events. This first flush was largely in the form of organic N and nitrate-N. Using the Kendal tau test, the negative trend was defined by a rejection probability of much less than 1%. This result suggests a definite decreasing trend in the data. After this initial flush, values fluctuate but remain relatively similar and no longer display a definite quantifiable trend, based on the Kendal tau test. This second stage is referred to as the "stabilization phase" and showed a zero-order discharge rate. Concentrations remained relatively constant throughout this phase. This result implies that the leaching from these columns has reached a steady state.

Similar first flush tendencies have been found in a number of other leachate studies, (Christensen, 1984; Kirchoff et al., 2003; Herrera Environmental Consultants, 2012). Christensen worked with 3-12 month old compost from municipal solids and waste-water sludge that resulted in 100-400 mg-N/L NH_4^+ and 100-700 mg-N/L NO_3^- in the initial 300 mm of leachate. These values were followed by much lower concentrations after 300 mm. In the 185th Pollutant Export Report, BSM amended with compost leached initial NO_x concentrations of over 100 mg-N/L which was followed by a drop to 10 mg-N/L after one month and finally 2 mg-N/L by the end of the nine months of sampling (Herrera Environmental Consultants, 2012).
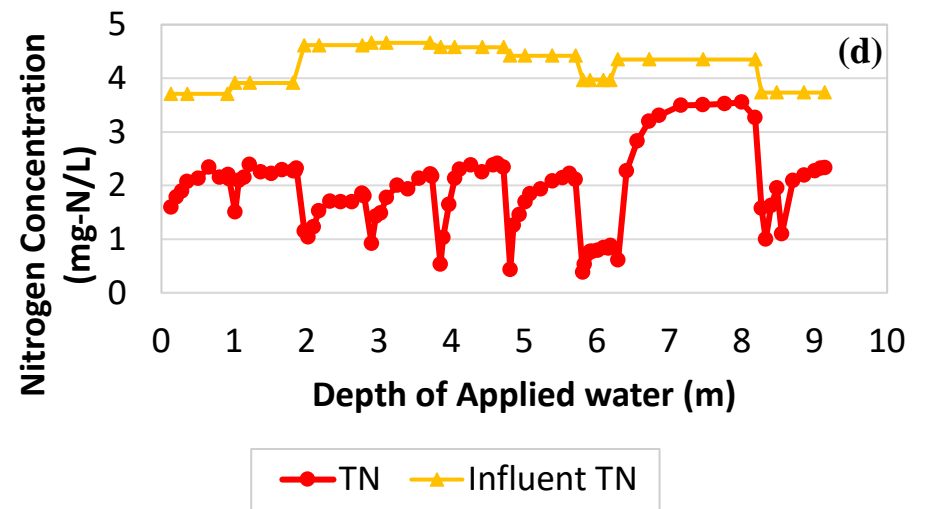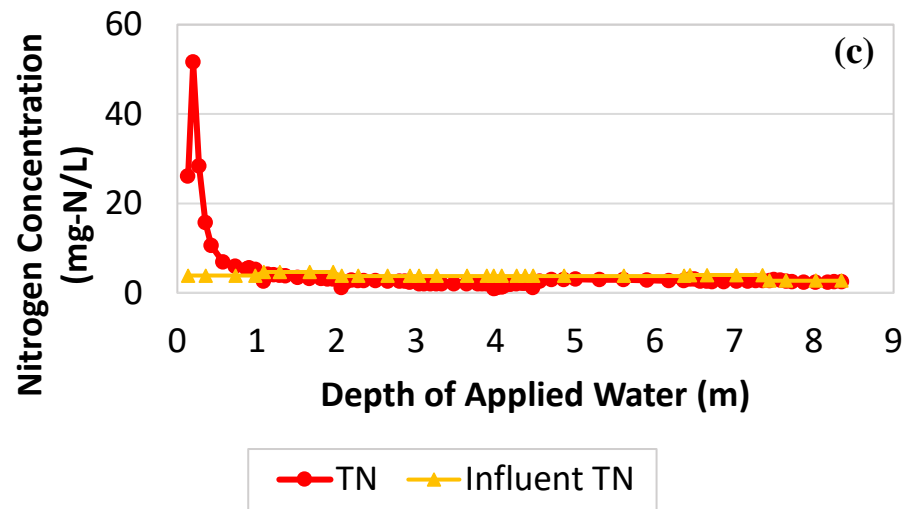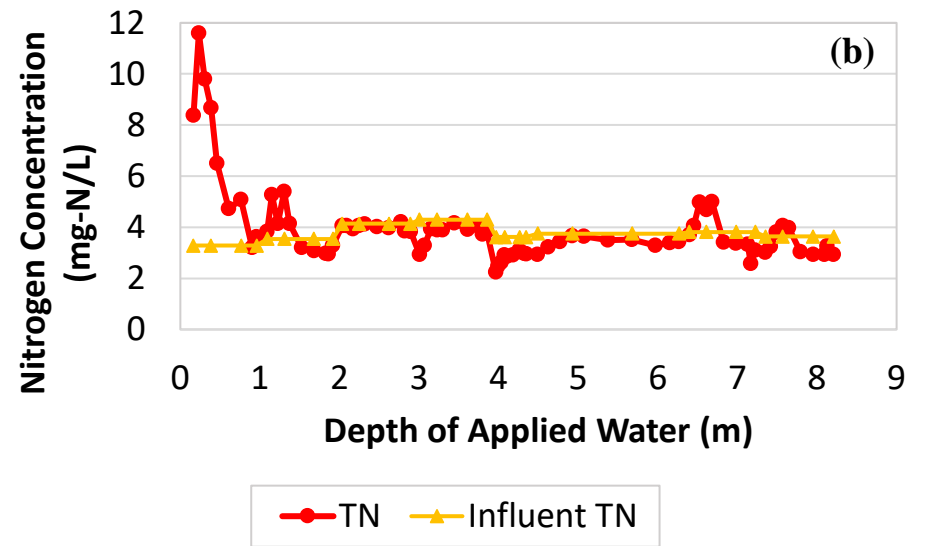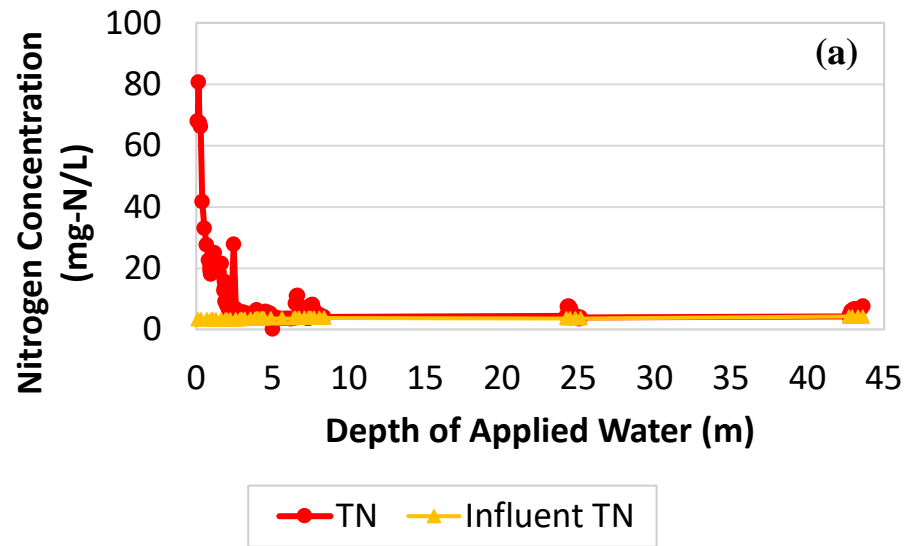
Figure 3.2: Total nitrogen concentrations across the three compost trials and control column. All values below the detection limit are represented at one-half the detection limit. Note that each axis is represented on a different scale for each plot. (Detection limit: 0.05 mg-N/L) a) 30% compost, 70% BSM; b) 15% compost, 85% BSM; c) 15% compost 4% WTR, 81% BSM; d) 100% BSM

As the trials progressed, the ratio of organic N to nitrate-N as the leading nitrogen source in the effluent decreased. This trend was seen in each large column: the 30% column had ratio values between 1 and 10 for the first three storms, this decreased to values between 0 and 0.8 for the remaining storms; the 15% and 15%+WTR columns both had initial ratios between 1 and 2 for the first two storms, that decreased to 0 – 0.9 and 0 – 0.8, respectively. A few points did not satisfy this trend from each trial, but the average was well above 1 for the first 2-3 storms and well below for the remaining storms.

A slight increase in the exported nitrogen can be seen after each drying period between storms. The drying period occurs roughly every meter of applied water. This increase begins to decline within the first hour of the storm. This phenomenon was seen throughout all column trials and was typically mimicked in either the organic N or nitrate-N.

No defined trend in the N data was seen from the control column data. An average effluent concentration was found to be 1.8 mg-N/L. Similar to the compost columns, each storm event began with a small value, roughly half the subsequent value, followed by a rapid increase to relatively constant export concentrations, with standard deviations of ~10%. All nitrogen concentrations from the control column were below the influent. Comparing the ratio of influent to effluent for the control column, at a depth of 7.5 m of applied water a concentration ratio minimum of 1.2 to 1 and maximum of 10.4 to 1 was found. These results are consistent with the general results found by Davis et al. (2001, 2003), Dietz and Clausen (2006), and Hunt (2006), which all showed a decrease in total nitrogen after bioretention treatment of stormwater. As is shown in the speciation data presented in the next section, this column also had limited efficiency in removing nitrate-N, which was seen in the above studies as well.

Not finding a definable trend in the control column was not unexpected. Extractions using 1 M KCl were done prior to this study and are presented in Table 3.1. Compost had far more extractable nitrogen than BSM or sand alone. This suggests that any effluent results that exceeded influent nitrogen concentrations are likely attributed to the compost addition and not the BSM or sand included in the column. These results also support the increasing effluent nitrogen concentration found with increased compost percentage, especially found with the 30% compost.

Table 3.1: Extractions of compost and other media in the columns. Each sample was tested three times to create an average and standard deviation. (Davis et al., 2016)

Sample Name	1 M KCl Extractable N	Mass N / Mass Dry Media	Standard Dev.	Coefficient of Variation
-	**(mg-N/L)**	**(mg/kg)**	**(mg/kg)**	**(%)**
Dickerson	85	799	42	5.3%
BSM	0.98	4.33	0.64	14.9%
Sand	0.50	2.07	0.67	32.2%

The 30% column had a consistently higher effluent nitrogen concentration than the influent and only had values below that of the influent water in 9 samples throughout the entire 44 m of applied water. A slight spike in the TN concentrations, largely in the form of nitrate-N, was found when the fescue tall grass was added to the columns. This occurred in the 30% column at around 6.5 m and 7.5 m of water applied. After a depth of 44 m of applied water, the 30% column still leached nitrogen concentrations greater than the influent. Although the first flush occurred within the first 3 m of applied water, the stabilization phase of the leaching process took far more time.

The stabilization phase was dominated largely by nitrate-N and organic N leaching. As the stabilization phase continued, organic N became less of a dominant factor and nitrate-N continued to leach at high levels. After 24 m of water had been applied, ammonium began to leach at similar levels to organic N, ~0.7 mg-N/L. In this phase it seems the nitrogen entering the column exits the system or replaces nitrogen species existing within. Ammonium was not added directly to the columns, but glycine was. The increase in ammonium toward the end of the trial suggests the breakdown of organic glycine. The ammonium would then be flushed from the system through cation exchange, most probably with calcium ions from the synthetic stormwater mix.

Both the 15% and 15%+WTR columns had very similar effluent N concentrations after the initial flush of nutrients, corresponding to the first 1-2 meters of applied water. A substantial difference in the initial effluent result between the 15% and 15%+WTR columns can be seen, which was most likely caused by the coarse filtering of the first few samples of the 15% column. Only the first two storms from the 15% column were filtered due to the high concentrations of particulates in the sample. The particulate matter prevented accurate readings for TP due to the nature of the colorimetric method. This filtering was unnecessary for all other columns. A break in the data occurs in the figures for the 15%+WTR column between 3 and 4 m applied water due to a loss of sample. The total N and P figures have an estimate value based on the averages from other storm events used to show the trend.

Based on previous research (Gallimore, 1999) WTR was not expected to have a negative effect on the capture or release of nitrogen in the first flush. After the first two storm events the 15%+WTR column results outperformed the 15% column in the removal of nitrogen, with average concentrations of 2.3±0.5 mg-N/L and 3.5±0.6 mg-N/L, respectively. Previous research

has shown either no increase or a reduction in nitrogen export with the addition of WTR to BSM. Previous reduction was approximately one third the overall influent (Gallimore, 1999; O'Neill, 2012).

All columns were run for 8 to 9 storm events, but the 30% column was run for an additional 37 storms, to observe long term effects on nutrient leaching or capture. A storm event that produces a 1 meter runoff depth, is equivalent to 5 cm of rainfall to the entire catchment area. The average rainfall in College Park, MD is 112 cm/yr. Every 22.4 meters of water applied to the columns in this trial is therefore equivalent to one year of rainfall in Maryland. At the end of the 8 synthetic storm events approximately 8 to 9 meters of rainfall had been applied to each column, this is the equivalent of 0.36 to 0.40 years of rainfall in College Park, MD. These calculations are explained in more depth in the next section.

The 30% column received approximately 2 years of rainfall by the end of this project. Results for the entire trial can be seen in Figure 3.2a. From these results it appears that after the initial reduction in effluent nitrogen there is no additional change in effluent concentrations. Average storm event values after 8 storm events, 26 storm events, and 45 storm events were all determined to be similar through the one-way ANOVA test for three sample sets, with individual event mean TN concentrations of 5.8 ± 1.6 mg-N/L, 5.4 ± 1.5 mg-N/L, and 6.2 ± 0.9 mg-N/L, respectively. This indicates that concentrations of nitrogen released beyond the first flush phase of nitrogen export remain at relatively consistent levels over time.

Cumulative Nitrogen Mass

Accumulated nitrogen mass discharge for each column was calculated on a mg-N basis for all four large column trials, up to a depth of 10 m of applied water (Figure 3.5). For the 15%+WTR column, values are estimated for the break in data mentioned earlier between 3 and 4 m of applied water for both the influent and effluent, respectively. These values were calculated based on averages calculated from the surrounding data points; the average TN values of the influent and effluent for the preceding storm and the following storm were inserted as the missing values. Figure 3.4 shows the control column and the extended 30% column.
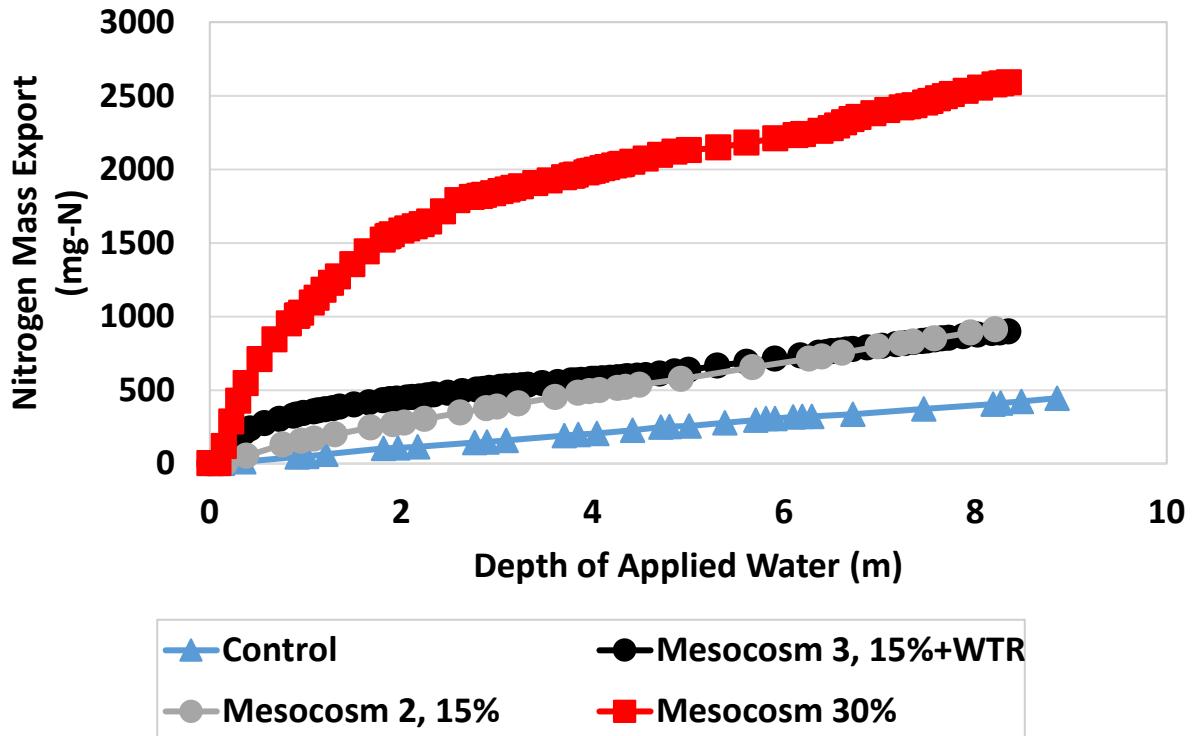
Figure 3.3: Cumulative nitrogen mass discharged for the three trials and control column including the influent water concentrations. The final two storms for the 30% column are not presented.
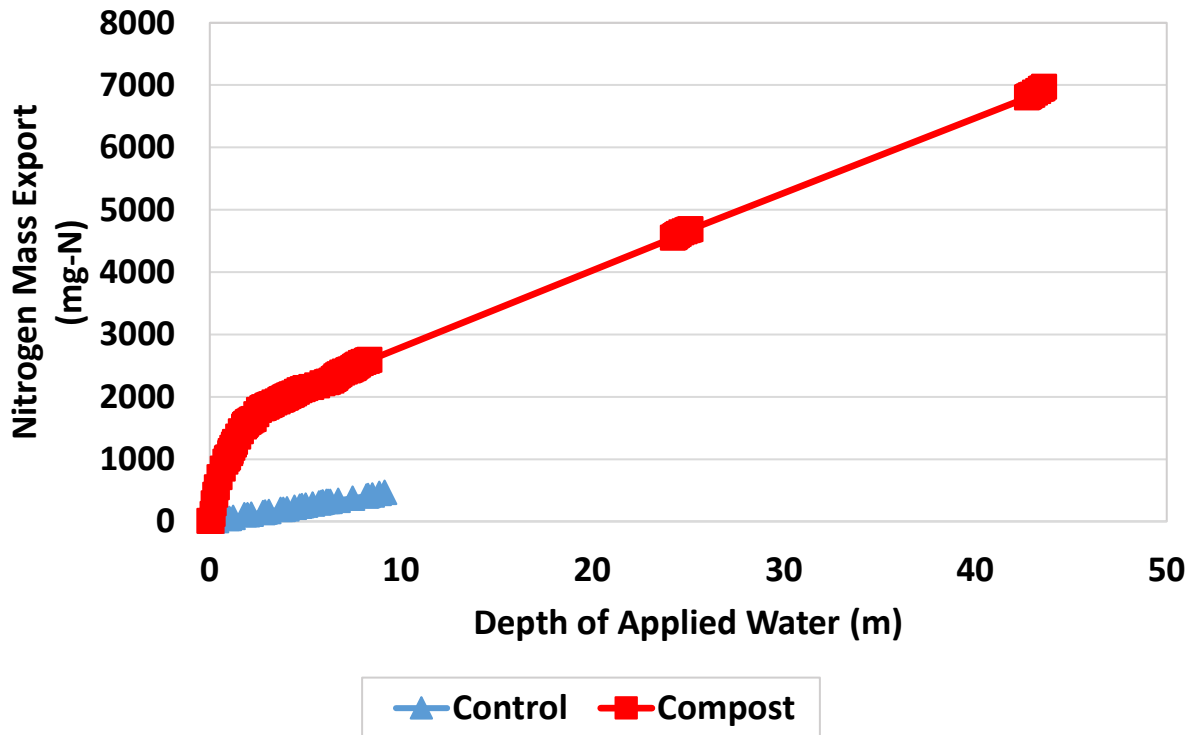
Figure 3.4: Accumulated nitrogen mass for the 30% column, after the extended storm trials, and the control column.

Without normalizing for influent nitrogen, the 30% column showed the highest total nitrogen mass export with 2591 mg-N. Based on the kg of compost added to the column, the 30% column discharged 1376 mg-N/kg dry compost after a depth of 8 m of applied water. The 15% and 15%+WTR columns exported nitrogen at 912 mg-N, 956 mg-N/kg dry compost and 897 mg-N, 1207 mg-N/kg dry compost, respectively. The control column had a total mass export of 463 mg-N and performed the best out of all four trials for nitrogen export. The total N mass applied to each column is presented in Table 3.2 along with the effluent results on a mg-N basis and the net mass of nitrogen exported.

Results from the accumulated effluent mass of nitrogen were also used to calculate event mean concentrations (EMC) for each column to compare influent and effluent values using the following equation:

$$EMC = \frac{mass\ accumulated\ (mg)}{applied\ volume\ (L)} \qquad 3(a)$$

These values are also summarized in Table 3.2, along with accumulation values. Only the control column and the 30% compost column had values significantly different from the influent values. The EMC for the 30% column increased by 7 mg-N/L which is 2.5 times higher than the influent concentration while the control column effluent was half that of the influent EMC.

Table 3.2: Nitrogen influent, effluent, and the net mass discharge and event mean concentrations after 8 m of applied water.

Influent/Effluent	Element Calculated	30%	15%	15%+WTR	100% BSM (Control)
Influent	Mass of nitrogen (mg-N)	846	879	901	1026
	EMC (mg-N/L)	3.5	3.7	3.7	4.2
Effluent	Mass of nitrogen (mg-N)	2591	912	897	463
	EMC (mg-N/L)	10.7	3.8	3.7	1.9
Net Export	Mass of nitrogen (mg-N)	1745	33	-6	-562

A significant mass of nitrogen was exported from all compost-amended columns, but the control and 15%+WTR columns showed a decrease in total exported nitrogen from the synthetic storms applied. Although there was a distinct difference between the 15% and 15%+WTR columns, previous research has not shown significant increase or decrease in nitrogen export with the addition of WTR to BSM (Gallimore, 1999; O'Neill, 2012). The first two storm events for the 15% column were filtered and may have caused the discrepancy between the two 15% columns. Some nitrogen may have been captured in the sediment diverted from the sample during the filtration process. This was the only instance in which samples were filtered before measuring TN.

