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Biofiltration Media Optimization – Phase I
FINAL REPORT

by

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SUMMARY FOR PRACTITIONERS

Biofiltration has become common in Minnesota's urban landscape because it is one of the most robust stormwater treatment practices available to designers. Stormwater professionals and practitioners, however, still face challenging decisions while designing these practices and often feel as if they are guessing when selecting media components and designing these practices. In particular, the most commonly used and recommended biofiltration media mixes have been shown to export phosphate, potentially contributing to water quality impairments. This increases environmental risk and uncertainty when attempting to implement Total Maximum Daily Load recommendations. Thus, the objectives of this research are to 1) **identify which local and sustainable biofiltration media are effective** for filtration rate and supporting plant growth and microbial function, while not releasing phosphate, and 2) **document local sources, simple tests or metrics, and/or design specifications** that can be used by practitioners to reliably and repeatably obtain a biofiltration practice that functions as expected. This study intends to fill the knowledge gap of the best available biofiltration media components that can be locally sourced in Minnesota and accurately specified. With this knowledge, practitioners will be empowered with confidence to design biofiltration practices with the best available knowledge and understanding of media components in Minnesota.

Mesocosm studies on various biofiltration media mixes were completed in the outdoor spillway adjacent to St. Anthony Falls Laboratory to evaluate the impact of media components on filtration rate, nutrient output, and vegetation growth during one rainy season. In addition to mesocosms with 100% clean washed concrete sand as baseline control, seven different biofiltration media amendments were added to clean washed concrete sand in various ratios (by volume) as follows:

- 10% food residue compost + 90% clean washed sand,
- 20% food residue compost + 80% clean washed sand,
- 10% leaf compost + 90% clean washed sand,
- 20% leaf compost + 80% clean washed sand,
- 15% biochar + 20% leaf compost + 65% clean washed sand,
- 5% spent lime + 20% leaf compost + 75% clean washed sand,
- 5% iron + 20% leaf compost + 75% clean washed sand,
- 20% sphagnum peat + 80% clean washed sand, and
- 20% reed sedge peat + 80% clean washed sand.

Fourteen simulated events each released approximately five gallons of phosphorus-enhanced water during summer and fall 2019. Flow rate through the mesocosms was measured and samples of the influent and effluent water were tested for nitrate and phosphate. In between events, settling, vegetation growth, and rainfall movement through each mesocosm were also monitored. The literature review, methods, results, and discussion are described in the full report (Erickson et al. 2021).

Summary of Results

Objective #1: Filtration Rate

The filtration rate was measured as the flow rate (volume per time) through the outdoor mesocosms. In summary, 50% of the influent volume passed out of the mesocosms within approximately 5 – 15 minutes on average for all media mixes and events. Approximately 70-80% of the influent volume passed through the mesocosms within approximately 20 minutes. Statistically, only the iron mix was significantly different (required less time) than 100% clean washed sand. Also, the time required for all mesocosms to reach 50% effluent volume increased from the first experiment (summer) to the last (autumn), as shown in Figure 1. Standing water in the mesocosms was only observed in one or two of the reed sedge peat mesocosms, and only in two events, which resulted in a larger standard deviation (error bars in Figure 1) and longer time to reach 50% effluent volume. All media mixes released between 80% and 98% of the influent volume at 120 minutes after the start of the experiment for all events. The full results and data of flow through the mesocosms is described in detail in section 4.2.1 of the full report (Erickson et al. 2021).

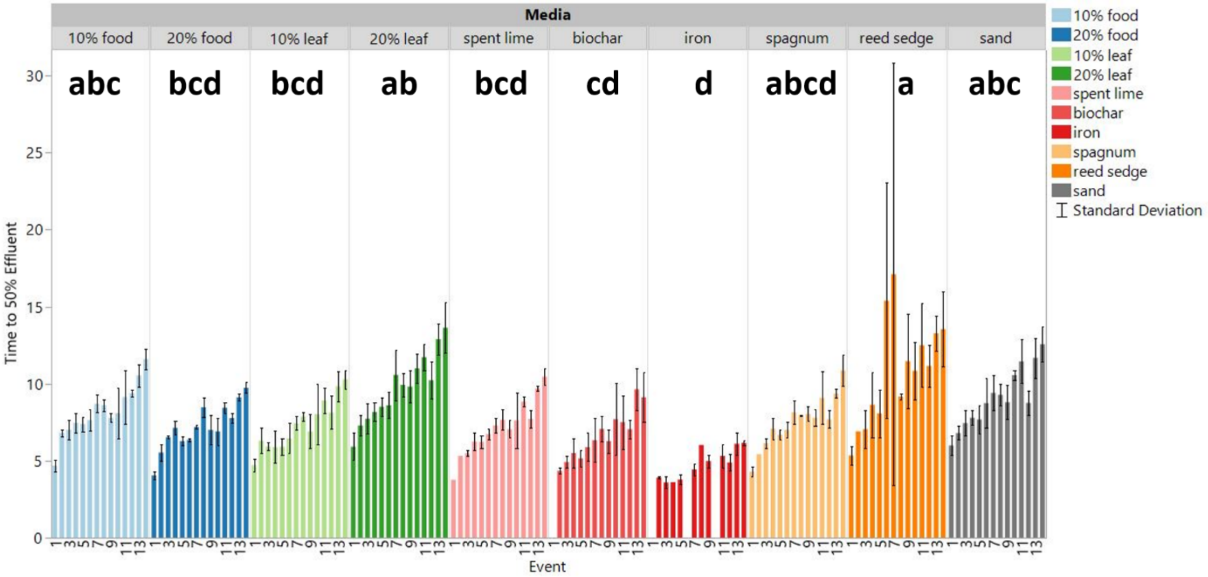

Figure 1: Time (minutes) to 50% effluent by media mix treatment over simulated stormwater events. Data are missing when the time to 50% effluent was less than the initial recording time. Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc, α = 0.05).

Objective #2: Supporting Vegetation Growth

The mesocosms were seeded with switchgrass and the maximum height of vegetation was measured approximately weekly. The average maximum height increased from germination until approximately 50 days after seeding (see Figure 2), after which the maximum height remained relatively constant. The maximum vegetation height and above-ground biomass measured near the time of senescence was greatest in the spent lime media mix, which was the only media mix that was statistically different (greater) than the 100% sand for both vegetation height and biomass. For biomass, the iron media mixes were statistically similar to sand and the biomass for all other treatments (food compost, leaf compost, biochar, reed-sedge peat, and sphagnum peat) were not significantly different from each other or significantly different from iron, sand, or spent lime. The full results and data of vegetation growth within the mesocosms is described in detail in section 4.2.3 of the full report (Erickson et al. 2021).

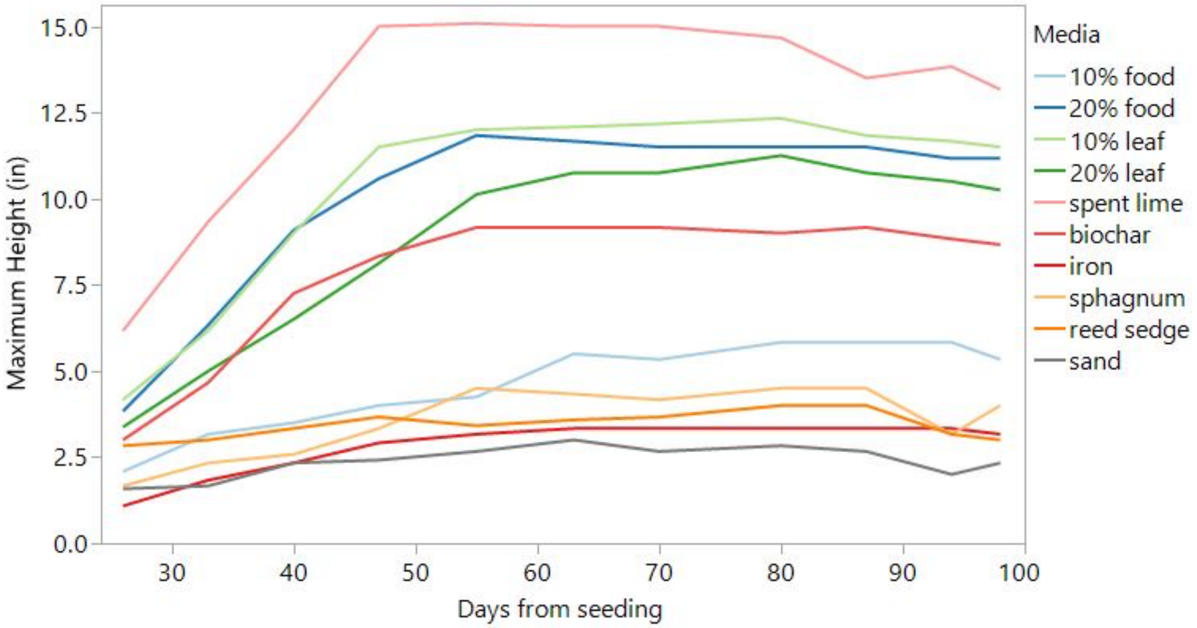

Figure 2: Average (n = 3) maximum height for each media mix treatment for switchgrass, excluding data from mesocosm 1 (20% leaf with no vegetation growth).

Objective #3: Limiting Phosphate Release

Phosphate was measured in the effluent after every simulated stormwater event (Figure 3). The effluent phosphate concentration from 10% and 20% food compost, 10% and 20% leaf compost, biochar, and spent lime media mix treatments were significantly larger than the inflow (tank). More compost (20% vs. 10%) increased the effluent phosphate concentration. Leaf-based compost also produced a larger effluent phosphate concentration compared to food residue compost. The effluent phosphate concentration from biochar and spent lime (both mixed with 20% leaf compost) was less than the phosphate concentration from 20% leaf compost alone but larger than the influent and 100% sand, suggesting that biochar and spent lime captured some but not all of the phosphate released from leaf compost.

In contrast, the effluent phosphate concentration from the iron, peat mixes (reed sedge and sphagnum), and 100% sand media mixes was statistically less than the influent tank (tank average = 197 µg/L), as shown in Figure 4. Compared to the tank phosphate concentration (average = 197 µg/L), the iron media mix captured phosphate from the influent and phosphate released from the 20% compost (20% leaf compost average = 1643 µg/L; see Figure 3) and reduced the phosphate concentration down to 13 µg/L, on average. The sphagnum and reed-sedge peats (30 µg/L and 26 µg/L phosphate, respectively) also captured phosphate from the influent.

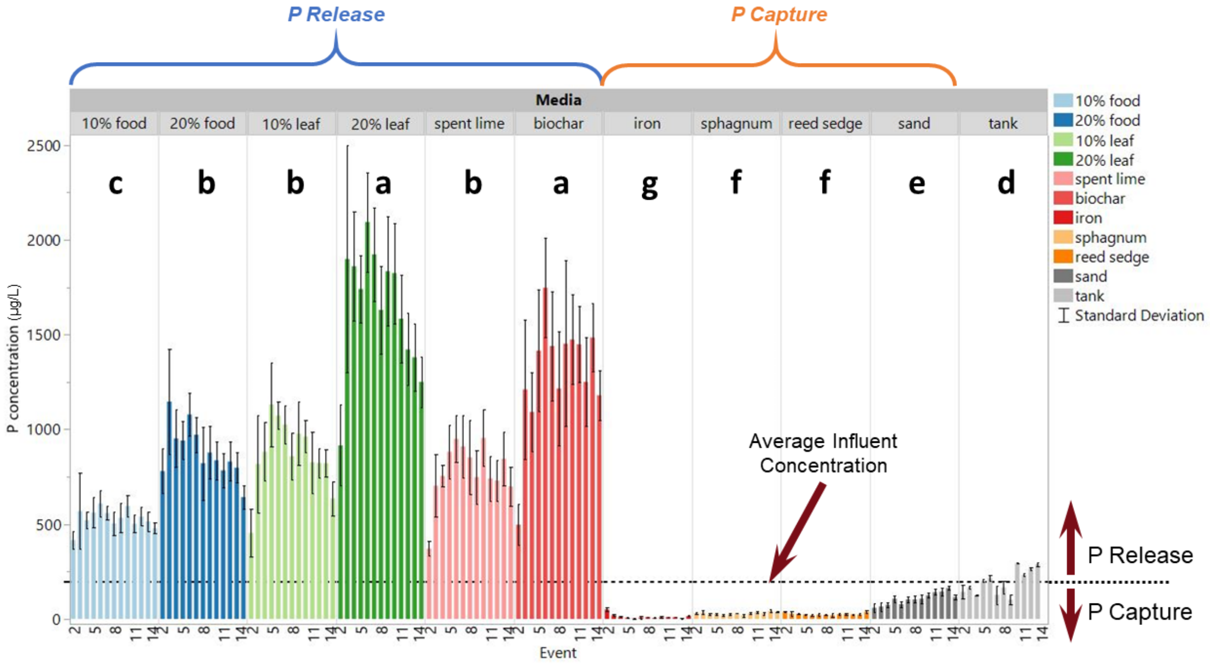

Figure 3: Phosphate as P concentration (µg/L) in effluent across events by media mix treatments and influent (tank). Dashed line indicates the average of the influent concentrations (197 µg/L). Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc on ln-transformed data, α = 0.05).

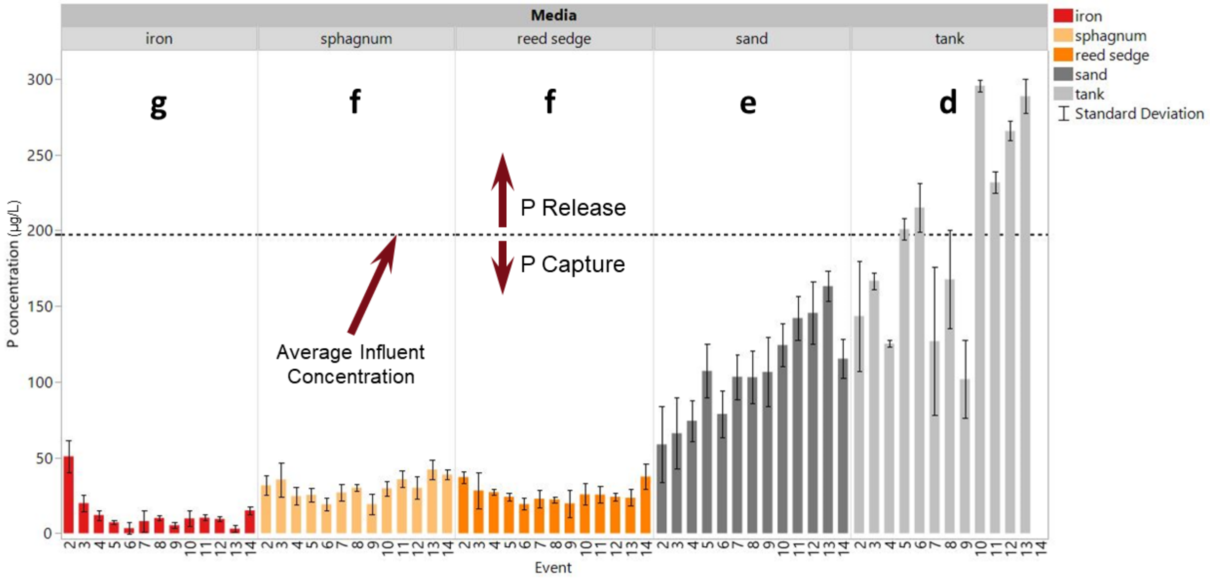

Figure 4: Phosphate as P concentration (µg/L) in effluent for iron, sphagnum peat, reed-sedge peat, 100% sand, and influent (tank). Dashed line indicates the average of the influent concentrations (197 µg/L). Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc on ln-transformed data, α = 0.05).

