Effects of Bioretention Cell Media Composition on the Removal of Nitrogen and Phosphorus

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Final Project and Report

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Concentration: Environmental Science
December 19, 2016

Abstract: Bioretention cells are engineered systems used in urban areas as stormwater treatment to remove unwanted nutrients from runoff. The objectives of the paper are to examine existing studies to determine effects of media composition, media depth, specific species of plants, and temperature on the removal/immobilization of nitrogen (N) and phosphorus (P) in bioretention cells. After reviewing studies performed to date, a number of conclusions can be reached regarding recommendations for bioretention cells to remove N and P. More times than not, N is removed through nitrification-denitrification within the media, and P is removed through sorption. Multiple studies investigating the appropriate media textures concluded that a sandy loam or sandy soil with the addition of at least 3% water treatment residuals (WTR) should be used in bioretention cells to help with removal of P. A specific organic matter (OM) recommendation could not be determined, but a positive correlation with NH_4 removal supports the Virginia Department of Conservation and Recreation guidelines of 3-5% addition of OM. N removal was higher when a saturated zone plus organic matter was used versus an unsaturated cell zone without organic matter. The pH of the bioretention cell should be between 6 and 7. The suggested media depth should be 50 to 90 cm. Certain species perform better with respect to nutrient removal efficiencies, and it is recommended that *Carex* spp. be utilized when possible. Nitrogen removal is higher when both vegetation and a saturated zone are present in a bioretention cell. Native species are convenient for cell maintenance purposes, but not all native species help remove N and P more efficiently. Although temperature does have an effect on nitrification-denitrification and P sorption through slowing infiltrations rates because of frozen soil, the results show that overall performance of the bioretention cell is not negatively affected.

Keywords: Bioretention, biofilter, nutrients, nitrogen, phosphorus, engineered media, vegetation, climate, organic matter, compost, soil, texture, P sorption, nitrification, denitrification

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1. **Introduction**

Bioretention cells, sometimes referred to as rain gardens, are engineered stormwater treatment systems used in urban areas to remove nutrients, sorb metals and organics, and sediment from runoff. The main purpose is to filter the water running off from urban areas, or areas that have a high excess of pollutants, before it gets to a waterway. These pollutants include nitrogen (N), phosphorus (P), heavy metals (e.g., copper, Cu; zinc, Zn), trace organics (e.g., polyaromatic hydrocarbons, PAHs), and total suspended solids (FAWB, 2008). Excessive amounts of N and/or P cause water quality impairment such as increased toxic algal blooms and loss of oxygen, fish, biodiversity, aquatic plant beds, and coral reefs (Carpenter et al., 1998). This paper will focus on N and P removal. These nutrients seem to be the least consistent to remove, in comparison to other pollutants, due to the difficulty and differences in the removal process via use of bioretention practices.

Nitrogen's main removal mechanism in bioretention cells is through nitrification and denitrification in the nitrogen cycle, as seen in Figure 1. For the necessary N transformations to occur, an aerobic zone must precede an anaerobic zone. Ammonium (NH_4) can be transformed into ammonia and either absorbed into the soil or released into the air (Stone, 2006). It can also go through oxidation through nitrification. The removal process starts off with nitrification, where bacteria converts ammonium to nitrite and then to nitrate (Stone, 2006). Immobilization can take place when microorganisms use ammonium or nitrate for decomposition of plant organic matter (Coletta, 2014). Then under anaerobic (anoxic) conditions nitrate is the next terminal electron acceptor and this is where denitrification converts nitrate to nitrogen gas

(Stone, 2006). Nitrogen gas is then released microorganisms into the atmosphere by using the oxygen in nitrate.

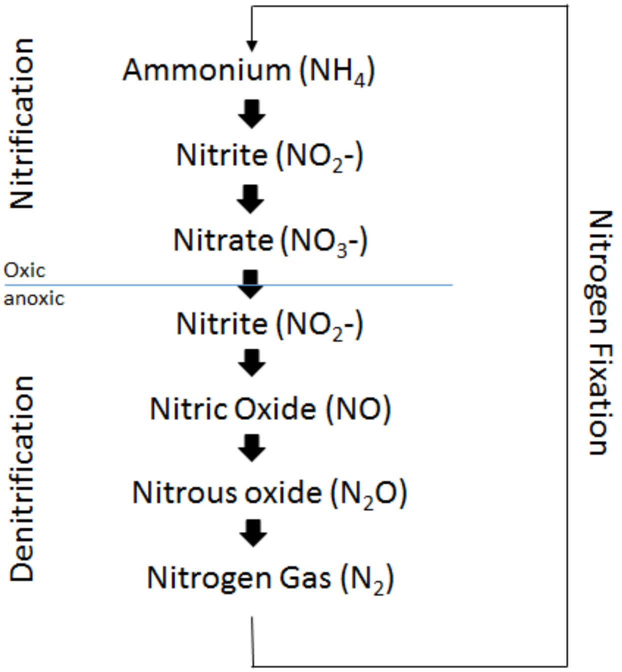


Figure 1. Nitrogen cycle in Bioretention cells.

Phosphorus removal mechanisms in bioretention cells can be through sedimentation and filtration or through adsorption, as seen in Figure 2. Particulate P removal happens through sedimentation and filtration, while dissolved P (PO_4) happens through adsorption with the presence of amorphous aluminum and iron oxides (Stone, 2006). The process of sedimentation and filtration starts when the water slows down within the bioretention cell and cannot carry pollutants. Vegetation in bioretention cells limits the amount of filtration and helps in sedimentation because when inflow water passes through vegetation, some of the pollutants can be picked up by the plant mass (Hunt, 2001). Since bioretention cells are not densely planted, filtration is typically limited. But sedimentation and filtration primary nutrient for removal is total suspended solids, litter and debris. If bioretention cells are not designed correctly, they could clog easily which is why they are rarely used for sedimentation control. The primary mechanism P is removed from in bioretention cells is absorption. Absorption is a chemical process that takes place in mulch and soil particles (Hunt, 2001). This occurs when inorganic P enters soil and is taken up my plants and converting to PO_4 (Coletta, 2014). These particles have charges that attract dissolved metals and soluble P, therefore retaining PO_4.

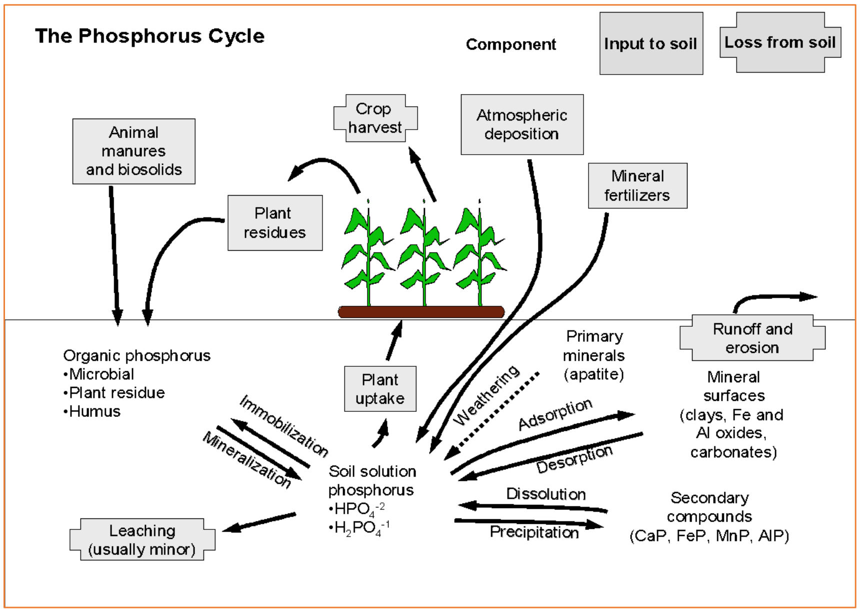


Figure 2. Phosphorus Cycle (Haering et al., 2006)

Bioretention cell (BRC) design is based on the surface area necessary to treat runoff from a particular landscape and the composition of the filtering medium, which is typically comprised of a mixture of sand, soil, and organic matter topped with mulch (Virginia DCR, 2011). The three main types of bioretention cells used today are Micro-Bioretention/Rain Gardens, Bioretention Basins and Urban Bioretention. These differ based on location and design of the cell. Micro-Bioretention/Rain Gardens are used mostly in smaller areas of runoff, such as personal rooftops, driveways, and single family developments (Virginia DCR, 2011). This type of system usually includes an underdrain where the runoff is directed for discharge after filtration (Fig. 3). Underdrains consist of a perforated pipe in a gravel layer under the bioretention cell. Bioretention basins are usually constructed in the vicinity of commercial or institutional areas and treat runoff from roadways and parking lots (Fig. 4). An underdrain is usually, but not always, included in these types of systems because it increases stormwater infiltration (Virginia DCR, 2011). Where underdrains are not included, the intent is to either promote exfiltration into surrounding soil or to further strengthen N removal (FAWB, 2008). Lastly, urban bioretention cells are commonly found in highly urbanized areas (Fig. 5). These are structures like tree pits, curb extensions and foundation planters in city streetscapes. Many factors determine the design requirements of bioretention cells, whose detailed design can be quite variable (Virginia DCR, 2011). Another important design feature in bioretention cells is a submerged zone. A submerged zone is a modification of the drainage configuration that creates a saturation zone and may have the addition of organic carbon in bioretention cells (Zhang et al., 2011). Usually when standard drainage configuration is used, it is located at the bottom of the cell (as seen in Figs. 3-5). When a submerged zone occurs, the external drainage outlet is above the bottom of the cell and helps support denitrification (Zhang et al., 2011).