Figure 3.5 shows the total mass of nitrogen with the influent water nitrogen mass subtracted out. This shows the overall addition or reduction of nitrogen throughout the eight storm events. The total net accumulations are presented in Table 3.2. The control, 15%, and 15%+WTR columns all began to reduce the load of total nitrogen exported by the end of the

trials; this corresponds to ~0.4 years of rainfall. Only the 15%+WTR and control columns showed total net mass reduction in the incoming nitrogen load, resulting in negative export accumulations. This result suggests that nitrogen was retained within the columns or denitrified. Figure 3.1(d) shows that the control column began capturing influent nitrogen from the beginning of the trial, but the 15% (b) and 15%+WTR (c) columns showed a significant initial spike in nitrogen export. After the first flush both columns began to capture exported nitrogen in their stabilization phases. The 15%+WTR column showed a more aggressive negative trend then that of the 15% column which has also been seen in other research (O'Neill, 2012); this research focused on the effects of WTR on phosphorus removal, but noticed a slight reduction in certain nitrogen species.
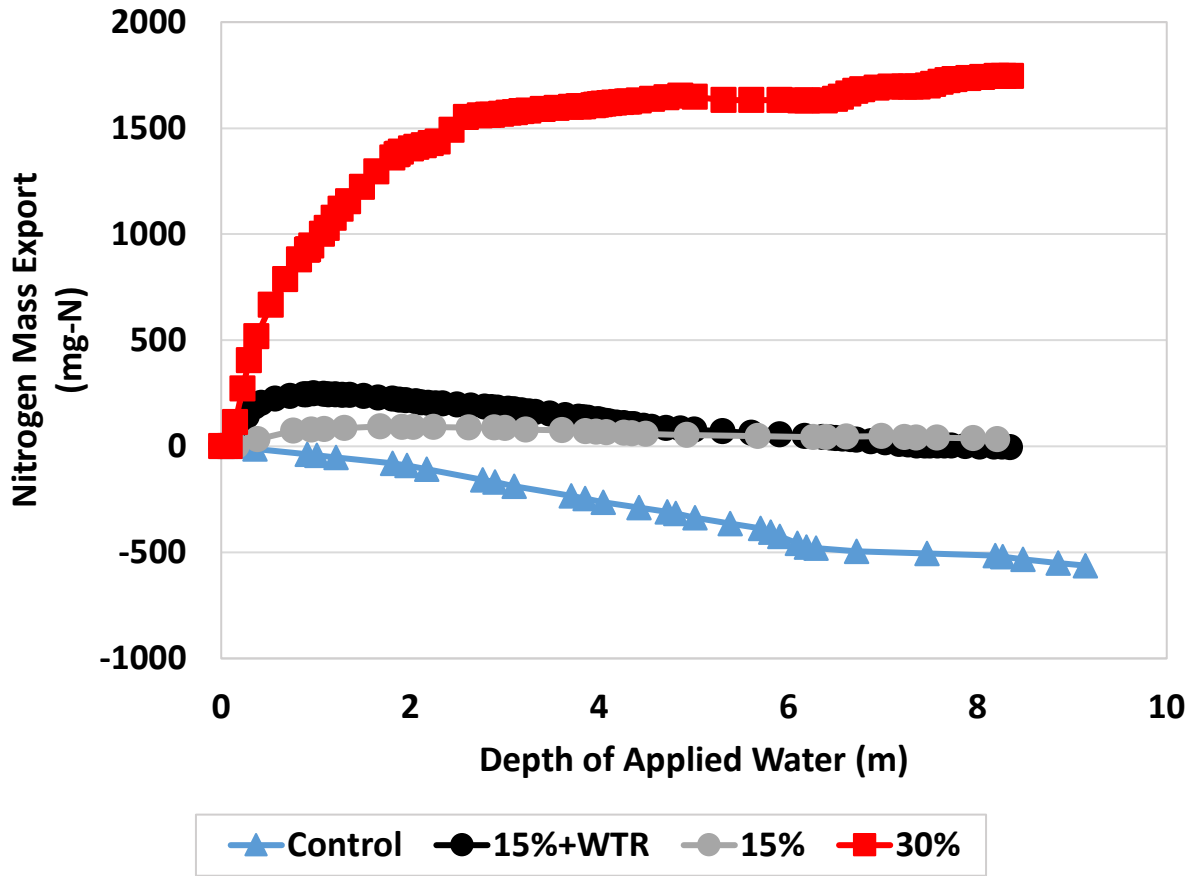
Figure 3.5: Cumulative net mass of exported nitrogen across the three trials and control column.

Equation 3(b) was used to calculate the annual mass load per unit drainage area (*L*) for each column. This equation assumes an average yearly rainfall of 112 cm/yr (*R*) ("College Park Weather Averages") and a catchment area (*A*) 20 times larger than the bioretention cell area (Environmental Services Division et al., 2007). The total accumulated mass of the nutrient is represented as *M* and the depth of applied water is *D*; these results are presented in Table 3.3.

$$L = \frac{MR}{AD} \hspace{6cm} 3(b)$$

The annual input N load for each column was 42 ± 2 kg-N/ha-yr, which is 3 times higher than the bioretention load estimated by Li and Davis (2013), who found total nitrogen loading of 14.0 kg-N/ha-yr. The number of years of urban watershed runoff can be calculated for each column by comparing input to output nitrogen loading. This comparison shows the runoff accumulation, in kg-N/ha-yr, from the input and how that number would be affected by the addition of a bioretention cell with compost or BSM addition. In one year of rainfall, the 30% column would accumulate the equivalent of three years' worth of N runoff produced from an urban site without the bioretention cell. For both 15% columns there was no change in the amount of N mass contributed by runoff without bioretention compared to a site with the bioretention cell, and the 100% BSM column resulted in the capture of roughly half the nitrogen runoff load produced from one year.

Table 3.3: Annual mass loads per unit drainage area for each column and the calculated equivalent years of urban watershed runoff. Values are calculated from accumulated mass after 8 meters of applied water, equivalent to ~0.4 years of rainfall.

	30%	15%	15%+WTR	100% BSM
Influent mass of nitrogen (kg-N/ha-yr)	40	42	42	44
Effluent mass of nitrogen (kg-N/ha-yr)	121	43	40	20
Years of equivalent urban watershed N export	3.03	1.02	0.95	0.45

Capture of the influent nitrogen concentration began after the first 2 meters of applied water for both 15% columns; this is equivalent to approximately 1 month of Maryland rainfall on a site 20 times the area of the bioretention cell. Net removal of nitrogen did not occur for the

15% column, despite the reduced effluent concentrations. The 15%+WTR column showed net removal in N mass exported after 8 m of applied water; 5 months of MD rainfall on a site 20 times the area of the bioretention cell. The control column reduced nitrogen export most effectively and had smaller concentrations from the start.

Looking at the long term study for the 30% column, the influent nitrogen loads increase to 43 kg-N/ha-yr and the effluent nitrogen load drops to 62 kg-N/ha-yr. This column received close to 2 years of equivalent MD rainfall by the end of the study. When the equivalent years of runoff are calculated for the extended 30% column, the equivalent years of urban watershed N export only increases by 1.44 years.

Nitrogen Speciation

The N speciation for each column trial is seen in Figure 3.6. Each column shows a dominance of particulate organic N and nitrate-N in the effluent throughout the trial. Initially high nitrate-N and organic N levels were found in both the 30% and 15%+WTR columns. These concentrations were quickly flushed out to more consistent values after the first 2 – 3 m of applied water.
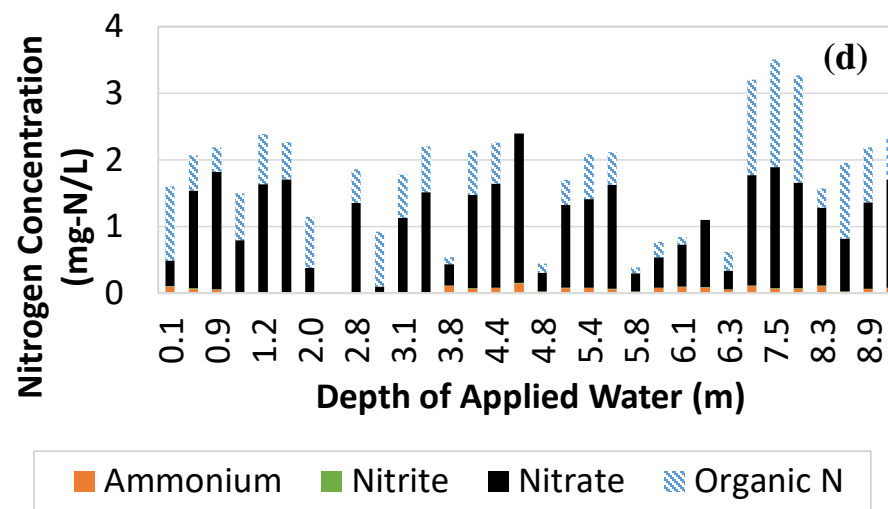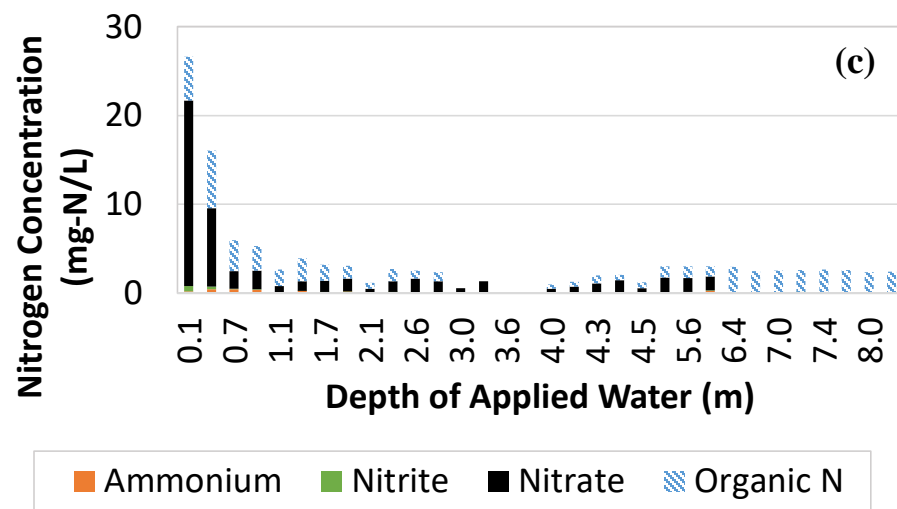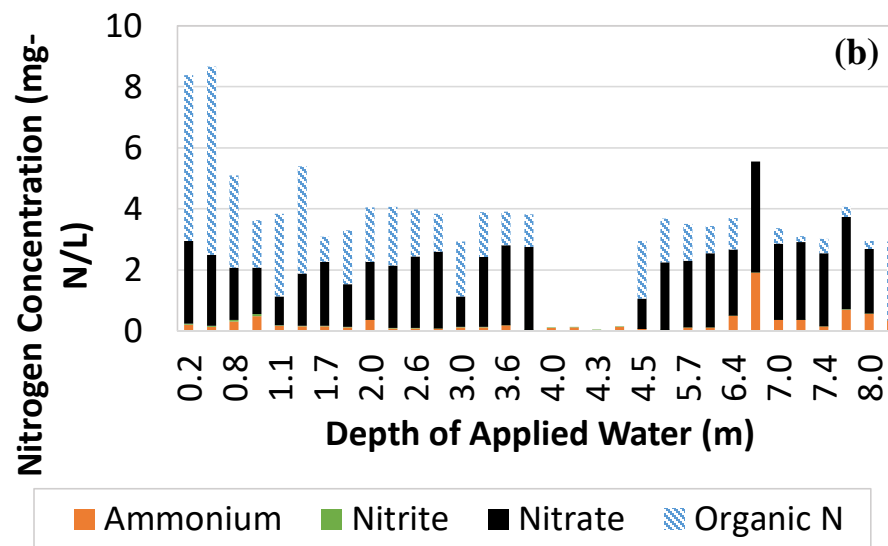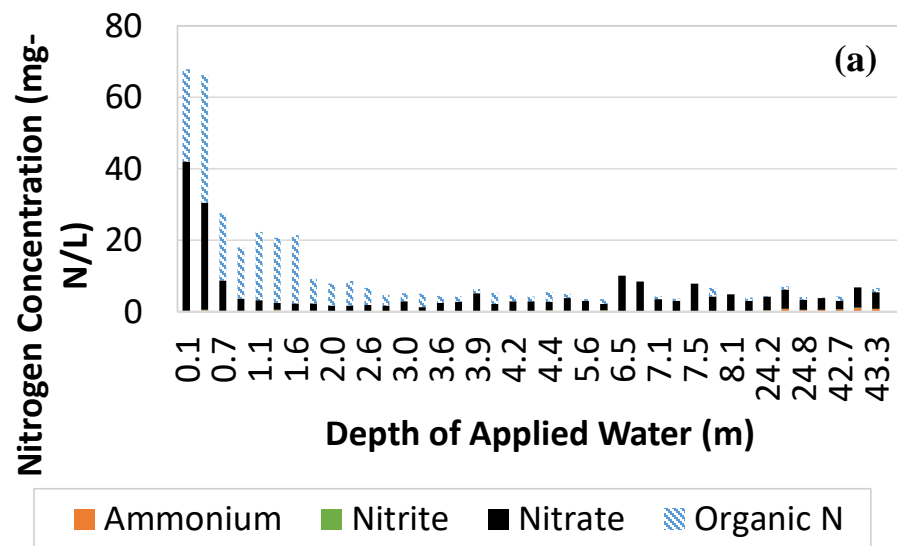
Figure 3.6: Comparison of nitrogen speciation concentrations across the three compost trials and control column. All values below the detection limit were represented at one-half the detection limit. Note that each axis is represented on a different scale for each plot. (Detection limit: Nitrite, 0.01 mg-N/L; Ammonium, 0.05 mg-N/L; Nitrate, 0.05 mg-N/L) a) 30% compost, 70% BSM; b) 15% compost, 85% BSM; c) 15% compost 4% WTR, 81% BSM; d) 100% BSM)

For the 30% column [Figure 3.6(a)], concentrations for nitrate-N and organic N begin at 42 mg-N/L and 26 mg-N/L, respectively. Nitrate-N concentrations drop to values between 1 and 4 mg-N/L after the first meter of water with an average effluent concentration of 3.4 ± 2 mg-N/L. Organic N for the 30% column also shows a first flush, but this flush continues throughout the trial and follows the TN flush more closely. Values begin to average around 1.2 mg-N/L after the first 3 m of applied water with a standard deviation of 1 mg-N/L.

The 15%+WTR column [Figure 3.6 (c)] shows a very similar story, but concentrations do not begin nearly as high and the initial flush of nutrients occurs much quicker. Initial concentrations for nitrate-N and organic N were 21 mg-N/L and 5 mg-N/L, respectively. After the first 0.75 meter, nitrate-N values begin to average around 1.2 ± 0.5 mg-N/L. These values were half those of the 30% column. Organic N had a longer first flush and had an average of 1.4 ± 0.9 mg-N/L after the first two meters of applied water, which corresponds closely with the TN first flush.

From the data collected, the 15% column [Figure 3.6 (b)] did not show a first flush trend for nitrate-N and organic N only had a slight flush. This could have partially been caused by the filtering mentioned before. Only the first two storms of the 15% column were filtered prior to TN testing. Nitrate values throughout the entire trial averaged 2.2 ± 0.6 mg-N/L. A maximum occurred after 6.6 m of water had been applied, and registered a concentration of 3.6 mg-N/L. Organic N had a maximum concentration of 6.2 mg-N/L after the first 0.4 m of water had been applied and showed a flush that followed the TN first flush. The remaining stabilization phase had an average of 1.1 ± 0.6 mg-N/L.

The control column [Figure 3.6 (d)] consistently showed effluent concentrations dominated by nitrate-N and organic N, but did not show the characteristic flush found in the

other three columns. The maximum nitrate-N and organic N values were 2.2 mg-N/L and 1.6 mg-N/L, respectively; neither of these maximums occurred near the beginning of the trial. Averages for nitrate-N and organic N were 1.1 ± 0.6 mg-N/L and 0.6 ± 0.4 mg-N/L, respectively.

Nitrite and ammonium were both relatively constant throughout all column trials. Like nitrate-N and organic N, however, a first flush was seen for nitrite. Nitrite peaks were 0.1 mg-N/L for the 30% column, 0.03 mg-N/L for the 15% column, 0.57 mg/l for the 15%+WTR column, and 0.01 mg-N/L for the control column. After the third storm, nitrite concentrations were below the detection limit of 0.01 mg-N/L and were represented as 0.005 mg-N/L, half the detection limit for all columns. The ammonium values were also low, never peaking above 1 mg-N/L in any column, but did appear to increase toward the end of the experiment in the 30% and 15% columns. The increase in ammonium values in the final two storm events was most apparent in the 30% column which had a 5-10 times higher ammonium effluent concentration than the effluent concentrations of the prior storms, an average of 0.2 mg-N/L before the final two storms, and 0.73 mg-N/L after. The 15% column showed an increase of 3-5 times in ammonium concentrations, an average of 0.14 mg-N/L before the final two storms, and 0.6 mg-N/L after. Ammonium averages over the entire experiment for the four columns were; 0.3 ± 0.2 mg-N/L for the 30% column, 0.3 ± 0.3 mg-N/L for the 15% column, 0.1 ± 0.1 mg-N/L for the 15%+WTR column, and 0.07 ± 0.03 mg-N/L for the control column. Unlike nitrite, ammonium was seen throughout the trials and continued to leach at low levels.

Initial effluent from the compost-amended columns was typically dark in color (Figure 3.1); this suggests high organic matter content. Nitrate is the most mobile and soluble of the nitrogen species and can be seen in the preceding data to be one of the major N species in the

effluent. Within the first two storms, most nitrate-N that was present in the compost and BSM added to the column was flushed out. As the columns flow, the color of the effluent becomes lighter in hue, suggesting a decrease in the organic matter present in the leachate. With less organic matter, less organic N is expected. The leaching of this organic N occurs throughout the experiment. In a field scenario, organic matter might increase as animal and plant material decays on top of the bioretention cell, this could potentially increase the organic N concentration.

Comparing effluent nitrogen to influent concentrations suggests biological and physical processes influencing the dominant species. Each storm event began with a slight increase in nitrate-N and TN followed by a continual decay. This increase in nitrate-N effluent has been seen in previous studies by Davis et al. (2001) and Hsieh and Davis (2005); it could be caused by the naturally aerobic conditions of the bioretention system that would favor nitrification during drying periods. Figure 3.8 shows an example of the possible soil aerobic biofilm design.

No ammonium was added to these columns, but it was found in the effluent at constant levels. This suggests the recurrent ammonium release from the compost as water saturates the system and the rapid breakdown of glycine within the column. The accumulation of ammonium is most likely defined by a combination of ammonification from heterotrophic microbial activity in the plant biomass and glycine cleaving from plant enzymes (Figure 3.8). This ammonium accumulated is then desorbed from the media in a process similar to the one seen in Figure 3.7 (Sparks, 2003; Subramaniam et al., 2016).
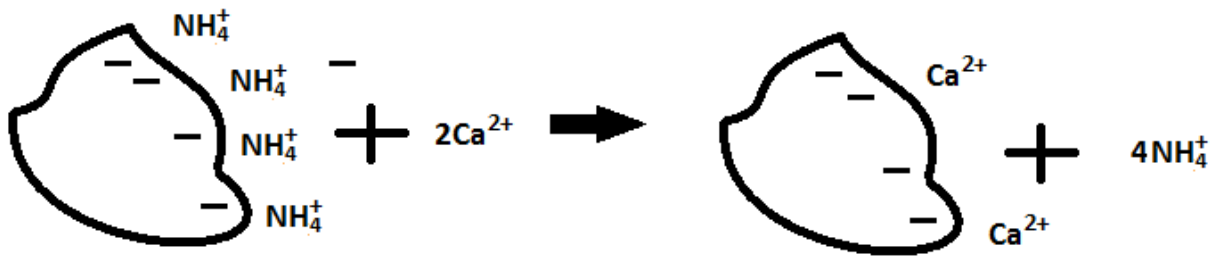
Figure 3.7: Example of cation exchange occurring in the columns as stormwater passes through the system.

The influent synthetic stormwater had high levels of both sodium and calcium, both of which can compete with ammonium for negatively charged sorption sites, (Figure 3.7). As biomass matures and ammonium is formed in the media it is likely stored in biofilm layers around the plant mass. During drying periods, the moisture around each soil particle can begin the nitrification process (Subramaniam et al., 2016). As the next application of synthetic

stormwater filters through the media, both nitrate-N and the non-nitrified ammonium leach from the system.
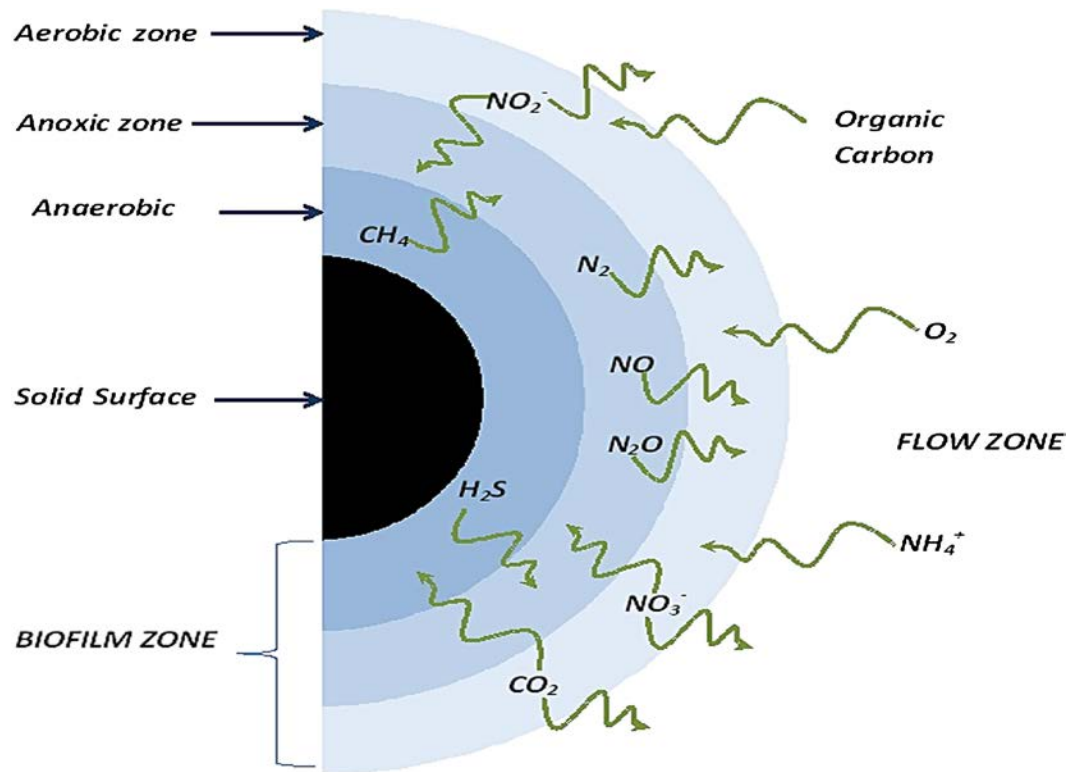
Figure 3.8: Mechanisms of diffusion in a soil biofilm during the drying periods between storm events (Subramaniam et al., 2016).

Effect of Velocity Variation

For all trials the inflow rate remained at 0.25 cm/min except for two storm events that were run at 0.13 cm/min and 0.51 cm/min for 6 hours each. Results for the 30% column are shown in Figure 3.6 for all species of nitrogen. The section of altered flow velocity is boxed in dashed lines and the split between the 0.13 cm/min and the 0.51 cm/min flow rates is designated by a solid vertical line inside the box.
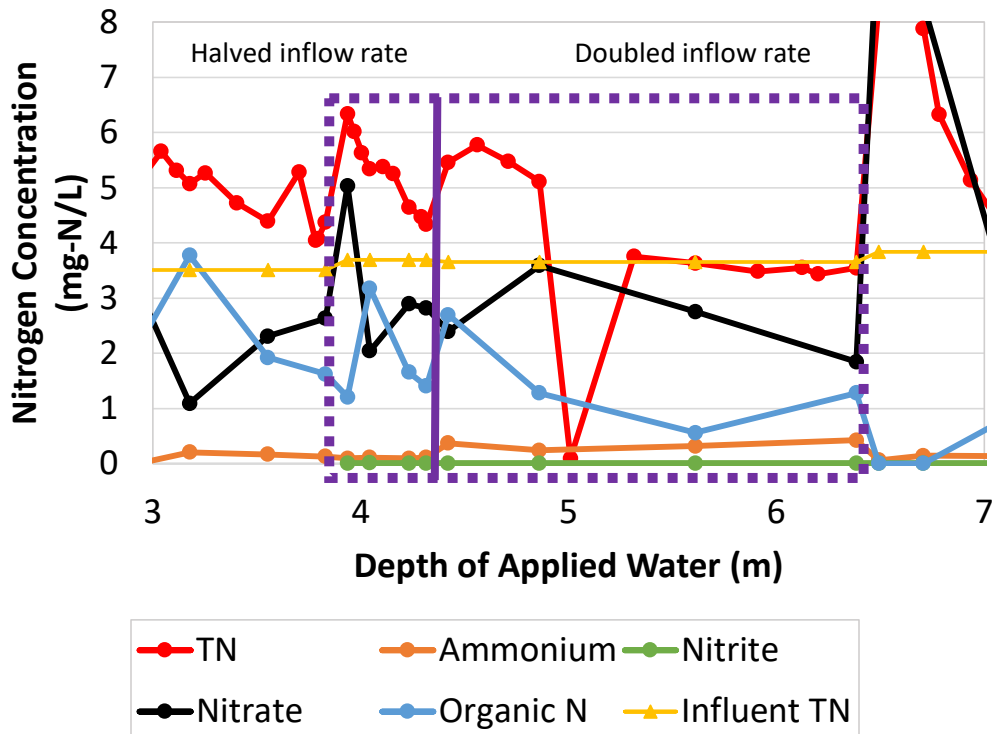
Figure 3.9: Velocity variation in the 30% compost, 70% BSM column. The section with altered flow velocities is boxed and the two different alterations are separated by a solid vertical line. All values below the detection limit are represented at one-half the test detection limit. (Detection limit: TN, 0.05 mg-N/L; Nitrite, 0.01 mg-N/L; Ammonium, 0.05 mg-N/L; Nitrate, 0.05 mg-N/L)

A single point occurs during the increased flow rate, at a depth of 5 meters of applied water, where an extremely low nitrogen concentration was measured. This value was unexpected and was tested with the modified Thompson Tau test for outliers; the point was determined to be an outlier. Due to the volume of water captured for testing, there was not enough sample to retest the point. The point, therefore, could not be associated with a testing issue or an extreme value, results are shown with and without the outlying point.