Nitrate transport was also measured in the mesocosm experiments. The effluent nitrate concentration from the 10% leaf, 20% leaf, biochar, and spent lime media mixes resulted in significantly more nitrate compared to the inflow (tank). This was especially true for the spent lime mix for the fourth event which resulted in a very large (>9 mg/L) nitrate release. The other media mixes (10% food, 20% food, iron, sphagnum peat, reed sedge peat, and 100% sand) were not significantly different than the influent nitrate concentration. The pH was also measured, and the spent lime media mix pH (average = 9.16) was statistically similar to 20% leaf compost and biochar, but greater than all other media mixes, including the tank (average pH = 8.87). The iron (average pH = 8.75), sphagnum peat, reed sedge peat, and 100% sand media mixes were statistically similar to each other and the tank, but less than all other media mixes. The full results and data of nutrient release and capture in the mesocosms is described in detail in Section 4.2.2 of the full report (Erickson et al. 2021).

<u>Objective #4: Simple Tests or Metrics</u>

Two HACH® phosphorus test kits (PO-19A High Turbidity; PO-14) were purchased and used to determine whether in-field batch tests could be used to directly estimate phosphate release from compost samples. While the instructions were easy to follow, the provided filtration system (filter paper) could not filter the sample via gravity due to a large amount of suspended compost particles. For an unfiltered sample, the resulting color of the sample could not be matched to the example colors on the provided color wheel. Turbidity and organic tannins may explain the challenge in matching the sample to the color wheel. Two separate junior scientists recommended that this procedure not be considered for practitioners.

Laboratory batch experiments were conducted to measure phosphate release from seven compost samples that were collected from five different sites (two food residue, four yard waste, and one blended (food + yard) compost). The compost samples were also submitted to a soil analytical lab to measure Olsen Phosphorus (mg/kg soil), Bray Phosphorus (mg/kg soil), phosphorus by ICP-OES (mg/kg), and Mehlich III Phosphorus (mg/kg soil). Finally, the compost samples were also analyzed according to the Solvita manufacturer instructions to measure CO_2 respiration, NH_3 respiration, and Solvita Maturity Index.

In summary, the phosphate release (µg P) increased as compost mass (g) increased for all composts and compost ratios. Phosphate release varied substantially between sites and compost types as shown in Figure 5. The phosphate release was then normalized by compost mass (µg P per g compost) and compared to the results from the Solvita and soil laboratory tests. The relationship between Solvita Maturity Index and phosphate release (µg P / g compost) was poorly correlated (slope = -0.041; $R^2 < 0.4$), so Solvita Maturity index is not a good predictor of phosphate release for the composts tested in this experiment.

The correlations between P release (µg P / g compost) and Olsen P, Bray P, ICP-OES P were weak ($R^2 \leq 0.29$), as shown in Figure 6. The correlation between P release (µg P / g compost) and Mehlich-III P (mg P /kg soil) was better, though still weak ($R^2 = 0.46$) and the 95% confidence interval bounds are large compared to the values of the regression. None of these methods appear to be strong predictors of phosphate release from compost. The full results and data of simple tests and metrics is described in detail in Section 3.2 of the full report (Erickson et al. 2021).

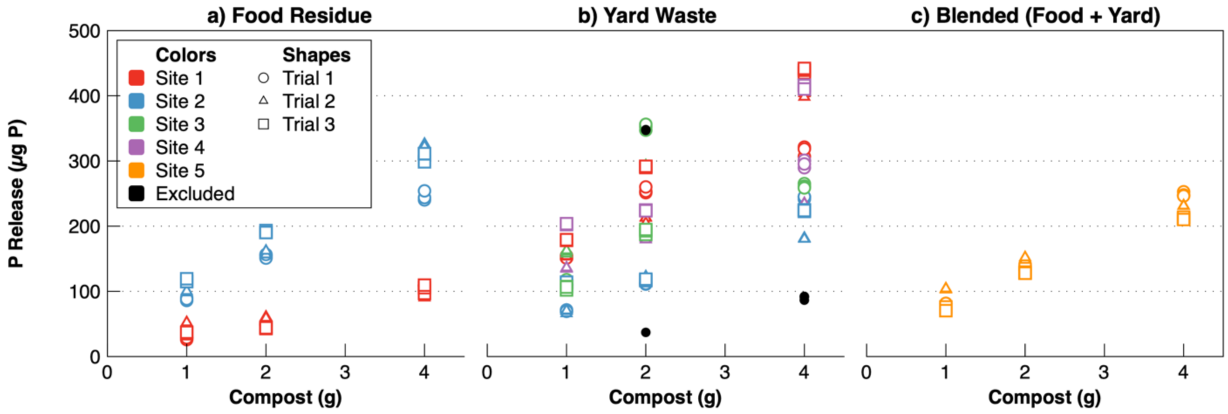

Figure 5: Food Residue Compost (2 sites) compared to Yard Waste compost (4 sites) and Blended (Food + Yard) compost (1 site).

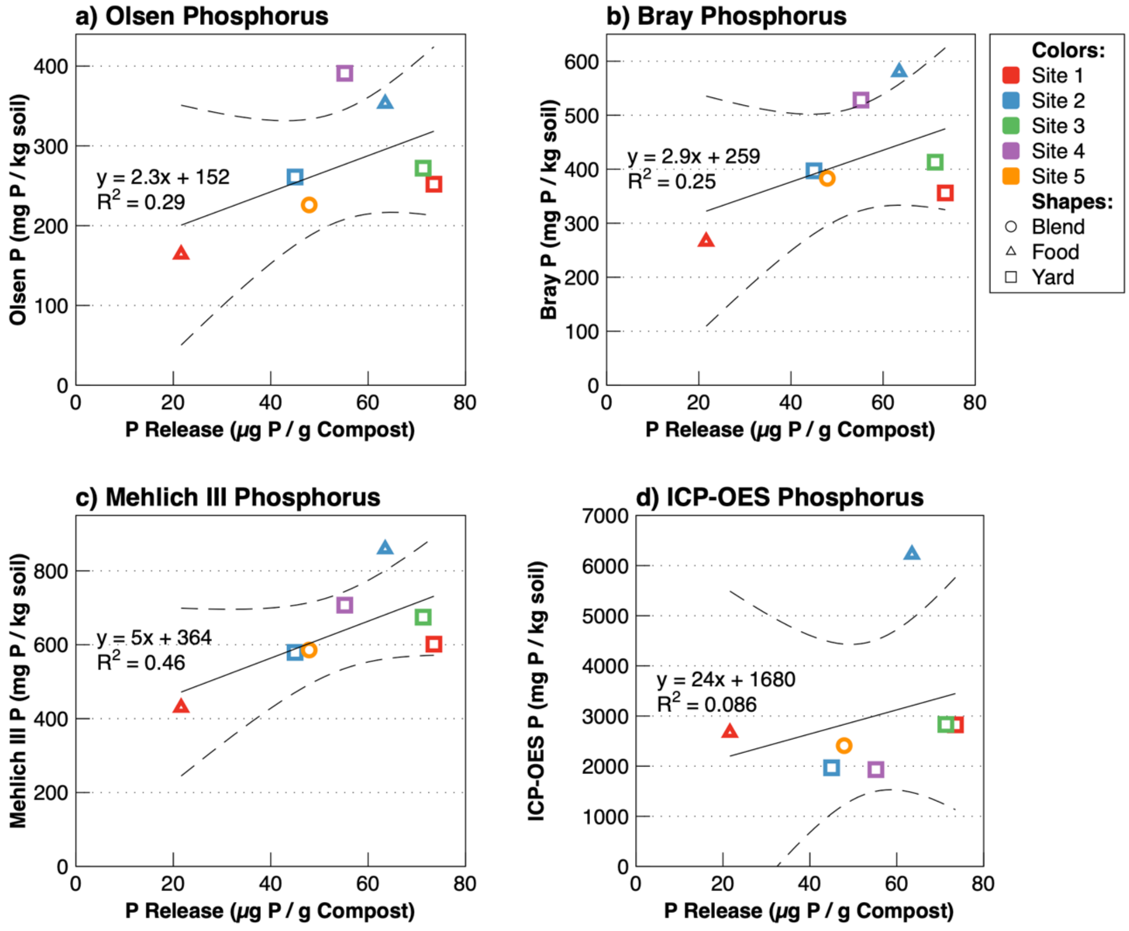

Figure 6: Olsen P, Bray P, Mehlich-III P, and ICP-OES P results compared to phosphate release (µg P / g compost).

Conclusions and Key Takeaways

Objective #1: Filtration Rate

All media mixes passed 50% of the influent volume within 5 – 15 minutes, and 80% – 98% of influent volume passed through all media mixes at 120 minutes after the start the experiments. Compared to flow through 100% sand (baseline control), flow through all media mixes was similar except for a few isolated ponding events in the reed sedge mixture. Statistically, iron media allowed water to pass through faster than 100% sand, but otherwise all media were statistically similar to each other and to 100% sand. Based on these results, there is no clear evidence that any of these mixtures have a major advantage or disadvantage for filtration rate within the first year of use. Further testing in subsequent years will elucidate if these patterns change as the mixtures age.

Objective #2: Supporting Vegetation Growth

While the vegetation growth varied between media mixes, vegetation reached maximum height approximately 50 days after seeding. Spent lime had the tallest vegetation and most biomass, which were statistically greater than 100% sand. The compost-amended mixes except for those with iron (leaf compost, food compost, biochar, and spent lime) had more vegetation biomass than the iron, peat, and sand media mixes though the differences were not statistically significant due to large variation in vegetation height and biomass among mesocosms. Note that one of the 20% leaf compost mesocosms did not grow any vegetation, which was excluded from all vegetation height and biomass analysis as an outlier. The iron media mixes had statistically similar vegetation biomass as the 100% sand, which suggests that adding iron limits the vegetation support provided by compost when iron and compost are mixed together.

Objective #3: Limiting Phosphate Release

The addition of 10% or more compost (leaf or food) to the media mixes significantly increased the effluent phosphate concentration. Spent lime and biochar additions reduced this release slightly, but only the addition of iron fully mitigated phosphate release from leaf-based compost. When compost is replaced with peat, both peat mixes reduced effluent phosphate concentrations compared to the influent. The environmental cost and sustainability of using peat in biofiltration media mixes needs to be determined.

All the compost mixtures released nitrate, though 10% leaf, 20% leaf, biochar, and spent lime media mixes resulted in statistically significantly more nitrate compared to the inflow (tank). The spent lime media mix exhibited elevated nitrate release in event 4 and the mechanisms for this are unclear. The pH was also measured, and the spent lime media mix pH (average = 9.16) was statistically similar to 20% leaf compost and biochar, but greater than all other media mixes, including the tank (average pH = 8.87). The iron (average pH = 8.76), sphagnum peat, reed sedge peat, and 100% sand media mixes were statistically similar to each other and the tank, but less than all other media mixes.

Objective #4: Simple Tests or Metrics

Two at-home or in-field phosphorus test kits were investigated for use in field batch experiments, but neither could be used to adequate determine the phosphate concentration of compost mixed with clean water. Laboratory batch experiments determined that phosphate concentration increased as compost mass increases and that phosphate release varies by compost site and type (food, leaf, and blend). Solvita, Olsen P, Bray P, ICP-OES P, and Mehlich-III P were all compared to phosphate release and none were found to correlate better than $R^2 = 0.46$.

Comparison of Media Mixes

To help readers consider all the factors presented above and compare the different media mixes evaluated in this project, Table 1 below compares the different media mixes for each of the three primary objectives for the mesocosm experiments. A primary purpose for adding compost to biofiltration and bioretention practices is to support vegetation growth. In these experiments, the filtration rate was unaffected by adding 10% or 20% leaf or food residue compost. More biomass and taller vegetation were observed in the leaf and food residue compost media mixes when compared to 100% sand. It is also evident from the mesocosm data that leaf and food residue compost both release phosphate, increasing the effluent concentration throughout the first rainy season. Food residue (both 10% and 20%) released less phosphate than leaf-based compost but had statistically the same filtration rate and vegetation growth (height and biomass). While compost increased the amount of vegetation compared to 100% sand, the increase in effluent phosphate concentration is a concern for stormwater managers.

Table 1: Comparison of Media Mixes.

Media	**#1: Filtration Rate**	**#2: Supporting Vegetation Growth**	**#3: Limiting Phosphate Release**	**#3a: Nitrate Release**
10% or 20% **Leaf** Compost	= Sand[1]	> Sand[2]	> Sand[1] & > Influent[1]	> Influent[1]
10% or 20% **Food** Residue Compost	= Sand[1]	> Sand[2]	> Sand[1] & < 20% Leaf[1]	> Influent[2]
5% **Spent Lime** + 20% Leaf Compost	= Sand[1]	> Sand[1]	> Sand[1] & < 20% Leaf[1]	> Influent[1]
15% **Biochar** + 20% Leaf Compost	= Sand[1]	> Sand[2]	> Sand[1] & = 20% Leaf[1]	> Influent[1]
5% **Iron** + 20% Leaf Compost	> Sand[1]	= Sand[1]	< Sand[1] & < 20% Leaf[1]	> Influent[2]
20% **Peat** (Sphagnum or Reed Sedge)	= Sand[1]	= Sand[1]	< Sand[1] & < 20% Leaf[1]	= Influent[1]
100% **Sand**	50% of influent within 5 – 15 minutes; up to 98% of volume within 120 minutes.	Seeded with Switchgrass	< Influent[1] & < 20% Leaf[1]	= Influent[1]

[1] *Statistically Significant (alpha = 0.05)*
[2] *NOT Statistically Significant (alpha = 0.05)*

Considering amendments, spent lime (5%) mixed with 20% leaf compost produced more vegetation than 100% sand (not statistically significant) and the same amount of vegetation as the 20% leaf compost media. The filtration rate was unaffected by adding 5% spent lime when compared to 100% sand or

20% leaf compost. The spent lime mitigated some of the phosphate released from the 20% compost, but the effluent concentration was still statistically greater than 100% sand and the influent. The spent lime also increased the nitrate concentration in the effluent, which was statistically significant compared to the influent (tank). Thus, spent lime provides little overall benefit when mixed with 20% leaf compost with regards to filtration rate, vegetation growth, and limiting phosphate release.