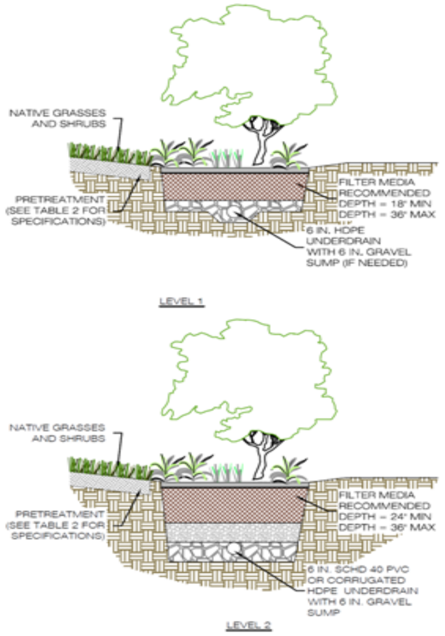


Figure 3. Example of a Micro-Bioretention Cell (Virginia DCR, 2011).

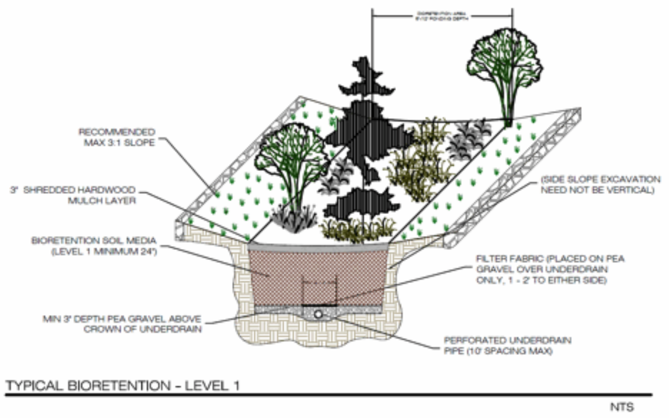


Figure 4. Example of a Bioretention Basin (Virginia DCR, 2011).

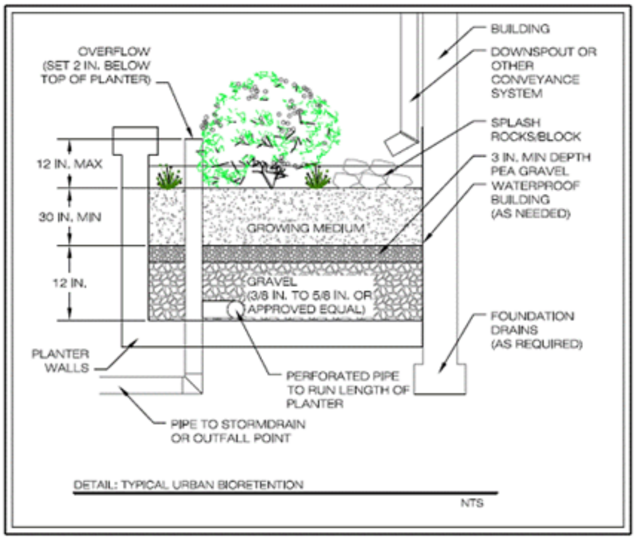


Figure 5. Example of an Urban Bioretention Cell (Virginia DCR, 2011).

Bioretention guidelines, such as those published by Virginia DCR and FAWB, have general specifications for the soil filter media. The media and surface cover of the bioretention cells are considered the most important elements that affect long-term performance. Saturated hydraulic conductivity (Ksat), which is the constant rate of infiltration, determines the location of the bioretention cell. The specifications for the saturated hydraulic conductivity is determined before installation by testing compacted media because uncompact media can show a very high saturated hydraulic conductivity, which essentially can decrease to the design value. The Ksat should approximately be 10 to 30 cm/hour for areas that are in temperate climates and 10-60 cm/hr for a tropical climate (FAWB, 2008). Bioretention cell depth can range from 45 to 120 cm; the latter is more important for tree establishment. Most bioretention systems cover the surface with 5.0-7.5 cm of shredded hardwood bark mulch (Virginia DCR, 2011). Mulch is the most common cover because it helps with plant survival, reduces weed growth, and pre-treats the runoff to some extent before it reaches the media. Even though these guidelines from FAWB and Virginia DCR are similar, difference can affect actual field performance.

Studies by Davis et al. (2006), Lucas and Greenway (2008), and Henderson (2009) have shown that vegetation included in bioretention cells increases removal of nutrients. Plant species vary in their optimum assimilative capacity of N and P (FAWB, 2008). The Virginia DCR outlines six of the most common types of vegetation styles, including turfgrass; perennial garden; perennial garden with shrubs; trees, shrub and herbaceous plants; turfgrass and tree; and herbaceous meadow.

Turf vegetation is recommended for micro-bioretention and should be chosen to maximize cover density and minimize growth rate (i.e., mowing) (Virginia DCR, 2011). Perennial garden vegetation is usually used in micro-bioretention or smaller bioretention systems that use herbaceous and native plants to create a seasonal effect. This type of vegetation often involves more work to maintain because of the weeding required. Perennial gardens with shrubs are used for bioretention systems where the filter bed is too small to support tree roots (Virginia DCR, 2011). This option of vegetation is comprised of shrubs and perennials that are a minimum height of 76.2 cm. The tree, shrub, and herbaceous plants vegetative system is the most traditional vegetation option and is usually recommended for bioretention basins. The goal of this type of vegetation system is to function like a native forest community (Virginia DCR, 2011). The turfgrass and tree vegetation option are very similar to the tree, shrub, and herbaceous option; but a low-maintenance turfgrass is used instead of mulch. For this vegetation option, trees planted in large islands surrounded by mulch so damage by mowing does not occur (Virginia DCR, 2011). The herbaceous meadow contains an herbaceous layer that looks and functions like a wildflower meadow. This the easiest and most natural vegetation to maintain. Research performed by William Hunt at North Carolina University on bioretention cells found that the dryness of the cell can indicate the type of vegetation that will thrive. From work performed in Maryland and North Carolina, it showed that facultative plants work best in bioretention cells. Facultative plants are plants that are likely to occur in both wetlands and non-wetland areas (Hunt, 2001). Since most bioretention cells are only wet during and after a rain storm, vegetation has to be drought tolerant. The Facility for Advanced Water Biofiltration (FAWB, 2008) provides more detail about the best plants for removing N and P. Such differences are due to root architecture and physiology (FAWB, 2008). *Carex*, *Melaleuca*, and *Juncus* species were the most effective species that can survive and assimilate N and P over a wide array of wet and dry conditions in bioretention cells. As mentioned before, the type of plants used for bioretention vary in the amount of nutrients they actually retain; therefore, the factors guiding the selection of the ideal vegetation should be determined by the location and the nutrient of greatest concern. It's important to point out that when herbaceous vegetation dies in the winter, the nutrients take up by those plants is then returned back into the system. This show that maintenance in removal of dead vegetation in bioretention cells is important to perform seasonally.

Maintenance of bioretention cells can differ depending on the type and composition of media and vegetation. Maintenance is usually higher in the beginning stages of the system because frequent weeding is needed and the young plants need to be watered during dry periods (FAWB, 2008). Within the first year, after rainfall of ½ inch or more, the site should be inspected two times to ensure that everything is working properly (Virginia DCR, 2011). The inspectors are mostly looking for spot reseeding in bare areas and areas of erosion. Additionally, inspectors may perform a one-time spot fertilization-where needed, after the initial planting (Virginia DCR, 2011). During the first two months, vegetation should be watered once per week if rainfall is sparse and then as needed during the first growing season. A final critical factor needed in maintenance in the first year is replacing dead plants, which typically averages about 10% of those planted (Virginia DCR, 2011). The amount of maintenance needed decreases once vegetation is mature. It is recommended to not let mosses develop because they can cause filtration problems within the cell (FAWB, 2008). Other recommendations for bioretention cells include a maintenance inspection and clean-up every spring. Virginia DCR (2011) recommends a list of general maintenance routines that should be followed, see Table 1. Not all bioretention cells require the same customized maintenance schedule due to variability in BRC type, landscape and surface cover.

Table 1. Suggested Annual Maintenance Activities for Bioretention (Virginia DCR, 2011).