Nitrate release at both flow rates have similar concentrations despite the velocity change. During the double-flow run, organic N showed a flush pattern similar to the first flush, while ammonium appeared to increase slightly. Although the increased flow rate exported more total mass of nitrogen, it did not change the pattern observed in the TN concentrations in the

stabilization phase. These results suggest that the nitrate-N concentration in the effluent was unaffected by flow velocity. The slight increase in ammonium concentration can be attributed to the increased volume of cations introduced to the system with the increased flow rate. This would increase the cation exchange potential and cause more ammonium release from the column. Most of the organic N remaining after the first flush was displaced from the column in the doubled flow rate storm. The concentrations did not increase with the addition of the grass or with continual treatment.

Figure 3.10 shows the flow altered results for the 15% and 15%+WTR columns. Similar to Figure 3.9, the sections with different flows are contained within the dotted box and the two segments are separated by a solid vertical line. Samples from the reduced flow segment were lost for the 15% column before nitrate-N measurements could be taken. These columns are shown together to compare similarities and differences.
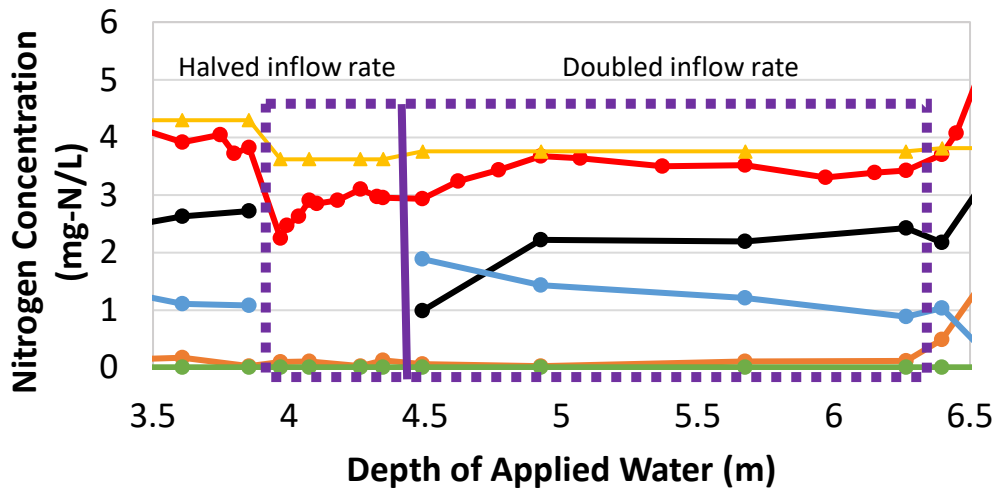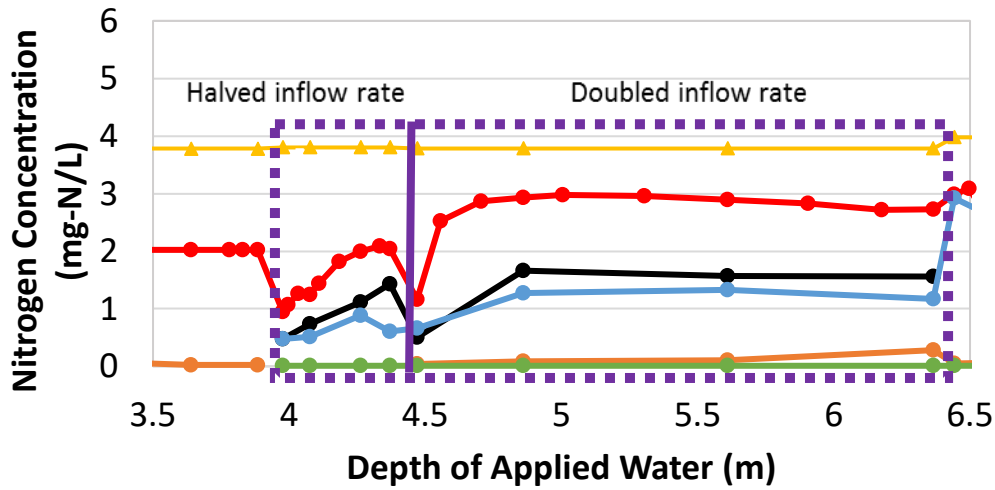
Figure 3.10: Velocity variation in the a) 15% and b) 15%+WTR columns. The section with altered flow velocities was boxed and the two different alterations were separated by a solid vertical line. All values below the detection limit were represented at one-half the test detection limit. (Detection limit: TN, 0.05 mg-N/L; Nitrite, 0.01 mg-N/L; Ammonium, 0.05 mg-N/L; Nitrate, 0.05 mg-N/L)

Between the two graphs in Figure 3.10, similar trends in the effluent nitrogen speciations can be seen. The concentration values were slightly different in magnitude, but this was likely due to the mass of compost in each column. (Columns were created on a volume % basis, the total mass of compost was different due to the addition of WTR which resulted in less compost by mass.)

Both columns show a slowly increasing effluent of nitrogen in the reduced flow scenario and an initially low value followed by an increase and gradual decrease in TN concentration throughout the double velocity event. Although comparisons cannot be made for the reduced flow, the increased flow shows agreement in the way the nitrogen species react. As was seen in the 30% column, the increased flow appears to flush more of the organic N out in both the 15% and 15%+WTR columns. The nitrate-N concentrations for the 15% and 15%+WTR columns increased slightly in the double velocity section, then remained constant; this was also seen in Figure 3.9. In Figure 3.10 a slight increase in the ammonium values can be seen for the 15% and 15%+WTR columns toward the end of the double velocity run. While the 15%+WTR column began with concentrations below detection limit and increased to 0.3 mg-N/L, the 15% column only had an increase of 0.02 mg-N/L from the beginning of the reduced flow to the end of the increased flow trials. Neither of these trends were as significant as the increase seen in the 30% column; 0.1 mg-N/L at the start of the reduced flow trial to 0.4 mg-N/L at the end of the double-flow trial.
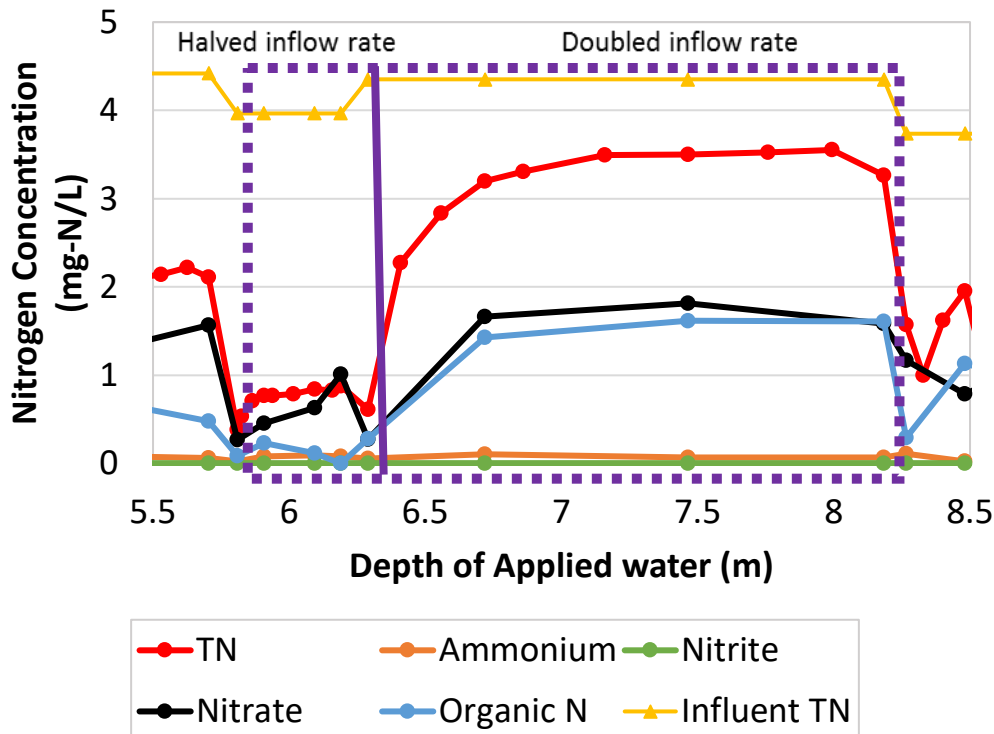
Figure 3.11: Velocity variation in the control column; 100% BSM. The section with altered flow velocities was boxed and the two different alterations were separated by a solid vertical line. All values below the detection limit were represented at one-half the test detection limit. (Detection limit: TN, 0.05 mg-N/L; Nitrite, 0.01 mg-N/L; Ammonium, 0.05 mg-N/L; Nitrate, 0.05 mg-N/L)

The adjusted flow section for the control column is presented in Figure 3.11. Results from this section appear almost identical, in trend, to those of the 15% and 15%+WTR columns. The magnitude of the concentrations in the reduced flow trial were the only major difference; values in the control column were half that of the 15%+WTR column and a quarter of the concentration values in the 15% column. Similar to Figure 3.10, nitrate-N and organic N were present at the highest concentrations in the effluent and both increased from the reduced velocity to the increased. Unlike the 30%, 15%, and 15%+WTR columns, a noticeable increase in ammonium in either of the altered flow storms was not seen.

In the 15%, 15%+WTR, and control columns an increase in TN concentrations with the increase in flow velocity was seen, although the concentration remained below the influent

nitrogen levels. This was most likely due to the increase in velocity through the soil pores. Nitrates carried by the synthetic stormwater and the compost have less time to be captured in bacterial biofilms in the column and organic N would break down and dislodge more rapidly with a higher velocity flow.

Nitrogen Summary

The 30% column produced an extreme in nitrogen release throughout the trial and showed no trend toward reducing the effluent concentrations. Ultimately, this volume of compost exported a net mass of 2.2 g-N of nitrogen after 2 years of equivalent rainfall applied. Reducing the volume of compost incorporated in the BSM mix to 15% resulted in a net mass of 0 g-N in nitrogen exported and showed a negative trend in nitrogen concentrations that did begin reducing the total mass load from the urban watershed after 5-6 months of equivalent MD rainfall applied. The addition of WTR showed a more negative trend that appeared to reduce the nitrogen mass load more rapidly and effectively after 5-6 months of equivalent MD rainfall applied, but this would need more research. The control column had the most effective removal of nitrogen and consistently exported lower concentrations in N species than the influent. The results for the BSM control column seen in this report are similar to the ones seen in other studies; Davis et al. (2001, 2003), Dietz and Clausen (2006), and Hunt (2006); which have all shown a reduction in exported nitrogen through the use of BSM with appropriate design specifications.

Phosphorus

Discrete column effluent total phosphorus concentrations are presented in Figure 3.12. Similar to the nitrogen results, total phosphorus (TP) measurements were highest in the 30% column and lower in the 15%, 15%+WTR, and the control column. Each storm event began with an initially low concentration of phosphorus which was followed by an immediate increase in magnitude that slowly diminished as the storm continued. Effluent concentrations for the 30% column reached below influent values only once over the 43 week study and were often 2 to 10 times greater than the influent; at one point the effluent measurement reached 18 times that of the influent. The 15% column never had total phosphorus concentrations below the influent. The lowest point occurred at the initial measurement 0.23 mg-P/L; this value occurred within the first storm event. Other effluent concentrations were typically 2-4 times the concentration of the influent.

The 30% column received an additional 37 storm events after the initial 8, to characterize long term leaching effects. As the experiment progressed, phosphorus effluent concentrations decreased to values close to the influent, but still 1.5 to 2 times greater than the influent. This trend suggests that as the bioretention site ages, the phosphorus exported will decrease.
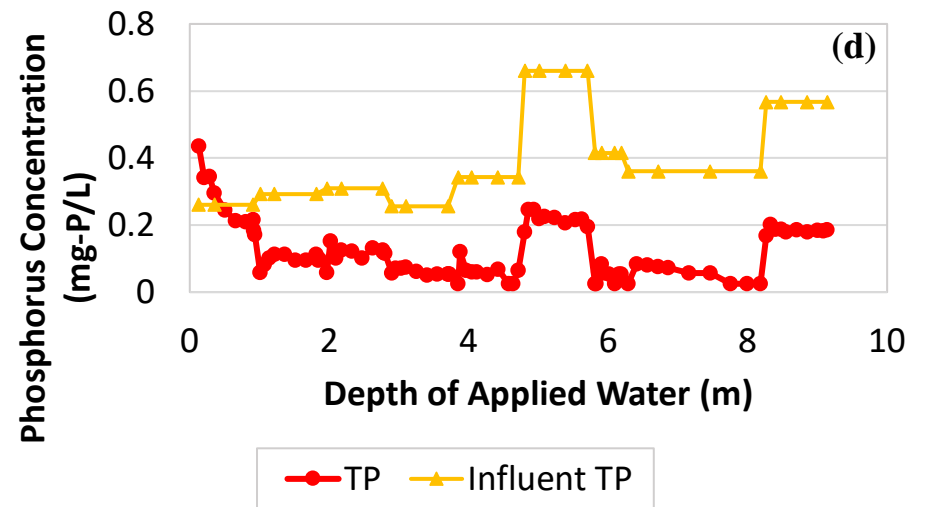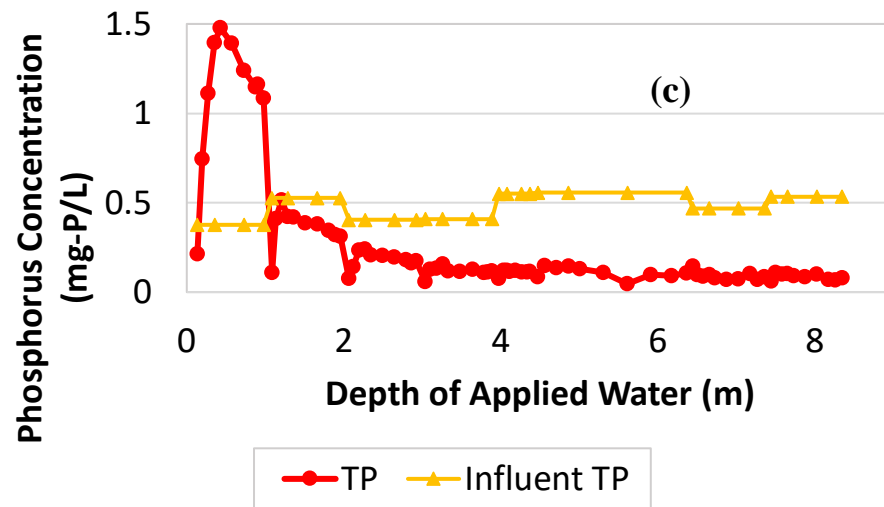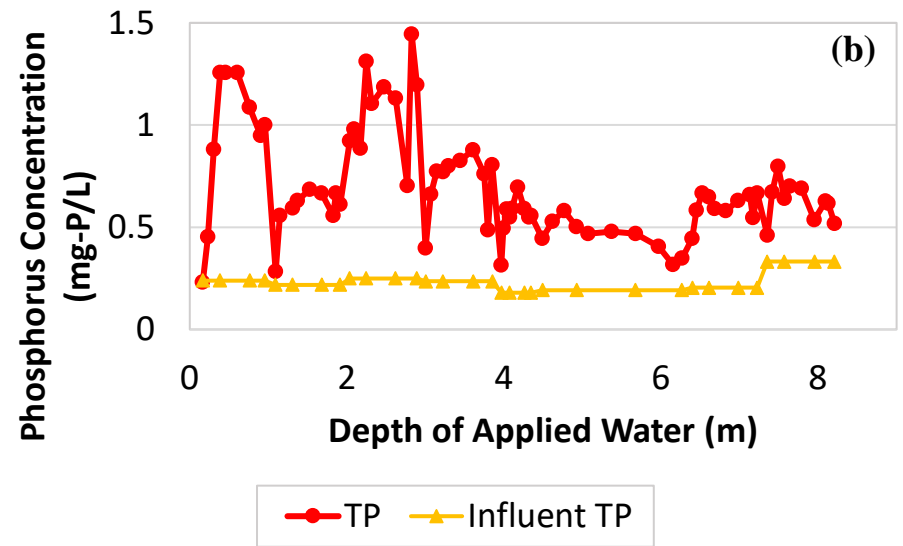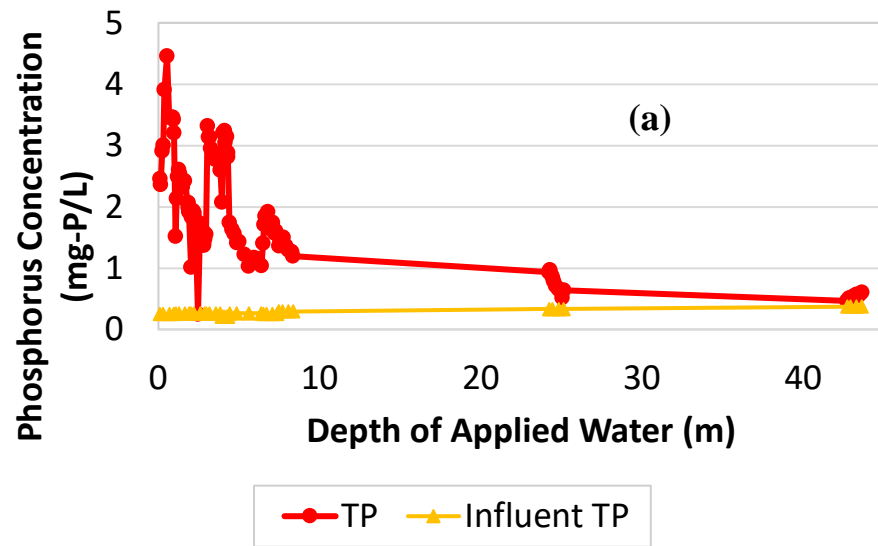
Figure 3.12: Total phosphorus concentrations across the three trials and control column. All values below the detection limit are represented at one-half the detection limit. Note that each axis is represented on a different scale for each plot. (Detection limit: 0.02 mg-P/L) a) 30% compost, 70% BSM; b) 15% compost, 85% BSM; c) 15% compost 4% WTR, 81% BSM; d) 100% BSM

In each trial, including the control, an initial first flush of phosphorus can be seen, followed by a more stabilized effluent concentration. This was also seen in the nitrogen concentrations, but the magnitude of the phosphorus concentrations is 5 to 10 times less than that of the nitrogen. This flush is less evident in the 15% column, presumably due to the filtering that occurred for the first two storm events. Unlike the nitrogen concentrations, there is a general negative trend seen throughout the entire 8+ storm events for all the compost-amended columns. This trend is confirmed by the Kendal tau test, implying that the release of phosphorus is a much more gradual process and occurs throughout the lifetime of a cell. While the control column does show a decreasing trend in the first storm event, the concentrations remain relatively constant after this event. Both the control and the 15%+WTR columns had values below the influent for all measured values except the first storm event.

A stabilization period occurs for both the 15%+WTR column and the control column. The stabilization period for the control column occurs after the first storm event after which the values fluctuate around an average of 0.11$\pm$0.06 mg-P/L. For the 15%+WTR column, the stabilization period occurs after the first 3 storms with an average of 0.10$\pm$0.02 mg-P/L. For both columns the influent phosphorus fluctuated between 0.25 mg-P/L and 0.65 mg-P/L. The effluent concentrations for the 15%+WTR and control columns did not respond identically. As the influent concentrations fluctuated for the control column, the effluent concentrations also fluctuated. This did not occur in the 15%+WTR column which showed no effluent fluctuations in phosphorus concentration. This implies a stronger adsorption potential for the WTR-amended column, as seen in previous studies (O'Neill, 2012; Liu, 2013).

Large phosphorus export has also been seen in other bioretention studies (Zhang et al., 2004; Hunt et al., 2006), but results have been inconsistent and are likely dependent on the BSM

mixture. Other research has also shown an increase in phosphorus removal in a bioretention setting (Hunt et al., 2006; Chatterjee et al., 2013). Research has generally shown that compost mixtures high in initial phosphorus content export higher net phosphorus from the system.

Extractions using Mehlich-3 and $CaCl_2$ were done prior to the study for both BSM and the Dickerson compost to characterize initial phosphorus content; these results are presented in Table 3.4. The results showed a high level of extractable phosphorus in the compost, 673 mg-P/kg media, and very little phosphorus in the BSM, 0.93 mg-P/kg media. A water soluble $CaCl_2$ extraction was also done during the study to determine an effective WTR/compost ratio for phosphorus reduction. The extractions were done on (WTR:compost) ratios of 3:20, 1:4, and 7:20. Ultimately the 1:4 ratio was used in the large column trial, 15%+WTR column.

Table 3.4: Extractions for compost and other media in the columns. NM: not measured (Davis et al., 2016)

Sample Name	Mehlich-3 Extractable P	Mass P / Mass Dry Media	Standard Deviation	Relative Deviation	0.01 M CaCl₂ Extractable P	Mass P / Mass Dry Media	Standard Deviation	Relative Deviation
-	(mg-P/L)	(mg-P/kg)	(mg-P/kg)	(%)	(mg-P/L)	(mg-P/kg)	(mg-P/kg)	(%)
Dickerson	24	673	35	5%	0.33	8.4	0.8	10%
Dickerson + 15% WTR	NM	NM	NM	NM	0.21	6.9	0.07	1%
Dickerson + 25% WTR	NM	NM	NM	NM	0.12	4.6	0.03	1%
Dickerson + 35% WTR	NM	NM	NM	NM	0.07	3.6	0.18	5%
BSM	0.09	0.93	0.08	9%	0.002	0.04	0.0	0%
Sand	0.03	0.31	0.13	42%	0.004	0.15	0.02	15%

For all columns, the initial concentration of TP measured in the export for each storm was generally 2/3 to 1/2 times lower than the concentrations measured in the remainder of the storm event. This was not the case for all storms; as the trials progressed the effluent concentrations became less variable within storm events.

Throughout the trials of each column, soluble reactive phosphorus (SRP) and particulate phosphorus were the major species of phosphorus exported. The initial flush for the 30%, 15%+WTR, and the control column was dominated largely by particulate P. As the trials progressed, SRP became the controlling species in TP release. The 30%, 15%, 15%+WTR, and the control columns had average SRP concentrations of 0.85±0.3 mg-P/L, 0.38±0.1 mg-P/L, 0.08±0.06 mg-P/L, and 0.02±0.006 mg-P/L, respectively. These values stayed relatively constant throughout the trial. This suggests that particulate phosphorus contained in the columns is physically flushed out initially while SRP persists in the media. The overall consistency found between all four columns suggests that initial extraction values could be associated with an expected SRP release.