Biochar (15%) mixed with 20% leaf compost produced more vegetation than 100% sand (not statistically significant) and the same amount of vegetation as the 20% leaf compost media. The filtration rate was unaffected when adding biochar to the media mix compared to both the 20% leaf compost and to 100% sand. The phosphate release from biochar-amended media was also statistically similar to the 20% leaf compost media, which means the biochar did not mitigate the release of phosphate from leaf compost. Thus, biochar provides little overall benefit with regards to filtration rate, vegetation growth, and limiting phosphate release.

Iron (5%) mixed with 20% leaf compost produced the same amount of vegetation as 100% sand, and significantly less vegetation than 20% leaf compost. The filtration rate through the iron media was statistically faster than through 100% sand, though all media mixes allowed >80% of the influent volume to pass within 120 minutes from the start of the experiment. The phosphate release from iron mixed with 20% leaf compost was statistically less than 20% leaf compost, 100% sand, and the influent concentration. Thus, iron mitigated not only the phosphorus released from 20% compost but also captured phosphate from the influent water as well. In summary, iron can capture phosphate and provide the same or better filtration rate compared to 100% sand but will also produce the same amount of vegetation as 100% sand, which is substantially less than 20% leaf compost. From these data it appears the 20% leaf compost when mixed with 5% iron provided no additional benefits in supporting vegetation growth.

Sphagnum (20%) and reed sedge (20%) peat are organic materials that have been suggested to replace compost in bioretention media mixes. The filtration rate was unaffected when replacing compost with either peat in the media mix, compared to 20% leaf compost and to 100% sand. Both peat mixes produced the same amount of vegetation as 100% sand, and less vegetation than 20% leaf compost (not statistically significant). The phosphate release from both peat mixtures was statistically less than 20% leaf compost, 100% sand, and the influent concentration. Thus, peat captured phosphate from the influent and did not release phosphate like what was observed in the 20% leaf compost mixes. In summary, peat can capture phosphate and provide the same filtration rate as 100% sand but will also produce the same amount of vegetation as 100% sand, which is less than 20% leaf compost. The environmental cost and sustainability of using peat in biofiltration media mixes also needs to be determined. From these data it appears that peat does not fulfill the purpose of replacing compost to support vegetation growth.

Cost Comparisons

It is important to consider the cost of materials when comparing media mixes. Material costs vary by location and over time and delivery costs will also vary by location and supplier. Because actual values will not be relevant beyond the publication date of this report, a relative cost was computed using the 100% sand media as the baseline cost. Thus, Relative cost = Cost of Media Mix / Cost of 100% Sand. The costs of the media used in this study were provided by a personal communication quote (Plaisted

Companies, 2021) from a local Twin Cities Metropolitan Area (TCMA) supplier and used to compute the relative cost of the media mixes:

- 100% Sand: Relative Cost = 1
- 90% Sand + 10% Leaf Compost: Relative Cost = 1.6
- 80% Sand + 20% Leaf Compost: Relative Cost = 1.7
- 90% Sand + 10% Food Compost: Relative Cost = 2.1
- 80% Sand + 20% Food Compost: Relative Cost = 2.5
- 80% Sand + 20% Sphagnum Peat: Relative Cost = 2.1
- 80% Sand + 20% Reed Sedge Peat: Relative Cost = 2.3
- 75% Sand + 20% Leaf Compost + 5% Spent Lime: Relative Cost = 2.6
- 65% Sand + 20% Leaf Compost + 15% Biochar: Relative Cost = 6.8
- 75% Sand + 20% Leaf Compost + 5% Iron: Relative Cost = 14.2

Future Research

Phase II for this research effort is funded by the Minnesota Stormwater Research and Technology Transfer Program administered by the University of Minnesota Water Resources Center through an appropriation from the Clean Water Fund established by Minnesota Clean Water Land and Legacy Amendment and from the Minnesota Stormwater Research Council with financial contributions for numerous agencies. This effort will continue the outdoor mesocosm experiments for three additional rainy seasons and reveal whether the filtration rate, nutrient release, and vegetation trends reported herein continue in subsequent years. Phase II will also investigate the impact of road salt application on media performance and expand vegetation research with a germination study of low-organic content (e.g., < 10% compost) media mixes. Education, outreach, and technology transfer will continue as described in Chapter 6 of this report, disseminating information from Phase I as well as incorporating findings from Phase II as they become available.

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TABLE OF CONTENTS

FIGURES

TABLES

CHAPTER 1: INTRODUCTION

Biofiltration has become common in Minnesota's urban landscape because it can capture several stormwater pollutants (LeFevre 2015), making it one of the most robust stormwater treatment practices available to designers. Stormwater professionals and practitioners, however, still face challenging decisions while designing these practices. What type and how much organic material is needed to support the vegetation? Will it leach phosphate? Should amendment(s) be added? What criteria need to be specified so contractors source it correctly? How quickly will the practice filter water once it's online? Practitioners often feel as if they are guessing when selecting media components and designing these practices, which results in increased environmental risk and uncertainty when attempting to implement TMDL recommendations.

Though some have studied biofiltration media (e.g., Herrera Environmental Consultants, 2015), studies in Minnesota are limited (e.g., LeFevre et al. 2012a, 2012b, 2015; Paus et al. 2014a, 2014b, 2014c) and do not address the questions posed by designers. In particular, the most commonly used and recommended biofiltration media mixes have been shown to export phosphate, potentially contributing to water quality impairments. Thus, this project investigates various biofiltration media components that are locally and sustainably sourced in Minnesota to document and determine which are effective at hydraulic performance (i.e., filtration rate), supporting vegetation growth, as well as capturing (or not releasing) pollutants such as phosphate. To do so, mesocosm experiments were performed with various media including compost (food and leaf), peat (sphagnum and reed sedge), and amendments (biochar, spent lime, and iron) and were compared to mesocosms with 100% sand. In addition, batch experiments were conducted to determine which, if any, simple tests or laboratory metrics could be used to predict phosphate release from compost of several different sites and types.

A thorough of bioretention literature is provided in Chapter 2, including phosphorus capture and release and the use of compost and media amendments. Chapter 3 describes indoor experiments used to evaluate tests and metrics that could be used to predict phosphate release potential from compost and other bioretention media. Chapter 4 presents outdoor mesocosm experiments used to investigate filtration rate, vegetation growth, and nutrient (phosphate and nitrate) capture or release from several different biofiltration media mixes. Chapters 5, 6, and 7 are the conclusions of our study, the education and technology transfer plan, and the lessons learned and expected future research on this topic, respectively.

CHAPTER 2: LITERATURE REVIEW

Urban stormwater can have extremely detrimental effects on the environment, and biofiltration is quickly emerging as a way to address these negative effects (Trowsdale et al. 2011). Urban stormwater runoff has been shown to contribute to eutrophication and cause harmful levels of phosphorus in water (Erickson et al., 2013; Jay et al. 2017; Li & Davis, 2016). Harmful levels of phosphorus can originate from fertilizers, automobile exhaust, living and decaying plants, animal remains, and detergents (USEPA, 1999) Limiting phosphorus (P) leaching, focusing on the removal of P, and a focus on media mix design has become a major theme within recent research.

Bioretention systems aid in the improvement of water quality through evapotranspiration, soil filtration, adsorption, biotransformation and other natural processes (Davis et al., 2006). They mimic natural ecological systems and thus have great potential in sustaining urban environments. The efficiency of these systems depends on media mixes, infiltration rates and vegetation. Media and vegetation vary regionally and thus a blend and design specific to Minnesota is crucial for optimal bioretention system performance.

2.1 PHOSPHORUS CAPTURE AND RELEASE

A main concern regarding the design of these bioretention systems is the leaching of phosphorus and how these systems can be designed to treat large storm events or floods. Various models regarding Phosphorus (P) have begun to emerge to aid in the design and implementation of these systems.

2.1.1 Column Experiments

A large-scale 125-column study undertaken in Melbourne Australia by (Bratieres et al., 2008) focused on developing the optimal design to remove sediment, P and N. A major component of their design was selecting the correct plant species. The columns were dosed with semi-natural stormwater twice a week and water samples were collected from the inflow and the outflow of the columns. TP removal was >77%. A large portion of its removal was assumed to be attributed to the filtration process because most of the phosphate was in particulate form in the inflow. *Carex appressa* proved most effective in removing P and N perhaps due to its extensive root system. Although TP removal was shown to be efficient in non-vegetated columns, this study concluded that vegetation is of great importance when it comes to the efficiency of these systems, but the species must be selected carefully and organic matter should be limited to decrease the potential for leaching.

In a batch and column study by Hsieh et al. (2007) the effectiveness of bioretention systems was examined. The media involved two types of sand, three types of soil, and a mulch. The batch experiment was carried out to determine the short-term sorption capacity of P of the various media. A continuous column test involving three columns with different media compositions was completed to determine P uptake. In addition, a repetitive column test involving two columns was carried out to investigate P removal and accumulation over periods of multiple loading (80-120 days). The first column (RP1) was designed to have a media with low hydraulic conductivity over a media with high conductivity. The second column (RP2) was the opposite or a media with high conductivity over a layer of media with low conductivity. The media involved in RP1 consisted of a top mulch layer, a middle porous soil layer and a bottom sand layer. RP2 consisted of a mixed top layer (mulch, soil and sand), a middle layer or sand and a bottom layer of soil. Runoff was pumped into the columns from the top and a sample of the effluent was collected every hour for a period of 6 hours. Results from the short-term P sorption column test showed sorption capacities were higher for the three soils than either of the sands, while mulch was the lowest. The repetitive columns tests showed a TP removal efficiency of 47 to 68% for RP1 and RP2 showed almost complete removal of TP within the first 7 repetitions. However, this efficiency showed a steady decrease and by the 14th repetition removal was only 56%. The less permeable bottom layer in RP2 allowed more contact time between DP and media and thus was more efficient in P removal overall. However, it is still recommended to include a bottom fine sand layer results in the most efficient P removal and also prevents leaching and clogging of the bioretention system.

In another study that took place in Australia, the hydraulic and pollutant removal performance of fine soils within the filter media were measured in a laboratory setting (Hatt et al., 2008). Six different media types were studied including fine sand, sandy loam, 80% sandy loam, 20% Hydrocell (a synthetic, commercially available soil ameliorant); 80% sandy loam, 10% vermiculite, 10% perlite; 80% sandy loam, 10% compost, 10% mulch; and 60% sandy loam, 20% compost, 20%mulch on a charcoal drainage layer. In terms of pollutant removal efficiency P was leached across all soil-based filters. Significant accumulation of P within the top 20cm of the filter was observed therefore it was concluded that these filters were able to capture P and it may have been the native materials that leached.

2.1.2 Mesocosm Experiments

Some studies have focused on vegetation as a major influencer regarding the presence of both P and N within the media and the effluent. In a study by Henderson et al., (2007) six mesocosm were built with a drainage port and tap. Three different media types were tested; gravel, fine sand and sandy loam each in a vegetated and non-vegetated system. The vegetated treatments contained 5 species of plants. Mesocosms were allowed to establish for a period of 12 months, thus this was a more mature biofiltration study. Two separate studies took place, one a dosing the other a flushing. The mesocosms were dosed with approximately 240L of synthetic stormwater and 22 samples of effluent were collected. In the flushing experiment each mesocosm was dosed with 108L of synthetic stormwater and left for 7 days. They were then irrigated with tap water and effluent was collected hourly for a period of 8 hours. Results from the dosing experiment showed that vegetated mesocosms and the non-vegetated sand mesocosm removed almost all of the P from the synthetic stormwater. Results from the flushing experiment showed very little P and TP was leached from the vegetated and non-vegetated sand mesocosms. This study showed that vegetated mesocosms were much more efficient at removing N and P from stormwater than the non-vegetated mesocosms. Plants flourished the most in a sand or sandy loam mixture and did not need any addition of organic material such as compost which limits the potential of leaching from the media.

In an extensive study by (Davis et al., 2006), bioretention systems were tested for their removal of N and P specifically. Two boxes were constructed, one large (305cm long by 152cm wide with a depth of 91cm) one small (107cm long by 76cm wide with a depth of 61cm), and two PVC pipes at different depths were installed in the small box and three pipes at various depths were installed in the large. Each box was filled with sandy loam soil and had a top layer of 2.5cm mulch. Six small creeping juniper plants were installed in the small box and 12 small and 12 large creeping junipers were installed in the large. The boxes were designed to contain both a bottom port and an upper port, the bottom port remained open. The boxes were treated with synthetic stormwater at a rate of 4.1cm/hr for 6 hours. Influent and effluent samples were taken. In the field, two sites were examined: one containing sandy loam and a mulch top layer as well as grasses the other containing construction sand, leaf mulch and topsoil with some grasses, bushes and small trees. Grab samples were collected every 25-30 minutes. Results from the box studies showed that for the lower duration/ lower intensity treatment, TP removal increased with depth, 77 to 87% at the bottom of the boxes or a P reduction of 0.06 to 0.1 mg/L. In the treatment that simulated a storm the boxes received 8.1cm/L of synthetic stormwater for 12 hours which caused an increased infiltration rate in both boxes. From the bottom port effluent TP removal was around 70% and were not found to be affected by the higher hydraulic loading. The TP removal at both field sites was 65 +/- 8% at the first and 87 +/- 2% at the second and effluent concentrations were just above 0.1mg/L. This showed excellent P removal capability. It was also noted that design and management of vegetation may play an important role in nutrient removal of both N and P. Maintenance of vegetation is also crucial as any plant matter left to decay will result in the release of assimilated nutrients.

Aside from selecting vegetation and bioretention soil mixes, another area of focus is how to structure the media layers. In a study based in China by Yang et al. (2020) three different lab scale bioretention units were built. The first had a 200 mm drainage layer, a 100 mm transition layer, and a 500 mm filter layer. The second had a 200 mm drainage layer, and a 500 mm filter layer and no transition layer and the third a 100 mm transition layer, and a 500 mm filter layer, and a 50 mm thick gravel underneath the transition layer. Effluent was collected in a plastic bucket. The columns were treated with synthetic stormwater based on measurement from the nearby city Kunshan with varying rainfall durations. Using synthetic stormwater, TP removal rate was 68%. Overall, this study showed the importance of all three of these layers and in the treatment of runoff. Overall TP removal with all three layers was 86.0%, with no transition later it was 85.4%, and with no drainage layer it was 71.8%. This research suggested that a design including both a transition and drainage layer provides for better runoff control and nutrient removal.