Maintenance Tasks	Frequency
Mowing of grass filter strips and bioretention turf cover	At least 4 times a year
Spot weeding, erosion repair, trash removal, and mulch raking	Twice during growing season
Add reinforcement planting to maintain desired the vegetation density Remove invasive plants using recommended control methods Stabilize the contributing drainage area to prevent erosion	As needed
Spring inspection and cleanup Supplement mulch to maintain a 7.6-cm layer Prune trees and shrubs	Annually
Remove sediment in pre-treatment cells and inflow points	Once every 2 to 3 years
Replace the mulch layer	Every 3 years

Most of the information given above details general guidelines that are not always the best options for all bioretention designs. One of the unknowns that needs to be researched is what species are best at removing pollutants within different environments. It is key to determine if there are species that perform better in wet or dry environments (FAWB, 2008). Climate of the bioretention cell may have an impact on performance of soils and vegetation in removal of N and P. Another unknown that needs further research is the media composition of a bioretention cell. The media plays a big role in the performance of the nutrient removal, so a lot of items need to be t considered when planning the design. These items include but are not limited to: location, size, target nutrients, and vegetation (Virginia DCR, 2011). Important factors affecting media performance in bioretention cells are the depth of the bioretention soils, organic matter, cover layer, and bottom layer that also need to be investigated. Determining how deep to make certain layers can have an effect on how much and which nutrients are removed (Virginia DCR, 2011). This also has an effect on the system's lifespan. The objectives of the paper will be to examine existing studies to determine if certain species of plants, media composition (including texture, organic matter content, chemical binding additives), and temperature have an effect on the removal/immobilization of N and P in bioretention cells.

2. Hypotheses

1. Null- Media composition, including media texture, organic matter content, additives such as WTRs, and pH of the engineered media in bioretention cell will not have an effect on the removal/immobilization N and P.

   Alternative- Media composition, including media texture, organic matter content, additives such as WTRs, and pH of the engineered media in bioretention cell will have an effect on the removal/immobilization N and P.

2. Null- The increases in media depth of bioretention cell does not improve performance in removal of N and P.

   Alternative- The increases in media depth of bioretention cell does improve performance in removal of N and P.

3. Null- Plant species do not have an effect on removal/immobilization of N and P in bioretention cells.

   Alternative- Plant species do have an effect on removal/immobilization of N and P in bioretention cells.

4. Null- Temperature do not affect media performance of the bioretention cell to remove excess nutrients from runoff.

   Alternative- Temperature do affect media performance of the bioretention cell to remove excess nutrients from runoff.

3. Results and Discussion

3.1 Bioretention Cell Media Composition

Most bioretention cell guidelines recommend specific recipes for the composition of media. This includes sand, fines, and organic matter to provide the best combination of filtration and removal of pollutants from stormwater. Research has been conducted to test a range of these parameters to determine if different factors play a large role in affecting bioretention cell N and P removal efficiency. These factors include texture, carbon (C) and/or organic matter content, infiltration rate, P sorption rate, pH, and media cation exchange capacity. Phosphorus and N have different mechanisms by which they are retained in bioretention cells, and it is of interest to evaluate if water treatment residuals (WTR) can be used in bioretention media. Water treatment residuals are the byproducts of water treatment, using the application of colloid-coagulating Fe and/or Al sulfates (e.g., alum) for removing sediment, organic matter and contaminants such as nutrients and metals. They usually consist of oxidized Al and/or Fe, traces of metals, suspended solids, organic chemicals, and biological particles. Prior to removing the solids through filtration, aluminum, usually as $Al_2(SO_4)_3$, is added to municipal drinking water to help the fine mineral particles and organic matter in untreated water flocculate. Therefore, the final solid product (WTR) is enriched with Al and SO_4 (Stone, 2013). Once drying and aeration of the WTR occur, the amorphous Al and iron (hydro)oxides are highly reactive to dissolved P and have a large surface area where adsorption can occur (Stone, 2013). The amorphous Al oxides have high P-binding capabilities is why bioretention cell media that is enriched with WTRs retains a high amount of P. Determining the factors that affect the removal/immobilization of N and P will help optimize media composition for use in bioretention cells and indicate if WTR addition could be an option.

3.1.1 Media Texture

Hydraulic conductivity in bioretention media is crucial in the design of a cell. A bioretention cell needs to have high hydraulic conductivity to filter the designed amount of runoff water. If infiltration is low in the cell, then large amounts of the runoff would pass over the bioretention and negate any reduction of contaminants (Hsieh and Davis, 2005). But having too high of a hydraulic conductivity can cause rapid decrease to the bioretention design because flow becomes too high, therefore not allowing the retention of excess nutrients (FAWB, 2008). Hydraulic conductivity in media is dependent on size and connectivity of the pores; larger inter-connected pores in media conduct water faster. Consequently, sandy media is favored over a high clay media because finer textures conduct water more slowly than sands. Some clays tend to swell after absorbing water and shrink while drying, causing problems with infiltration (Hsieh and Davis, 2005). However, fine soils seem to be the most chemically active, so a balance of sandy and finer soil particles needs to be determined optimize removal of pollutant characteristics. Hsieh and Davis (2005) found that soil texture had no effect on the removal of nitrite and ammonium and that removal of nitrate in sand texture was ineffective. While mulch dominated cells was most effective at removing nitrate. They determined that the removal of total phosphorus (TP) varied and seemed to be correlated with chemical properties and flow behavior of the media (Hsieh and Davis, 2005). The authors recommended from their findings that bioretention media texture should consist of a layer of mixed coarse sand with a sandy loam texture.

Table 2. Summary of research data on the effects of media texture on bioretention cells N and P removal

Type of Study	Media Texture	P Removal (%)	N Removal (%)	Reference
Lab^	Sandy loam	TP: 70-80	TKN: 68-75, NH_{4+}: 60-70,	Davis et al. (2001)

			NO_3: 24	
Column^	Sandy loam	TP: 88, Ortho-P: 83	TN: 46	Bratieres et al. (2008)
Field^	Sandy loam	TP: -398	TN: -7 NO_x: -13 NH_{4+}: 64	Hatt et al. (2009)
Field^	Sandy loam	TP: 86	TN: 37 NO_x: -17 NH_{4+}: 96	Hatt et al. (2009)
Mesocosms`	Gravel	TP: 30	TN: 34 Nitrogen Oxides: 47	Lucas and Greenway. (2008)
Mesocosms`	Sand	TP: 28	TN: 29 Nitrogen Oxides: 67	Lucas and Greenway. (2008)
Mesocosms`	Loam	TP: 36	TN: 58 Nitrogen Oxides: 97	Lucas and Greenway. (2008)
Field`	Clay Loam	TP: 24 Ortho-P: 9.3	TN: 40 NO_3: 75 TKN: 4.9 NH_3: .99	Hunt et al. (2006)
Field`	Clay, Clay Loam and silty clay	TP: 65 Ortho-P: 69	TN: 40 NO_3: 13 TKN: 45 NH_3: 86	Hunt et al. (2006)
Field^	Loamy clay	TP: 53 Ortho-P: 52	TKN: 48 NH_3: 78 $NO_{2,3}$: 43 TN: 56	Passeport et al. (2009)
Field^	Sandy Loam	TP: 68 Ortho-P: 77	TKN: 68 NH_3: 88 $NO_{2,3}$: 1 TN: 47	Passeport et al. (2009)
Field^	Sand, newspaper	TP: 74	NO_3: 78	Davis (2007)
Field^	Sand, topsoil, hardwood mulch	TP: 68	NO_3: 86	Davis et al. (2006)

Mesocosm^	TerraSolve Media 15% mix of coir and peat, 9% shredded hardwood mulch, 12% WTRs, and 58% sand	TP: 98.9	TKN: 51.5	Liu et al. (2014)
Mesocosm^	Biofilter Media 25% saprolite, 20% papermill sludge compost, and 55% sand	TP: 96	TKN: 83	Liu et al. (2014)
Mesocosm^	VT mix Media 3% WTR, 15% saprolite, 25% YWC, and 57% medium sand	TP: 98.2	TKN: -57.9	Liu et al. (2014)

^ Removal data was determined by concentration
` Removal data was measured on mass

Nine studies were performed comparing the effects of media texture and percentage amounts on N and P removal retention, which are summarized in Table 2 above. The results show that P (TP and Ortho-P) removal is variable throughout different studies. Regardless, P seemed to be removed at higher amounts when the soil texture sandy loam was used as the bioretention media. A trend is seen with media texture that includes sand that shows there is usually a higher removal of P in the cell. Phosphorus, unlike N, has no ecological pathway where it can be converted into a gaseous form (Davis et al., 2006). Therefore, the P removal pathway usually occurs through vegetative uptake or through absorption in soil media most likely supports why sand has a higher removal of P. These studies supported the findings from Sharkey's (2006) study finding that the retention of P was also affected by soil texture, where a sandy loam produced the lowest P outflow concentrations. Sharkey suggested that soil that contains between 75% and 85% sand will accomplish the most removal of P (Sharkey, 2006).

Additional components are being explored to add to bioretention media, like water treatment residuals (WTR). It has been demonstrated that textural class may have more dominant control over the movement of water in bioretention cells and texture has a great effect on removing P (Thompson et al., 2008). In addition to the Liu et al. (2014) study presented in Table 2, many studies found that the addition of WTRs to bioretention media helps retain P at higher levels (Stone, 2013; Palmer et al., 2013). Liu et al. (2014) found that using <10% fine soil plus 3% of amorphous Al (for P adsorption) from WTR, 3-5% total organic carbon from compost, and a low concentration of plant-available nutrients was best for retention of excess nutrients (N, P, K, Ca, Mg, etc.) in comparison to several other types of media textures.