Each column received 8 to 9 storm events, but the 30% compost column received an additional 37 storms. This column was designed to characterize the long term leaching effects of compost-amended bioretention sites. From the results in Figure 2.9, phosphorus can still be seen in increased concentrations after approximately 2 years of applied rainfall, based on the 112 cm/yr average in College Park, MD. Although the concentrations found in the effluent of the extended trial were higher than the influent (at a depth of ~25 meters of applied water, concentrations were 2.3 times higher and at ~43 meters, concentrations were 1.4 times higher than influent) the trend in data suggests a declining export of phosphorus from the system (defined by the Kendal Tau test). After 2 years of applied water a stabilization phase was not

achieved, noted by the changing ratio of influent to effluent, for the 30% column; it is unknown whether the phosphorus levels will continue to decrease or reach a steady state with the influent concentration of phosphorus.

Cumulative Phosphorus Mass

Cumulative phosphorus export was calculated on a mg-P basis and can be seen in Figure 2.12 for all four large column trials, up to 10 m of applied water. Figure 2.13 shows the extended 30% column storms along with the control column.
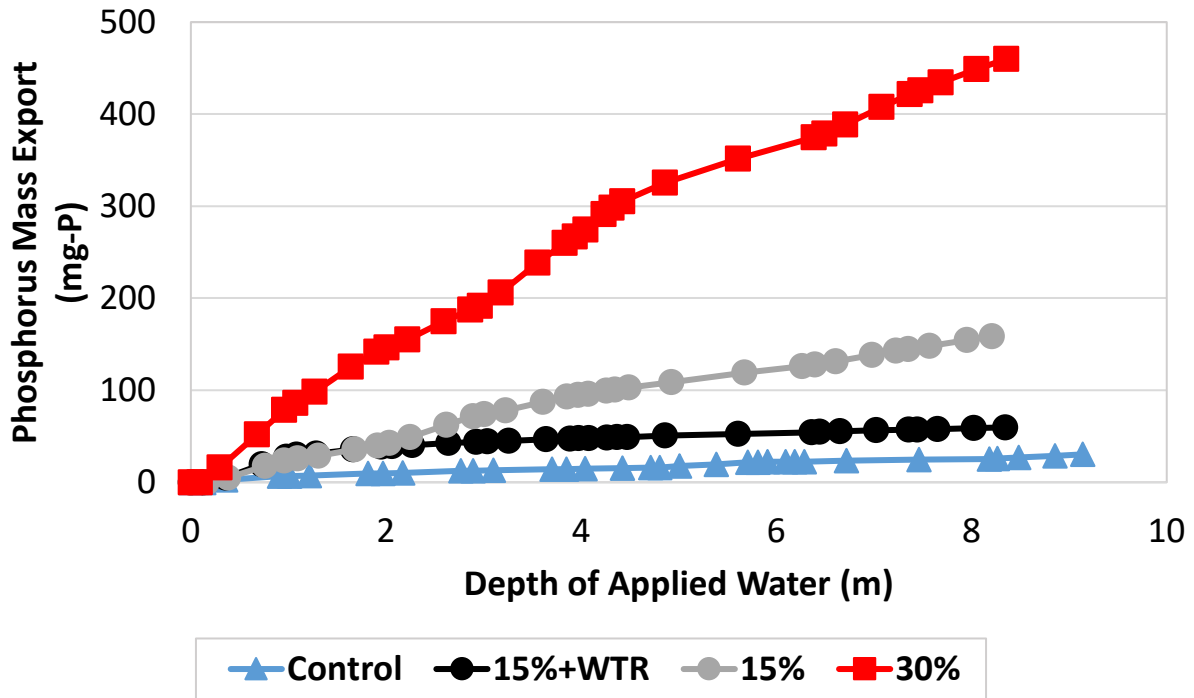
Figure 3.13: Cumulative phosphorus mass discharged for the three trials and control column including the influent water concentrations. The final two storms for the 30% column are not presented.

.
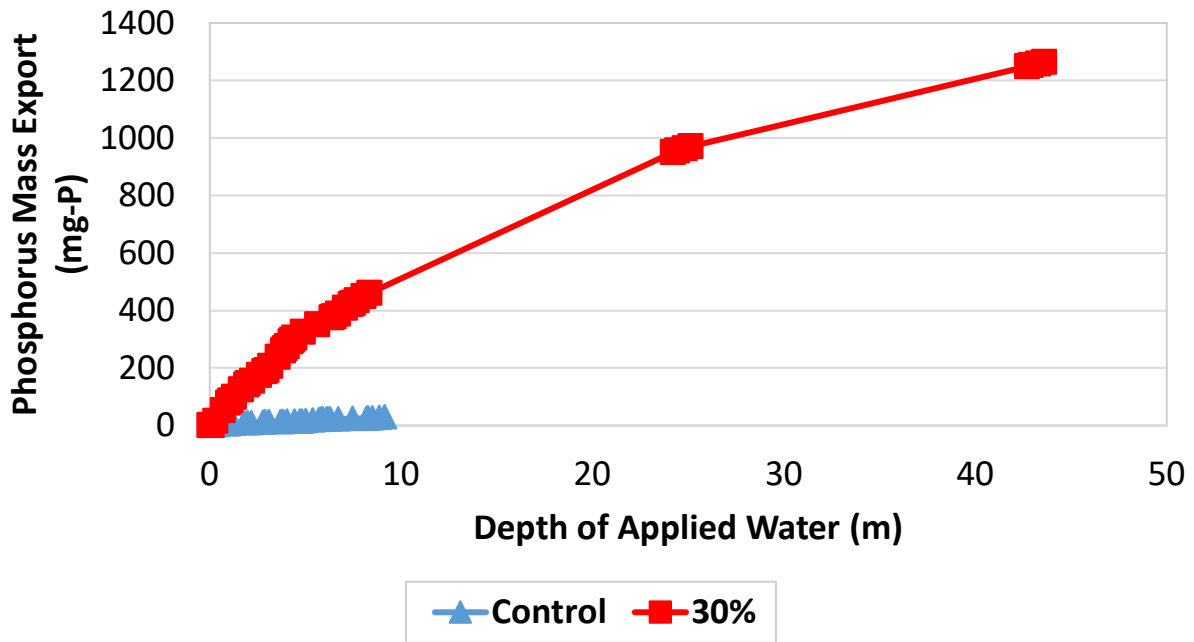
Figure 3.14: Accumulated phosphorus mass for the 30% column, after the extended storm trials, and the control column.

The 30% column showed the highest total phosphorus mass export at 460 mg-P, but the 15% column had a much higher export of phosphorus per kg of compost added: 30% column, 241 mg-P/kg dry compost; 15% column, 427 mg-P/kg dry compost. Both the 15%+WTR and the control columns had very low export of phosphorus; 15%+WTR exported 60 mg-P and 87 mg-P/kg dry compost, the control column exported 30 mg-P. The control column had the best overall performance of all four trials. Table 3.5 summarizes the results for each column trial along with the influent mg-P and the EMC for each trial [Equation 3(a)].

Influent and effluent P values are significantly different for each column. The 30% and 15% columns increased the exported phosphorus from the synthetic storm by 8 and 3 times respectively. The control and 15%+WTR columns, however, reduced the total exported phosphorus to a third and half the original nutrient concentration, respectively. EMC influent values for the 15%+WTR and control columns are close to double the influent values for the 30% and 15% columns (0.48 mg-P/L and 0.38 mg-P/L vis-à-vis 0.24 mg-P/L and 0.22 mg-P/L, respectively). This phenomenon was a consequence of using the existing phosphorus in the tap water and resulted in a less consistent imported concentration. This does not appear to have affected the final trends in any way, and further displays the reliability of the WTR amended column and the control column to reduce phosphorus effluent loading.

Table 3.5: Phosphorus influent, effluent, and the net mass discharge and event mean concentrations after 8 m of applied water.

Influent/Effluent	Element Calculated	30%	15%	15%+WTR	100% BSM
Influent	Mass of phosphorus (mg-P)	57	53	115	100
	EMC (mg-P/L)	0.24	0.22	0.48	0.38
Effluent	Mass of phosphorus (mg-P)	460	159	60	30
	EMC (mg-P/L)	1.9	0.67	0.25	0.11
Net Effluent	Mass of phosphorus (mg-P)	403	106	-55	-70

Similar to the results found for total nitrogen, the 30% and 15% columns exported a substantial mass of phosphorus. However, the 15%+WTR column performed far better, and produced values comparable to the control column. Although a significant difference in exported phosphorus can be seen when comparing the 15% and 15%+WTR columns, the differences between the two may have been more substantial had the initial two storm events for the 15% column not been filtered. As was mentioned in the nitrogen section, the first two storm events for the 15% column were coarse filtered to remove particulates that were affecting measurements. This process may have caused the removal of some particulate or captured phosphorus in the sediment diverted from the sample. This was the only instance in which samples were filtered before measuring TP

Figure 3.15 shows the net gain or removal of phosphorus mass exported from the columns as the accumulated import subtracted from the export accumulation. These values were calculated by subtracting the influent mass from the exported mass of phosphorus. As was seen in Table 2.5, the control and 15%+WTR columns greatly reduced the total phosphorus exported

and resulted in a negative total accumulation in the effluent. Unlike the nitrogen results, the 15% column never began to reduce the mass of phosphorus exported and the concentrations (Figure 3.12(b)) only reached below the influent level once, at the initial point. The results found for the 15%+WTR and control columns suggest that phosphorus was significantly retained within the two columns. Figure 3.12(b and d) shows that the control column began reducing influent phosphorus within the first storm; however, the 15%+WTR column began with a much larger initial flush that took the entire first storm event before effluent levels reached below influent concentrations. Although the 15%+WTR column had a larger initial flush, there is a significantly more negative trend seen in these results than that of the control column. Reduction in phosphorus export with the addition of WTR has also been seen in other research (O'Neill, 2012; Liu 2013). Extrapolating Figure 3.15 beyond 9 m, it appears that another 1 to 2 storms would result in lower accumulation of phosphorus in the 15%+WTR column than in the control.

In O'Neill's (2012) work the effluent EMCs for TP were 0.016 mg-P/L and 0.245 mg-P/L for the WTR-amended and control column, respectively, this is a net reduction of 0.226 mg-P/L. The EMC values found in the current study were 0.67 mg-P/L and 0.25 mg-P/L for the 15%+WTR and 15% columns, respectively, this is a net reduction of 0.42 mg-P/L. The reduction in effluent phosphorus is more evident in this study. This result implies that the addition of WTR does not only have the ability to reduce runoff influent phosphorus effectively, but it can greatly mitigate the leaching of TP from already nutrient-rich soils and media.
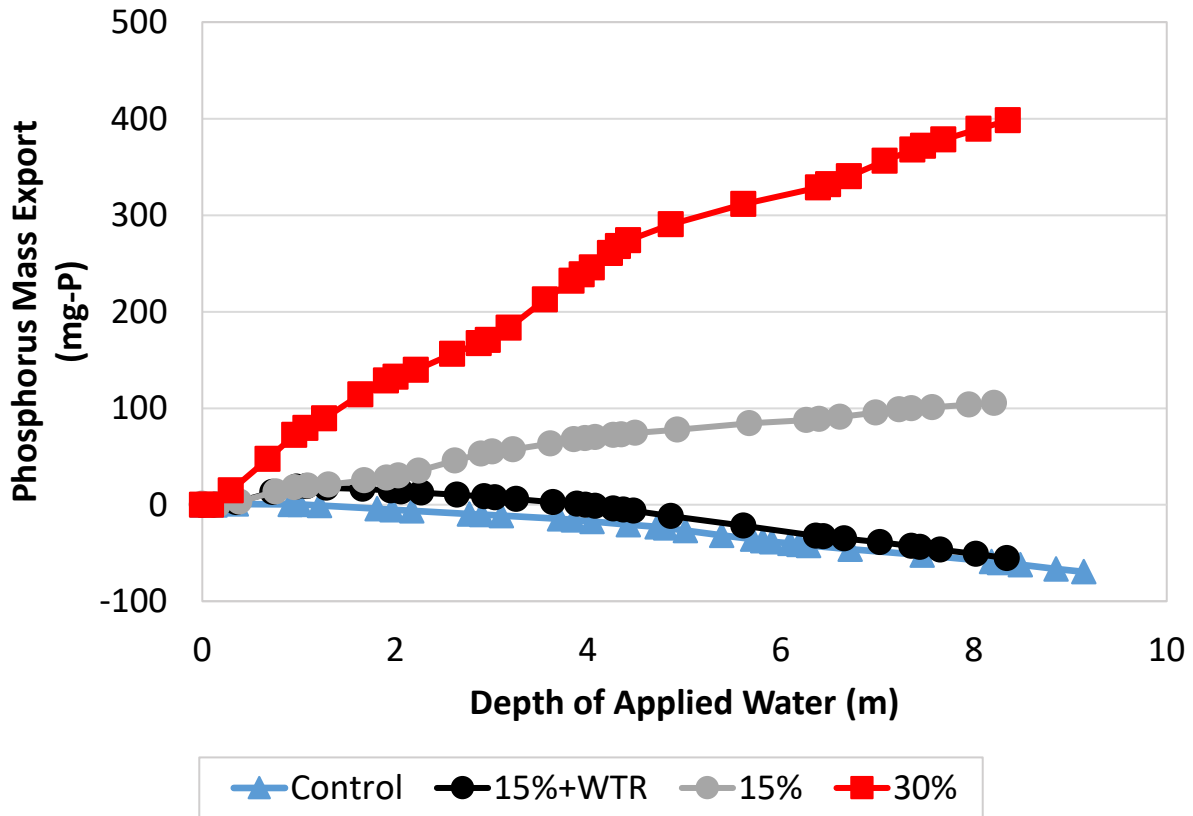
Figure 3.15: Net mass of exported phosphorus across the three trials and control column.

Following the assumptions and calculations made in Equation 3(b), the phosphorus annual mass load per unit drainage area values for each column are presented in Table 3.6. The annual input P load for each column ranged from 2.5 to 5.4 kg-P/ha-yr with an average of 3.8 $\pm$ 1 kg-N/ha-yr which is 130% higher than the bioretention load estimated by Liu and Davis (2013), who found total phosphorus loading of 3.0 kg-P/ha-yr after 17 rainfall events. To find the equivalent years of urban watershed runoff for each column, the influent and effluent phosphorus mass values were compared. One year of runoff treatment from the 30% column would produce the equivalent P mass load of over 7 years of the urban runoff P accumulation. One year of treatment through the 15% column produces a P effluent release of over 5 years of untreated urban watershed runoff. Both the control and the 15%+WTR columns, however, showed a

significant reduction in the phosphorus loading per year from the equivalent urban watershed

runoff. These results are summarized in Table 3.6.

Table 3.6: Annual mass loads per unit drainage area for each column and the calculated equivalent years of urban watershed runoff. Values are calculated from accumulated mass after 8 meters of applied water, equivalent to ~0.4 years of rainfall.

	MT-1, 30%	MT-2, 15%	MT-3, 15%+WTR	Control, 100% BSM
Influent mass of phosphorus (kg-P/ha-yr)	2.9	2.5	5.4	4.3
Effluent mass of phosphorus (kg-P/ha-yr)	21.5	13.5	2.8	1.3
Years of equivalent urban watershed P export	7.4	5.3	0.52	0.30

Continuing this calculation for the additional storm events in the 30% column, the

influent phosphorus loads after 45 storms increases to 3.6 kg-P/ha-yr and the effluent phosphorus

load drops to 11.3 kg-N/ha-yr. After 45 storms, this column received close to 2 years of MD

rainfall. When the equivalent years of urban watershed runoff are calculated for the extended

30% column, the P export is equivalent to 3.14 years of urban watershed runoff. These results,

similar to the nitrogen results, may suggest that the export of phosphorus from these treatment

cells will eventually decrease to the point of imitating the original runoff of the watershed.

Phosphorus Speciation

The P speciation for each column trial can be seen in Figure 3.16. Each column shows a

relatively constant export of SRP and DOP with a varying concentration of particulate P. Two

instances occur in Figure 3.16 that show an elevated DOP level, one in the 15% column and the

other in the control column. Both instances appear isolated and do not occur consistently

between trials. They were suspected to be outliers because their concentrations were greater than

the total phosphorus measurement. Each of these sample points were tested with the modified

Thompson tau test for outliers and determined to be outliers. Due to the volume of water

captured for testing, there was not enough sample to retest the points. The points, therefore,

could not be associated with a testing issue or an extreme value, results are shown with and

without the outlying points.
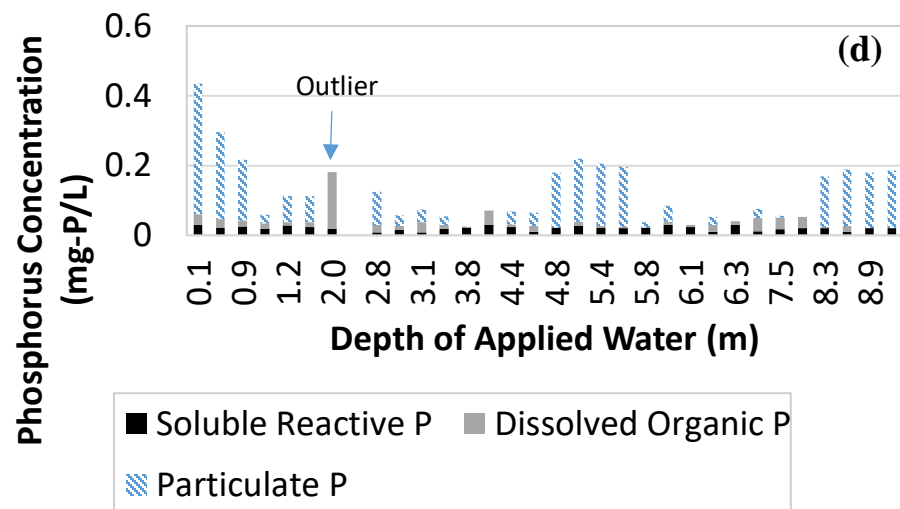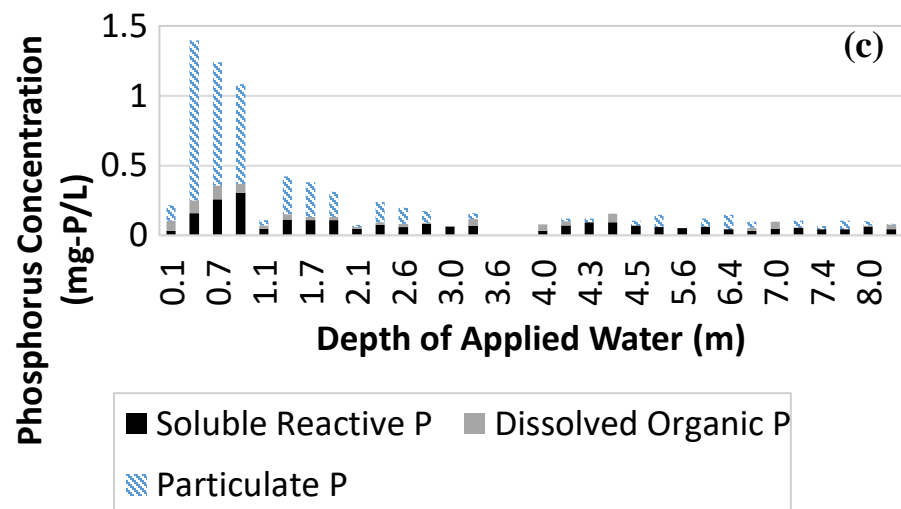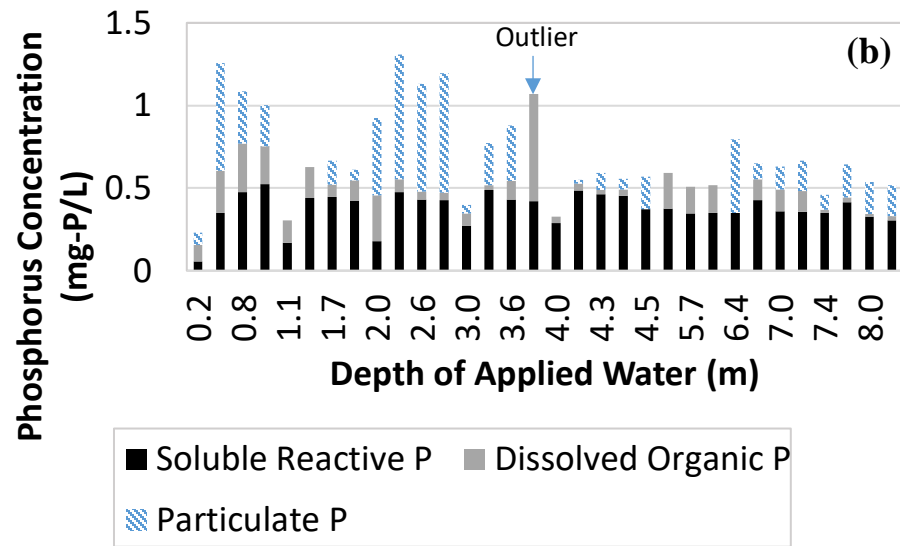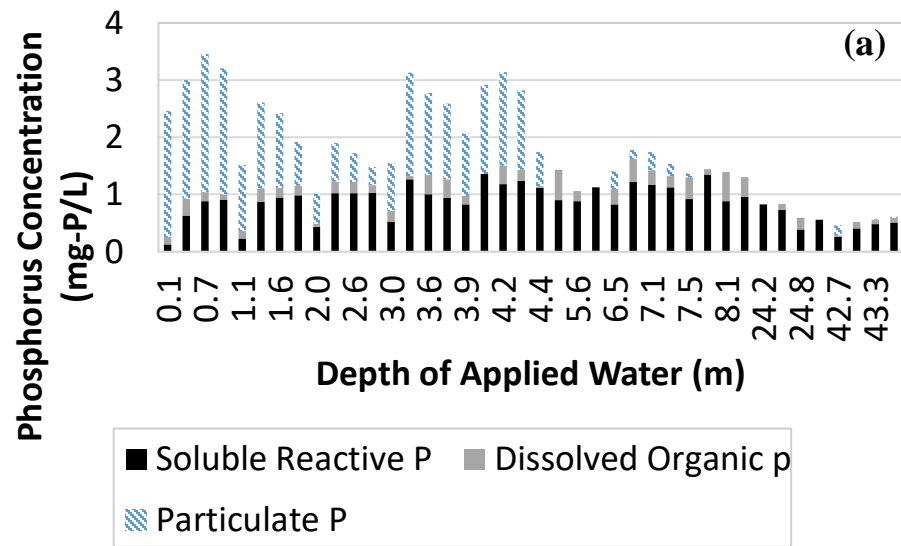
Figure 3.16: Comparison of phosphorus speciation concentrations across the three compost trials and control column. All values below the detection limit were represented at one-half the detection limit. Note that each axis is represented on a different scale for each plot. (Detection limit: Soluble reactive P, 0.05 mg-P/L; Dissolved organic P, 0.05 mg-P/L) a) 30% compost, 70% BSM; b) 15% compost, 85% BSM; c) 15% compost 4% WTR, 81% BSM; d) 100% BSM)

Similar to the first flush of nitrogen seen in Figures 3.2 and 3.6, phosphorus shows a slight first flush tendency in particulate P. This is particularly noticeable in the control and 15%+WTR columns. For both of these columns, the first two storms show an increased release of particulate P, 0.16 ± 0.12 mg-P/L and 0.45 ± 0.38 mg-P/L respectively. These values were followed by low concentrations of 0.07 ± 0.07 mg-P/L and 0.04 ± 0.04 mg-P/L, respectively. There are two storms for the control column that show an increase in the levels of particulate P; this is not seen in the 15%+WTR column. These events occurred when the influent phosphorus concentration increased. These increased P levels can be seen in Figure 3.12(d) between 4.8 and 5.8 meters of applied water and between 8.1 and 9.1 meters of applied water.