2.1.3 Field Studies

Because bioretention systems are a newly emerging practice, field studies are limited. Following this laboratory study, Hatt et al. (2009) examined three different biofiltration sites in the field. At the first site, flow rate was measured and samples were collected to measure water quality for 14 storm events. At the second site, four storm events were simulated using semi synthetic stormwater and effluent samples were collected. At the third site, auto samplers collected time-weighted water quality samples. The first site showed effluent P concentrations were higher than the influent and increased with flow rate, most likely due to leaching of DP. The second site showed substantial reductions in TP and correlated with flow. The third site pollutant concentrations remained fairly constant. Overall, the three sites show significant reduction in TSS and heavy metal removal, but nutrient removal was much more variable. Use of a filter media with low organic content is recommended to prevent significant leaching of P and the influence of flow rate on effluent pollutant concentrations must be considered when designing these systems. The data from this study suggested that higher infiltration rates may lead to higher effluent concentrations of particulates and their pollutants.

In one study in North Carolina by Hunt et al., (2006), an auto sampler was used to collect the effluent from the underdrain. It was discovered that outflow concentration of nutrients was higher than the inflow concentration indicating the media was not effective in nutrient capture. TP removal rates varied from 65% removal to a 240% increase which was most likely due to the type of media in the cell and its level of P saturation. The soil from all the varying cells were analyzed using the Mehlich-3 methodology and provided a P-index which is an indicator of a soil's ability to adsorb or release P. The cells that had a lower P-index showed less TP in the outflow. The P-index measurement can help determine which media to include in sites that are more vulnerable to P pollution.

2.1.4 Models

In a paper by Roy-Poirier et al. (2010), the objective was to identify and characterize the bioretention P cycling processes with a focus on a P transport model. After reviewing several previous numerical models, it was determined that there remains a need for a simple numerical equation to represent the rate of particulate phosphorus dissolution and soluble phosphorus precipitation. None of the models reviewed were found to be applicable to modeling the bioretention system. The authors concluded that a new model was deemed crucial in order to predict the amount of P that would be removed from a proposed design of a bioretention system.

Li & Davis (2016) showed that the fate of phosphorus, or the concentration in the effluent, can be predicted by flow, volume and run time and varies significantly with influent P concentration. It can be used to describe both short- and long-term P removal conditions. Data from previous bioretention studies was used in order to devise the model. During both short-term and long-term studies, the effluent P concentration, C_e, is controlled by the equilibrium concentration, C_{eq}. During the event-term, variation of C_{eq} is influenced by dry duration time and the composition of the media. Longer dry time and weaker media, in terms of adsorption, will lead to larger variance of media C_{eq}. C_{eq} varies less in media with Al and Fe than in un-modified BSM. During the event and short-term studies, the concentration relationship is $C_{eq} > C_e > C_0$ for high-P media and is $C_{eq} < C_e < C_0$ for low-P media. In the long-term studies, the overall concentration relationship approaches C_{eq} $(C_{eq^*}) \approx C_e \approx C_{0.}$ Under natural conditions, C_{eq} (C_{eq^*}) will increase or decrease slowly and approach C_0. This process can take a long time, especially if the BSM contains Al and Fe.

In a study by Jay et al. (2017) the Phosphorus Saturation Ratio (PSR) and the Phosphorus Saturation Index (PSI) were tested across a variety of BSMs. The PSI and PSR were calculated using the formula: P/(Al+Fe), where Al = Aluminum and Fe = Iron. The difference being for PSR, P, Fe, and Al represent the Mehlich-3 extractable molar concentration of each element (Maguire & Sims, 2002). Columns were constructed and fourteen different Bioretention soil medias (BSMs) were tested with four duplicates of each. The BSMs consisted of high Fe biosolids, composts from two different feedstocks (yard waste and food scrap), Water Treatment Residual (WTR), oyster shells, soil and sawdust. All the various mixtures included sand as a component of the BSM. The columns were treated with synthetic stormwater at various volumes that reflected a bioretention system designed to collect 90% of runoff. Leachate from the columns was collected during the event and 4 hours after. Highest P concentrations in the leachate came from the biosolids and yard compost. The addition of WTR to BSMs containing compost resulted in a significant reduction in P of the effluent. High Fe biosolids and sawdust also showed a significant reduction in P but overtime the decline of P in the effluent was not consistent. Both the calculated PSR and PSI were compared to the results via testing regressions. PSR proved to be the best predictor for total and dissolved P with an R^2 of 0.733 and 0.681, respectively. The PSR could potentially be used as a predictor across different regions and with different BSM ingredients.

2.1.5 Phosphorus Summary

As research continues regarding the design of bioretention systems, P leaching is of great concern and varies greatly based on the BSM. The development and use of P transport models could potentially aid in the design and implementation of these systems and aid in the predictability of how certain BSMs will perform in various regions. Removal of P appears to increase with the addition of certain vegetation while adding organic matter to the BSM often contributes to P leaching. In addition, infiltration rate was also shown to influence the concentration of P in the effluent.

2.2 BIORETENTION MIXES WITH COMPOST

Compost is commonly used in bioretention media mixes because it can retain moisture to support the vegetation. In addition, it has been shown to remove pollutants. However, studies have suggested that compost is not always necessary to establish plant growth or a minimal amount, if any, should be considered in the BSM design to reduce P leaching.

With a focus on the importance of saturation and nutrient leaching potential Hurley et al. (2017) showed that saturation duration did have an effect of P leaching. Compost was collected from three different locations within Vermont in addition to a thermophilic sample and vermicompost sample. These samples were compared to two engineered bioretention mixes; one containing 40% compost the other with 4%. Four different saturation times were tested: 10 minutes, 1 day, 5 days and 10 days. A modified version of the U.S. Geological survey leach test (Hageman et al., 2007) was set up to obtain measurement and samples were treated with deionized water. P levels were lowest in the engineered mixes for all saturation durations. The P concentration increased with time of saturation for all compost samples. The engineered BSM containing 40% compost showed significantly more P leaching than the BSM containing 4% and pure compost samples showed significantly higher P leaching than either of the engineered BSM. It was concluded that compost should be avoided in environments with high saturation potential or if it is necessary a low P compost should be used to limit the P leaching potential.

In the Seattle Tacoma region of Washington State, 6-month and 24-month aged compost consisting of 80% yard waste and 20% food waste, was irrigated to simulate a storm event passing through a bioretention cell (Mullane et al., 2015). A total of six columns were constructed and treated with an irrigation rate of 33.5 mm/day based on a 6-month 24-hour storm for that region. The beginning TP measurement for the 6-month compost was 2.9 ± 0.6 g/kg whereas the final was 2.5 ± 0.3 g/kg. The 24-month old compost had an initial TP measurement of 2.7 ± 0.1 g/kg and a final of 2.7 ± 0.4 g/kg. This suggested that P leaching concentrations from mature compost decrease with each individual rainstorm. With initial leaching apparent, it was suggested that bioretention systems containing compost have restricted outflow during the first several storms.

In a bioretention study by Shrestha et al. (2020) one cell was built without compost or vegetation, the second was planted with just one plant species and no compost and the third consisted of a low P compost and vegetation. All three of the cells showed TP and SRP reductions. Average influent TP concentrations were higher compared to effluent concentrations. Cell 1 had a 95.6% TP reduction from three events; cell 2 had a 94.2% TP reduction from seven events, and cell 3 had a 92.6% TP reduction from six events. Effluent average SRP in Cell 1 showed a 94.8% reduction, cell 2 had a 96.1% SRP reduction from eight outflow events, and cell 3 had a 94.1% SRP reduction from six outflow events.

Slightly higher effluent concentrations from the cell containing low P compost suggest there was some leaching. The use of compost appeared to have short term effects aiding plants in establishment but may not be a necessary media to add to these systems because they can attribute to P leaching long term. Vegetation did not appear to have any effect on the removal of pollutants but may be more beneficial once the plants are more established.

Another study by Jia Liu et al. (2014) examined three different media blends specifically for N and P removal. Those blends included Terrasolve, Biofilter and a Virginia Tech (VT) mix. The VT and Terrasolve mix included WTR and Biofilter and VT mix included yard waste compost. Additionally, the Terrasolve included a mixture of coir and peat. Columns with vegetation were not as efficient in nutrient removal. The study also had a focus on hydraulic retention time. An increased retention time resulted in greater P removal across all media. Terrasolve proved to be the most efficient in removing P followed by the VT mix and finally the Biofilter. It was the addition of WTR that aided in P removal as was discovered in other studies (Brown et al. 2010; Lucas & Greenway, 2011)

Logsdon & Sauer (2016) compared a mixture of cow manure and yard clippings, a fine loamy mixture and a 50% sand, 26% silt, and 24% clay media within columns. These mixtures were additionally compared to three treatments that had soil and two that did not. The treatments containing soil had a mixture of 1/3 compost,1/3 sand and 1/3 soil. The treatments without compost contained 20% compost and 80% sand. Columns with soil showed significantly lower levels of TP than columns without soil and P that was leached from compost was not sorbed by the sand. It was concluded that compost derived from manure should not be used in these systems and that other forms of compost should be added in small amounts as plant growth may result from organic material already present within the media.

Compost has shown some effectiveness in the uptake of heavy metals such as zinc. In a column and batch study conducted in Australia it was effective in reducing the amount of zinc in the effluent until the compost reached its metal sorption capacity (Al-Mashaqbeh & McLaughlan, 2012). Results indicated that when compost particles were greater than 1.18mm limited uptake of Zinc occurred suggesting that particle size is something to consider in the design of these systems when heavy metal uptake is to be addressed. In another column experiment by Lim et al. (2015) compost showed a removal efficiency of more than 90% on the heavy metals Cu, Zn, Pb and Cd.

In a batch and column study that involved three different types of compost all were shown to be effective in capturing cadmium and zinc (Paus et al., 2014). Compost samples were collected from two different locations in Minnesota and one in Texas. Ten continuous flow columns were constructed and treated with synthetic stormwater and flow rate was monitored daily. Cu was effectively removed from all columns and total Cu uptake increased with the percentage of compost in the media. It was determined that pollutant breakthrough is not of concern regarding compost because dissolved metals were shown to be removed through sorption. The columns that contained 30% and 50% compost showed a substantial release in both P and dissolved P. P leaching potential was addressed by carrying out batch experiments involving 0.1-1.0g of compost and 230mL deionized water. The batch experiments showed P leaching; one of the samples collected from Minnesota showed 203 ± 24 mg P per kg compost. Thus, the significant P leaching was of concern.

2.2.1 Compost Summary

Overall, the use of compost needs further study because while it has shown potential in removal of heavy metals such as copper (Chahala et al., 2016; Silvertooth & Nason, 2014, not discussed above). Research has shown it significantly leaches phosphorus (Hurley et al., 2017, Paus et al., 2014). It is recommended that if compost is included in the media mix then the design should include two layers. One layer should address toxic metal and pollution retention and another with sand containing Fe to address Phosphorus removal (Paus et al., 2014). In addition, it is not yet deemed essential in the growth and prosperity of vegetation.

2.3 BIORETENTION MEDIA AMENDMENTS

Certain studies have focused on using amendments and enhancements to aid the bioretention media mixture in its ability to capture phosphorus from source stormwater or any P leached from organic materials such as compost.

2.3.1 Water Treatment Residuals

Water treatment residuals (WTR) have been a popular cost-effective amendment and have shown to be efficient in capturing phosphorus. An aluminum heavy WTR was used in both a batch and column study by (O'Neill & Davis, 2012a, 2012b). Two large gravity controlled vegetated columns were built. The base bioretention soil media (BSM) was developed in their earlier batch and mini column study and consisted of 77% sand, 14% silt and 8% clay. One column consisted of a mixture of 69% BSM, 5% WTR, 22% additional sand, and 3% hardwood bark mulch and the control without the WTR was 74% BSM, 22% additional sand, and 3% hardwood bark mulch. Synthetic storm water was used as based on previous studies (US EPA 1983, Bratieres et al., 2008) and columns were treated with 182 mL min^{-1} for a continuous 6-hr period. Overall, the column with WTR had an average adsorption of 3.18mg P kg^{-1}. The column without WTR showed an export of P at 2.38mg P kg^{-1}. Therefore, just 5% WTR in the media is capable of removing sufficient P from stormwater.

In an amendment study by Li et al. (2018) 12 columns were built and modified with different fillers. The BSM was a mix of 30% soil, 65% sand, and 5% wood chips. Twelve different columns were built consisting of filler layers containing; soil, 30% planting soil 70% sand, 30% planting soil, 65% sand and 5% wood chips, BSM + 10% WTR, BSM + 10% green zeolite, BSM + 10% medical stone, BSM + 10% fly ash, BSM + 5 % vermiculite, BSM + 5% peat soil, BSM + 5% coconut chaff, BMS + 5% medical stone: peat soil 1:1 and BSM + 5% green zeolite: peat soil 1:1. The analysis focused on TP and SRP and results showed that BSM + 10% WTR had the best median TP removal of 96.80% and the best average TP removal of 97.13%. Overall WTR was deemed the most efficient in P removal. In another mini column study (Zhang et al., 2018) using the same BSM, static isothermal adsorption experiments were carried out for P using a single filler as well as modified fillers. The columns contained the following; soil, BSM, BSM + 10% maifanite, BSM + 10% maifanite, BSM + 10% WTR, BSM + 10% zeolite. The results from the single filler static isothermal adsorption showed that saturation ranked as follows; WTR > fly ash > zeolite > maifanite > soil. The modified filler with 10% WTR reached an adsorption capacity of 94.29mg/kg which was roughly 3.5 - 4.5 times more than the BSM and the other fillers and was the recommended bioretention amendment.

Shrestha et al., 2019 examined the use of spent lime as a BSM amendment for nutrient uptake in a two-part study involving a field-based mesocosm experiment and a laboratory column study. In the field study, eight different soil medias were used and replicated four times in a raised bed design. Different levels of manure were used in the plots as opposed to synthetic storm water to dose the plots with varying levels P and N. This was a comparative study between plot that had the spent lime and those that did not, soil treatments were randomly assigned. The effluent from each mesocosm was collected on a weekly basis. The volume of compost greatly increased the amount of P leached and spent lime showed significantly less P in the effluent. In the lab, eleven PVC columns were constructed with various media mixes of compost, sand, spent lime and coir. Fourteen 20-second rainfall simulations were conducted using tap water which did not contain any P and the effluent was collected. The laboratory study showed the same as the mesocosms: that the volume of compost in the column increased P leaching and decreased with spent lime and a mixture or spent lime and coir. In conclusion, spent lime performed well in the field and in the lab and is suggested as a cost-effective amendment for BSM design.

In Maryland (Jiayu Liu & Davis, 2014) were able to study an already existing bioretention cell with an underdrain for a period of 22 months. A 5% WTR media was mixed with the top 40cm of the media already in the site and any removed vegetation was replanted. Discrete sampling was used for both inputs and outputs and 12 samples were collected per event. For TP the peak decreased from 0.66 mg/L in influent to 0.12 mg/L in effluent and for PP 0.61 mg/L in influent to 0.06 mg/L in effluent. Concentrations of SRP in the effluent were essentially constant and ranged from less than 0.01 to 0.09 mg/L. In addition to measuring P concentrations, the flow rate was monitored and WTR showed no effect on filtration rate. This study was significant in that WTR demonstrated the ability to reduce stormwater P loads in a bioretention system that was amended after its installation proving it be a good enhancement in stormwater treatment.