The nine studies (Table 2) conducted on the effects of media texture on removal of N show that N removal from stormwater is variable depending on media texture. All the studies found that N is not as dependent on soil texture as P is because no trends can be seen with the removal of N based off of media texture. Nitrogen removal in bioretention cells is mostly through denitrification by active microbial populations (Davis et al., 2006). The active microbes are supported by vegetation and organic matter in the soil media, but are also affected by media temperature and pH. Therefore, these results do not support part of the null hypothesis that media composition of the engineered media in bioretention cell will not have an effect on the removal N and P because media texture only affects removal of P. A sandy loam or sandier texture showed to be more effective at the removal of P, in addition to a small amount of WTR (3%). The addition of amorphous Al during filtration at the municipal facility to WTR positively helps the binding of P for better retention within in the cell. There was no evidence that media texture affects N removal efficiency base off the data collected.

3.1.2 Media C and/or organic matter content

The addition of organic matter to bioretention media has been a controversial topic, since the amount and type of organic matter added can increase leaching of nutrients, especially P (Hatt et al., 2009; Brateries et al., 2008; Mullane et al., 2015). There are many beneficial factors that come from adding organic matter to bioretention media, often via the addition of compost. Organics in bioretention media should consist of well decomposed natural C-containing organic materials like peat moss, humus, pink bark fines, etc. Organic matter can help plant growth in the systems by providing nutrients, improving water holding capacity and enhancing soil structure (Mullane et al., 2015). While P present in organic matter can leach during a rainstorm, metals and organics seem to have a higher retention rate that can help clean stormwater runoff (Mullane et al., 2015). Not only does it seem that the addition of organic matter in the media has a potential to affect pollutant removal, but it also has an effect on the performance with respect to infiltration, bulk density, water capacity and hydraulic conductivity in bioretention cells (Thompson et al., 2008; Olson et al., 2013). Many studies and guidelines for bioretention cell designs establish that some amount of organic matter is presumably beneficial to help remove N and P from runoff stormwater. Liu et al. (2014) found that using 3-5% total organic carbon from compost and a low concentration of plant-available nutrients was best for retention of excess nutrients. Another study found an organic matter content of 3.2% helps retain the most N and P (Chen et al., 2013). However, problems occur when compost (which contains organic matter, nitrate and P) leach these components into ground and surface water causing contamination (Iqbal et al., 2015).

Hunt et al. (2012) performed a study on bioretention cells containing organic matter and took measurements on N and P removal throughout the year. The results that are represented for Hunt et al. (2012) in the Table 2 as having a media texture of clay loam media texture, contains organic matter. The other cell represented by Hunt et al. (2012) as clay, clay loam and silty clay media texture does not have organic matter addition (Hunt et al., 2012). The results show that nitrate removal is increased in the cell with organic matter, but this is an average throughout the year. Nitrate removal may have been affected during winter but it was not captured in the study.

Table 3. Summary of research data on the effects of organic matter on bioretention cells N and P removal/leaching

Type of Study	Organic Matter	P Removed (%)	N Removed (%)	Reference
Lab^	0.6%	TP: 70-80	TKN: 68-75, NH_4^+: 60-70, NO_3^-: 24	Davis et al. (2001)
Column^	10% leaf compost	TP: 40, Ortho-P: -70	TN: 46	Bratieres et al. (2008)
Field^	5%	TP: -398	TN: -7 NO_x: -13 NH_4^+: 64	Hatt et al. (2009)
Mesocosm`	15% compost	TP: -32 Ortho-P: 74	NO_3^-: 3.25 TN: -171.75	Palmer et al. (2013)
Mesocosms`	0.3 %	TP: 28	TN: 29 Nitrogen Oxides: 67	Lucas and Greenway. (2008)
Mesocosms`	0.5%	TP: 36	TN: 58 Nitrogen Oxides: 97	Lucas and Greenway. (2008)
Field^	5% (yard waste)	TP: 53 Ortho-P: 52	TKN: 48 NH_3: 78 $NO_{2,3}$: 43 TN: 56	Passeport et al. (2009)
Field^	5% (yard waste)	TP: 68 Ortho-P: 77	TKN: 68 NH_3: 88	Passeport et al. (2009)

			$NO_{2,3}$: 1 TN: 47	
Mesocosm^	20% papermill sludge compost	TP: 96	TKN: 83	Liu et al. (2014)
Mesocosm^	25% yard waste compost	TP: 98.2	TKN: -57.9	Liu et al. (2014)

Type of Study	Organic Matter	P Leached (%)	N Leached (%)	Reference
Column`	6-month old: 100% compost (80% yard waste, 20% food waste)	TP: 8.07	TN: 7.63	Mullane et al. (2015)
Column`	24-month old: 100% compost (80% yard waste, 20% food waste)	TP: 7.37	TN: 7.63	Mullane et al. (2015)
Column`	100% compost	TP: 3.0 Ortho-P: 2.9	TN: 7.8 NO_3, NO_2: 5.2	Iqbal et al. (2015)

^ Removal data was determined by concentration
` Removal data was measured on mass

A summary of nine studies appears in Table 3 of the effects of compost on N and P removal or leaching in bioretention cells. The results varied highly in all studies, no matter the amount of OM or type (compost, newspaper, yard waste, etc.). In studies where only organic matter in small amounts (0.3-0.6%) was used, TP removal ranged from -398 to 80%. Some of the variability seen in the P removal results is due to some being averages of multiple storm events. Hatt et al. (2009) study observed rain events which all varied in effluent concentrations, as well as variation in losses, therefore explaining why TP can be -398%. Studies with the addition of compost are inconsistent with respect to TP removal, showing 5% compost removes 53-68%, 10% compost removes 40%, 15% compost removes -32% and 25% compost removes

98.2%. These inconsistencies are most likely due to other factors within the bioretention cells, like media texture and the specific type of compost (yard waste, leaf, etc.). Phosphorus leached from bioretention cells with compost in media seems to be lower in older more stable compost (24 months) compared to younger compost (6 months). The dissolved P removal is dependent on the design and actual media selection, resulting in mostly dissolved P leaching from the bioretention cell when high amounts of organic matter are mixed in with media (Hunt et al., 2012).

The results of the nine studies summarized in Table 3 also show that organic matter produces varied results for the removal of N in bioretention cells. Similar to TP removal, TN removal ranges from -7 to 58%, and TKN removal ranged from -57.9 to 83%. The highest percentage of TKN removal (83%) was associated with 25% papermill sludge compost and the lowest percentage of TKN removal (-57%) was associated with 25%-yard waste compost, where leaching was seen. The leaching percent, which is the percent of TN applied that leached out of the system, was an average of 7% when 100% compost was used in bioretention media. While all other forms of N seemed to be varied, $NH_{3,4}$ was removed positively when any amount of organic matter was used. From the data collected on the removal of $NH_{3,4}$ the addition of OM to media was from 0.3 to 5%. Organic matter plays a large role in helping denitrification within the system, which can be seen here as helping with the remove of N. The reason for such varied results between the different forms of N may be the effects the media composition could be the composition of the compost and the effects it has on nitrogen's primary removal mechanism, nitrification-denitrification reactions.

One major factor that has been related to positive removal of N has been the addition of a saturated zone. A study performed containing a media comprised of WTR, 10% compost, sand, and bark with saturated zones showed retention of up to 71% of N. This occurred through the process of denitrification, compared to 33% retention of N in the treatments without a saturated zone (Palmer et al., 2013). The saturated layer is efficient at removing N from bioretention cells because this is where the denitrification process occurs and helps block against colder atmospheric conditions (Hunt et al., 2012). Also, the saturated zone has a low infiltration rate to allow for the complete nitrification-denitrification reactions to have enough time to occur in the bioretention media (Hunt et al., 2012; Roberts, 2012).

The overall suggestions from the studies summarized in Table 3 are too varied to suggest an exact amount of organic matter to positively help retain N and P effectively in bioretention media. There were positive effects on N removal when a saturation zone plus organic matter was used. The organic matter increases C content, and a saturated layer promotes denitrification and reduces the formation of leachable nitrate-N under anaerobic conditions (Hunt et al., 2012; Roberts et al., 2012; Zhang et al., 2011). While results were variable, addition of OM promoted removal of N. These data do not support the null hypothesis that organic matter concentrations and type affect the removal of N and P in bioretention cells. The data were unable to identify an exact range of OM needed for removal of N via denitrification. There was no correlation between the amount of organic matter and the removal P.

3.1.3 Media Infiltration Rate

Soil size composition plays a key component in infiltration rate in bioretention media. Small variations in media sizes or heterogeneity can affect runoff infiltration rates (Hsieh and

Davis, 2005). Media chemical properties may mitigate the transport and detrimental effects of pollutants through different mechanisms and efficiencies. Accordingly, infiltration rates and pollutant removal ability in bioretention cells can vary differently depending on the media components (Hsieh and Davis, 2005). Other variables like compaction, root growth and density, and surface clogging also are also key components in determining infiltration rates in bioretention cells (Carpenter and Hallam, 2010). Overall, infiltration rate affects the processes by which N and P are retained in or removed from a bioretention cell but will vary over time. So usually a permeability rate is used, and is typically 2.5-15.25 cm per hour (Hunt, 2001).