The first flush is less evident in the 30% and 15% columns. The 30% column shows a flush of particulate P through the first two storms, but there is a resurgence of particulate P in the fourth and fifth storm events. Particulate P begins with concentrations around 2.22 mg-P/L for the first storm and drops to 0.5 mg-P/L in the third storm. The fourth and fifth storms increase to 1.4 mg-P/L, but concentrations return to values much less than 0.5 mg-P/L for the remainder of the trial and often result in concentrations below 0.05 mg-P/L for particulate P. The 15% column did not have the high levels of particulate P that were seen in the first two storms for the other columns, this is likely due to the filtering process mentioned before. Phosphorus is strongly adsorbed to charged soil material and sediment diverted by the filtering process could have large concentrations of particulate P.

Concentrations of SRP and DOP for all columns remained relatively consistent throughout the trials. The average SRP and DOP concentrations for the 30% column were 0.85 ± 0.3 mg-P/L and 0.18 ± 0.13 mg-P/L, respectively. The average SRP and DOP concentrations for the 15% column were 0.38 ± 0.1 mg-P/L and 0.11 ± 0.08 mg-P/L, respectively.

The DOP concentration presented excludes the outlier found at 3.9 meter of applied water; including this point changes the average to 0.13±0.13 mg-P/L.

Evaluating the results for the 15%+WTR column, a very evident first flush occurs within the first storm event. This flush seems to occur for both particulate P and, to a lesser extent, SRP. Within this first storm, the highest values of particulate P and SRP are measured at 1.14 mg-P/L and 0.37 mg-P/L, respectively. These values dropped to low, more consistent values from that point forward. After the first storm event, SRP values exhibited an average of 0.06±0.02 mg-P/L. DOP did not show the same first flush tendency and remained low throughout the trial with an average of 0.03±0.3 mg-P/L.

The control column reacted very similar to the 15%+WTR column with a first flush of particulate P and consistently low levels of DOP and SRP. However; unlike the 15%+WTR column, no initial flush of SRP appeared. Particulate P had two increased steps in concentration with increased concentrations in the influent P. Particulate P had a maximum concentration of 0.44 mg-P/L which dropped to concentrations around 0.07±0.03 mg-P/L after the first storm event. This excludes the two storm events between 4.8 and 5.7 meters of applied water and 8.2 and 9.1 meters of applied water where the concentrations increased to 0.22±0.02 mg-P/L and 0.18±0.01 mg-P/L, respectively. SRP and DOP concentrations were relatively constant throughout the trial with averages of 0.02±0.01 mg-P/L and 0.01±0.01 mg-P/L, respectively. The DOP value excludes the outlier of 0.16 mg-P/L; with this point the average increases to 0.02±0.03 mg-P/L.

Finding high concentrations of particulate P evident in each column's effluent was not surprising. Filtering samples for SRP and DOP testing was more difficult earlier in each column

trial and became easier as the each trial continued. This suggests that less particulate matter was present in each sample, effectively reducing the particulate P as well.

Comparing the 15% and the 15%+WTR columns, the reduction in effluent phosphorus is clear. The addition of the WTR effectively eliminated the leaching that occurred from the addition of the compost. SRP values were reduced from 0.38 ± 0.1 mg-P/L to 0.06 ± 0.02 mg-P/L after the first flush, for the 15% and 15%+WTR columns, respectively. This reduction in soluble phosphorus was also seen in a number of other WTR studies (Elliott et al., 2002; O'Neill et al., 2012; Liu et al., 2013). From the results in Figures 3.16(b and d) and Figure 3.12(b and d) the effluent phosphorus was greatly reduced with the addition of WTR.

Effect of Velocity Variation

For all trials the flow rate remained at 0.25 cm/min except for two storm events that were run at 0.13 cm/min and 0.51 cm/min for 6 hours each. Results for the 30% column are shown in Figure 3.17 for all species of phosphorus. The section of altered flow velocity is boxed in dashed lines and the split between the 0.13 cm/min and the 0.51 cm/min flow rates is designated by a solid vertical line inside the box.
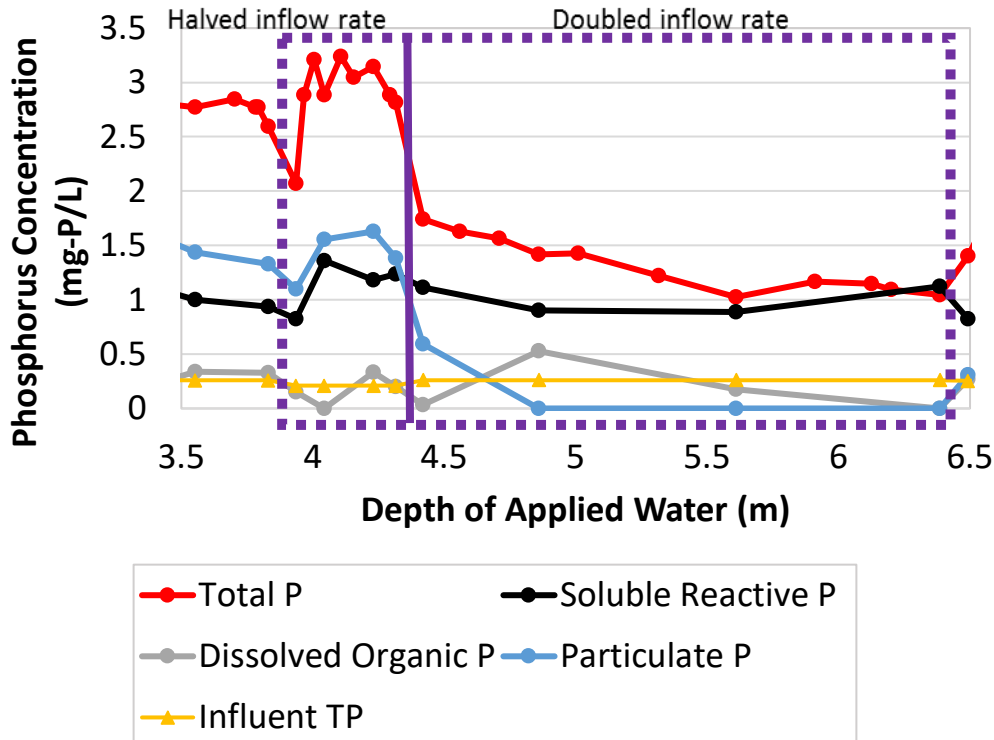
Figure 3.17: Velocity variation in the 30% compost, 70% BSM column. The section with altered flow velocities is boxed and the two different alterations are separated by a solid vertical line. All values below the detection limit are represented at one-half the test detection limit. (Detection limit: TP, 0.05 mg-P/L; DOP, 0.05 mg-P/L; SRP, 0.05 mg-P/L)

SRP and DOP release for both flow rates is relatively constant in concentration at an average of 1.1 ± 0.2 mg-P/L and 0.18 ± 0.17 mg-P/L, despite the velocity change and the increased TP release in the reduced flow. TP concentrations decrease from the reduced flow to the increased flow by a factor of 2. These results suggest that rapid flow through the column may reduce the amount of phosphorus released. This phenomenon was not seen in any of the other trials, which all showed little to no differences in the effluent concentrations of phosphorus.

Figure 3.18 shows the flow-altered results for the 15% and 15%+WTR columns. Between the two graphs in Figure 3.18, some similarities occur. Through both flow velocities, SRP and TP values remain relatively constant for both bioretention mixes. The major difference

between the two columns is the magnitude of the different concentration values. TP and SRP values for the 15% column were 5 to 5.5 times those of the 15%+WTR column.

Despite the similarities found in the TP and SRP patterns, particulate P and DOP values between the two trials differ greatly. Similar to the 30% column, the 15% column had a flush of particulate P in the increased flow rate event that began at 0.2 mg-P/L and decreased to values has less than 0.05 mg-P/L, but this trend was lacking in the 15%+WTR column. The particulate P concentrations for the 15%+WTR column appeared to do the opposite of the 30% and 15% columns. Concentrations in the 15%+WTR column increased slightly with the additional flow. This opposing pattern is mirrored in the DOP measurements. The 15% column had higher DOP with the increased flow rate while the 15%+WTR column had no calculated DOP.
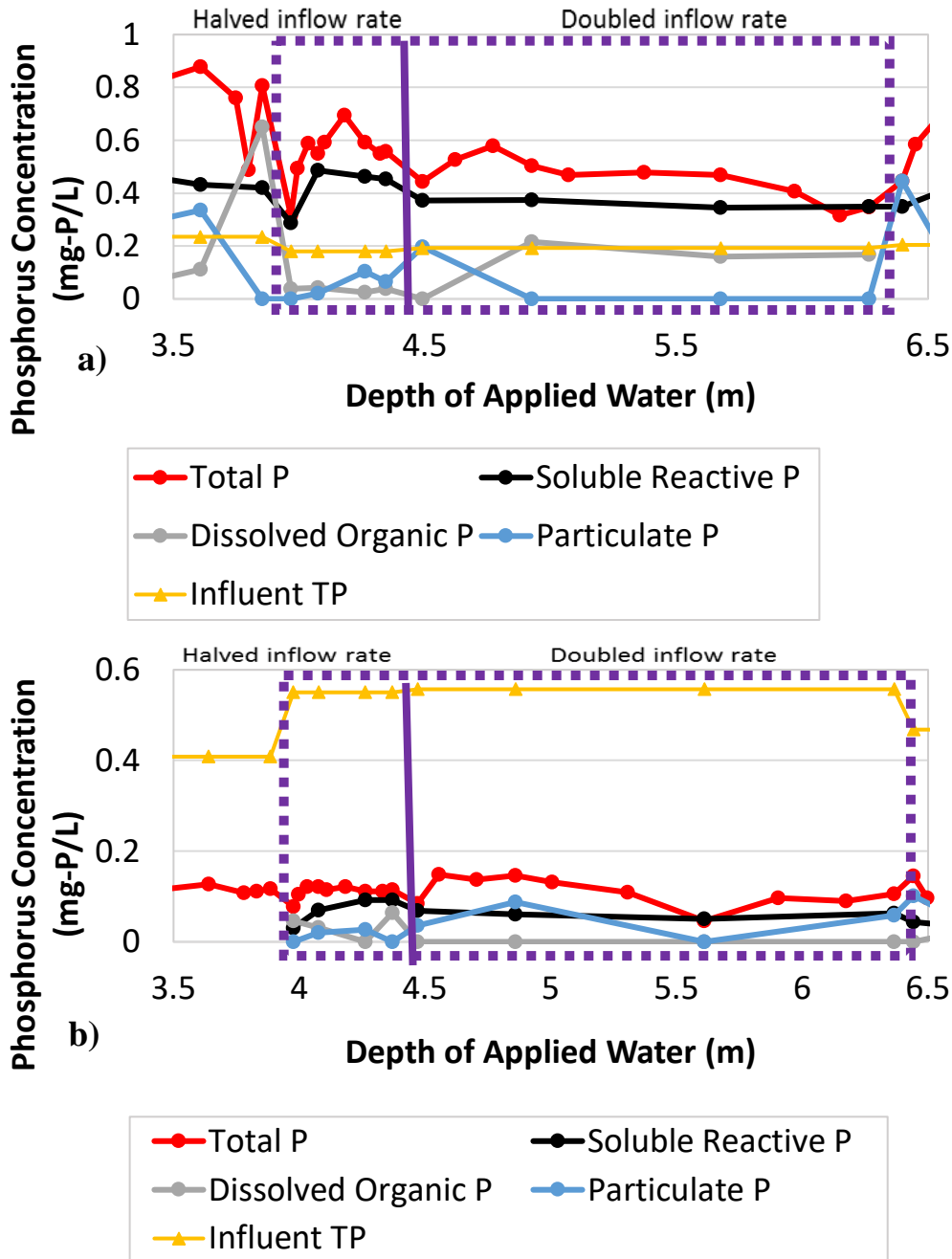
Figure 3.18: Velocity variation in the a) 15% and b) 15%+WTR columns. The section with altered flow velocities was boxed and the two different alterations were separated by a solid vertical line. All values below the detection limit were represented at one-half the test detection limit. (Detection limit: TP, 0.05 mg-P/L; DOP, 0.05 mg-P/L; SRP, 0.05 mg-P/L)

The modified flow section for the control column is presented in Figure 3.19. Results from this section appear to share a number of similarities with the 15% and 15%+WTR columns. Both the SRP and TP concentrations were relatively constant between the two events with an average of 0.02±0.01 mg-P/L and 0.050.05±0.02 mg-P/L, respectively. Further similarities between the 15%+WTR and the control columns exist in the magnitude of the concentrations in both and the pattern found in the particulate P. Both the 15%+WTR and control column showed no definable change in particulate P from one flow rate to the other. However, the control column showed a slight increase in DOP throughout the increased flow event, a trend that was also seen in the 15% column.
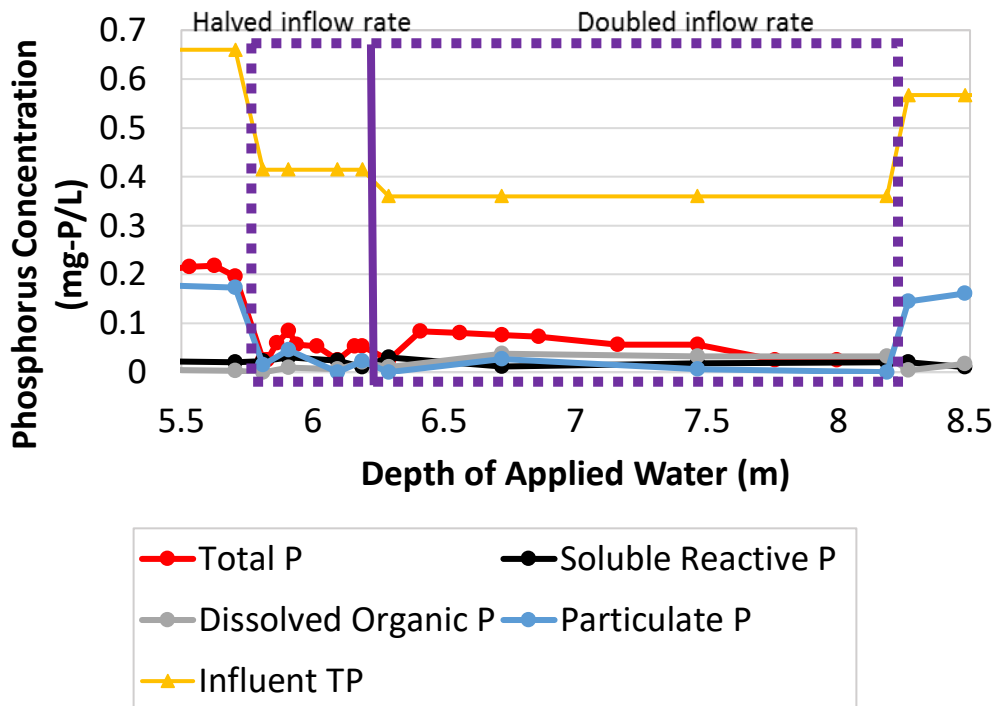
Figure 3.19: Velocity variation in the control column; 100% BSM. The section with altered flow velocities was boxed and the two different alterations were separated by a solid vertical line. All values below the detection limit were represented at one-half the test detection limit. (Detection limit: TP, 0.05 mg-P/L; DOP, 0.05 mg-P/L; SRP, 0.05 mg-P/L)

Phosphorus Summary

Similar to the results found for nitrogen, a larger volume of compost mixed with BSM resulted in an increased mass of exported P. By the end of the extended trial, the 30% column exported an additional 860 mg-P compared to the untreated synthetic stormwater after 2 years of equivalent watershed runoff applied. The reduction in compost applied to the system (15%) reduced the impact on the runoff by approximately half. With compost accounting for 15% of the volume of a BSM mix the system adds 100 mg-P to the untreated urban watershed runoff after 5 months of MD rainfall, 3-time the untreated P export. This research does not take into account the possible continued reduction in P concentrations after 5 months for the 15% column. If the trend found in the extended 30% column were to occur for the 15% column then this could result in a net neutral concentration or possible removal with further rainfall applied. After 1 month of rainfall, both the control and 15%+WTR columns showed a reduction in the overall mass load of P in the runoff. After 5 months of applied rainfall, the 15%+WTR column retained 50% of the influent P and the control column retained 70% of the influent P. The 15%+WTR column also prevented the effluent P from the 15% compost added which exported 3-time the influent. Extending the results from the 15% column, the 15%+WTR column reduced the exported P by approximately 83%. The reduction in phosphorus seen in the 15%+WTR column was also seen in previous studies (Elliott et al., 2002; O'Neill et al., 2012; Liu et al., 2013). After 5 months of rainfall there were no signs of phosphorus breakthrough, P was still being adsorbed, in either the control or 15%+WTR columns.

Compost addition into the bioretention design has the potential to greatly improve the function of these facilities as stormwater control measures (SCMs). The ability of compost to naturally improve a soil's porosity, water holding capacity, buffering capacity, and metal uptake all have immediate benefits for bioretention (He et al., 1992; Mitchell, 1997; Weng et. al., 2002; Kirchoff, 2003; Paus et al., 2014). However, each of these benefits comes coupled with a significant increase in the nutrient load, specifically nitrogen and phosphorus. Through the use of large column studies, this research analyzed many of the possible consequences of compost addition to the BSM mix.

Three different columns, 30% by volume Dickerson source-separated compost, 15% compost, and 15% compost with 4% aluminum based WTR, were created and evaluated with at least 8 different simulated storm events. The effluent from these columns was analyzed for nitrogen and phosphorus and compared to the effluent concentrations of a 100% BSM column. From the results presented, all of the initial objectives were met, the research sponsor (SHA) can make an informed decision moving forward, and possible future research ideas have been discovered.

Objectives

Prior to the implementation of this project, three objectives were outlined and a fourth was created after initial results were analyzed. These objectives were to 1) determine possible concentrations and masses of leached nitrogen and phosphorus; 2) categorize the species of

nitrogen and phosphorus leached; 3) compare different nutrient leaching performances of compost/BSM mixtures; and 4) analyze a possible solution to nutrient leaching found from compost addition to BSM.

The addition of compost to BSM had significant effects on the release of nitrogen and phosphorus from the bioretention site. For the 30%, 15%, and 15%+WTR columns the maximum concentrations for total nitrogen (TN) and total phosphorus (TP) were 81 mg-N/L and 4.5 mg-P/L, 11.6 mg-N/L and 1.5 mg-P/L, and 52 mg-N/L and 1.5 mg-P/L, respectively. These values are compared to the BSM control column that had N and P maximum concentrations of 3.6 mg-N/L and 0.4 mg-P/L, respectively. These N and P maxima often occurred within the first or second storm event for all columns observed. Also seen within the first 2-3 storm events was a 'first flush' of nutrients. In this first flush, the greatest amount of mass export for N and P occurred. The control column did not exhibit a first flush for nitrogen which indicates that this first flush is attributable to the compost.

For the 15% and 15%+WTR columns the nitrogen initial flush was the only instance where effluent N concentrations were above the influent concentrations. This resulted in a net neutral export of nitrogen for both of these columns after the equivalent of 5 months of synthetic stormwater was applied. Although the nitrogen results were similar among the columns, the phosphorus leaching behavior was different for each column. The 15% column only had one effluent P concentration below the influent value throughout the entire trial. This resulted in a threefold increase in the total mass of the exported phosphorus, compared to the mass of the input. After the addition of WTR, the 15%+WTR column had phosphorus concentrations above the influent concentrations only for the first storm event, concentrations remained below the influent for the remainder of the trial. This behavior resulted in a decrease of phosphorus and the

column captured 48% of the total input mass of P. WTR addition had little effect on the nitrogen release, but greatly affected the phosphorus mass export.

As the percentage of compost increased, the concentrations and accumulation of N and P measured in the effluent also increased. The 30% column, which ran for the equivalent of 2 years, never reached concentrations below the influent, resulting in a much larger mass of N and P exported, 1.5 and 3-times the influent mass loads, respectively. These increases are substantially greater than both of the 15% columns. Conversely, the control column never had nitrogen values above the influent concentrations, resulting in a large mass removal; 55% of the influent N mass and 70% of the influent P mass were captured within the column.

Categorizing the species of N and P found in the effluent of each column yielded a few similarities. Although concentrations compared across different column setups differed in magnitude, they often exhibited the same patterns. Throughout the entire trial for each column, organic N and nitrate were the dominant N species. These two species had maximum concentrations within the first two storms and controlled the nitrogen first flush seen in the compost-amended columns. Nitrite rarely had measurements above the detection limit of 0.01 mg-N/L. Although ammonium was not a dominant N species, it did have persistent concentrations throughout the trials for all columns.

For all columns, soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) persisted throughout the trials at relatively constant concentrations. The variable controlling TP was often the particulate P; this species also defined the first flush. The addition of the WTR to create the 15%+WTR column resulted in a reduction in all species of phosphorus, but SRP and particulate P were predominantly affected.

Further Research

This project has successfully established the framework necessary to begin refining the use of compost in BSM. More information is necessary to understand the benefits that might be found for plant growth and possible nutrient capture, water holding capacity, pH buffering, and capture of heavy metals. Additionally, analyzing other compost/BSM mixtures would be beneficial in determining a range of effluent mass loads expected for N and P. Only one mixture of compost and WTR was analyzed in this research. With additional information on other ratios of WTR to compost, a minimum 'neutralizing' amount of WTR/compost could be found to offset the P leaching. Biochar has been suggested to remove nitrate as a BSM amendment (Knowles et al. 2011); possible addition of this element to compost might also reduce nitrogen loads.

Recommendations to the SHA

From the research presented, it is not advisable to implement any bioretention designs with more than 15% source-separated compost by volume. With the use of 15% compost, an additional 4% by volume of WTR should be mixed into the BSM to control phosphorus export. Implementing a 15% compost with 4% WTR was effective in reducing phosphorus and resulted in net removal of P after one storm event. After the equivalent of 5 months of use, net removal of nitrogen was also demonstrated with these specifications.

APPENDICES

Appendix A: State Highway Specifications

A.1 – Spec. 920.02.05 for composts

(a) **Compost Types.** Compost shall be either Type A (biosolids) or Type B (source-separated), and will be subject to approval by the Landscape Operations Division as follows:

    (1) **Biosolids Compost (Type A).** Type A Compost shall be approved for distribution by the Maryland Department of the Environment (MDE).

    (2) **Source-Separated Compost (Type B).** Type B Compost shall be produced by a compost operator certified by the Maryland Department of Agriculture (MDA). Type B Compost shall be tree leaf compost or non-tree leaf compost. Type B Compost produced from lawn clippings shall be tested for contaminants in conformance with Maryland law and regulations.

(b) **Stability.** Compost shall be biologically mature and no longer able to reheat to thermophilic temperatures.

(c) **pH.** Compost shall have a pH of 6.0 to 7.5 except when specified in Sections 710 and 711 where it shall have a pH of 6.0 to 7.0.

(d) **Soluble Salts.** Type A Compost shall have a soluble salt concentration less than 10.0 mmhos/cm, and Type B Compost shall have soluble salts concentration less than 5.0 mmhos/cm.

(e) **Moisture.** Compost shall have a moisture content of 30 to 55 percent.

(f) **Particle Size and Grading.** Com post shall be screened so that it has a uniform particle size of 0.5 in. or less, with grading analysis as follows.

COMPOST GRADING ANALYSIS	
SIEVE SIZE mm	**PASSING BY VOLUME Maximum %**
4.75	90
0.425	25
0.75	2.2

A.2 – Spec. 920.01.05 for BSM

A homogeneous mixture composed by loose volume of 5 parts Coarse Sand, 3 parts Base Soil, and 2 parts Fine Bark. BSM shall conform to the following:

(a) **Components.** Components of BSM shall be sampled, tested and approved before mixing as follows:

    (1) **Coarse Sand.** MSMT 356. Coarse Sand shall be washed silica sand or crushed glass that conforms to ASTM Fine Aggregate C-33. Coarse Sand shall include less than 1% by weight of clay or silt size particles, and less than 5% by weight of any combination of diabase, greystone, calcareous or dolomitic sand.