2.3.2 Biochar

Biochar has been studied as a BSM addition to bioretention systems because it has been shown to adsorb heavy metals, and nutrients (Cao et al. 2009). It has also been shown to enhance plant biomass (Kasak et al.2018). A biochar specific study by Iqbal et al. (2015) examined its effectiveness when mixed with compost in preventing the leaching of N, P and organic carbon. 6-month aged compost and biochar from forest slash were obtained locally. The biochar was also mixed with an 80% yard and 20% food-based compost obtained from the same facility. Nine columns total were built containing: 100% biochar, 100% compost, 100% sand, 100% co-composted biochar, 75% compost/ 25% biochar, 75% compost / 25% co-composted biochar, 30% compost / 70% sand, 30% compost/ 70% layered sand. Each treatment was replicated three times and the columns containing compost and other media were thoroughly mixed aside from the one containing the layered sand. Deionized water was used to irrigate the columns at a flow rate to mimic 6-month 24-hr storms. Adding biochar to the media did not show a reduction in P leaching. There was no difference in the amount of P leached between the compost-layered sand and compost-biochar compared to the pure compost. However, more P was leached from the compost – co-composted biochar mix overall and less leached from the compost-sand blend. This study demonstrated that biochar did not have any positive effect on P leachates and should be used in these systems to address certain metals rather than nutrients.

In a study involving 5 columns, differing filter media and an iron-coated biochar in a saturation zone was examined for its removal potential of N and P (Xiong et al. 2019). Each column had the same media composition: a submerged layer, mulch layer, filter media layer and gravel drainage layer. The filter layer was different for each column; 88% concrete sand and 12% soil (T1), 95% T1 and 4% rice husk biochar and 96% T1 and 4% iron-coated biochar. The two remaining columns had biochar added to the upper layers of the media to explore denitrification. The columns were treated with synthetic runoff at a rate of 3.47 mm/h for 6 h. Overall, there was no significant difference in N removal within the columns. The columns that contained biochar showed lower removal rates for TP which may have been a result of the biochar itself leaching P. The iron-coated biochar showed higher removal of TP and thus the team concluded that adding iron-coated biochar to the upper layers of the media in bioretention cells may enhance P removal. (Xiong et al. 2019). Adding rice husk biochar is not recommended if P leaching is of concern.

In other studies, biochar has been shown to be effective in treating certain contaminants in urban stormwater runoff (Reddy et al. 2014). In a column study with a focus on biochar derived from waste wood pellets, the columns were designed to have a layer of biochar in between layers of pea gravel with the same thickness to allow for uniform flow conditions through the biochar. The columns were treated with synthetic stormwater and contaminant concentrations were compared between the influent and effluent. Flushing the columns with synthetic stormwater with a phosphate concentration of 0.82mg/L resulted in P concentrations in the effluent of 0.4 to 0.52mg/L, with a removal efficiency of 47%. For N, there was a removal efficiency of over 85% and cadmium, chromium, copper, lead, nickel, and zinc concentrations were decreased by 18, 19, 65, 75, 17, and 24%, respectively. Contrary to other studies, overall the biochar showed a significant reduction in P when the influent and effluent concentration were compared and showed to be an effective medium for nutrient removal and certain contaminants.

2.3.3 Fly Ash, Iron, Red Mud, and Other Amendments

Three different types of BSM were tested in a study by Yu et al., 2015 including sludge pyrolysis and two types of soils. P adsorption kinetics and P adsorption isotherms were both measured using batch experiments. Al, Fe, and Ca were found to be the main components in all three media, and the Al and Ca were higher in the sludge pyrolysis residue. Adsorption kinetics of P proved to be faster with the sludge pyrolysis and results from the adsorption isothermal experiment showed that the sludge pyrolysis residue is an effective adsorbent to remove P from water. Overall, this amendment showed promise in working as a filter media with bioretention systems.

Other common enhancements to the media include fly ash, iron and red mud and sludge pyrolysis residue. In Oklahoma, four bioretention cells were constructed with the main filter media being a blend of sand and fly ash (Kandel et al., 2017). These cells were analyzed by collecting soil samples and three of the cells' influent and effluent were compared. Various techniques were used to measure TP, SRP and Mehlich phosphorus. Examination of the soil samples revealed that TP concentration increased over time within the topsoil and filter media of all four cells, however it was not statistically significant. When influent and effluent P concentrations of water samples were compared, TP showed a reduction of 64% to 75% and TP mass showed a reduction of 76% to 93% at the three sites. There was a lot of variability in P concentrations below the cell top layer reflecting the need for a better mixing method if fly ash is to be used as an amendment in the future.

A vegetated mesocosm study focused on the use of WTR, red mud and kraznosem soil and the potential of each to remove P (Lucas & Greenway, 2011). There were seven media mixes total: 10% kraznosem (7% kraznosem soil and 93% turf sand), 20% kraznosem (14% kraznosem soil and 86% turf soil) , 40% kraznosem (30% kraznosem soil and 70% turf soil), 6% red mud (75% turf soil 20% top soil and 5% red mud), 10% red mud (71% turf soil 20% top soil and 9% red mud), 30% WTR (80% turf sand and 20% WTR), and a seventh with a mix of 15% WTR and 40% kraznosem (71% turf sand, 20% kraznosem soil and 9% WTR) . The columns were analyzed for two separate 80-week periods and influents and effluents were compared during different loading regimes. The red mud columns were shown to retain more P than the kraznosem soil columns. The columns containing WTR had an effluent concentration that was below 0.10 mg/L for 90% of the runs when the columns were treated with wastewater. They performed equally well when treated with stormwater retaining up to 99% of P over simulated three decades worth of stormwater. The 10% and 20% kraznosem treatments became ineffective after the second and third stormwater dosings. Red mud showed too much P leaching potential and is not a recommended amendment. The 40% kraznosem mix showed an increase in P uptake until the final dosing. This study also showed the effectiveness of vegetation in aiding P uptake and deemed vegetation essential for the longevity of these systems.

In a review by Penn et al. (2017) over 40 studies were examined for cumulative P removal as a function of cumulative P loading. In addition, retention time, P inflow concentration and the type of P sorption material were also analyzed. In wastewater treatment shale, soil and sand were shown to be the least effective due to their low P sorption capacity which was calculated at a cumulative 21% overall. Fe-based P sorption material was more efficient than Ca in systems with shorter retention times and lower P inflow. For material involving Ca, retention times must be maximized to increase efficiency. Flow rate and retention time are majorly influenced by the P sorption material and its hydraulic conductivity. Further research into P sorption material re-use rather than replacement will make these systems more cost effective and increase their overall use in stormwater treatment.

2.3.4 Amendments Summary

In the studies reviewed biochar showed conflicting results when added to the BSM to remove P and further research may be necessary to determine its efficiency. Fly ash and sludge pyrolysis showed promise in TP removal but fly ash may require a better mixing method when added to the BSM. Red mud and kraznosem soil were not effective at removing P unless WTR was also in the mix. Overall, WTR seems the most efficient amendment for these systems but further research is necessary to determine how this could change with flow conditions (O'Neill & Davis, 2012). In addition, further research is necessary to determine if any amendments could potentially cause blockage and decrease the productivity of the bioretention system (Li et al., 2018).

2.4 MINNESOTA SPECIFIC DESIGNS

Previous studies have provided significant insight into improving the design, performance and maintenance of biofiltration practices in cold climates and what factors, such as frost, may influence their performance. However, Minnesota is lacking in resources and tools that aid in the design of a system that reduces the leaching of phosphorus.

There have been studies that have focused specifically on bioretention performance and cold weather climates. One such study that was specific to Minnesota showed that bioretention systems continued to infiltrate at varying levels throughout the winter (Lefevre et al., 2009). The study had a duration of three years and four existing bioretention cells were selected for analysis within the greater Twin Cities area. Hydrologic performance, infiltration and frost type analysis were performed at all the sites. A well-draining soil was noted as an essential design characteristic to maintain good infiltration rates. If the soil quality is poor, an underdrain is necessary to maintain function. It was also discovered that the type of frost that forms has a stronger influence on infiltration than the presence of frost or its depth.

In a cold temperature specific column study in Sweden by (Blecken et al., 2010), mesocosms were kept in three separate temperature-controlled rooms at an average of 2, 7 and 20°C. The BSM consisted of a top layer of sand and fine gravel and a bottom layer of medium to fine sand. Semi-artificial stormwater (which included natural sediment from a stormwater gully pot and laboratory grade chemicals added to tap water) was used and the concentration of target pollutants was measured. Each column was dosed with 15mL of stormwater twice a week for 12 weeks. Inflow was compared to outflow and TP average removal was 91.4 ± 6.6% and removal was not influenced by temperature but improved with run time. The percentage of dissolved P in the outflow was higher and increased with temperature. The average DP after two sampling events was 12.7%, 15.5% and 17.8% at 2, 7 and 20 °C, respectively. TSS was not significantly affected by temperature, N removal was poor, and N leaching was shown to increase with temperature which may have been attributed to the vegetation selected.

In Finland a study by Valtanen et al. (2017) took place in a large scale lysimeter facility where bioretention systems were underground in a bunker and the tops were exposed to open air. Eight lysimeters were built containing an organic soil layer, sand filter layer, transition layer of fine gravel, drainage layer of coarse gravel and saturated layer of coarse gravel. Each system was irrigated 6 times during the experiment, one in autumn, three in spring and two in summer. No irrigations were performed in the winter because no runoff is generated in freezing temperatures. Based on stormwater measurements from a nearby town, Zn, Cu, Al, P and N were studied. Inflow and outflow measurements were compared and all systems showed close to 100% P retention throughout each season. On the contrary, N was not well retained during the first irrigations but retention increased over time. This large-scale study showed that biofiltration systems perform in cold climates, but there is a need for a longer-term study to determine their efficacy.

An examination of low impact development designs in cold climates included two bioretention systems at the University of New Hampshire Stormwater Center field facility (Roseen et al., 2009). A total of 27 rainwater events were examined during two winters and two summers. Frost penetration did not influence the overall hydraulic performance of the systems, and it was determined that frozen media may still have significant permeability. Influent concentrations of various contaminants were compared to their effluent concentrations and TP removal in the bioretention systems did not show a significant decline in performance in winter months.

The effect of freeze thaw cycles on bioretention media was examined in a study by Ding et al. (2019). Four soil samples were collected and three ended up being used, from an existing bioretention site in Ontario, Canada. The cell had mulch on the top and was amended with a media enriched with Al and Fe oxides before installation. To evaluate the effects of the freeze thaw cycles (FTC), six replicate injection experiments were performed. The injection solution of 25 mg/L each of $PO_4 3-$ (8.33 mg/L of PO_4^{3-}-P), NO_3^- (5.65 mg/L of NO_3^--N), and bromide (Br^-) was prepared in 0.01 M calcium chloride ($CaCl_2$) to mimic contaminated surface runoff. Concentrations of N and P were higher than average stormwater to test the systems under extreme conditions. Overall, more than 98% of TDP was removed from the columns during all of the FTCs. The effluent P concentrations fell below 0.15 mg/L and ≤2% of the added stormwater phosphate was present in the effluent. Further research is needed to study more variables regarding FTC but overall, this study found that when designed properly cells will perform well in cold climates.

In a critical literature review by Kratky et al., 2017 it was noted that various studies suggest that removal of organics, heavy metals and nutrients is temperature dependent yet also may be dependent on BSM. Another obstacle with cold climates is the freeze thaw cycle that may influence plant root growth and cause some clogging and may also influence the systems permeability. In addition, plants must be selected for winter hardiness, nitrogen degradation and must be salt tolerant. More research is needed to examine the relationship between coarse media and cold weather hydraulic performance, amendments that will enhance contaminant removal and longevity in these climates.

2.5 LITERATURE REVIEW SUMMARY

As the bioretention practice becomes more accepted as an effective way to treat stormwater runoff, more research is required to determine the cost effectiveness of design including the potential cost of maintenance to maintain their optimal performance and longevity in pollutant and nutrient removal. Certain studies have shown that the top layer must be removed every two years to prevent clogging of the filter (Hatt et al., 2009). Another study has shown that vegetation removal and maintenance is an effective way to increase nutrient removal as well as prevent leaching (Davis et al. 2006). As research continues, and the dangers of P leaching are addressed, it is evident that the effectiveness of these systems is region specific in terms of BSM and vegetation selection and therefore further developing an optimal design for Minnesota is crucial when it comes to addressing local stormwater treatment.

CHAPTER 3: INDOOR TESTS AND METRICS EVALUATION EXPERIMENTS

The purpose of these tests is to identify characteristics, tests, or metrics that can be used by designers in specifications to ensure biofiltration media components provide adequate filtration rate, support plant growth and microbial function, and do not release phosphate from the media. Tests or metrics are considered "simple" if they can be performed or measured in the field (preferable) or quickly in a lab, such that material characteristics do not change between the time of measurement and the time of installation. For these experiments, several compost materials were obtained, and the phosphate release was measured with simple batch experiments. The phosphate release was then compared to several laboratory techniques and 'at-home' or 'in-field' test kits to determine correlations.

3.1 METHODS AND MATERIALS

3.1.1 Compost Collection

Seven compost samples were collected on August 19th, 2020 from five different sites; Creekside Soils in Hutchinson MN, Empire Mulch in Rosemount MN, Cologne compost site in Cologne MN, Cottage Grove Compost Site in Cottage Grove MN and the Shakopee Mdewakanton Sioux Community (SMSC) Organics in Shakopee MN. Two sites (named Site 1 and Site 2 hereafter) provided a yard waste sample and an organic (food residue) sample. Two other sites (Sites 3 & 4) provided only yard waste samples. One site (Site 5) provided a blended sample, which is a mix of yard waste and food residue.

3.1.2 Compost Sample Preparation

A sub-sample of each compost sample was added to 273mL of MilliQ water (18.2MΩ-cm) in a 500mL acid-washed glass bottle in three different amounts 1 gram, 2 grams, and 4 grams of compost for three triplicates of each mixture. Each bottle was placed on an orbital shaker table for 15 minutes at 1500rpm and then a 50mL subsample of the supernatant was poured into a 50mL conical tube and centrifuged at 2800rpm for 15 minutes. Using a syringe and a 0.45µm filter, the 50-mL samples were filtered into three 15mL subsamples and stored in conical tubes.

3.1.3 Solvita Compost Maturity Index

Two sub-samples from each compost (14 total) were collected and processed according to the Solvita manufacturer instructions (Brinton, 2019). The methodology produces ordinal number values for CO_2 respiration, NH_3 respiration, and Solvita Maturity Index. The ordinal values for CO_2 respiration and NH_3 respiration correspond to concentrations of their respective gasses as described in Table 2 (Brinton and Evans, 2006). The ordinal values for CO_2 respiration (varies from 1 to 8) and NH_3 respiration (varies from 1 to 5) are then used to determine the Solvita Maturity Index according to Figure 7.