Optimizing infiltration rates in media attempts to strike a balance between preventing the medium from becoming too saturated by moving water rapidly, while also permitting adequate contact of P with adsorptive surfaces. Appropriate infiltration rates are important in helping remove nutrients like N and P from bioretention cells (Lucas and Greenway, 2011a). A shorter amount of retention time (meaning higher percolation rates) does not provide N enough time to be microbially processed effectively and can therefore be washed out of the bioretention cell. The N removal processes improve when infiltration rates decline, which is a result of a longer retention time and increasing denitrification (Lucas and Greenway, 2008). A study by Davis et al. (2006) showed that there was very good removal of P under higher flow rates, whereas TKN removals suffered from the high flow rates. A study by Fahui et al. (2013) showed that P was removed better at higher rates, while N removal was low once again. They also found that a wetting/drying period was an important factor that influenced infiltration rates and the removal of N in bioretention cells (Fahui et al, 2013). Hsieh and Davis (2005) found similar results in that high infiltration rates were effective for removing particulate-P but not effective for removing N.

These authors suggest that if N removal is an objective, that a layer of sandy loam or coarse sand could promote denitrification if it is amended with organic matter, thus providing the C source of electrons for denitrification (Hsieh and Davis, 2005; Hunt et al, 2012).

3.1.4 Media P Sorption Capacity

As mentioned earlier, P is retained in bioretention cell media primarily through sorption and a small amount of microbial biomass. There are two different reactions P can go through, fast or slow reactions (Hsieh et al., 2007). The faster reaction is reversible sorption of P onto reactive media surfaces. The slower reactions are stronger, irreversible P sorption reactions with aluminum oxide minerals and the precipitation of calcium phosphates (Hsieh et al., 2007). The slow reactions are highly pH-dependent. These two reactions are also dependent on filtration processes, vegetation uptake, microorganism degradation processes, and sedimentation rates (Hsieh et al., 2007). Only a small amount of P is available for plant uptake. This occurs because organic matter decomposes in the soil and C compounds are then produced through microbial action (Guppy et al., 2005). This could possibly react directly with P sorption sites in soil, therefore potentially increase the P phytoavailability. When investigating column studies on different short and long-term sorption capacity for P, Reddy et al. (1999) found that a media with a higher amount of short-term dissolved P sorption was able to retain more P from runoff that contained a high amount of P. Short-term dissolved P sorption occurs through assimilation into vegetation or incorporation into detrital tissue but is usually released back into the bioretention cell after decomposition of the vegetation (Reddy et al., 1999). The authors found that media texture affected the short-term dissolved P sorption capacity. Soils tested that were sandy loams showed higher sorption capacities ranging from 128-137 μg/g (Hsieh et al., 2007). Sand media tested had short-term dissolved P sorption capacity from 20-89 μg/g, and mulch was even lower at 5 μg/g. The short-term dissolved P sorption capacity is linked to the slow reaction. It is determined by subtracting the total amount of P retained by the total amount of short-term dissolved P, thus, giving an estimated amount of slow reaction P retention in the cell (Hsieh et al., 2007). Long-term retention mainly depends on media sorption properties and is correlated with fast reactions of P sorption (Lucas and Greenway, 2011b). It is important to note that P removal can be highly variable over short-term studies, possibly due to increased microbial and plant uptake in bioretention cells with vegetation (Henderson, 2009).

Although Hsieh et al. (2007) showed that soil texture and vegetation play a large role in short-term dissolved P sorption, the most effective P sorption is through amorphous hydroxides of aluminum and iron. Amorphous aluminum and iron have greater surface area and more surface charge compared to more crystalline oxides for P sorption (Lucas and Greenway, 2011b). As was mentioned in Section 3.1.1, WTRs are made up of mineral colloids with aluminum or iron sulfate. Aluminum WTRs are comprised of mostly aluminum hydroxides, which are a large proportion of the most effective amorphous form for P sorption (Lucas and Greenway, 2011b). This same study found that 1.4 g of P per kg was retained of the Al-WTR, showing more long-term P loads were removed from stormwater (Lucas and Greenway, 2011b). Overall, the cells that used WTRs in bioretention media retained up to 99% of the PO4-P. Comparing these results of sorption capacity to Hsieh et al. (2007), the sorption capacity was substantially less, suggesting that WTR mixtures could be considered as an option for further P removal in bioretention cells (Lucas and Greenway, 2011b). The results from Hsieh et al. (2007) and Lucas and Greenway (2011b) help refute the null hypothesis that media composition of engineered media in bioretention cells will not have an effect on the removal/immobilization of P. The main P removal mechanism in bioretention cells is through P sorption. Phosphorus sorption has been shown by the previous studies to be affected by media composition, thus high sorption rates when a sandy loam is used and even better P retention with the addition of WTR to media, as seen in Table 2.

3.1.5 Media pH

Bioretention design guidelines recommend that media be between pH of 6 or 7 (Virginia DCR, 2011). It should be noted that pH is not a factor in research because of the narrow pH range (6-7.5) of the bioretention media under which most of the N and P transformations occurred. This range is specified/designed because of the ability to support plant growth and make essential plant nutrients readily available. This is because N and P mechanisms of removal are affected by pH. The slow reaction mentioned in section 3.1.4 on Media P Sorption, states the reaction between P and metal oxide minerals are strongly pH-dependent (Hsieh et al., 2007; Lucas and Greenway, 2011b; LeFevre et al., 2014). Phosphorus sorption to mineral surfaces is lowest between pH 4.5 and 5.5, then increases as pH increases due to sorption to Al oxide surfaces that form from soluble Al as pH rises from 5.5 to 6.0. Phosphorus desorption increases as pH rises above 6. Nitrogen form is also affected by pH. This can be seen through the form of nitrogen, ammonium (NH_4^+), that dominates stormwater that is acidic (LeFevre et al., 2014). The typical pH value for stormwater containing NH_4^+ is around 6. Stormwater pH, in general, can range from 4.5 to 8.7 due to differences the local amount of local sulfur dioxide and nitrogen oxide emissions in the upwind area (Makepeace et al., 1995).

Table 4. Summary of research data on the effects of media pH on bioretention cells N and P removal

Type of Study	Media pH	P Removal (%)	N Removal (%)	Reference
Lab^	6.4	TP: 70-80	TKN: 68-75, NH_4^+: 60-70, NO_3^-: 24	Davis et al. (2001)
Field^	6.2-6.6	TP: 24 Ortho-P: 9.3	TN: 40 NO_3^-: 75 TKN: 4.9 NH_3: .99	Hunt et al. (2006)
Field^	5.4-6.0	TP: 65 Ortho-P: 69	TN: 40 NO_3^-: 13 TKN: 45 NH_3: 86	Hunt et al. (2006)
Field*^	7.1	TP: 90	NO_3^-: 2 NH_4^+: 9	Hsieh and Davis. (2005)
Field*^	6.8	TP: 93	NO_3^-: 7 NH_4^+: 50	Hsieh and Davis. (2005)
Field*^	7.0	TP: 51	NO_3^-: 5 NH_4^+: 12	Hsieh and Davis. (2005)
Field*^	5.4	TP: 75	NO_3^-: 5 NH_4^+: 9	Hsieh and Davis. (2005)
Field*^	6.8	TP: 99	NO_3^-: 5 NH_4^+: 12	Hsieh and Davis. (2005)
Field*^	7-7.7	TP: 38	NO_3^-: 8 NH_4^+: 7	Hsieh and Davis. (2005)
Mesocosm^	6.95	TP: 98.9	TKN: 51.5	Liu et al. (2014)
Mesocosm^	6.24	TP: 96	TKN: 83	Liu et al. (2014)
Mesocosm^	6.60	TP: 98.2	TKN: -57.9	Liu et al. (2014)

*Nitrogen and P removal % are estimations based off a bar graph presented in study

^ Removal data was determined by concentration

Four studies that show the effects media pH on the removal of N and P within bioretention cells are summarized in Table 4. Phosphorus removal is usually increased at pH ≥7 (due to the formation of Ca phosphates) and ≤6 (due to sorption to Al oxides surfaces). Phosphorus desorption from mineral surfaces is greatest between pH 6-7. All the results for P removal from Liu et al. (2014) were for a pH in the range of 6 and all show high amounts of P retention (96-98.9%). Similar results were seen in studies in by Hsieh and Davis (2005) and Davis et al. (2001) when the bioretention media is between 6-7 pH. Although the Hunt et al. (2006) study shows that a more acidic pH removes more P in bioretention cells, this could be due the media composition of the cells tested. As mentioned earlier, P removal can be affected by media texture through infiltration and P sorption effects. The first cell by Hunt et al. (2006) listed in Table 4 was comprised of a clay loam and the second was made up of clay, clay loam, and silty loam. While many of the cells tested in Hsieh and Davis (2005) and Davis et al. (2001) were sandy loam or sand media textures.

The results from Table 4 on the effects of media pH on N removal indicate that N is unaffected and/or variable. The Liu et al. (2014) results show that when media pH is between 6-7, N removal percentage varied randomly. While in Hsieh and Davis (2005), all N removal percentages stayed the same no matter what the pH was. The other studies from Table 4 also show the variability of N removal percentage, therefore proving N removal is not affected by the tested range of media pH in bioretention cells.