    (2) **Base Soil.** Base Soil shall be tested and certified by the producer to conform to the following requirements:

    (3) **Fine Bark.** Fine Bark shall be the bark of hardwood trees that is milled and screened to a uniform particle size of 2 in. or less. Fine Bark shall be composted and aged for 6 months or longer, and be free from sawdust and foreign materials. A 1 to 2 lb sample of Fine Bark shall be submitted to the Landscape Operations Division for examination.

COMPOSITION - BASE SOIL		
TEST PROPERTY	**TEST METHOD**	**TEST VALUE AND AMENDMENT**
Prohibited Weeds	—	Free of seed and viable plant parts of species in 920.06.02(a)(b)(c) when inspected.
Debris	—	No observable content of cement, concrete, asphalt, crushed gravel or construction debris when inspected.

Grading Analysis	T 87	**Sieve Size**	**Passing by Weight Minimum %**
		2 in.	100
		No. 4	90
		No. 10	80

Textural Analysis	T 88	**Particle**		**% Passing by Weight**	
		Size	**mm**	**Minimum**	**Maximum**
		Sand	2.0 – 0.050	50	85
		Silt	0.050 – 0.002	5	45
		Clay	less than 0.002	5	10

Soil pH	D 4972	pH of 5.7 to 6.9.
Organic Matter	T 194	1.0 to 10.0 % by weight.
Soluble Salts	EC1:2 (V:V)	500 ppm (1.25 mmhos/cm) or less.
Harmful Materials	—	920.01.01(a)

COMPOSITION- BIORETENTION SOIL MIX (BSM)						
TEST PROPERTY	**TEST METHOD**	**TEST VALUE AND AMENDMENT**				
Weeds	—	Free of seed and viable plant parts of species in 920.06.02(a)(b)(c) when inspected.				
Debris	—	920.01.05(a)(2)				
Textural Analysis	T 88		**Particle**		**% Passing by Weight**	
		Size	**mm**	**Minimum**	**Maximum**	
		Sand	2.0 – 0.050	55	85	
		Silt	0.050 – 0.002	–	20	
		Clay	less than 0.002	1	8	
Soil pH	D 4972	pH of 5.7 to 7.1.				
Organic Matter	T 194	Minimum 1.5 % by weight.				
Nutrient Analysis and Soluble Salts	Mehlich-3		**Concentration**			
		Element	**Minimum**		**Maximum**	
			ppm	**FIV**	**ppm**	**FIV**
		Calcium (Ca)	32	25	no limit	no limit
		Magnesium (Mg)	15	25	no limit	no limit
		Phosphorus (P)	18	25	92	100
		Potassium (K)	22	25	no limit	no limit
		Sulfur (SO4)	25	n/a	no limit	no limit
	EC1:2 (V:V)	Soluble Salts	40	n/a	500	n/a
Harmful Materials	—	920.01.01(a).				

(a) Composition. BSM shall be sampled and tested according to the requirements of MSMT 356 and conform to the following:

(b) Amendment or Failure. BSM that does not conform to composition requirements for pH or nutrient analysis shall be amended as specified by the NMP. BSM that exceeds maximum phosphorus concentration or fails other composition requirements will not be accepted, and shall not be delivered or used as BSM.

(c) Storage. 920.01.02(b). BSM shall be stored in a stockpile that is protected from weather under tarp or shed. BSM stored for 6 months or longer shall be resampled, retested, and reapproved before use.

Appendix B: Column flow rates

Table B: Control column nitrogen and phosphorus raw speciation data. All nitrogen data is presented in mg-N/L and all phosphorus data is presented in mg-P/L.

Flow Rate		Dates the Column was Run			
(in/hr)	(cm/hr)	MT-1	MT-2	MT-3	Control
6	15.24	9/2/15 9/9/15 9/16/15 9/23/15 10/16/15 10/26/15 3/2/16 7/11/16	1/7/16 1/14/16 1/21/16 1/29/16 2/24/16 3/2/16	5/10/16 5/24/16 6/6/16 6/9/16 7/1/16 7/6/16	2/22/16 3/3/16 3/10/16 3/22/16 3/30/16 4/6/16 4/29/16
12	30.48	10/7/15	2/10/16	6/28/16	4/27/16
3	7.62	10/2/15	2/5/16	6/13/16	4/15/16

Appendix C: Control Column Data

Table C1: Control column nitrogen and Phosphorus raw data. All nitrogen data is presented in mg-N/L and all phosphorus data is presented in mg-P/L. First five storm events.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied	TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
2/22/2016	7:57:00 AM	1:57:00 PM	1	8:45:00 AM	8:49:00 AM	0.07	0.87	0.07	0.01	0.130	1.600	0.098	0.384	0.005	1.113	0.435	0.060	0.030	0.030	0.375
1			2	9:17:00 AM	9:21:00 AM	0.07	1.40	0.60	0.09	0.210	1.787					0.341				
	Foil, dead grass, regular speed		3	9:45:00 AM	9:49:00 AM	0.07	1.87	1.07	0.16	0.280	1.895					0.345				
			4	10:15:00 AM	10:19:00 AM	0.07	2.37	1.57	0.24	0.355	2.071	0.061	1.472	0.010	0.528	0.296	0.046	0.022	0.024	0.250
			5	11:15:00 AM	11:19:00 AM	0.07	3.37	2.57	0.38	0.505	2.135					0.244				
			6	12:15:00 PM	12:19:00 PM	0.07	4.37	3.57	0.53	0.655	2.337					0.213				
			7	1:15:00 PM	1:19:00 PM	0.07	5.37	4.57	0.68	0.805	2.156					0.209				
			8	1:57:00 PM	2:01:00 PM	0.07	6.07	5.27	0.79	0.910	2.186	0.051	1.762	0.005	0.368	0.216	0.042	0.025	0.017	0.174
			9	2:01:00 PM	2:05:00 PM	0.07	6.13	5.33	0.80	0.920	2.201					0.185				
			10	2:05:00 PM	2:11:00 PM	0.10	6.23	5.43	0.82	0.935	2.118					0.171				
2/22/2016			Feed water								3.710					0.261				
3/3/2016	7:42:00 AM	1:42:00 PM	1	8:00:00 AM	8:13:00 AM	0.22	0.52	0.22	0.85	1.013	1.502		0.790	0.005	0.707	0.058	0.035	0.019	0.016	0.023
2			2	8:30:00 AM	8:35:00 AM	0.08	0.88	0.58	0.90	1.067	2.096					0.082				
			3	9:00:00 AM	9:04:00 AM	0.07	1.37	1.07	0.98	1.140	2.149					0.102				
			4	9:30:00 AM	9:34:00 AM	0.07	1.87	1.57	1.05	1.215	2.388		1.629	0.005	0.754	0.112	0.038	0.029	0.010	0.074
			5	10:30:00 AM	10:34:00 AM	0.07	2.87	2.57	1.20	1.365	2.256					0.112				
			6	11:30:00 AM	11:34:00 AM	0.07	3.87	3.57	1.35	1.515	2.225					0.095				
			7	12:30:00 PM	12:34:00 PM	0.07	4.87	4.57	1.50	1.665	2.289					0.095				
			8	1:30:00 PM	1:34:00 PM	0.07	5.87	5.57	1.65	1.815	2.268		1.706	0.005	0.557	0.112	0.038	0.024	0.014	0.074
			9	1:42:00 PM	1:46:00 PM	0.07	6.07	5.77	1.68	1.845	2.268					0.095				
			10	1:46:00 PM	1:51:00 PM	0.08	6.15	5.85	1.69	1.858	2.322					0.098				
3/3/2016			Feed water								3.914					0.293				
3/10/2016	8:07:00 AM	2:07:00 PM	1	8:39:00 AM	8:51:00 AM	0.20	0.73	0.20	1.72	1.967	1.145		0.374	0.005	0.766	0.058	0.181	0.019	0.162	0.000
3			2	9:09:00 AM	9:13:00 AM	0.07	1.10	0.57	1.78	2.023	1.038					0.152				
			3	9:39:00 AM	9:43:00 AM	0.07	1.60	1.07	1.85	2.098	1.225					0.102				
			4	10:09:00 AM	10:13:00 AM	0.07	2.10	1.57	1.93	2.173	1.528					0.125				
			5	11:09:00 AM	11:13:00 AM	0.07	3.10	2.57	2.08	2.323	1.706					0.122				
			6	12:09:00 PM	12:13:00 PM	0.07	4.10	3.57	2.23	2.473	1.694					0.102				
			7	1:09:00 PM	1:13:00 PM	0.07	5.10	4.57	2.38	2.623	1.694					0.132				
			8	2:07:00 PM	2:11:00 PM	0.07	6.07	5.53	2.52	2.768	1.856		1.348	0.005	0.503	0.125	0.030	0.009	0.021	0.095
			9	2:11:00 PM	2:16:00 PM	0.08	6.15	5.62	2.54	2.780	1.831					0.119				
			10	2:16:00 PM	2:23:00 PM	0.12	6.27	5.73	2.55	2.798	1.809					0.115				
3/10/2016			Feed water								4.615					0.309				
3/22/2016	8:48:00 AM	2:48:00 PM	1	9:15:00 AM	9:27:00 AM	0.20	0.65	0.20	2.58	2.895	0.920		0.086	0.014	0.819	0.057	0.027	0.015	0.011	0.031
4			2	9:45:00 AM	9:50:00 AM	0.08	1.03	0.58	2.64	2.953	1.423					0.071				
			3	10:15:00 AM	10:19:00 AM	0.07	1.52	1.07	2.71	3.025	1.485					0.071				
			4	10:45:00 AM	10:49:00 AM	0.07	2.02	1.57	2.79	3.100	1.777		1.122	0.005	0.650	0.075	0.037	0.009	0.028	0.038
			5	11:45:00 AM	11:49:00 AM	0.07	3.02	2.57	2.94	3.250	2.007					0.061				
			6	12:45:00 PM	12:49:00 PM	0.07	4.02	3.57	3.09	3.400	1.931					0.051				
			7	1:45:00 PM	1:49:00 PM	0.07	5.02	4.57	3.24	3.550	2.136					0.054				
			8	2:45:00 PM	2:50:00 PM	0.08	6.03	5.58	3.39	3.702	2.207		1.508	0.005	0.694	0.054	0.030	0.019	0.011	0.024
			9	2:50:00 PM	2:54:00 PM	0.07	6.10	5.65	3.40	3.713	2.199					0.054				
			10	2:54:00 PM	3:00:00 PM	0.10	6.20	5.75	3.41	3.727	2.172					0.054				
3/22/2016			Feed water								4.661					0.256				
3/30/2016	11:45:00 AM	5:45:00 PM	1	12:18:00 PM	12:33:00 PM	0.25	0.80	0.25	3.45	3.847	0.533	0.109	0.323	0.005	0.096	0.025	0.024	0.022	0.002	0.001
5			2	12:45:00 PM	12:46:00 PM	0.02	1.02	0.47	3.49	3.880	1.028					0.121				
			3	1:18:00 PM	1:20:00 PM	0.03	1.58	1.03	3.57	3.965	1.649					0.064				
			4	1:48:00 PM	1:51:00 PM	0.05	2.10	1.55	3.65	4.043	2.134	0.069	1.398	0.005	0.662	0.060	0.071	0.030	0.041	0.000
			5	2:18:00 PM	2:19:00 PM	0.02	2.57	2.02	3.72	4.113	2.298					0.060				
			6	3:18:00 PM	3:20:00 PM	0.03	3.58	3.03	3.87	4.265	2.377					0.053				
			7	4:18:00 PM	4:22:00 PM	0.07	4.62	4.07	4.03	4.420	2.256	0.080	1.557	0.005	0.614	0.068	0.031	0.024	0.007	0.037
			8	5:21:00 PM	5:23:00 PM	0.03	5.63	5.08	4.18	4.573	2.385					0.025				
			9	5:45:00 PM	5:47:00 PM	0.03	6.03	5.48	4.24	4.632	2.407					0.025				
			10	6:05:00 PM	6:20:00 PM	0.25	6.58	6.03	4.32	4.715	2.339	0.148	2.239	0.005	0.000	0.064	0.027	0.010	0.017	0.037
3/30/2016			Feed water								4.583					0.343				

Table C2: Continued results for the control column. Storm events 6-9.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied	TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
4/6/2016	9:05:00 AM	3:05:00 PM	1	9:30:00 AM	9:41:00 AM	0.18	0.60	0.18	4.35	4.805	0.434	0.025	0.279	0.005	0.125	0.179	0.022	0.022	0.000	0.157
6			2	10:00:00 AM	10:01:00 AM	0.02	0.93	0.52	4.40	4.855	1.261					0.246				
			3	10:30:00 AM	10:31:00 AM	0.02	1.43	1.02	4.47	4.930	1.457					0.246				
			4	11:00:00 AM	11:03:00 AM	0.05	1.97	1.55	4.55	5.010	1.692	0.073	1.247	0.005	0.367	0.219	0.040	0.027	0.012	0.179
			5	11:30:00 AM	11:32:00 AM	0.03	2.45	2.03	4.63	5.083	1.840					0.226				
			6	12:30:00 PM	12:31:00 PM	0.02	3.43	3.02	4.77	5.230	1.933					0.223				
			7	1:30:00 PM	1:33:00 PM	0.05	4.47	4.05	4.93	5.385	2.078	0.081	1.326	0.005	0.666	0.206	0.027	0.022	0.005	0.179
			8	2:30:00 PM	2:31:00 PM	0.02	5.43	5.02	5.07	5.530	2.142					0.216				
			9	3:05:00 PM	3:09:00 PM	0.07	6.07	5.65	5.17	5.625	2.218					0.218				
			10	3:25:00 PM	3:41:00 PM	0.27	6.60	6.18	5.25	5.705	2.108	0.060	1.566	0.005	0.477	0.196	0.023	0.021	0.003	0.173
4/6/2016			Feed water								4.421					0.660			0.000	0.660
4/15/2016	10:09:00 AM	4:09:00 PM	1	11:13:00 AM	11:33:00 AM	0.33	1.40	0.33	5.30	5.810	0.381	0.025	0.270	0.005	0.080	0.025	0.010	0.022	0.000	0.015
7	1/2 flow		2	11:43:00 AM	11:46:00 AM	0.05	1.62	0.55	5.33	5.826	0.534					0.025				
			3	12:13:00 PM	12:16:00 PM	0.05	2.12	1.05	5.41	5.864	0.708					0.060				
			4	12:43:00 PM	12:51:00 PM	0.13	2.70	1.63	5.49	5.908	0.768	0.080	0.458	0.005	0.225	0.085	0.040	0.030	0.009	0.045
			5	1:13:00 PM	1:16:00 PM	0.05	3.12	2.05	5.56	5.939	0.769					0.056				
			6	2:13:00 PM	2:17:00 PM	0.07	4.13	3.07	5.71	6.015	0.790					0.053				
			7	3:13:00 PM	3:20:00 PM	0.12	5.18	4.12	5.87	6.094	0.840	0.090	0.633	0.005	0.111	0.025	0.030	0.024	0.007	0.000
			8	4:09:00 PM	4:12:00 PM	0.05	6.05	4.98	6.00	6.159	0.828					0.053				
			9	4:29:00 PM	4:36:00 PM	0.12	6.45	5.38	6.06	6.189	0.877	0.084	1.014	0.005	0.000	0.053	0.030	0.010	0.020	0.023
4/15/2016			Feed water								3.967					0.415				
4/27/2016	8:53:00 AM	2:53:00 PM	1	9:06:00 AM	9:13:00 AM	0.12	0.33	0.12	6.07	6.289	0.610	0.056	0.275	0.005	0.275	0.025	0.041	0.030	0.010	0.000
8	2X flow		2	9:36:00 AM	9:37:00 AM	0.02	0.73	0.52	6.13	6.409	2.274					0.084				
			3	10:06:00 AM	10:07:00 AM	0.02	1.23	1.02	6.21	6.559	2.833					0.080				
			4	10:36:00 AM	10:39:00 AM	0.05	1.77	1.55	6.29	6.719	3.199	0.106	1.664	0.005	1.424	0.076	0.049	0.011	0.038	0.027
			5	11:06:00 AM	11:07:00 AM	0.02	2.23	2.02	6.36	6.859	3.310					0.072				
			6	12:06:00 PM	12:07:00 PM	0.02	3.23	3.02	6.51	7.159	3.496					0.056				
			7	1:06:00 PM	1:08:00 PM	0.03	4.25	4.03	6.66	7.464	3.501	0.068	1.815	0.005	1.613	0.056	0.051	0.018	0.032	0.006
			8	2:06:00 PM	2:07:00 PM	0.02	5.23	5.02	6.81	7.759	3.527					0.025				
			9	2:53:00 PM	2:54:00 PM	0.02	6.02	5.80	6.93	7.994	3.552					0.025				
			10	3:14:00 PM	3:32:00 PM	0.30	6.65	6.43	7.02	8.184	3.265	0.069	1.584	0.005	1.607	0.025	0.053	0.020	0.033	0.000
4/27/2016			Feed water								4.350					0.360				
4/29/2016	8:42:00 AM	2:42:00 PM	1	9:08:00 AM	9:15:00 AM	0.12	0.55	0.12	7.04	8.266	1.572	0.109	1.168	0.005	0.290	0.169	0.024	0.021	0.003	0.145
9			2	9:38:00 AM	9:40:00 AM	0.03	0.97	0.53	7.10	8.329	0.997					0.202				
			3	10:08:00 AM	10:09:00 AM	0.02	1.45	1.02	7.17	8.401	1.622					0.187				
			4	10:38:00 AM	10:41:00 AM	0.05	1.98	1.55	7.25	8.481	1.953	0.025	0.790	0.005	1.133	0.188	0.027	0.010	0.017	0.161
			5	11:08:00 AM	11:09:00 AM	0.02	2.45	2.02	7.32	8.551	1.095					0.179				
			6	12:08:00 PM	12:09:00 PM	0.02	3.45	3.02	7.47	8.701	2.091					0.185				
			7	1:08:00 PM	1:10:00 PM	0.03	4.47	4.03	7.62	8.854	2.190	0.065	1.290	0.005	0.830	0.179	0.020	0.021	0.000	0.159
			8	2:08:00 PM	2:09:00 PM	0.02	5.45	5.02	7.77	9.001	2.269					0.184				
			9	2:42:00 PM	2:43:00 PM	0.02	6.02	5.58	7.86	9.086	2.319					0.182				
			10	3:02:00 PM	3:05:00 PM	0.05	6.38	5.95	7.91	9.141	2.330	0.081	1.616	0.005	0.629	0.186	0.020	0.021	0.000	0.166
4/29/2016			Feed water								3.738					0.567				

Appendix D: 30% Compost Column

Table D1: 30% column nitrogen and Phosphorus raw data. All nitrogen data is presented in mg-N/L and all phosphorus data is presented in mg-P/L. First five storm events.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied	TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
9/2/2015	12:38:00 PM	6:38:00 PM	1	1:03:00 PM	1:15:00 PM	0.20	0.62	0.20	0.03	0.09	67.9	0.20	41.9	0.05	25.7	2.46	0.26	0.13	0.14	2.19
			2	1:33:00 PM	1:37:00 PM	0.07	0.98	0.57	0.09	0.15	80.6					2.36				
1			3	2:03:00 PM	2:08:00 PM	0.08	1.50	1.08	0.16	0.23	67.3					2.91				
0			4	2:33:00 PM	2:37:00 PM	0.07	1.98	1.57	0.24	0.30	66.2	0.37	30.0	0.16	35.7	3.00	0.93	0.63	0.30	2.07
			5	3:04:00 PM	3:08:00 PM	0.07	2.50	2.08	0.31	0.37	41.7					3.91				
			6	4:04:00 PM	4:08:00 PM	0.07	3.50	3.08	0.46	0.52	33.0					4.46				
			7	5:05:00 PM	5:09:00 PM	0.07	4.52	4.10	0.61	0.68	27.6	0.23	8.47	0.09	18.8	3.46	1.04	0.88	0.16	2.42
			8	6:05:00 PM	6:09:00 PM	0.07	5.52	5.10	0.76	0.83	22.5					3.46				
			9	6:38:00 PM	6:42:00 PM	0.07	6.07	5.65	0.85	0.91	20.5					3.46				
			10	6:42:00 PM	6:46:00 PM	0.07	6.13	5.72	0.86	0.92	19.2					3.42				
			11	6:52:00 PM	7:00:00 PM	0.13	6.37	5.95	0.89	0.95	18.0	0.23	3.45	0.08	14.2	3.20	1.00	0.91	0.10	2.20
9/2/2015			Feed water								3.2	0.03	1.43	0.01	1.76	0.25	0.36	0.37	0.00	0.00
9/9/2015	11:00:00 AM	5:00:00 PM	1	11:31:00 AM	11:46:00 AM	0.25	0.77	0.25	0.93	1.07	22.4	0.27	3.02	0.04	19.1	1.52	0.36	0.23	0.13	1.16
2			2	12:01:00 PM	12:05:00 PM	0.07	1.08	0.57	0.98	1.12	24.5					2.13				
			3	12:31:00 PM	12:35:00 PM	0.07	1.58	1.07	1.05	1.19	24.9					2.50				
7			4	1:01:00 PM	1:05:00 PM	0.07	2.08	1.57	1.13	1.27	20.8	0.49	1.92	0.05	18.3	2.60	1.11	0.88	0.23	1.49
			5	1:31:00 PM	1:35:00 PM	0.07	2.58	2.07	1.20	1.34	19.0					2.54				
			6	2:31:00 PM	2:35:00 PM	0.07	3.58	3.07	1.35	1.49	18.5					2.31				
			7	3:31:00 PM	3:35:00 PM	0.07	4.58	4.07	1.50	1.64	21.5	0.27	1.99	0.04	19.1	2.42	1.12	0.94	0.17	1.31
			8	4:31:00 PM	4:42:00 PM	0.18	5.70	5.18	1.67	1.81	12.6					2.06				
			9	4:59:00 PM	5:02:00 PM	0.05	6.03	5.52	1.72	1.86	13.5					2.06				
			10	5:02:00 PM	5:06:00 PM	0.07	6.10	5.58	1.73	1.87	15.5					1.99				
			11	5:12:00 PM	5:20:00 PM	0.13	6.33	5.82	1.77	1.91	9.22	0.20	2.11	0.04	6.87	1.92	1.15	0.99	0.16	0.77
9/16/2015	12:42:00 PM	6:42:00 PM	1	1:13:00 PM	1:23:00 PM	0.17	0.68	0.17	1.79	2.01	7.92	0.15	1.62	0.03	6.12	1.02	0.50	0.44	0.06	0.52
3			2	1:43:00 PM	1:47:00 PM	0.07	1.08	0.57	1.85	2.07	7.37					1.83				
			3	2:13:00 PM	2:17:00 PM	0.07	1.58	1.07	1.93	2.14	6.37					1.94				
14			4	2:43:00 PM	2:47:00 PM	0.07	2.08	1.57	2.00	2.22	8.57	0.28	1.48	0.03	6.78	1.90	1.23	1.02	0.21	0.67
			5	3:13:00 PM	3:17:00 PM	0.07	2.58	2.07	2.08	2.29	5.06					1.79				
			6	4:12:00 PM	4:16:00 PM	0.07	3.57	3.05	2.22	2.44	27.7					0.25				
			7	5:13:00 PM	5:16:00 PM	0.05	4.57	4.05	2.37	2.59	6.74	0.17	1.70	0.03	4.83	1.72	1.22	1.02	0.20	0.50
			8	6:12:00 PM	6:16:00 PM	0.07	5.57	5.05	2.52	2.74	3.48					1.62				
			9	6:42:00 PM	6:48:00 PM	0.10	6.10	5.58	2.60	2.82	3.83					1.41				
			10	6:48:00 PM	6:52:00 PM	0.07	6.17	5.65	2.61	2.83	4.34					1.37				
			11	6:57:00 PM	7:07:00 PM	0.17	6.42	5.90	2.65	2.87	4.69	0.13	1.68	0.02	2.85	1.48	1.16	1.03	0.13	0.31
9/16/2015			Feed water								3.26					0.26				
9/23/2015	12:51:00 PM	6:51:00 PM	1	1:21:00 PM	1:29:00 PM	0.13	0.63	0.13	2.67	2.96	5.27	0.03	2.88		2.36	1.55	0.72	0.52	0.20	0.83
4	added aluminum foil to columns		2	1:56:00 PM	2:00:00 PM	0.07	1.15	0.65	2.75	3.04	5.66					3.31				
			3	2:25:00 PM	2:29:00 PM	0.07	1.63	1.13	2.82	3.11	5.31					3.13				
21			4	2:51:00 PM	2:55:00 PM	0.07	2.07	1.57	2.89	3.18	5.07	0.21	1.09		3.77	3.13	1.32	1.26	0.06	1.82
			5	3:21:00 PM	3:25:00 PM	0.07	2.57	2.07	2.96	3.25	5.26					2.95				
			6	4:21:00 PM	4:25:00 PM	0.07	3.57	3.07	3.11	3.40	4.72					2.81				
			7	5:22:00 PM	5:25:00 PM	0.05	4.57	4.07	3.26	3.55	4.39	0.17	2.31		1.92	2.77	1.34	1.00	0.34	1.44
			8	6:21:00 PM	6:25:00 PM	0.07	5.57	5.07	3.41	3.70	5.28					2.85				
			9	6:51:00 PM	6:57:00 PM	0.10	6.10	5.60	3.49	3.78	4.04					2.77				
			10	6:57:00 PM	7:01:00 PM	0.07	6.17	5.67	3.50	3.79	4.07					2.77				
			11	7:06:00 PM	7:16:00 PM	0.17	6.42	5.92	3.54	3.83	4.38	0.13	2.63		1.62	2.59	1.27	0.94	0.33	1.33
9/23/2015			Feed water								3.51					0.26				
10/2/2015	11:12:00 AM	5:12:00 PM	1	12:23:00 PM	12:37:00 PM	0.23	1.42	0.23	3.57	3.94	6.34	0.09	5.03	0.01	1.21	2.07	0.97	0.82	0.15	1.10
5	Run at halved speed		2	12:53:00 PM	1:02:00 PM	0.15	1.83	0.65	3.64	3.97	6.02					2.88				
			3	1:23:00 PM	1:32:00 PM	0.15	2.33	1.15	3.71	4.01	5.63					3.21				
30			4	1:53:00 PM	2:03:00 PM	0.17	2.85	1.67	3.79	4.04	5.34	0.11	2.04	0.01	3.18	2.88	1.33	1.36	0.00	1.56
			5	2:24:00 PM	2:53:00 PM	0.48	3.68	2.50	3.91	4.11	5.37					3.24				
			6	3:23:00 PM	3:33:00 PM	0.17	4.35	3.17	4.01	4.16	5.26					3.05				
			7	4:23:00 PM	4:33:00 PM	0.17	5.35	4.17	4.16	4.23	4.65	0.10	2.89	0.01	1.66	3.14	1.51	1.18	0.33	1.63
			8	5:12:00 PM	5:22:00 PM	0.17	6.17	4.98	4.29	4.29	4.47					2.88				
			9	5:31:00 PM	5:40:00 PM	0.15	6.47	5.28	4.33	4.32	4.34	0.11	2.82	0.01	1.40	2.82	1.44	1.24	0.20	1.38
10/2/2015			Feed water								3.69					0.21				