Table 2: Solvita Ordinal Numbering of Visual Optical Scale in Relation to Concentration of Gases (Brinton and Evans 2006).

Ordinal Number for CO_2 Test Result	Approximate CO_2 Concentration (mg/L)	Ordinal Number for NH_3 Test Result	Approximate NH_3 Concentration (mg/L)
8	2,000	N/A	N/A
7	5,000	N/A	N/A
6	10,000	N/A	N/A
5	20,000	5	<100
4	40,000	4	800
3	75,000	3	2,000
2	140,000	2	8,000
1	200,000	1	25,000

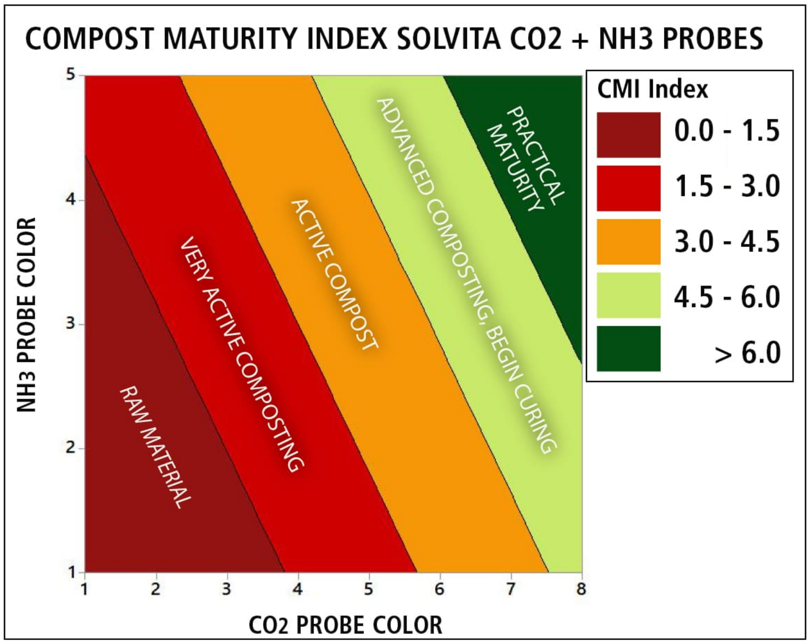


Figure 7: Compost Maturity Index as a function of CO2 and NH3 Ordinal Values (https://solvita.com/cmi-calculator/).

3.1.4 Wet Chemistry Analytical Techniques

Phosphate concentration was measured using flow injection analysis by the Lachat Instruments (Milwaukee, Wisconsin) Quick-Chem model 8000, Method 10-115-01-1-M with a statistically determined detection limit (as determined in water) of 5 µg P/L. The Lachat was calibrated using prepared phosphorus standards ranging from 0 - 2000 µg P/L. These standards were also used during the sample run as check standards; one for every 10 samples. Analysis was repeated (duplicated) on one sample after every 10 samples for quality assurance and quality control (QA/QC). The system was rinsed with

Disodium ethylenediaminetetraacetic acid (EDTA) and MilliQ (high degree deionized water) immediately after calibration standards and after each check standard or sample duplicate. Calibration curves and measured concentrations were recorded digitally by the Lachat software and exported into Excel for additional data and QA/QC analysis.

3.1.5 Compost Soil Analytical Techniques

A single sample of each compost (seven total) was submitted to Research Analytical Laboratories (http://ral.cfans.umn.edu/) for analysis of Olsen Phosphorus (mg/kg soil), Bray Phosphorus (mg/kg soil), 27-Element analysis by ICP-OES including phosphorus (mg/kg), and Mehlich III Phosphorus (mg/kg soil). The methods for these analyses are provided below, quoted from the RAL website at http://ral.cfans.umn.edu/tests-analysis/soil-analysis (Accessed 11/12/2020):

- *"Phosphorus, Bray-1 Extractable, for non-calcareous soils: Phosphorus is extracted by shaking 1 g of air dried soil in 10 mL of 0.025 M HCl and 0.03 M NH_4F for 5 minutes. Phosphorus is determined on the filtrate by the molybdate-blue method using ascorbic acid as a reductant. Color development is measured at 880 nm on a Brinkmann PC 900 probe colorimeter.* [Source] *Frank K., D. Beagle and J. Denning. Phosphorus. p.21-29. in Recommended Chemical Soil Test Procedures for the North Central Region. North Central Regional Research Publication No. 221 (Revised). Jan. 1998. Missouri Agricultural Experiment Station SB 1001.*
- *"Phosphorus, Olsen Bicarbonate Extractable, for calcareous soils: Phosphorus is extracted by shaking 1 g of air dried soil in 20 ml of 0.5 M $NaHCO_3$, pH 8.5, for 30 minutes. Phosphorus is determined on the filtrate by the molybdate-blue method using ascorbic acid as a reductant. Color development is measured at 900 nm on a Brinkmann PC 900D probe colorimeter.* [Source] *Frank K., D. Beagle and J. Denning. Phosphorus. p.21-29. in Recommended Chemical Soil Test Procedures for the North Central Region. North Central Regional Research Publication No. 221 (Revised). Jan. 1998. Missouri Agricultural Experiment Station SB 1001.*
- *"Total phosphorus (S31): Total P Microwave Procedure: digest 0.5 g of air dried soil with 10 mL of HNO_3 in a 50 mL quartz vessel using microwave digestion for 6.5 minutes at 175°C. Determination of P, K, Na, Ca, Mg, Al, B, Fe, Mn, Cu, Zn, Cd, Ca, Ni, Pb, Co, Mo, Si, S, As, Ti, Be, Sr, Rb, Li, V, and Ba by ICP-AES.* [Source] *Tadon, H., M.P. Cuescas, and E.H. Tyner. 1968. An acid-free vanadate-molybdate reagent for the determination of total P in soils. Soil Sci. Soc. Am. Proc. 32:48-51.*
- *"Mehlich III Extractable Nutrients: A 3 g sample of air dried soil is shaken with 30 mL of Mehlich III extracting solution [0.2 N CH_3COOH, 0.25 N NH_4NO_3, 0.015 N NH_4F, 0.013 N HNO_3, and 0.001 NEDTA] for 5 min. and then centrifuged. The supernatant is analyzed for Ca, Cu, K, Mg, Mn, P, and Zn by ICP-AES.* [Sources] *(Mehlich A. 1984. Mehlich 3 soil test extractant: a modification of mehlich 2 extractant. Commun. in Soil Sci. Plant Anal. 15:1409-1416.) (Fassel, V.A., and R.N. Kniseley. Nov. 1974. Inductively Coupled Plasma Optical Emission Spectroscopy. Anal. Chem. 46 (13):1110A-1120A. Also: Dahlquist, R.L. and J.W. Knoll. 1978. Inductively Coupled Plasma-Atomic Emission Spectrometry: Analysis of biological materials and soils for major trace, and ultra-trace elements. Appl. Spectroscopy 32:1-30. ICP: ARL (Fisons) Model 3560 ICP-AES Thermo Instrument Systems Inc. (Fisons Instruments Inc. Division) 81 Wyman Street PO Box 9046 Waltham, MA 02254."*

3.2 RESULTS AND DISCUSSION

3.2.1 Batch Tests for Phosphorus Release

The phosphate release from each compost in controlled batch test experiments is illustrated in Figures 8, 9, and 10. There are two important conclusions to draw from this information:

1) the amount of phosphate released (µg) increases as the amount of compost (g) increases; and
2) the amount of phosphate release varies by site and by compost type (yard vs. food residue).

For all composts, the amount of phosphate released increases as the compost mass increases, as indicated by the positive slope of the linear regression between phosphate release (µg) and compost mass (g). It is important to note, though, that the intercept of the linear regression does not equal zero for any of the fits. The intercept represents the phosphate release when compost mass equals zero and is a positive value for all regressions. The positive intercept for all regressions and lack of fit for some experiments suggests that the relationship between phosphate release and compost mass may not be linear for all compost masses. It is likely nonlinear as the compost mass approaches zero.

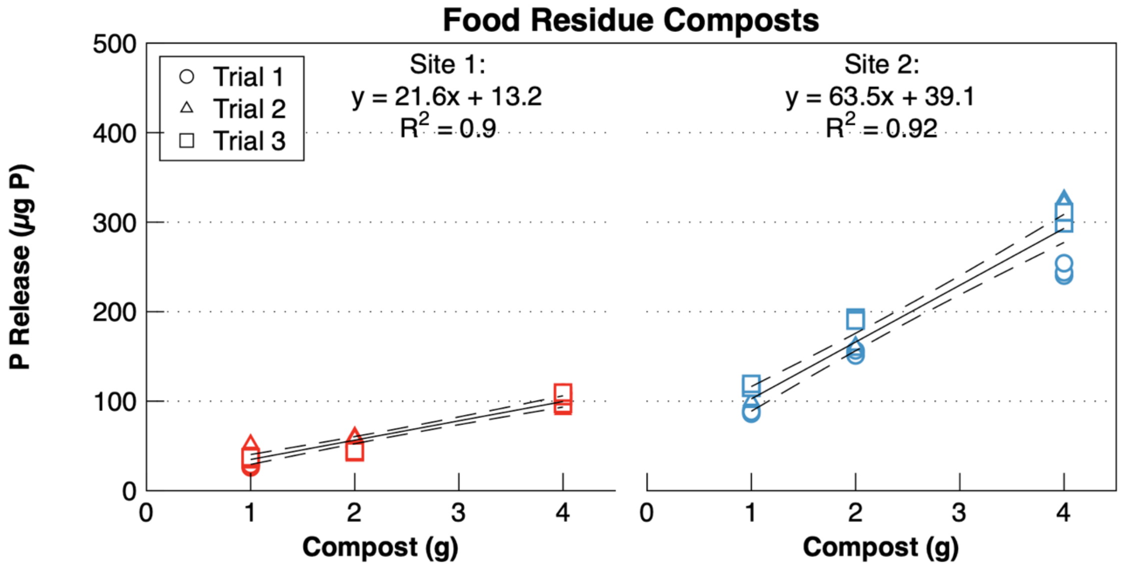


Figure 8: Phosphate release from food residue composts. Dashed lines represent 95% confidence interval on the regression.

Two sites provided food residue composts as shown in Figure 8. The regressions appear to fit the data well ($R^2 \geq 0.9$) and all trials appear to provide consistent data (95% confidence interval bounds are close to the regression line). The slope of the linear regressions represents the amount of phosphate released (µg) per mass of compost (g). These values (21.6 µg P / g compost for Site 1; 63.5 µg P / g compost for Site 2) will be used in later analysis. Compared to each other, Site 2 released more phosphate than Site 1, which demonstrates the variability in phosphate release from different sites.

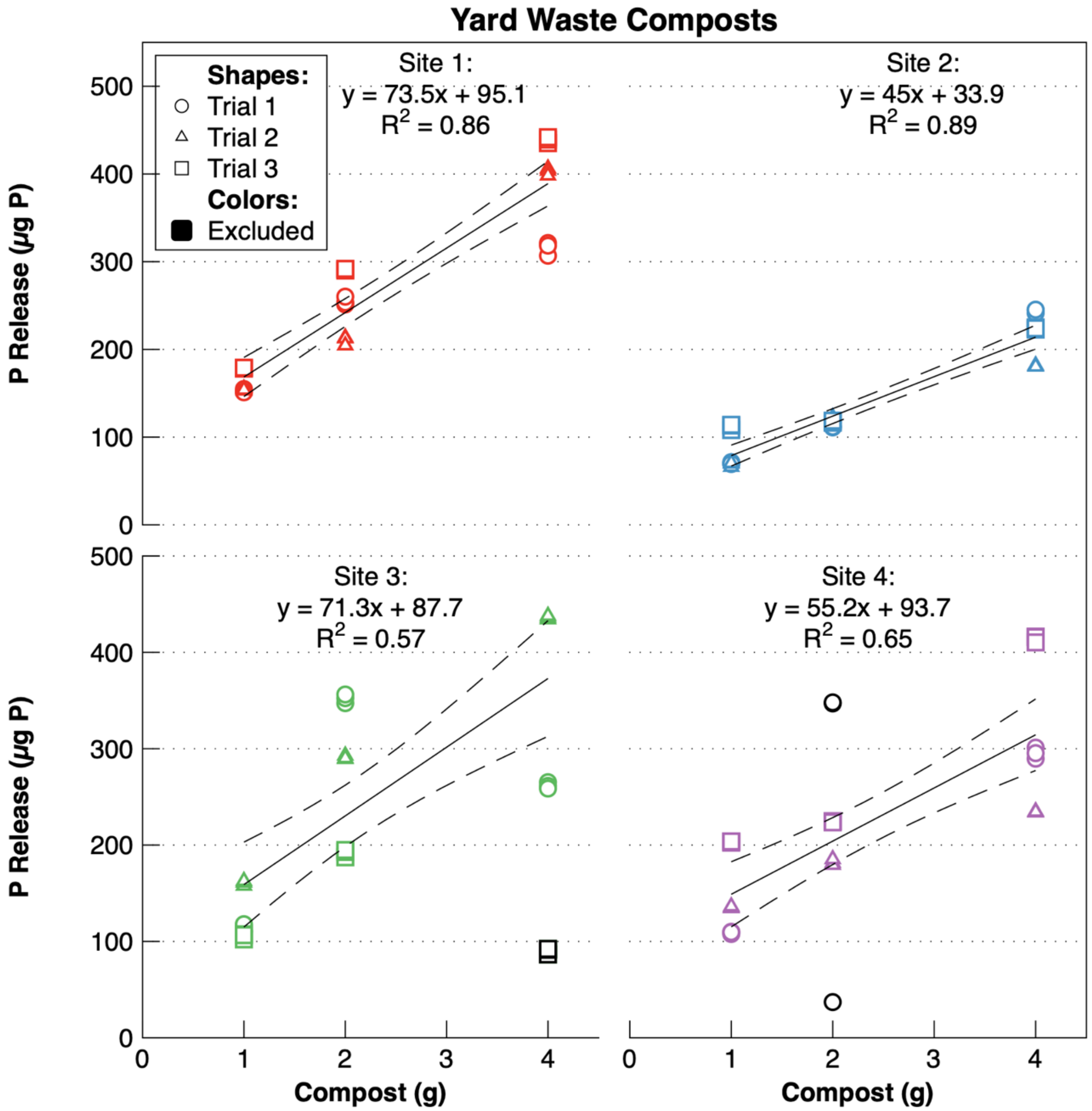


Figure 9: Phosphate release from yard waste composts. Dashed lines represent 95% confidence interval on the regression.