3.1.6 Media Cation Exchange Capacity

Nitrogen sorption in bioretention cells happens through organic and inorganic substrates that adsorb ammonia (Kadlec and Wallace, 2009). This occurs because of the positive charge on the NH_4^+ ion, which then becomes subject to cation exchange. The adsorbed ammonium is retained by the media substrate and can be released when water chemistry conditions change (Kadlec and Wallace, 2009; Hsieh et al., 2007; LeFevre et al., 2014). The sorption of ammonium usually occurs when the filter dries out and the ammonium then undergoes biological nitrification, resulting in leaching loss of nitrate. Nitrate and nitrite anions do not adsorb and removal of these compounds is often poor in fast-draining bioretention systems (Chen et al., 2013; Davis et al., 2006). Therefore, different strategies need to be put in place in bioretention cells for removal of nitrate and nitrite. These include some items that have been previously mentioned like saturation zones, soil additions to promote denitrification (OM), vegetation, and accounting for seasonal differences (Chen et al., 2013). Many studies have found that ammonium removal by adsorption in bioretention media occurs during stormwater dosing and then is followed by nitrification on dry days (Cho et al., 2009; Chen et al., 2013). The study by Cho et al. (2009) found that the ammonium adsorption was seen in media that contained silt and clay greater than 3%. The authors also determined that nitrate leaching in the cell was caused by nitrification during the dry days (Cho et al., 2009). Their results showed that a CEC 5 meq/100 g or cmol$^+$ /kg or above removed the most NH_4 in the bioretention cells.

3.2 Media Depth

The depth of bioretention media plays an important role in the removal of N and P. Often, bioretention cells have limited media depths due to their location (sometimes in urban areas where space and depth are limited). Shallower depths are usually desired to help with other factors in constructing a bioretention cell, including decreasing compaction and by easing construction. Particulate-bound P is more effectively retained in bioretention cells, rather than dissolved P, because particulate P is retained by filtration and dissolved P is retained by chemical sorption (Hunt et al., 2012). To remove particulate P, only a shallow media layer needs to be present because the particulate P gets trapped with the total suspended solids. When additional reaction time is given, positive effects on P removal has been seen. Therefore, leading to recommendations of media depth of equal to or greater than 0.9 m allowing for longer reaction times (Hsieh et al., 2007). A study by Chen et al. (2013) examined N removal by determining that nitrification and denitrification genes decrease in function the deeper the media is in a bioretention cell. The authors looked into nitrogen transformation processes of denitrification, which consist of four reaction steps facilitated by four groups of enzymes (Chen et al., 2013). By looking at the 16S rDNA gene through the bioretention cell, they could determine where denitrification was occurring and at what depths. Although, there was no significant trend below 15 cm of any of the four properties (pH, soil OM content %, Mehlich P, and NO3) tested as a function of depth (Chen et al., 2013).

Table 5. Summary of research data on the effects of media depth on bioretention cells N and P removal

Type of Study	Media Depth	P Removal (%)	N Removal (%)	Reference
Lab^	0-25cm	TP: -179	TKN: 38, NH_4^+: 54, NO_3^-: -96	Davis et al. (2001)
Lab^	26-56cm	TP: 73	TKN: 61, NH_4^+: 87, NO_3^-: -205	Davis et al. (2001)
Lab^	57-91cm	TP: 81	TKN: 68, NH_4^+: 79, NO_3^-: 24	Davis et al. (2001)
Column^	30 cm	TP: 91, Ortho-P: 83	TN: 63	Bratieres et al. (2008)
Column^	50 cm	TP: 93, Ortho-P: 87	TN: 72	Bratieres et al. (2008)
Field^	0.6 m	TP: 53 Ortho-P: 52	TKN: 48 NH_3: 78 $NO_{2,3}$: 43 TN: 56	Passeport et al. (2009)
Field^	0.9 m	TP: 68 Ortho-P: 77	TKN: 68 NH_3: 88 $NO_{2,3}$: 1	Passeport et al. (2009)

			TN: 47	
Field`	0.6 m	TP: 44 Ortho-P: -39	TN: 19 TKN: 42 NO$_{2,3}$: -48 NH$_3$: 78	Brown and Hunt. (2011)
Field`	0.9 m	TP: 10 Ortho-P: -8.6	TN: 21 TKN: 57 NO$_{2,3}$: -104 NH$_3$: 77	Brown and Hunt. (2011)

^ Removal data was determined by concentration
` Removal data was measured on mass

Four studies investigating effects of media depth on bioretention removal of N and P are summarized in Table 5. The results show that removal of P increases as depth increases in most cases. This can be explained due to the fact that P removal is higher when there is a longer total retention or contact time. Therefore, in shallower depth systems, P would not be given enough time to be adsorbed. At deeper depths there are longer retention times, giving more time for P sorption. The only differing result is from the study performed by Brown and Hunt (2011), who found that at shallower depths more TP was retained.

The four studies (Table 5) on effects of media depths on N removal report similar results to those for P removal. In most of the occurrences, all forms of N are removed at higher percentages with thicker media. This is most likely due to nitrification-denitrification being enhanced with thicker media and greater depth. Overall, the results from Table 5 support rejecting the null hypothesis that media depth of bioretention cell does not improve performance in removal of N and P. Overall, the four studies show that N and P removal improve with increasing media depth and that P is retained to a larger extent in deeper bioretention cells.

3.3 Vegetation in Bioretention Cells

Vegetation in bioretention systems has been proven to increase the retention of excess nutrients in many different studies, along with having other benefits. Vegetation helps slow influent flow in the bioretention cells (Davis et al, 2006). Lucas and Greenway (2011c) concluded that vegetated bioretention mesocosms retained greater N than unvegetated mesocosms as demonstrated by the appearance of less NO_3 and total nitrogen (TN) in effluent. An earlier study by Lucas and Greenway (2008) determined that there was greater removal of N and P in vegetated mesocosms than in bare mesocosms. Averaged over the different media, the vegetated mesocosms retained more nutrients (Lucas and Greenway, 2008). Increased microbial immobilization and plant assimilation will also increase P retention (Henderson, 2009). The next section will discuss effects of different species, native versus non-native species, submerged zones and rooting factors on removal/immobilization of N and P in bioretention cells.

3.3.1 Differences in plant species

There are certain vegetation types that can be selected to maximize removal efficiencies (Lucas and Greenway, 2008). Read et al. (2008, 2010) performed two studies to investigate whether different plant species can increase removal of N and P in bioretention cells. Both studies found that the effluent N and P levels were usually lower in systems with vegetation than without. They also found that certain species were better at removing N and P in bioretention cells (Read et al., 2008, 2010).

Table 6. Summary of research data on the effects of plant species used in bioretention cells for N and P removal

Type of Study	Plant Species	P Removal (%)	N Removal (%)	Reference
Column^	None	TP: 81, PO_4^{3-}: 50	TN: -201	Bratieres et al. (2008)

Column^	*Carex*	TP: 95, PO$_4^{3-}$: 90	TN: 71	Bratieres et al. (2008)
Column^	*Dianella*	TP: 78, PO$_4^{3-}$: 44	TN: -152	Bratieres et al. (2008)
Column^	*Microleana*	TP: 83, PO$_4^{3-}$: 61	TN: -151	Bratieres et al. (2008)
Column^	*Leucophyta*	TP: 77, PO$_4^{3-}$: 40	TN: -241	Bratieres et al. (2008)
Column^	*Melaleuca*	TP: 84, PO$_4^{3-}$: 74	TN: 46	Bratieres et al. (2008)
Field^	*Carex appressa*, *Carex tereticaulis*, *Lomandra longifolia*, *Isolepis nodosa*, *Caleocephalus lacteus*, and *Juncus spp*	TP: -398	TN: -7, NH$_4^+$: 64	Hatt et al. (2009)
Field^	*Dianella*, *Carex appressa*	TP: 86	TN: 37, NH$_4^+$: 96	Hatt et al. (2009)
Columns*^	None	TP: 87 PO$_4^{3-}$: 81	TN: -200--85	Fletcher et al. (2007)
Columns*^	*Carex*	TP: 91 PO$_4^{3-}$: 87	TN: 50-65	Fletcher et al. (2007)
Columns*^	*Dianella*	TP: 86 PO$_4^{3-}$: 78	TN: -150--50	Fletcher et al. (2007)
Columns*^	*Microleana*	TP: 87 PO$_4^{3-}$: 82	TN: -150--20	Fletcher et al. (2007)
Columns*^	*Leucophyta*	TP: 87.5 PO$_4^{3-}$: 81	TN: -240--75	Fletcher et al. (2007)
Columns*^	*Melaleuca*	TP: 86.5 PO$_4^{3-}$: 82	TN: -25-50	Fletcher et al. (2007)

*Nitrogen and P removal % are estimations based off a lines graph presented in study
^ Removal data was determined by concentration

There were three studies (Table 6) that presented data on the difference of vegetation species effects on removal of N and P in bioretention cells. These indicated that the genus *Carex* appears to retain more P; however, differences were not significant. While TP removal was in the 90% range, parallel columns with no vegetation showed TP removal in the 80% range. The results for PO_4 are more variable because Bratieres et al. (2008) showed that PO_4 removal are lower for other and non-species columns than for *Carex*. Other studies show that *Carex* species reduce concentration of pollutants in bioretention cells more than other species (Read et al., 2008, 2010). Hatt et al. (2009) showed that a large variety of species (high diversity) in one cell resulted in less P removal, whereas a cell with only two species retained more P (Table 6). Promoting high species diversity is not a recommended practice for bioretention systems, possibly due to reduced plant P availability under competition that occurs with high species diversity (Güsewell, 2004).