Table D2: Continued results for the 30% column. Storm events 6-8, 26, and 45.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied	TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
10/7/2015	10:37:00 AM	4:37:00 PM	1	10:54:00 AM	10:58:00 AM	0.07	0.35	0.07	4.34	4.42	5.46	0.37	2.39	0.01	2.69	1.74	1.15	1.11	0.03	0.60
6	Run at 2X speed		2	11:24:00 AM	11:26:00 AM	0.03	0.82	0.53	4.41	4.56	5.77					1.63				
			3	11:54:00 AM	11:56:00 AM	0.03	1.32	1.03	4.49	4.71	5.47					1.56				
35			4	12:24:00 PM	12:26:00 PM	0.03	1.82	1.53	4.56	4.86	5.11	0.24	3.59	0.01	1.28	1.42	1.43	0.90	0.53	0.00
			5	12:54:00 PM	12:56:00 PM	0.03	2.32	2.03	4.64	5.01	0.09					1.43				
			6	1:55:00 PM	1:57:00 PM	0.03	3.33	3.05	4.79	5.32	3.75					1.22				
			7	2:54:00 PM	2:56:00 PM	0.03	4.32	4.03	4.94	5.61	3.63	0.32	2.75	0.01	0.56	1.03	1.06	0.89	0.17	0.00
			8	3:54:00 PM	3:56:00 PM	0.03	5.32	5.03	5.09	5.91	3.48					1.17				
			9	4:37:00 PM	4:39:00 PM	0.03	6.03	5.75	5.19	6.13	3.55					1.15				
			10	4:47:00 PM	4:54:00 PM	0.12	6.28	6.00	5.23	6.20	3.43					1.10				
			11	5:07:00 PM	5:31:00 PM	0.40	6.90	6.62	5.32	6.39	3.55	0.42	1.84	0.01	1.28	1.04	1.06	1.13	0.00	0.00
10/7/2015	Feed water										3.66					0.26				
10/16/2015	12:08:00 PM	6:08:00 PM	1	12:42:00 PM	12:51:00 PM	0.15	0.72	0.15	5.35	6.49	8.35	0.06	10.01	0.01	0.00	1.40	1.09	0.83	0.27	0.31
7	Added grass, tall frescue		2	1:12:00 PM	1:17:00 PM	0.08	1.15	0.58	5.41	6.56	10.92					1.71				
			3	1:42:00 PM	1:47:00 PM	0.08	1.65	1.08	5.49	6.63	11.08					1.85				
44			4	2:12:00 PM	2:17:00 PM	0.08	2.15	1.58	5.56	6.71	7.89	0.14	8.32	0.01	0.00	1.78	1.62	1.22	0.40	0.16
			5	2:42:00 PM	2:47:00 PM	0.08	2.65	2.08	5.64	6.78	6.33					1.92				
			6	3:42:00 PM	3:48:00 PM	0.10	3.67	3.10	5.79	6.94	5.14					1.64				
			7	4:42:00 PM	4:46:00 PM	0.07	4.63	4.07	5.93	7.08	4.33	0.13	3.43	0.01	0.76	1.75	1.42	1.17	0.25	0.32
			8	5:42:00 PM	5:46:00 PM	0.07	5.63	5.07	6.08	7.23	3.78					1.57				
			9	6:08:00 PM	6:13:00 PM	0.08	6.08	5.52	6.15	7.30	3.64					1.61				
			10	6:28:00 PM	6:41:00 PM	0.22	6.55	5.98	6.22	7.37	3.65	0.10	3.02	0.01	0.52	1.54	1.32	1.13	0.20	0.22
10/16/2015	Feed water										3.84					0.25				
10/26/2015	10:26:00 AM	4:26:00 PM	1	10:57:00 AM	11:10:00 AM	0.22	0.73	0.22	6.25	7.48	7.74	0.12	7.79	0.01	0.00	1.36	1.31	0.92	0.38	0.06
8			2	11:27:00 AM	11:32:00 AM	0.08	1.10	0.58	6.31	7.53	7.88	5.82				1.46				
			3	11:57:00 AM	12:03:00 PM	0.10	1.62	1.10	6.39	7.61	8.02	1.56				1.43				
54			4	12:27:00 PM	12:33:00 PM	0.10	2.12	1.60	6.46	7.69	6.68	0.16	4.09	0.01	2.42	1.43	1.44	1.35	0.10	0.00
			5	12:57:00 PM	1:02:00 PM	0.08	2.60	2.08	6.53	7.76	5.73					1.50				
			6	1:57:00 PM	2:00:00 PM	0.05	3.57	3.05	6.68	7.90	5.21					1.36				
			7	2:57:00 PM	3:00:00 PM	0.05	4.57	4.05	6.83	8.05	4.70	0.15	4.75	0.01	0.00	1.30	1.39	0.89	0.51	0.00
			8	3:57:00 PM	4:01:00 PM	0.07	5.58	5.07	6.98	8.21	4.28					1.26				
			9	4:26:00 PM	4:30:00 PM	0.07	6.07	5.55	7.05	8.28	3.91					1.26				
			10	4:46:00 PM	5:01:00 PM	0.25	6.58	6.07	7.13	8.36	4.02	0.09	3.09	0.01	0.84	1.20	1.30	0.96	0.34	0.00
10/26/2015	Feed water										3.78					0.29				
3/2/2016	10:07:00 AM	4:07:00 PM	1	10:27:00 AM	10:33:00 AM	0.10	0.43	0.10	7.15	24.22	4.50	0.40	3.89	0.01	0.21	0.94	0.40	0.83	0.00	0.00
~26	18 weeks later		2	10:57:00 AM	10:59:00 AM	0.03	0.87	0.53	7.21	24.28	7.38	5.40				0.97				
	24.15		3	11:27:00 AM	11:28:00 AM	0.02	1.35	1.02	7.28	24.35	7.53	1.52				0.91				
182			4	11:57:00 AM	12:00:00 PM	0.05	1.88	1.55	7.36	24.43	7.20	0.83	5.34	0.01	1.02	0.85	0.83	0.74	0.10	0.00
26			5	12:27:00 PM	12:29:00 PM	0.03	2.37	2.03	7.44	24.51	6.67					0.79				
			6	1:27:00 PM	1:28:00 PM	0.02	3.35	3.02	7.58	24.65	4.89					0.71				
			7	2:27:00 PM	2:31:00 PM	0.07	4.40	4.07	7.74	24.81	4.21	0.60	2.83	0.01	0.79	0.66	0.60	0.39	0.21	0.00
			8	3:27:00 PM	3:29:00 PM	0.03	5.37	5.03	7.89	24.96	4.15					0.63				
			9	4:07:00 PM	4:09:00 PM	0.03	6.03	5.70	7.99	25.06	3.43					0.52				
			10	4:27:00 PM	4:41:00 PM	0.23	6.57	6.23	8.07	25.14	4.00	0.56	3.23	0.01	0.20	0.64	0.56	0.56	0.00	0.00
3/2/2016	Feed water										3.64					0.33				
7/11/2016	10:30:00 AM	4:30:00 PM	1	10:57:00 AM	11:07:00 AM	0.17	0.62	0.17	8.09	42.71	4.31	0.78	2.35	0.01	1.17	0.46	0.29	0.26	0.03	0.17
~45	19 weeks later		2	11:27:00 AM	11:29:00 AM	0.03	0.98	0.53	8.15	42.76	4.84	6.20				0.47				
	42.615		3	11:57:00 AM	11:59:00 AM	0.03	1.48	1.03	8.22	42.84	6.01	0.94				0.51				
313			4	12:27:00 PM	12:32:00 PM	0.08	2.03	1.58	8.30	42.92	5.81	1.09	5.68	0.01	0.00	0.51	0.52	0.41	0.11	0.00
44.71428571	37		5	12:57:00 PM	12:59:00 PM	0.03	2.48	2.03	8.37	42.99	6.48					0.52				
			6	1:57:00 PM	1:59:00 PM	0.03	3.48	3.03	8.52	43.14	6.73					0.54				
			7	2:57:00 PM	2:59:00 PM	0.03	4.48	4.03	8.67	43.29	6.70	0.85	4.67	0.01	1.18	0.57	0.56	0.49	0.07	0.01
			8	3:57:00 PM	3:59:00 PM	0.03	5.48	5.03	8.82	43.44	6.76					0.55				
			9	4:30:00 PM	4:32:00 PM	0.03	6.03	5.58	8.90	43.52	6.80					0.58				
			10	4:50:00 PM	5:10:00 PM	0.33	6.67	6.22	9.00	43.62	7.56			0.01	7.55	0.61	0.59	0.51	0.08	0.02
7/11/2016	Feed water										4.24					0.37				

Appendix E: 15% Compost Column

Table E1: 15% column nitrogen and Phosphorus raw data. All nitrogen data is presented in mg-N/L and all phosphorus data is presented in mg-P/L. First four storm events.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied	TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
1/7/2016	11:11:00 AM	5:11:00 PM	1	12:12:00 PM	12:17:00 PM	0.08	1.10	0.08	0.01	0.165	8.379	0.200	2.709	0.033	5.437	0.230	0.155	0.056	0.098	0.075
1			2	12:42:00 PM	12:44:00 PM	0.03	1.55	0.53	0.08	0.232	11.600					0.453				
	Foil, dead grass, regular speed		3	1:12:00 PM	1:14:00 PM	0.03	2.05	1.03	0.16	0.308	9.791					0.881				
			4	1:42:00 PM	1:45:00 PM	0.05	2.57	1.55	0.23	0.385	8.664	0.126	2.324	0.041	6.173	1.257	0.606	0.350	0.256	0.651
			5	2:12:00 PM	2:14:00 PM	0.03	3.05	2.03	0.31	0.458	6.500					1.257				
			6	3:12:00 PM	3:14:00 PM	0.03	4.05	3.03	0.46	0.608	4.729					1.257				
			7	4:13:00 PM	4:16:00 PM	0.05	5.08	4.07	0.61	0.763	5.093	0.306	1.707	0.057	3.023	1.086	0.768	0.476	0.292	0.318
			8	5:11:00 PM	5:13:00 PM	0.03	6.03	5.02	0.75	0.905	3.201					0.949				
			9	5:31:00 PM	5:34:00 PM	0.05	6.38	5.37	0.81	0.958	3.621	0.480	1.534	0.062	1.545	1.000	0.754	0.523	0.231	0.246
1/7/2016			Feed water								3.286					0.240				
1/14/2016	10:42:00 AM	4:42:00 PM	1	11:28:00 AM	11:36:00 AM	0.13	0.90	0.13	0.83	1.093	3.832	0.158	0.953	0.017	2.704	0.283	0.265	0.168	0.097	0.018
2			2	11:58:00 AM	11:59:00 AM	0.02	1.28	0.52	0.88	1.150	5.270					0.557				
			3	12:28:00 PM	12:29:00 PM	0.02	1.78	1.02	0.96	1.225	4.152									
			4	12:58:00 PM	1:02:00 PM	0.07	2.33	1.57	1.04	1.308	5.391	0.145	1.712	0.019	3.515	0.593	0.587	0.439	0.148	0.006
			5	1:28:00 PM	1:29:00 PM	0.02	2.78	2.02	1.11	1.375	4.145					0.630				
			6	2:28:00 PM	2:29:00 PM	0.02	3.78	3.02	1.26	1.525	3.197					0.685				
			7	3:28:00 PM	3:31:00 PM	0.05	4.82	4.05	1.41	1.680	3.083	0.138	2.086	0.033	0.825	0.666	0.479	0.446	0.034	0.187
			8	4:28:00 PM	4:29:00 PM	0.02	5.78	5.02	1.56	1.825	2.975					0.557				
			9	4:42:00 PM	4:43:00 PM	0.02	6.02	5.25	1.59	1.860	2.944					0.666				
			10	5:02:00 PM	5:05:00 PM	0.05	6.38	5.62	1.65	1.915	3.291	0.108	1.410	0.018	1.755	0.611	0.510	0.423	0.087	0.102
1/14/2016			Feed water								3.543					0.219				
1/21/2016	10:30:00 AM	4:30:00 PM	1	11:08:00 AM	11:18:00 AM	0.17	0.80	0.17	1.67	2.035	4.051	0.359	1.903	0.005	1.784	0.923	0.457	0.179	0.278	0.465
3			2	11:38:00 AM	11:40:00 AM	0.03	1.17	0.53	1.73	2.090	4.057					0.981				
			3	12:08:00 PM	12:12:00 PM	0.07	1.70	1.07	1.81	2.170	3.927					0.886				
			4	12:38:00 PM	12:42:00 PM	0.07	2.20	1.57	1.88	2.245	4.069	0.084	2.053	0.005	1.927	1.310	0.552	0.476	0.075	0.758
			5	1:08:00 PM	1:10:00 PM	0.03	2.67	2.03	1.95	2.315	4.122					1.105				
			6	2:11:00 PM	2:13:00 PM	0.03	3.72	3.08	2.11	2.473	4.027					1.186				
			7	3:08:00 PM	3:12:00 PM	0.07	4.70	4.07	2.26	2.620	3.980	0.081	2.349	0.005	1.546	1.131	0.478	0.431	0.046	0.653
			8	4:08:00 PM	4:12:00 PM	0.07	5.70	5.07	2.41	2.770	4.213					0.703				
			9	4:30:00 PM	4:33:00 PM	0.05	6.05	5.42	2.46	2.823	3.856					1.445				
			10	4:50:00 PM	5:00:00 PM	0.17	6.50	5.87	2.53	2.890	3.841	0.071	2.527	0.005	1.239	1.197	0.471	0.426	0.045	0.726
1/21/2016			Feed water								4.135					0.250				
1/29/2016	10:30:00 AM	4:30:00 PM	1	11:09:00 AM	11:16:00 AM	0.12	0.77	0.12	2.55	3.005	2.929	0.117	0.999	0.005	1.808	0.398	0.304	0.271	0.033	0.094
4			2	11:39:00 AM	11:41:00 AM	0.03	1.18	0.53	2.61	3.068	3.289					0.661				
			3	12:09:00 PM	12:13:00 PM	0.07	1.72	1.07	2.69	3.148	3.936					0.775				
			4	12:40:00 PM	12:44:00 PM	0.07	2.23	1.58	2.77	3.225	3.895	0.118	2.304	0.005	1.468	0.771	0.474	0.489	0.000	0.298
			5	1:09:00 PM	1:11:00 PM	0.03	2.68	2.03	2.83	3.293	3.901					0.799				
			6	2:09:00 PM	2:11:00 PM	0.03	3.68	3.03	2.98	3.443	4.163					0.827				
			7	3:13:00 PM	3:17:00 PM	0.07	4.78	4.13	3.15	3.608	3.909	0.172	2.623	0.005	1.108	0.879	0.504	0.431	0.072	0.375
			8	4:11:00 PM	4:13:00 PM	0.03	5.72	5.07	3.29	3.748	4.044					0.761				
			9	4:30:00 PM	4:33:00 PM	0.05	6.05	5.40	3.34	3.798	3.721					0.488				
			10	4:50:00 PM	4:55:00 PM	0.08	6.42	5.77	3.39	3.853	3.825	0.025	2.714	0.005	1.081	0.806	0.993	0.420	0.573	0.000
1/29/2016			Feed water								4.296					0.235				

Table E2: Continued results for the 15% column. Storm events 5-8.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied	TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
2/5/2016	7:58:00 AM	1:58:00 PM	1	9:15:00 AM	9:30:00 AM	0.25	1.53	0.25	3.43	3.968	2.244	0.093		0.005		0.315	0.326	0.287	0.039	0.000
5	Run at halved speed		2	9:45:00 AM	9:50:00 AM	0.08	1.87	0.58	3.48	3.993	2.469					0.495				
			3	10:15:00 AM	10:24:00 AM	0.15	2.43	1.15	3.57	4.035	2.630					0.588				
			4	10:45:00 AM	10:55:00 AM	0.17	2.95	1.67	3.64	4.074	2.905	0.105		0.005		0.550	0.529	0.486	0.043	0.021
			5	11:12:00 AM	11:17:00 AM	0.08	3.32	2.03	3.70	4.101	2.846					0.592				
			6	12:15:00 PM	12:19:00 PM	0.07	4.35	3.07	3.85	4.179	2.904					0.695				
			7	1:15:00 PM	1:25:00 PM	0.17	5.45	4.17	4.02	4.261	3.097	0.025		0.005		0.592	0.488	0.463	0.025	0.103
			8	2:04:00 PM	2:14:00 PM	0.17	6.27	4.98	4.14	4.323	2.971					0.550				
			9	2:23:00 PM	2:32:00 PM	0.15	6.57	5.28	4.19	4.345	2.948	0.129		0.005		0.557	0.492	0.454	0.038	0.065
2/5/2016			Feed water								3.619					0.180				
2/10/2016	11:04:00 AM	5:04:00 PM	1	11:28:00 AM	11:33:00 AM	0.08	0.48	0.08	4.20	4.490	2.936	0.062	0.988	0.005	1.881	0.444	0.210	0.371	0.000	0.235
6	Run at 2X speed		2	11:58:00 AM	11:59:00 AM	0.02	0.92	0.52	4.26	4.620	3.233					0.527				
			3	12:28:00 PM	12:29:00 PM	0.02	1.42	1.02	4.34	4.770	3.433					0.579				
			4	12:58:00 PM	1:00:00 PM	0.03	1.93	1.53	4.42	4.925	3.672	0.025	2.214	0.005	1.428	0.503	0.495	0.375	0.120	0.000
			5	1:28:00 PM	1:29:00 PM	0.02	2.42	2.02	4.49	5.070	3.638					0.469				
			6	2:28:00 PM	2:29:00 PM	0.02	3.42	3.02	4.64	5.370	3.497					0.479				
			7	3:28:00 PM	3:30:00 PM	0.03	4.43	4.03	4.79	5.675	3.513	0.107	2.193	0.005	1.207	0.469	0.429	0.345	0.084	0.000
			8	4:28:00 PM	4:29:00 PM	0.02	5.42	5.02	4.94	5.970	3.298					0.406				
			9	5:04:00 PM	5:05:00 PM	0.02	6.02	5.62	5.03	6.150	3.389					0.317				
			10	5:24:00 PM	5:28:00 PM	0.07	6.40	6.00	5.09	6.265	3.427	0.114	2.422	0.005	0.886	0.348	0.436	0.349	0.087	0.000
2/10/2016			Feed water								3.752					0.192				
2/24/2016	7:11:00 AM	1:11:00 PM	1	7:54:00 AM	8:04:00 AM	0.17	0.88	0.17	5.11	6.398	3.702	0.487	2.173	0.005	1.037	0.445		0.350		0.445
7			2	8:24:00 AM	8:25:00 AM	0.02	1.23	0.52	5.16	6.450	4.069					0.584				
			3	8:54:00 AM	8:55:00 AM	0.02	1.73	1.02	5.24	6.525	4.974					0.667				
			4	9:24:00 AM	9:29:00 AM	0.08	2.30	1.58	5.32	6.610	4.677	1.913	3.640	0.005	0.000	0.648	0.505	0.428	0.077	0.143
			5	9:54:00 AM	9:57:00 AM	0.05	2.77	2.05	5.39	6.680	4.992					0.592				
			6	10:54:00 AM	10:56:00 AM	0.03	3.75	3.03	5.54	6.828	3.423					0.581				
			7	11:54:00 AM	11:58:00 AM	0.07	4.78	4.07	5.70	6.983	3.365	0.356	2.488	0.005	0.516	0.629	0.428	0.359	0.069	0.202
			8	12:54:00 PM	12:56:00 PM	0.03	5.75	5.03	5.84	7.128	3.325					0.660				
			9	1:11:00 PM	1:13:00 PM	0.03	6.03	5.32	5.88	7.170	2.585					0.547				
			10	1:31:00 PM	1:35:00 PM	0.07	6.40	5.68	5.94	7.225	3.094	0.353	2.546	0.005	0.190	0.667	0.426	0.354	0.071	0.241
2/24/2016			Feed water								3.810					0.205				
3/2/2016	10:07:00 AM	4:07:00 PM	1	10:51:00 AM	10:58:00 AM	0.12	0.85	0.12	5.96	7.353	3.008	0.145	2.388	0.005	0.469	0.460	0.370	0.350	0.021	0.090
8			2	11:21:00 AM	11:23:00 AM	0.03	1.27	0.53	6.02	7.415	3.250					0.673				
			3	11:51:00 AM	11:52:00 AM	0.02	1.75	1.02	6.09	7.488	3.819					0.798				
			4	12:21:00 PM	12:25:00 PM	0.07	2.30	1.57	6.17	7.570	4.056	0.692	3.041	0.005	0.318	0.642	0.444	0.413	0.032	0.198
			5	12:51:00 PM	12:54:00 PM	0.05	2.78	2.05	6.25	7.643	3.985					0.700				
			6	1:51:00 PM	1:53:00 PM	0.03	3.77	3.03	6.39	7.790	3.036					0.690				
			7	2:53:00 PM	2:58:00 PM	0.08	4.85	4.12	6.56	7.953	2.943	0.567	2.113	0.005	0.258	0.535	0.343	0.328	0.016	0.192
			8	3:51:00 PM	3:54:00 PM	0.05	5.78	5.05	6.70	8.093	2.938					0.627				
			9	4:07:00 PM	4:09:00 PM	0.03	6.03	5.30	6.73	8.130	3.276					0.617				
			10	4:27:00 PM	4:41:00 PM	0.23	6.57	5.83	6.81	8.210	2.927	0.337		0.005	2.585	0.517	0.330	0.305	0.024	0.187
3/2/2016			Feed water								3.640					0.333				