Four sites provided yard waste compost as shown in Figure 9. The regressions appear to fit the data well for sites 1 and 2 ($R^2 \geq 0.86$) and all trials appear to provide consistent data (95% confidence interval bounds are close to the regression line). The regressions for Sites 3 and 4 are less predictive of the data ($R^2 \leq 0.66$) and the results from the different trials varied more (large bounds for 95% confidence intervals). Some data were excluded from the regressions for both Sites 3 (compost = 4g, trial 3) and 4 (compost = 2g, trial 1) because they appear to be outliers. The variability is apparent in the remaining data for Sites 3 and 4 and demonstrate the inherent variability within compost from a single site. In other words, a small sample of a compost from a specific site may vary compared to a small sample from the same site at the same time. This appears to be true for Sites 3 and 4, and less true for Sites 1 and 2. The slope values (73.5 µg P / g compost for Site 1; 45 µg P / g compost for Site 2; 71.3 µg P / g compost for Site 3; 55.2 µg P / g compost for Site 4) will be used in later analysis.

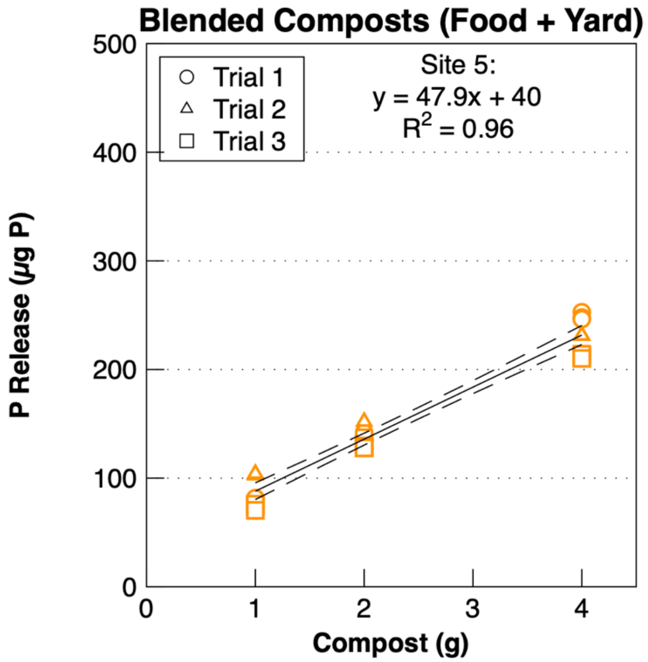


Figure 10: Phosphate release from blended (food + yard) compost. Dashed lines represent 95% confidence interval on the regression.

One site provided a blended (food + yard) compost as shown in Figure 10. The regression appears to fit the data well ($R^2 \geq 0.96$) and all trials appear to provide consistent data (95% confidence interval bounds are close to the regression line). The slope value (47.9 μg P / g compost for Site 5) will be used in later analysis.

The three types of compost are compared in Figure 11. The food residue (Figure 11a) composts released less phosphate on average compared to yard waste (Figure 11b), and more than the blended (Figure 11c) compost. Site 1 food residue compost released less phosphate than Site 1 yard waste compost, but the inverse is true for Site 2 (food residue released more phosphate than yard waste). This demonstrates the variability between types of composts and between sites. The variability between sites is further illustrated by the range of phosphate release for each type of compost in Figure 11. For example, the phosphate release for yard waste composts (Figure 11b) ranges from 70 μg to over 200μg at 1g of compost and from 180μg to nearly 450μg for 4g of compost.

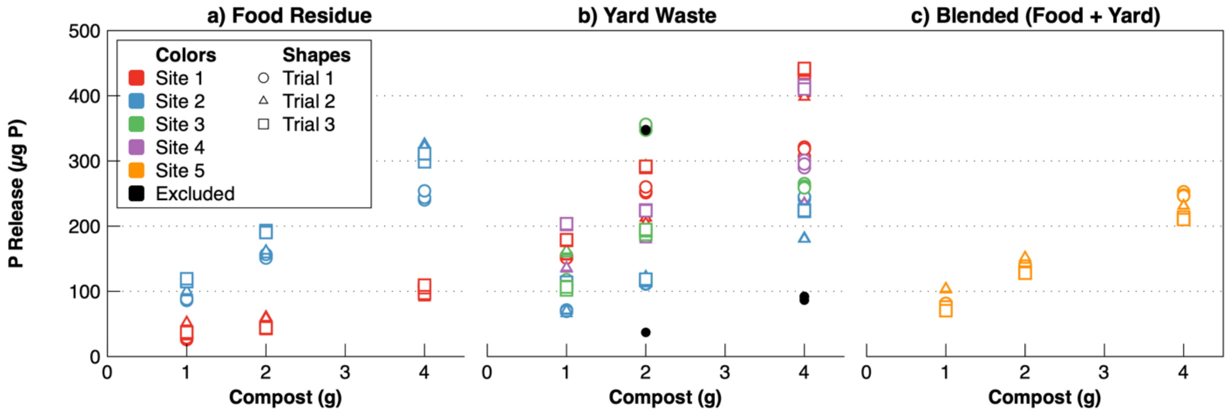


Figure 11: Food Residue Compost (2 sites) compared to Yard Waste compost (4 sites) and Blended (Food + Yard) compost (1 site).

3.2.2 Solvita Tests for Compost Maturity

The Solvita test kits yielded data for CO_2, NH_3, and Solvita Maturity Index, which are illustrated in Figure 12 as a function of the phosphate release in µg P per g of compost. The phosphate release (µg P / g compost) values used in this plot correspond to the slope of the linear regressions from Figures 8, 9 and 10. The CO_2 values varied from 4 to 7 for all samples. One replicate out of 14 total samples produced an NH_3 value of 4, while all other samples produced a value of 5. As such, the NH_3 values had minimal effect on the Solvita Maturity Index Calculation. It's important to note that Solvita values greater than 4.5 are considered "Advanced composting" and values greater than 6 are considered "Practical Maturity," according to Figure 7. The relationship between Solvita Maturity Index and phosphate release (µg P / g compost) is poorly correlated ($R^2 < 0.4$) and the 95% confidence interval on the regression vary between ±1 and ±2 over the range of the data. Thus, Solvita Maturity index is not a good predictor of phosphate release.

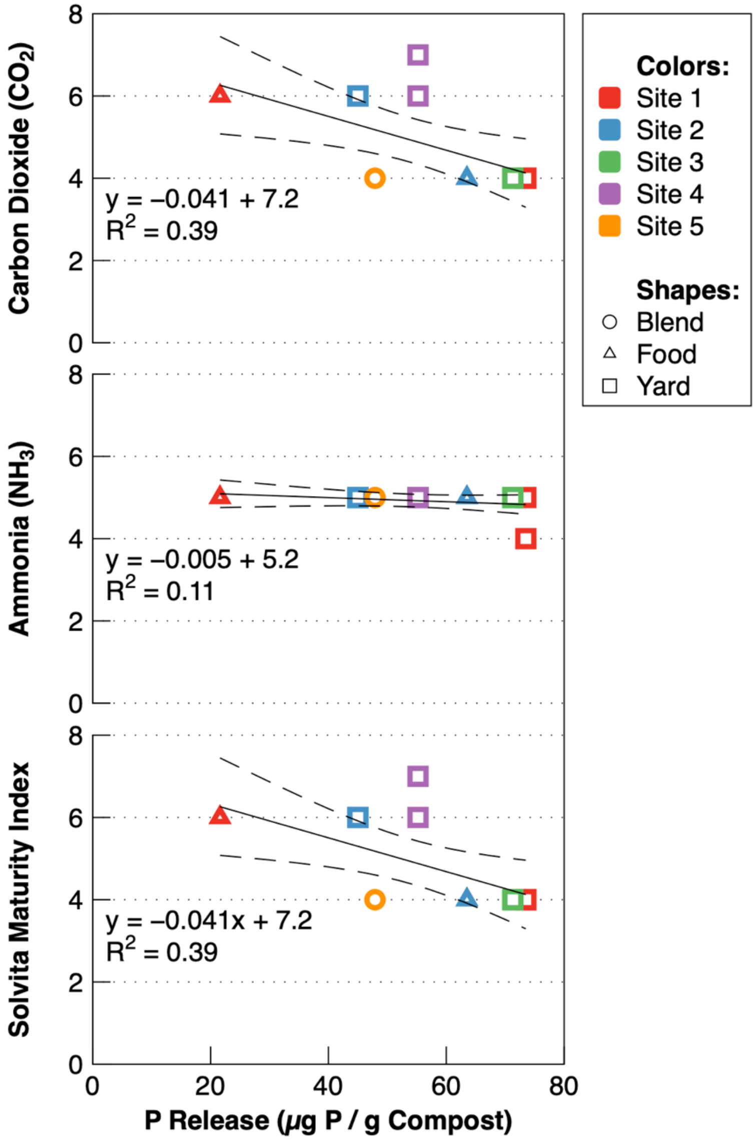


Figure 12: Carbon Dioxide, Ammonia, and Solvita Maturity Index for seven compost samples.

3.2.3 Soil Characteristic Tests

The results from Olsen P, Bray P, Mehlich-III P, and ICP-OES P are shown in Figure 13 as a function of the phosphate release in µg P per g of compost. Of these four laboratory analytical techniques, the Mehlich-III P (mg P /kg soil) data correlated best with P release (µg P / g compost), though the correlation is weak (R^2 = 0.46) and the 95% confidence interval bounds are large compared to the values of the regression. The correlations between P release (µg P / g compost) and Olsen P, Bray P, ICP-OES P were weak ($R^2 \leq 0.29$).

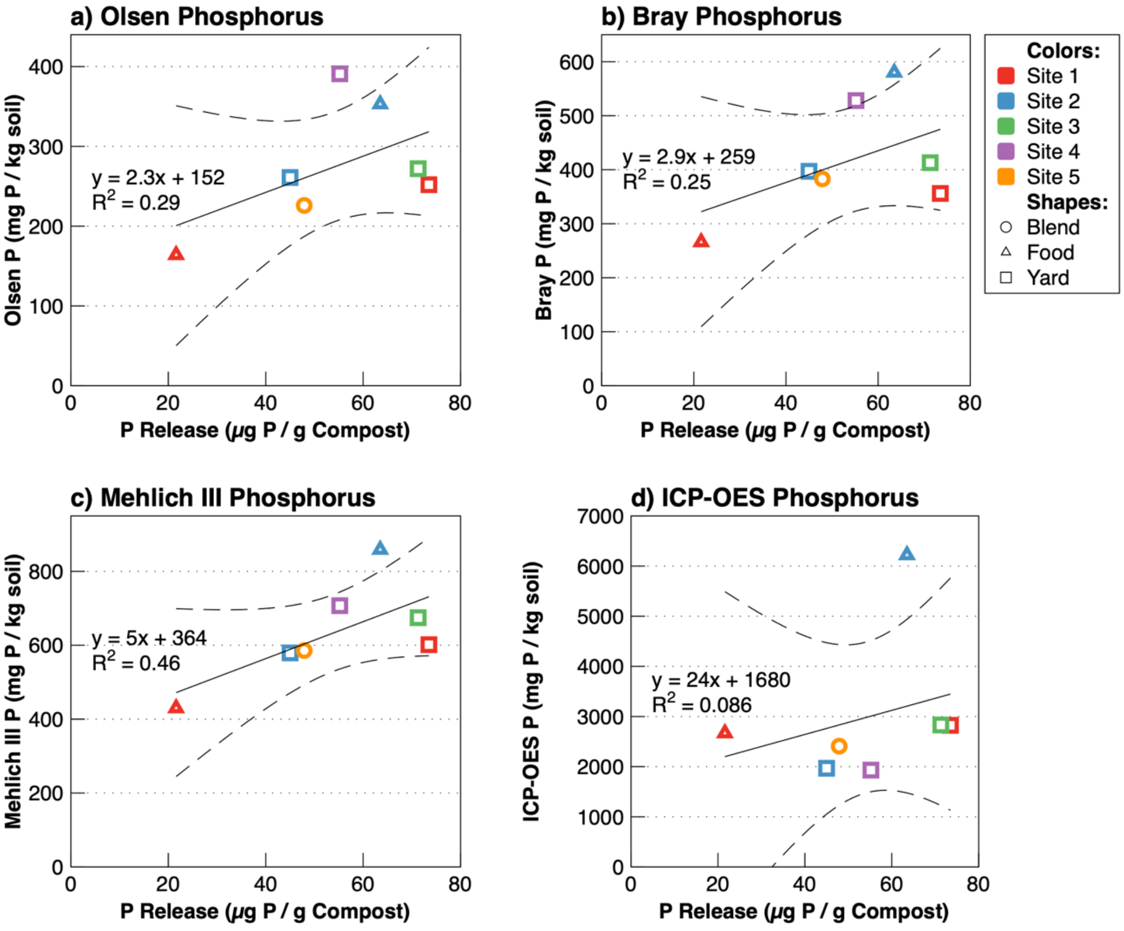


Figure 13: Olsen P, Bray P, Mehlich-III P, and ICP-OES P results compared to phosphate release (µg P / g compost).

3.2.4 In-field Batch Experiments

Two HACH® phosphorus test kits (PO-19A High Turbidity; PO-14) were purchased and used to determine whether in-field batch tests could be used to directly estimate phosphate release from compost samples. Approximately 40 grams (1/4 cup) compost was mixed with 273 mL (1 cup = 8 fl.oz) of water and placed on an orbital shaker table for 15 minutes at 1500rpm. A sample of the water was then processed according to the test kit instructions to determine the P concentration. Two junior scientists conducted the experiments independently and neither could determine the P concentration. While the instructions were easy to follow, the provided filtration system (filter paper) could not filter the sample via gravity due to a large amount of suspended compost particles. For an unfiltered sample, the resulting color of the sample could not be matched to the example colors on the provided color wheel. It is suspected that the turbidity affected the color of the samples, making it challenging to match the sample to the color wheel. It is also possible that tannins from the compost also influence the color. Both junior scientists recommended that this procedure not be considered for practitioners.

CHAPTER 4: OUTDOOR MESOCOSM EXPERIMENTS

4.1 METHODS AND MATERIALS

To evaluate the impact of biofiltration media mixes on filtration rate, nutrient output, and vegetation growth, mesocosm studies were completed in the outdoor spillway adjacent to St. Anthony Falls. Fourteen simulated events released approximately five gallons of phosphorus-enhanced water into different soil treatments beginning on July 18, 2019 and ending on October 24, 2019 to measure flow rate through the various media. Samples of the effluent water from these events were tested for nitrate and phosphate. In between events, settling, vegetation growth, and rainfall movement through each mesocosm were monitored.

4.1.1 Mesocosm Setup

These mesocosm studies were performed on ten different biofiltration media mixes. The following amendments were provided and mixed by a local aggregate supplier (Plaisted Companies, Inc.; https://plaistedcompanies.com/) unless otherwise noted: leaf compost, food compost (The Mulch Store; Rosemount, MN, https://www.mulchstoremn.com/empire.html), sphagnum peat, reed sedge peat, spent lime (St. Paul Regional Water Treatment Facility, https://www.stpaul.gov/departments/water-services), biochar (#4 size provided by Plaisted Companies, sourced from Royal Oak Charcoal), and iron filings (d_{50} ~0.75mm; provided by Plaisted Companies, sourced from Connelly GPM, Inc.). The amendments were mixed with sand by volume in proportions listed in Figure 14.