The three studies that are summarized in Table 6 also show that N removal is affected by species. Unlike P removal, N removal clearly varies by species, and *Carex* results in greatest removal. Bratieres et al. (2008) and Fletcher et al. (2007) determined that *Carex* removes 50-71% of TN, while most other species add TN to the system. Hatt et al. (2009) showed similar N removal by Carex. In a bioretention cell with a large variety of species, TN removal was negative and NH_4^+ removal was 64% of the input. When comparing this cell to a cell only containing two vegetation types, the cell with two species outperformed for removal of both TN and NH_{4+}. Overall, the results in Table 6 do not support the null hypothesis that plant species do not have an effect on removal/immobilization of N and P in bioretention cells. Although P removal ranges between different species was minimal, a small improvement was seen when *Carex* was used. *Carex* also helped improve N removal in bioretention cells significantly compared to other species. This most likely has to do with *Carex's* ability to uptake N; thus, a possible reason for the increased N removal.

3.3.2 Native vs Non-native

It is considered that native plants are more tolerant of the climate where the bioretention cell is located and easier to maintain (Stuber, 2012). However, when Coletta (2014) evaluated the differences between native and ornamental plant species ability to capture pollutants in bioretention cells, he found that non-natives worked just as well. Four native species (*Calamagrostis canadensis* P. Beauv. (Bluejoint Grass), *Carex stricta* Lam. (Tussock Sedge), *Pycnanthemum virginianum* L. (Virginia Mountain Mint), and *Rudbeckia hirta* L. (Black-eyed Susan)) and four ornamental species (*Calamagrostis x acutiflora* F.'Overdam' (Feather Reed Grass), *Carex muskingumensis* Schwein (Palm Sedge), *Pycnanthemum muticum* Pers. (Clustered Mountain Mint), and *Rudbeckia fulgida* Aiton 'Goldsturm' (Goldsturm Black-eyed Susan)) were used at eight bioretention sites (Coletta, 2014). The results are summarized in Table 7, where neither the native nor the ornamental genus of *Calamagrostis*, *Carex*, and *Pycnanthemum* showed any differences among the amount of nutrient removal from runoff water in the column experiment. The ornamental *Rudbeckia* (*Rudbeckia fulgida*) increased the removal of NO_3, ortho-P, TN and TP over the native *Rudbeckia hirta* (Coletta, 2014). The author examined plant cover over two years in the field study. Two of the genera, *Calamagrostis* and *Pycnanthemum*, that were cultivated both as native and ornamental provided 100% ground cover both years (Coletta, 2014); whereas the ornamental *Carex muskingumensis* outperformed the native genus *Carex stricta*. The native *Rudbeckia* survived only one year, while the ornamental did not survive flooding (Coletta, 2014). Plant selection for performance in bioretention cells should not be limited to natives. It is normally suggested that native plants be used, due to ease of maintenance, but there isn't evidence that they improve removal of N and P in bioretention cells (Stuber, 2012).

Table 7. Summary of research data on Coletta's (2014) study on effects of native vs. non-native plant species used in bioretention cells for N and P removal

Native or Non-native	Plant Species	P Removal (%)	N Removal (%)
Native	*Calamagrostis canadensis*	TP: 74.99, Ortho-P$^-$: 68.78	TN: 71.41 NO_3: 67.92
Non-native	*Calamagrostis 'Overdam'*	TP: 79.93, Ortho-P$^-$: 63.67	TN: 74.20 NO_3: 70.38
Native	*Carex stricta*	TP: 76.52, Ortho-P$^-$: 61.74	TN: 61.54 NO_3: 42.83
Non-native	*Carex muskingumensis*	TP: 78.49, Ortho-P$^-$: 58.94	TN: 64.79 NO_3: 49.90
Native	*Pycnanthemum virginianum*	TP: 80.50, Ortho-P$^-$: 75.65	TN: 71.74 NO_3: 72.39
Non-native	*Pycnanthemum muticum*	TP: 76.47, Ortho-P$^-$: 68.79	TN: 71.91 NO_3: 71.88
Native	*Rudbeckia hirta*	TP: 68.51, Ortho-P$^-$: 59.70	TN: 77.30 NO_3: 57.37
Non-native	*Rudbeckia fulgida var. sullivantii 'Goldsturm'*	TP: 77.35, Ortho-P$^-$: 24.96	TN: 83.50 NO_3: 82.26

3.3.3 Submerged zone within a cell with vegetation

It was discussed in Section 3.1.2 that a submerged zone (saturated zone) is beneficial to N removal processes. A study in Washington state by Zhang et al. (2011) investigated N and P removal in bioretention cells with four plant species in the presence of a submerged zone to determine if there are any performance increases under a wet-dry seasonal (Mediterranean) climate. By examining all nutrient forms, the authors assumed they could account for all different forms for N and P while determining which nutrients were most likely retained by a bioretention cell. The different experimental columns contained four separate species (*Baumea juncea* R.Br., *Melaleuca lateritia* A. Dietr., *Baumea rubiginosa* G. and *Juncus subsecundus* N.A.Wakef.) with a submerged area or without. There was also a control with no plants but with a submerged zone. Zhang et al. (2011) observed that N removal was higher in cells that had any type of vegetation with a submerged zone. The P removal was lower with a submerged zone, regardless of the presence of vegetation. Nitrogen was mostly removed via denitrification, which benefited from the combination of a submerged zone with carbon addition (Zhang et al., 2011). The P removal mechanism is mostly adsorption through media in bioretention cells and low redox lead to Fe-oxides being reduced and lowering P-sorption capacity. This is probably why the researchers observed no significant differences in P removal between vegetated and unvegetated bioretention cells with a submerged zone. The highest P concentrations were found in the topsoil, likely due to high P adsorption by media (Zhang et al., 2011). There was a significant difference in N removal among the four different species with submerged zones for only NH_4-N. The results showed the NH_4-N was lower with *M. lateritia* than other species (except *B. juncea*) in cells with submerged zones (Zhang et al., 2011). These result indicate all species removed the same amount of P over time when there was no submerged zone in the bioretention cell. While N removal was higher in plots with a submerged zone, there was only a small difference in the removal of NH_4-N. These results still do not give enough evidence to pick one species over another to help the performance of N and P removal in bioretention cells because the results show that the presence of submerged zones, not species, has the primary effect on nutrient removal performance. Palmer et al. (2013) supported this research with their study finding that vegetation with a saturated zone had no major effects on removal of P. However, saturated zones with vegetation that have longer roots is key to the removal of N.

3.3.4 Root Factors

Rooting characteristics of plants are important factors in the immobilization of N and P. It has been shown that length of root, root diameter and root mass have all been correlated to effective removal of N and P from runoff (Stuber, 2012). Plant species with larger and longer roots have been found to be more effective at removing N and P (Stuber, 2012; Li et al., 2009). Vegetation roots may also help loosen media to prevent clogging from other debris within the cell (Li et al., 2009).

When examining studies on root systems in bioretention cells, it seems the evidence points to more N removal when roots have a higher surface area to volume ratios (Bratieres et al., 2008). This same study finds that the vegetation rooting depth affected TN removal in bioretention cells. Table 5 shows that *Carex* provided the best TN removal, retaining 71% of TN from runoff stormwater. Analysis of *Carex* plants show their roots have high numbers of microscopic fine hairs that increase the area of soil exploitable by the plant (Bratieres et al., 2008). An earlier study by Read et al. (2008) found that effluent pollutant concentrations per unit root mass were correlated, as seen in Figure 6. The authors concluded that *Carex, Melaleuca* and *Juncus* spp. are the most effective at reducing pollutant concentrations per unit root mass. Read et al. (2010) found that total root lengths, rooting depths, root masses, and N and P removal were greatest for *Carex, Melaleuca* and *Juncus* species. These results were supported by Bratieres et al. (2008) who found that *Care*x and *Melaleuca* were more efficient at removing N because of their dense root systems. These results support the data from section 3.3.1 of this paper, in that N removal is mostly affected by plants because dense root systems help the process of N removal in bioretention cells. Phosphorus retention appears to increase when plants with dense root systems are used, because they typically assimilate more soil P.