Appendix F: 15% Compost and 4% WTR Mesocosm

Table F1: 15%+WTR column nitrogen and Phosphorus raw data. All nitrogen data is presented in mg-N/L and all phosphorus data is presented in mg-P/L. First four storm events.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied	TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
5/10/2016 **1** Foil, regular speed	12:22:00 AM	6:22:00 AM	1	1:10:00 AM	1:16:00 AM	0.10	0.90	0.10	0.01	0.135	26.040	0.225	20.910	0.574	4.331	0.216	0.104	0.034	0.070	0.112
			2	1:40:00 AM	1:41:00 AM	0.02	1.32	0.52	0.08	0.198	51.560					0.745				
			3	2:10:00 AM	2:11:00 AM	0.02	1.82	1.02	0.15	0.273	28.390					1.113				
			4	2:40:00 AM	2:44:00 AM	0.07	2.37	1.57	0.24	0.355	15.720	0.444	8.846	0.303	6.127	1.395	0.252	0.160	0.092	1.144
			5	3:10:00 AM	3:12:00 AM	0.03	2.83	2.03	0.31	0.425	10.530					1.478				
			6	4:10:00 AM	4:11:00 AM	0.02	3.82	3.02	0.45	0.573	6.845					1.392				
			7	5:10:00 AM	5:14:00 AM	0.07	4.87	4.07	0.61	0.730	5.903	0.445	1.961	0.080	3.417	1.242	0.356	0.258	0.098	0.885
			8	6:10:00 AM	6:12:00 AM	0.03	5.83	5.03	0.75	0.875	5.307					1.149				
			9	6:22:00 AM	6:24:00 AM	0.03	6.03	5.23	0.78	0.905	5.495					1.163				
			10	6:42:00 AM	6:54:00 AM	0.20	6.53	5.73	0.86	0.980	5.212	0.373	2.112	0.075	2.652	1.084	0.368	0.302	0.065	0.717
5/10/2016			Feed water								3.835					0.376				
5/24/2016 **2**	9:57:00 AM	3:57:00 PM	1	10:27:00 AM	10:39:00 AM	0.20	0.70	0.20	0.89	1.085	2.584	0.025	0.705	0.081	1.773	0.108	0.071	0.048	0.022	0.037
			2	10:57:00 AM	10:59:00 AM	0.03	1.03	0.53	0.94	1.135	4.098					0.412				
			3	11:27:00 AM	11:29:00 AM	0.03	1.53	1.03	1.02	1.210	3.971					0.516				
			4	11:57:00 AM	11:59:00 AM	0.03	2.03	1.53	1.09	1.285	3.899	0.236	1.092	0.010	2.560	0.423	0.151	0.112	0.039	0.272
			5	12:27:00 PM	12:29:00 PM	0.03	2.53	2.03	1.17	1.360	3.705					0.419				
			6	1:27:00 PM	1:29:00 PM	0.03	3.53	3.03	1.32	1.510	3.439					0.387				
			7	2:27:00 PM	2:30:00 PM	0.05	4.55	4.05	1.47	1.663	3.187	0.137	1.245	0.010	1.796	0.380	0.131	0.109	0.022	0.249
			8	3:27:00 PM	3:29:00 PM	0.03	5.53	5.03	1.61	1.810	3.191					0.344				
			9	3:57:00 PM	3:59:00 PM	0.03	6.03	5.53	1.69	1.885	3.064					0.323				
			10	4:15:00 PM	4:27:00 PM	0.20	6.50	6.00	1.76	1.955	3.065	0.183	1.454	0.010	1.419	0.312	0.133	0.111	0.022	0.179
5/24/2016			Feed water								4.664					0.527				
6/6/2016 **3** Grass added 27	7:19:00 AM	1:19:00 PM	1	7:52:00 AM	8:02:00 AM	0.17	0.72	0.17	1.78	2.062	1.136	0.025	0.464	0.010	0.637	0.075	0.058	0.048	0.010	0.018
			2	8:22:00 AM	8:24:00 AM	0.03	1.08	0.53	1.84	2.117	2.337					0.143				
			3	8:52:00 AM	8:54:00 AM	0.03	1.58	1.03	1.91	2.192	2.795					0.236				
			4	9:22:00 AM	9:25:00 AM	0.05	2.10	1.55	1.99	2.270	2.738	0.134	1.190	0.010	1.405	0.240	0.093	0.073	0.020	0.147
			5	9:52:00 AM	9:54:00 AM	0.03	2.58	2.03	2.06	2.343	2.726					0.208				
			6	10:52:00 AM	10:54:00 AM	0.03	3.58	3.03	2.21	2.493	2.661					0.204				
			7	11:52:00 AM	11:54:00 AM	0.03	4.58	4.03	2.36	2.642	2.551	0.067	1.582	0.010	0.892	0.197	0.083	0.058	0.025	0.114
			8	12:52:00 PM	12:53:00 PM	0.02	5.57	5.02	2.51	2.790	2.597					0.183				
			9	1:19:00 PM	1:21:00 PM	0.03	6.03	5.48	2.58	2.860	2.606					0.165				
			10	1:39:00 PM	1:46:00 PM	0.12	6.45	5.90	2.64	2.922	2.372	0.090	1.266	0.010	1.007	0.175	0.090	0.084	0.006	0.086
6/6/2016			Feed water								3.754					0.404				
6/9/2016 **4**	7:19:00 AM	1:19:00 PM	1	7:58:00 AM	8:05:00 AM	0.12	0.77	0.12	2.66	3.038		0.025	0.543	0.010	0.000	0.060	0.068	0.065	0.004	0.000
			2	8:28:00 AM	8:30:00 AM	0.03	1.18	0.53	2.72	3.100						0.128				
			3	8:58:00 AM	9:02:00 AM	0.07	1.72	1.07	2.81	3.180						0.133				
			4	9:29:00 AM	9:33:00 AM	0.07	2.23	1.58	2.88	3.258		0.084	1.224	0.010	0.000	0.159	0.115	0.066	0.048	0.044
			5	9:58:00 AM	10:00:00 AM	0.03	2.68	2.03	2.95	3.325						0.119				
			6	10:58:00 AM	11:00:00 AM	0.03	3.68	3.03	3.10	3.475						0.116				
			7	12:02:00 PM	12:06:00 PM	0.07	4.78	4.13	3.26	3.640		0.025				0.127				0.127
			8	1:00:00 PM	1:02:00 PM	0.03	5.72	5.07	3.40	3.780						0.108				
			9	1:19:00 PM	1:22:00 PM	0.05	6.05	5.40	3.45	3.830						0.111				
			10	1:39:00 PM	1:44:00 PM	0.08	6.42	5.77	3.51	3.885		0.025				0.117				0.117
6/9/2016			Feed water								3.780					0.408				

Table F2: Continued results for the 15%+WTR column. Storm events 5-8.

Day run	Start Time	End time	Sample #	Start Time	End time	within trial	from start	from start of drip	Meters of treated water	Meters of water applied		TN	Ammonia	Nitrate	Nitrite	Oranic N	TP	DP	SRP	DOP	PP
6/13/2016	6:57:00 AM	12:57:00 PM	1	7:52:00 AM	8:10:00 AM	0.30	1.22	0.30	3.55	3.976		0.948		0.472	0.010	0.466	0.077	0.077	0.031	0.046	0.000
5	Run at halved speed		2	8:22:00 AM	8:26:00 AM	0.07	1.48	0.57	3.59	3.996		1.066					0.105				
			3	8:52:00 AM	8:55:00 AM	0.05	1.97	1.05	3.67	4.032		1.259					0.122				
			4	9:22:00 AM	9:30:00 AM	0.13	2.55	1.63	3.76	4.076		1.245		0.732	0.010	0.503	0.122	0.101	0.070	0.031	0.021
			5	9:52:00 AM	9:56:00 AM	0.07	2.98	2.07	3.82	4.109		1.444					0.115				
			6	10:52:00 AM	10:56:00 AM	0.07	3.98	3.07	3.97	4.184		1.823					0.122				
			7	11:52:00 AM	11:59:00 AM	0.12	5.03	4.12	4.13	4.262		1.993		1.113	0.010	0.870	0.111	0.084	0.092	0.000	0.027
			8	12:52:00 PM	12:55:00 PM	0.05	5.97	5.05	4.27	4.332		2.091					0.111				
			9	1:12:00 PM	1:25:00 PM	0.22	6.47	5.55	4.34	4.370		2.038		1.430	0.010	0.598	0.115	0.156	0.092	0.064	0.000
6/13/2016			Feed water									3.803					0.550				
6/28/2016	7:34:00 AM	1:34:00 PM	1	7:40:00 AM	7:54:00 AM	0.23	0.33	0.23	4.38	4.470		1.159	0.038	0.501	0.010	0.610	0.084	0.048	0.069	0.000	0.036
6	Run at 2X speed		2	8:10:00 AM	8:11:00 AM	0.02	0.62	0.52	4.42	4.555		2.526					0.148				
			3	8:40:00 AM	8:41:00 AM	0.02	1.12	1.02	4.50	4.705		2.867					0.137				
			4	9:10:00 AM	9:12:00 AM	0.03	1.63	1.53	4.57	4.860		2.932	0.085	1.662	0.010	1.175	0.147	0.059	0.061	0.000	0.088
			5	9:40:00 AM	9:41:00 AM	0.02	2.12	2.02	4.65	5.005		2.978					0.132				
			6	10:40:00 AM	10:41:00 AM	0.02	3.12	3.02	4.80	5.305		2.962					0.109				
			7	11:40:00 AM	11:42:00 AM	0.03	4.13	4.03	4.95	5.610		2.898	0.103	1.569	0.010	1.216	0.046	0.046	0.050	0.000	0.000
			8	12:40:00 PM	12:41:00 PM	0.02	5.12	5.02	5.10	5.905		2.825					0.097				
			9	1:34:00 PM	1:35:00 PM	0.02	6.02	5.92	5.23	6.175		2.714					0.090				
			10	1:54:00 PM	2:13:00 PM	0.32	6.65	6.55	5.32	6.365		2.730	0.281	1.563	0.010	0.876	0.105	0.048	0.063	0.000	0.058
6/28/2016			Feed water									3.785					0.557				
7/1/2016	8:53:00 AM	2:53:00 PM	1	9:14:00 AM	9:24:00 AM	0.17	0.52	0.17	5.35	6.442		2.988	0.054		0.010	2.924	0.145	0.044	0.044	0.000	0.101
7			2	9:44:00 AM	9:46:00 AM	0.03	0.88	0.53	5.40	6.497		3.093					0.096				
			3	10:14:00 AM	10:16:00 AM	0.03	1.38	1.03	5.48	6.572		2.504					0.089				
			4	10:45:00 AM	10:49:00 AM	0.07	1.93	1.58	5.56	6.655		2.507	0.066		0.010	2.431	0.099	0.057	0.032	0.025	0.042
			5	11:14:00 AM	11:16:00 AM	0.03	2.38	2.03	5.63	6.722		2.465					0.081				
			6	12:14:00 PM	12:15:00 PM	0.02	3.37	3.02	5.78	6.870		2.497					0.072				
			7	1:14:00 PM	1:17:00 PM	0.05	4.40	4.05	5.93	7.025		2.535	0.069		0.010	2.456	0.075	0.099	0.047	0.052	0.000
			8	2:14:00 PM	2:15:00 PM	0.02	5.37	5.02	6.08	7.170		2.599					0.102				
			9	2:53:00 PM	2:54:00 PM	0.02	6.02	5.67	6.18	7.268		2.620					0.070				
			10	3:13:00 PM	3:29:00 PM	0.27	6.60	6.25	6.26	7.355		2.624	0.140		0.010	2.474	0.084	0.037	0.057	0.000	0.047
7/1/2016			Feed water									3.981					0.469				
7/6/2016	8:55:00 AM	2:55:00 PM	1	9:20:00 AM	9:30:00 AM	0.17	0.58	0.17	6.29	7.443		2.670	0.030		0.010	2.630	0.062	0.037	0.043	0.000	0.025
8			2	9:50:00 AM	9:52:00 AM	0.03	0.95	0.53	6.34	7.498		2.961					0.110				
			3	10:23:00 AM	10:25:00 AM	0.03	1.50	1.08	6.43	7.580		2.786					0.101				
			4	10:50:00 AM	10:53:00 AM	0.05	1.97	1.55	6.50	7.650		2.612	0.047		0.010	2.555	0.105	0.041	0.043	0.000	0.064
57.00			5	11:21:00 AM	11:23:00 AM	0.03	2.47	2.05	6.57	7.725		2.454					0.092				
			6	12:20:00 PM	12:22:00 PM	0.03	3.45	3.03	6.72	7.873		2.301					0.086				
			7	1:20:00 PM	1:22:00 PM	0.03	4.45	4.03	6.87	8.023		2.370	0.060		0.010	2.300	0.102	0.069	0.063	0.006	0.033
			8	2:20:00 PM	2:22:00 PM	0.03	5.45	5.03	7.02	8.173		2.351					0.071				
			9	2:55:00 PM	2:56:00 PM	0.02	6.02	5.60	7.10	8.258		2.385					0.068				
			10	3:15:00 PM	3:31:00 PM	0.27	6.60	6.18	7.19	8.345		2.396	0.070		0.010	2.316	0.080	0.078	0.043	0.035	0.002
7/6/2016			Feed water									2.705					0.533				

REFERENCES

Borggaard, O. K., Raben-Lange, B., Gimsing, A. L., & Strobel, B. W. (2005). Influence of humic substances on phosphate adsorption by aluminum and iron oxides. *Geoderma*, 127, 270-279.

Castle, S. (2009). Soil inorganic nitrogen: KCl extraction. In *Aridlands Ecology Lab Protocol.* Boulder: University of Colorado.

Chatterjee, N., Flury, M., Hinman, C., & Cogger, C. G. (2013). *Chemical and physical characteristics of compost leachates, A review.* Pyallup, WA: Washington State Department of Transportation.

Christensen, T. (1983). Leaching from land disposed municipal composts: 2. nitrogen . *Waste management & research*, 1(2), 115-125.

Chubu Ecotec Co., L. (1994). Composting Overview. *http://www.chueco.co.jp/English/inst01.files/inst01.html*.

Cimbala, J. M. (2011). Outliers. *Penn State University*.

Daniel, W. W. (1990). *Applied nonparametric statistics.* PWS-Kent Publ.

Database, I. S. (n.d.). *The national stormwater quality database.* Retrieved July 20, 2016, from http://www.bmpdatabase.org/nsqd.html

Davis, A. P., & McCuen, R. H. (2005). *Stormwater management for smart growth.* Springer, New York.

Davis, A. P., Gardina, C., Mangum, K., & Owen, D. (2016). Evaluation of Compost Addition to Stormwater Control Measure (SCM) Performance. *(Unpublished).*

Davis, A. P., Shokouhian, M., Sharma, H., & Minami, C. (2001). Laboratory study of biological retention for urban stormwater management. *Water Environ. Res.*, 73(1), 5-14.

Davis, A. P., Shokouhian, M., Sharma, H., & Minami, C. (2006). Water quality improvement through bioretention media: Nitrogen and phosphorus removal. *Water Environ. Res.*, 78(3), 284-293.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C., & Winogradoff, D. (2003). Water quality improvement through bioretention: Lead, copper, and zing removal. *Water Environ. Res.*, 75(1), 73-82.

Davis, A. P., Traver, R. G., Hunt, W. F., Lee, R., Brown, R. A., & Olszewski, J. M. (2012). Hydrologic performance of bioretention storm-water control measures. *Journal of hydrologic engineering*, 604-614.

Diaz, L., De Bertoldi, M., & Bidlingmaier, W. (2007). *Compost science and technology.* Elsevier.

Dunne, N., Hanson, B., & Brooklyn Botanic Garden. (2013). *Easy Compost.* Brooklyn, N.Y.: Brooklyn Botanic Garden.

Elliott, H. A., O'Connor, G. A., Lu, P., & Brinton, S. (2002). Influence of water treatment residuals on phosphorus solubility and leaching. *Journal of Environmental Quality*, 31(4), 1362-1369.

Environmental Servises Division, Department of Environmental Resources, & The Prince George's County, Maryland. (2007). *The Bioretention Manual.*

Gallimore, L. E., Basta, N. T., Storm, D. E., Payton, M. E., Huhnke, R. H., & Smolen, M. D. (1999). Water treatment residual to reduce nutrients in surface runoff from agricultural land. *Journal of Environmental Quality*, 28:1474-1478.

Glass, C., & Bissouma, S. (2005). Evaluation of a parking lot bioretention cell for removal of stormwater pollutants. *Ecosystemts and sustanable developement*, 81, 10.

Hatt, E., Fletcher, D., & Deletic, A. (2007). Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes. *Water Science and Technology*, 56(12), 11-19.

He, X. T., Traina, S. J., & Logan, T. J. (1992). Chemical properties of municipal solid waste composts. *Journal of Environmental Quality*, 21, 318-329.

Herrera Environmental Consultants, INC. (2012). *Pollutant export from bioretention soil mix; 185th avenue NE, Redmond, Washington.* Redmond, Washington.

Hubbard, A. T. (2002). *Encyclopedia of Surface and Colloid Science Volume 1.* New York, NY: Marcel Dekker, INC.

Hunt, W. F., Davis, A. P., & Traver, R. G. (2012). Meeting hydrologic and water quality goals through targeted bioretention design. *Journa of environmental engineering*, 698-708.

Hunt, W. F., Jarrett, A. R., Smith, J. T., & Sharkey, L. J. (2006). Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. *J. Irrig. Drain Eng.*, 10.1061/(ASCE)0733-9437(2006)132:6(600), 600–608.

Kang, J., Hesterberg, D., & Osmond, D. L. (2009). Soil organic matter effects on phophorus sorption: a path analysis. *Soil Sci. Soc. Am. J.*, 73(2), 360-366.

Khaleel, K., Reddy, K. R., & Overcash, M. R. (1981). Changes in soil physical properties due to organic waste applications: A review. *Journal of Environmental Quality*, 10, 133-141.

Kim, H.-Y., Lim, S.-S., Kwak, J.-H., Lee, S.-I., Lee, D.-S., Hao, X., . . . Choi, W.-J. (2011). Soil and compost type affect phosphorus leaching from inceptisol, ultisol, and andisol in a column experiment. *Communications in soil science and plant analysis*, 42(18), 2188-2199.

Kim, L.-H., Ko, S.-O., Jeong, S., & Yoon, J. (2007). Characteristics of washed-off pollutants and dynamic EMCs in parking lots and bridges during a storm. *Sci Total Environ.*, 376(1-3): 178-84.

Kirchoff, C. J., Malina, J. F., & Barrett, M. E. (2003). Characteristics of Composts: Moisture Holding and Water Quality Improvement. *CRWR Online Report 03-09*.

Li, H., & Davis, A. P. (2008). Heavy metal capture and accumulation in bioretention media. *Environ. Sci. Technol.*, 42(14), 5247-5253.

Li, H., & Davis, A. P. (2009). Water quality improvement through reductions of pollutant loads using bioretention. *Journal of environmmental engineering*, 567-576.

Li, L., & Davis, A. P. (2014). Urban Stormwater Runoff Nitrogen Composition and Fate in Bioretention Systems. *Environmental Science & Technology*, 48.6: 3403-3410.

Li, Y. C., Stoffella, P. J., Alva, A., Calvert, D., & Graetz, D. (1997). Leaching of Nitrate, Ammonium, and Phosphate From Compost Amended Soil Columns. *Compost Science & Utilization*, 5:2, 63-67.

Liu, J., & Davis, A. P. (2013). Phosphorus speciation and treatment using enhanced phophorus removal bioretention. *Environmental Science & Technology*, 48(1), 607-614.

Mitchell, D. (1997). State Highway Departments Find it Pays to Use Compost. *Bio Cycle*, 38(8), 67-72.

Murphy, J., & Riley, J. R. (1977). A modified single solution method for the determination of phosphate in natural waters. *Anal. Chem.*, 27, 37-36.

O'Neill, S. W., & Davis, A. P. (2010). Use of drinking water treatment residuals as a soil amendment for stormwater nutrient treatment. *Department of Civil and Environmental Engineering, Thesis*, 1-255.

O'Neill, S. W., & Davis, A. P. (2012). Water treatment residual as a bioretention amendment for phosphorus II: long-term column studies. *Journal of environmental engineering*, 328-336.

Palmer, E. T., Poor, C., Hinman, C., & Stark, J. (2013). Nitrate and phosphate removal through enhanced bioretention media: mesocsom study. *Water Environmental Research*, 85, 9, 823-832.

Parka, M.-H., Swamikannub, X., & Stenstromc, M. K. (2009). Accuracy and precision of the volume-concentration method for urban stormwater modeling. *Water Research*, 43, 11, 2773-2786.

Paus, K., Morgan, J., Gulliver, J., & Hozalski, R. (2014). Effects of bioretention media compost volume fraction on toxic metals removal, hydraulic conductivity, and phosphorus release. *Journal of Environmental Engineering*, 140, 04014033(9).

Pierzynski, G. M., & Kovar, J. L. (2009). *Methods of phosphorus analysis for soils, sediments, residuals, and waters.* Blacksburg, VA: Virginia Tech University.

Pitt, R., Field, R., Lalor, M., & Brown, M. (1995). Urban stormwater toxic pollutants: assessment, sources, and treatability. *Water Environment Research*, 67(3), 260-275.

Planet Natural. (n.d.). Carbon-to-Nitrogen Ratios. *Planet Natural*. Retrieved July 10, 2016, from https://www.planetnatural.com/composting-101/c-n-ratio/

Planet Natural. (n.d.). The Finished Product. *Planet Natural*. Retrieved July 10, 2016, from https://www.planetnatural.com/composting-101/how-to-use/

Rynk, R. (1998). Getting to know your feedstocks. *Bio Cycle*, 58-62.

Snedecor, G. W., & Cochran, W. G. (1989). *Statistical Methods.* Eighth Edition: Iowa State University Press.

Subramaniam, D., Mather, P., Russell, S., & Rajapakse, J. (2016). Dynamic of nitrate-nitrogen removal in experimental stormwater biofilters under itermittent wetting and drying. *Journal of environmental engineering*, 142(3): 04015090.

Sun, X., & Davis, A. P. (2007). Heavy metal fates in laboratory bioretention systems. *Chemosphere*, 66(9), 1601-1609.

U.S. Climate data. (2016). Climate College Park - Maryland. Retrieved August 2016, from http://www.usclimatedata.com/climate/college-park/maryland/united-states/usmd0100

U.S. EPA. (1983). Results of the nationwide urban runoff program. *United States Environmental Protection Agency*, NTIS PB84-185552.

U.S. EPA. (2000). Low impact development (LID), a literature review. *United States Environmental Protection Agency*, EPA-841-B-00-005.

U.S. EPA. (2002). National water quality inventory, 2000 report. *United States Environmental Protection Agency*, EPA-841-R-02-001.

Weng, L., Temminghoff, E. J., Lofts, S., Tipping, E., & Van Riemsdijk, W. H. (2002). Complexation with Dissolved Organic Matter and Solubility Control of Heavy Metals in a Sandy Soil. *Environmenal Science and Technology*, 36, 4804-4810.