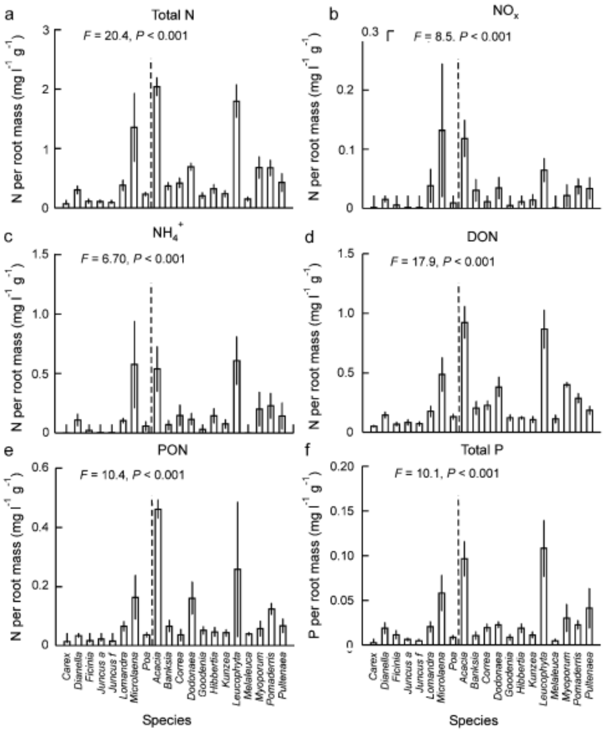


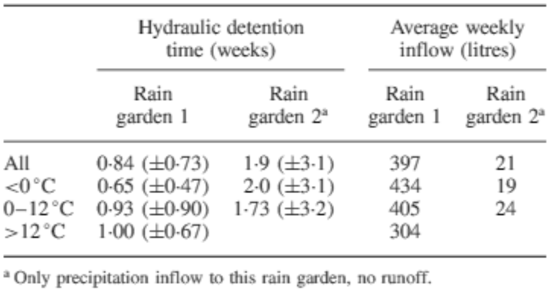
Figure 6. Comparisons of effluent N and P concentrations among species after adjustment for root mass (Read et al., 2008). (Reprinted from Water Research, 42(4), Read, J., Wevill, T., Fletcher, T., & Deletic, A., Variation among plant species in pollutant removal from stormwater in biofiltration systems, 893-902, Copyright (2008), with permission from Elsevier)

3.4 Temperature

Air temperature and climate have an effect on the performance of removing nutrients in bioretention cells. Denitrification is affected by soil temperature, which is the process that helps remove N from bioretention cells (Blecken et al., 2010). Additionally, it seems that temperature has effects on NH_4 fixation and microbial nitrogen uptake (Blecken et al., 2010). Retention of P through sorption increases with temperature (Blecken et al., 2010). Vegetation growth also varies seasonally, thus affecting plant nutrient uptake. Investigating the dependence of climate and location on bioretention cells is important because there are still high levels of nutrient runoff in cold climates and locations. These high contaminant levels are usually created when pollutants are stored and piled up in snowpacks and through the application of de-icing salts agents on roadways (Blecken et al, 2010). De-icing salts usually contain P (in the de-caking agents applied) that can runoff into the environment during a storm event (DeBusk and Wynn, 2011). If we can determine a way to make sure a bioretention cell is working at full capacity all year long, then the most nutrients will be retained and ensure a cleaner environment.

LeFevre et al. (2009) performed a field study to determine if bioretention cells still infiltrate efficiently during the winter. Their results showed that the bioretention cell maintained its hydrologic function in the cold climate. The most interesting finding was that the type of frost had the biggest influences on performance. The type of frost restricted or facilitated infiltration by either being “concrete frozen” or “granular frozen” (LeFevre et al., 2009). Concrete frost conditions occur when saturated soil freezes and creates a layer of ice, therefore restricting infiltration. Whereas, granular frost occurs when unsaturated soils have a small amount of moisture that freezes and facilitates rapid infiltration (LeFevre et al., 2009). Muthanna et al. (2008) performed a similar study in Norway, investigating hydraulic detention, storm lag time and peak flow reduction. They found that lag time and hydraulic detention were lowest in winter when snow melts rates were highest. This could mean that snow melts decrease lag and detention time (Muthanna et al., 2008). Table 8 shows the seasonal hydraulic detention time and average weekly inflows at different temperatures. The data shown indicate a lower detention time in Rain garden 1, meaning water infiltrates faster. Rain garden 2 has a higher detention time during colder temperatures. However, due to the standard error overlap in both rain gardens, overall there was no difference in performance of the bioretention cells when temperatures were below freezing and during snowmelt events.

Table 8. Seasonal hydraulic detention time and average weekly inflows of a bioretention cell (Muthanna et al, 2008) (Reprinted from Hydrological Processes, 22(11), Muthanna, T. M., Viklander, M., Thorolfsson, S. T., Luleå tekniska universitet, Institutionen för samhällsbyggnad och naturresurser, & Arkitektur och vatten., Seasonal climatic effects on the hydrology of a rain garden., 1640-1649, Copyright (2008), with permission from John Wiley and Sons)



	Hydraulic detention time (weeks)		Average weekly inflow (litres)	
	Rain garden 1	Rain garden 2[a]	Rain garden 1	Rain garden 2[a]
All	0·84 (±0·73)	1·9 (±3·1)	397	21
<0 °C	0·65 (±0·47)	2·0 (±3·1)	434	19
0–12 °C	0·93 (±0·90)	1·73 (±3·2)	405	24
>12 °C	1·00 (±0·67)		304	

[a] Only precipitation inflow to this rain garden, no runoff.

A study by Moghadas et al. (2016) investigated infiltration of water in two frozen engineered soils throughout the whole year to determine the effect of media texture on N and P. Two types of engineered soils were used for this study: one coarse soil based on recommendations of the studies by Blecken et al. (2010) and Søberg et al. (2014), and one fine soil based on recommendations from the FAWB (2008) and Washington State University

(Moghadas et al., 2016). The authors believed that a coarse soil that is well-drained would avoid blocking by ice and would retain hydraulic performance during freezing temperatures. Muthanna et al. (2008) supports a coarse soil media texture by explaining that sandier soil is used to improve winter infiltration. Moghadas et al. (2016) found that a critical factor in the thawing process was the soil water content. When the temperature in the column drops to freezing, the soil moisture freezes and blocks pores. This requires energy from the infiltration water to melt the frozen soil in the bioretention cell media, therefore possibly creating blockage of pores if soil is concrete frozen (Moghadas et al., 2016). The study showed that soils with higher initial water content take longer to thaw, with water breakthrough time taking longer. Lastly, the authors found that there was more compaction in the column of finer-textured soils, resulting in reduced porosity and increased thawing time (Moghadas et al, 2016).

The results from this section support the null hypotheses that temperature does not affect ability of the bioretention cell media to remove excess nutrients from runoff. However, if the bioretention cell is saturated and freezing occurs, stormwater runoff may not be able to flow through the system. The freezing of the bioretention cell did not seem to have an effect on retention of N and P over the winter season. After careful research, it seems that P removal is not affected because the physical removal mechanism of passive sedimentation is not correlated with temperature. The data presented over the seasons shows that bioretention N removal performance is maintained. This is most likely due to the fact that the N removal mechanism of denitrification is less effective at lower temperatures.

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4. Conclusions

After extensive research, some overall conclusions can be made for the recommendation on bioretention cell designs, but for other factors more research is needed. More often than not, N is removed through nitrification-denitrification within the soil and P is removed through sorption. These mechanisms are affected positively and negatively by different factors within the cell. Some of the factors are bioretention media composition, vegetation and climate/temperature, and within those factors there are other components that affect removal.

There were nine studies that investigated differing media textures and concluded that only P is affected by media texture. It is suggested that a sandy loam or sandier texture with a small amount of WTR (3%) is the most effective at removing P in bioretention cells. It is also noted that the addition of amorphous Al to WTR helps bind P for better retention within the cell. The conclusions on organic matter type and content are too varied to make a recommendation on the exact amount of organic matter to add to media in bioretention cells to help removal of N and P. But since there seemed to be a positive correlation with $NH_{3,4}$ removals in the range of 0.3 to 5%, we can conclude that Virginia DCR recommendations of 3-5% addition of OM would be an efficient. Nitrogen was retained at higher amounts when a saturation zone plus organic matter was used compared to a cell with no saturation zone. The organic matter helps to enhance creation of a reduced saturated layer to help with denitrification. This then leads to lower nitrogen release in effluents during anaerobic conditions. The pH of the bioretention cell should be 6-7. Higher pH levels have been shown to cause less retention of P and lower pH level retained less P from effluent, whereas N removal shows no correlation to pH.

The media depth of bioretention cells plays an important role in the removal of N and P. Deeper media depths show positive removal of P and N. The suggested depth of media in a bioretention would be 50 to 90 cm. Greater depths mean longer contact times, giving more time for P sorption. Therefore, this also suggests that nitrification-denitrification is enhanced with deeper media.

Vegetation in bioretention systems has been proven to increase the retention of excess nutrients. It was determined that certain species perform better and it is recommended to use *Carex* in bioretention design for better removal of N. Phosphorus removal was minimally affected by vegetation species, but a small increase in removal was seen with *Carex*. The plan genus *Carex*, has also been shown to have longer, denser root systems. This helps with the removal of N through denitrification. Plant selection for performance in bioretention cells should not be limited to natives because there was no significant difference seen between native and non-native plants in the Coletta (2004) study. But it should be noted, that the use of native plants has other benefits other than just nutrient removal. Some of these reasons are native species are lower maintenance and better growth performance. Non-native or invasive species can cause major problems to not only other bioretention plants, but nearby plant communities. There was a correlation between vegetation and a submerged zone, showing N removal is higher when both are present in a bioretention cell. The correlation between vegetation, submerged zone and N removal mostly likely occurs because of N removal mechanisms, primarily denitrification.

Although climate/temperature does have an effect on nitrification-denitrification and P sorption through slowing infiltration rate, these effects were not seen in the data reviewed. Slower infiltration rates and differences in media texture were detected, but were not significant enough to have a negative effect on N and P removal. More research is needed on this topic to help determine if climate/temperature affects removal of N and P in bioretention cells.

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