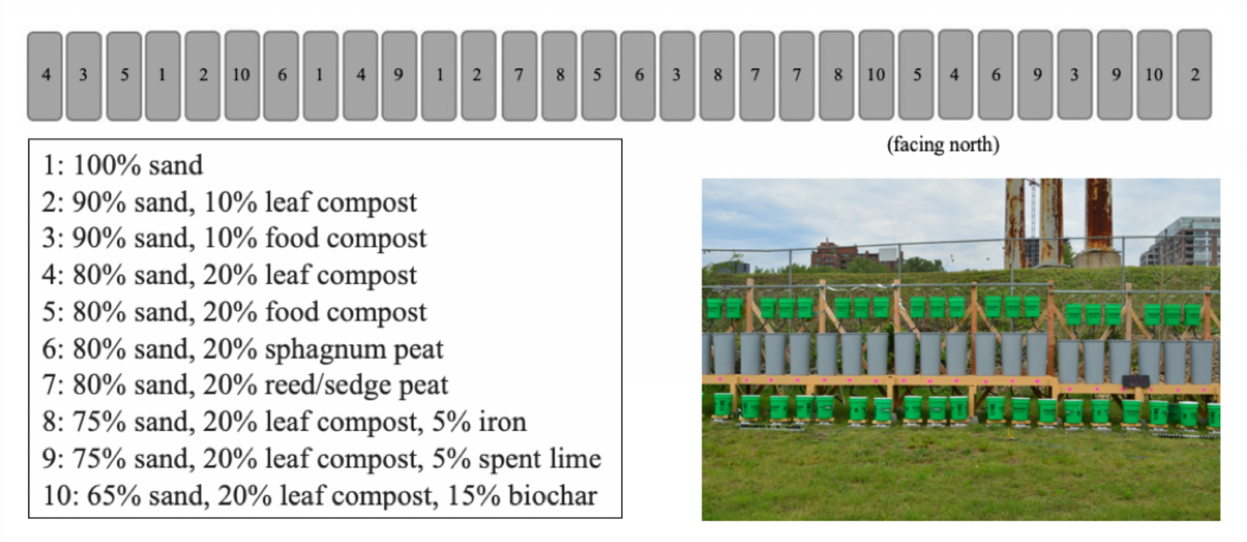


Figure 14: Diagram of soil treatment placement (top), biofiltration media mixes (bottom left), and photo of completed setup (bottom right).

Thirty 22-gallon round trash cans, 30 inches in height and 15.75 inches in diameter, were purchased, rinsed and scrubbed with phosphorus-free soap and tap water, and lined up on an outdoor platform which elevated them between 22.5 and 27 inches above the ground. Holes drilled into the bottom of each column allowed for insertion of a plastic bulkhead and ~20-inch long, 3/4 inches inner diameter, UV-resistant opaque PVC tubing (McMaster-Carr). Black tubing was selected over clear tubing to minimize photosynthetic reactions which would inhibit water flow. Approximately 4 inches of pre-washed pea gravel (d_{50} = 0.5 cm; Plaisted Companies), was added to the bottom of each column for drainage. Each dry biofiltration media mix treatment was added in approximately four 4.5-inch lifts until approximately 18 inches of media had settled in each column. In between each lift, the sides of the column were tapped with a rubber mallet to promote settling of particles. For each mixture, the same mass was added for two additional replicates (three replicates total for ten mixtures resulted in 30 mesocosms). A schematic of the mesocosm construction and dimensions is shown in Figure 15. A diagram of the randomized placement of each treatment is shown in Figure 14.

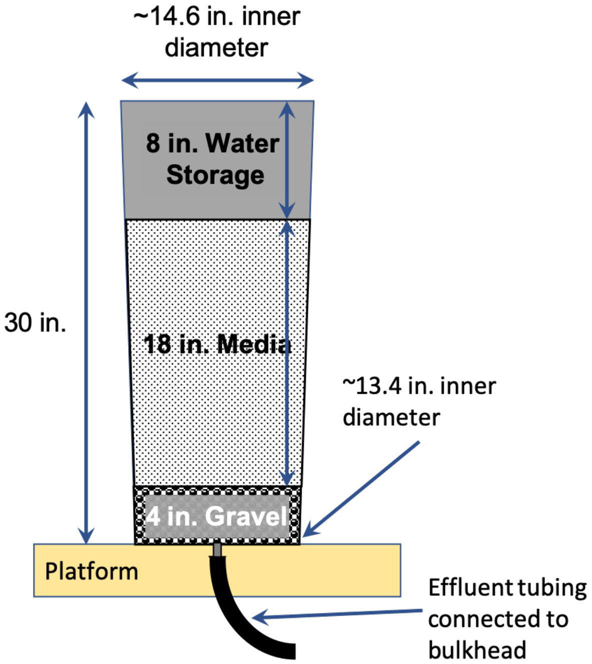


Figure 15: Mesocosm schematic with approximate dimensions (not to scale).

The experimental setup for simulated runoff events consisted of 5-gallon influent buckets elevated 13 inches above the surface of each mesocosm, with 11-inch long black tubing (5/8-inch diameter) and an inline valve (~4 inches from the end of the tubing). In front of, and below the mesocosm was a 5-gallon bucket to catch effluent from the mesocosms, which was leveled on an electronic scale. The scales had an average error of 0.32%. A flow dissipater (Figure 16) was centrally placed on the soil surface of each mesocosm to minimize scouring of particles during inflow.

Figure 16: Side (left) and aerial (right) photos of dissipater columns.

The ~8-inch tall, 4-inch diameter dissipater columns (Figure 16) were constructed by securing mesh wire around 4-inch plastic caps and filling with pea gravel placed around PVC pipes, which would stabilize influent tubing during experiments. Each was stabilized with wooden dowels pressed against the inner sides of the mesocosm to prevent the dissipater from tipping.

Each mesocosm was seeded with 0.4 g of switchgrass seeds (Prairie Restorations, Princeton, MN, http://www.prairieresto.com/) on July 5, 2019 by evenly scattering across four 0.34 ft^2 quadrants. After seeding, mesocosms were watered with 1 L of water approximately twice a week prior to the start of experiments. Each mesocosm was covered with transparent plastic until the start of experiments to prevent mesocosm disruption from rainfall and to promote seed germination.

Between simulated events, filtered rainwater and any residual experiment effluent that drained from each mesocosm was collected in clear, 6-quart plastic containers (13 5/8 inches long, 8 1/4 inches wide, and 4 7/8 inches tall, Figure 17). The effluent tubing from each mesocosm - 31 inches in length - was fitted through a hole drilled into each container's lid. An additional lid-less container was placed beside the experimental setup to collect rainwater between August 6, 2019 and October 28, 2019.

Figure 17: Rainwater collection bins underneath mesocosms.

4.1.2 Simulated Stormwater Runoff Events

The series of fourteen simulated stormwater events took place approximately once a week beginning in July 2019 and ending in October 2019. Each event consisted of 20.4 L ± 0.2 L of phosphorus-enhanced Mississippi River water added to each mesocosms. Effluent flow rate was measured and collected effluent was sampled and tested for phosphate (14 events) and nitrate (4 events).

4.1.2.1 Pre-Event Setup

Both the influent and effluent buckets were prepared initially by rinsing and scrubbing with phosphorus-free soap and tap water prior to use. A 550-gallon storage tank was rinsed and scrubbed with phosphorus-free soap and Mississippi River water. In between experiments, influent buckets were stored outside under a tarp and effluent collection buckets were stored indoors. Influent buckets were rinsed with Mississippi River one day prior to each experiment, and collection buckets were rinsed and scrubbed with deionized water and phosphorus-free soap in the week leading up to each experiment.

Prior to each simulated stormwater event, the tank was scrubbed and any leftover water and residue was removed. Mississippi River water was pumped into the tank from the Outdoor StreamLab headbox until approximately 250 gallons filled the tank. Three 50 mL samples of this river water were collected from the hose – following standard rinsing and dumping protocol three times – once water had been flushed through the hose. These samples were immediately stored in the freezer. K_2PO_4 which had been dehydrated in a 250°F oven for one hour and then measured out into a 914.74 mg sample, was added to the tank roughly halfway through filling. A large paddle was used to stir this mixture for roughly one minute. The lid was secured tightly on the tank overnight with its vents open.

On the day of simulated stormwater event, thirty scales (ACCUTECK All-in-1 Series W-8250; sold by https://www.amazon.com/) were placed on leveled concrete tiles positioned in front of and below the mesocosms. A wooden brace was placed on each scale below the collection bucket to both stabilize the buckets and to elevate buckets above the scale screens (Figure 18). Effluent tubing from each mesocosm was fitted through a hole drilled into the lid of each collection bucket. Each scale was set to kilograms and tared.

Figure 18: Collection buckets placed above wooden braces, scales, and leveled pavers.

The thirty influent buckets were hung above the mesocosms and filled to the brim with tank water using a sump pump. A tarp was placed over the tops of the mesocosms during filling to minimize spillage before the start of each experiment. Influent tubing was fitted into the PVC pipe portion of the gravel dissipaters sitting on top of each mesocosm. Three tank samples were collected: one before filling any influent buckets, one in the middle of filling influent buckets, and one after all influent buckets were filled. The temperature of the tank water was recorded after all buckets were filled.

4.1.2.2 Simulated Event

Each mesocosm had a unique stopwatch. At the start of the simulated events, each influent bucket valve was opened and stopwatches were started simultaneously. The valves were opened consecutively starting at a randomly selected mesocosm. After all water had had a chance to drain freely, influent buckets were manually tipped to ensure complete drainage of all water. Effluent mass data recording began as soon as possible following the opening of valves. Recording occurred rapidly at the beginning of infiltration, gradually slowed down, and typically tapered off around two hours.

4.1.2.3 Post-Event Sampling

After approximately two hours of recording was completed, triplicate 50 mL water samples were gathered from each collection bucket. All water samples were collected in new 50 mL plastic tubes. Water was collected, rinsed, and dumped from each tube three times before collecting and saving the sample. The temperature of each bucket was recorded after its samples were collected. All samples were stored in coolers until transferred to freezers.

4.1.3 Monitoring In Between Simulated Events

4.1.3.1 Vegetation

Overhead photos of each mesocosm were taken on a weekly basis to document vegetation growth. To monitor growth throughout the experiment, the number of switchgrass sprouts, the height of the tallest sprout, and the height of the shortest sprout in each mesocosm were measured. A more robust determination of soil treatment’s impact on vegetation success involved gathering the above ground biomass in each mesocosm in paper bags on October 11, 2019 (98 days after seeding), dehydrating it in an oven until it was completely desiccated, and massing it. Any non-switchgrass biomass was measured separately.

4.1.3.2 Settling

Consolidation (i.e., settling) of the media within the mesocosms was tracked by measuring the depth of the soil surface relative to the top of the mesocosm on the same weekly interval as the vegetation measurements. Overall, there was no statistical difference in settling between the treatments and settling within all columns averaged 0.73 inches ± 0.35 inches (standard deviation).

4.1.3.3 Rainfall

Plastic tubs placed below the mesocosms in between experiments allowed for rough tracing of water and nutrient concentration movement through each column. Both rainfall and residual experimental water contributed to these. Either scales or graduated cylinders with thermometers were employed for water mass measurements. Standard sampling protocol applied when enough water was in the tubs.

4.1.4 Data Recording & Analysis

Field data sheets were used to collect filtration rate, water temperature, and observational data on experiment days. They were then scanned, entered, and error corrected. All other notes, observations, and data regarding rainfall, vegetation, and sediment settling measurements were recorded in a field notebook.

During flow rate data processing, inflow volume was adjusted when necessary and mass was converted to volume using temperature recordings. Outflow data was validated by comparing field notes, checking for outliers, and discarding nonphysical data. The initial flow rate was determined and the percent outflow was extrapolated to 120 minutes.

4.1.5 Wet Chemistry Analytical Techniques

After samples were collected in 50mL conical tubes, samples were frozen until ready for analysis for phosphate and nitrate concentration. Samples were removed from the freezer and either 1) allowed to thaw at room temperature for a period of approximately 14 hours, or 2) allowed to thaw in a refrigerator at 5°C for approximately 48-72 hours, prior to analysis. Thawed samples were centrifuged for 15 minutes at 2500 rpm. Samples were then immediately filtered using a 10mL syringe and 0.45-micron filter. The sample was sub-sampled into 3 separate 15mL conical tubes; one each for phosphate, nitrogen and supplemental for potential additional parameter testing. Nitrogen and supplemental samples were immediately frozen and all phosphate samples were either immediately analyzed or stored at 5°C and analyzed within 2 days.

Phosphate concentration was measured using flow injection analysis by the Lachat Instruments (Milwaukee, Wisconsin) Quick-Chem model 8000, Method 10-115-01-1-M with a statistically determined detection limit (as determined in water) of 5 µg P/L. The Lachat was calibrated using prepared phosphorus standards ranging from 0 - 2000 µg P/L. These standards were also used during the sample run as check standards; one for every 10 samples. Analysis was repeated (duplicated) on one sample after every 10 samples for quality assurance and quality control (QA/QC). The system was rinsed with Disodium ethylenediaminetetraacetic acid (EDTA) and MilliQ (high degree deionized water) immediately after calibration standards and after each check standard or sample duplicate.

Nitrate samples were submitted to the Research Analytical Laboratory (RAL) at the University of Minnesota (http://ral.cfans.umn.edu/) for colorimetric analysis at 520 nm by the cadmium reduction method on a Lachat 8500 flow injection analysis instrument.

Calibration curves and measured concentrations were recorded digitally by the Lachat software and exported into Excel for additional data and QA/QC analysis. Sample status and location (frozen, thawed, analyzed, etc.) were recorded digitally along with important dates for thawing, centrifuging and filtering, and chemical analysis.

4.1.6 Data processing techniques

4.1.6.1 Filtration Rate Data Analysis

For each event, the total volume of influent added to each mesocosm was 20.4 L which corresponded to a height of 20.8 cm (8.2 in) above the mesocosm soil surface. This volume was adjusted if any influent was recorded remaining in the influent bucket. The initial flow through each mesocosm happened very quickly (see Figure 19) and then plateaued at a level approximately 75-85% of the influent. From the effluent timeseries, two parameters were calculated to represent: a) the initial rate of flow through the mesocosm, and b) the plateau volume of effluent. These parameters were represented by the time required for 50% of the effluent to exit the mesocosm, T50, and the % of effluent that exited the mesocosm at 120 minutes, per120, respectively. T50 was calculated by normalizing the effluent by influent and interpolating between measurement points. The percent flow through at 120 minutes was calculated by fitting a piece-wise linear regression to the plateau.

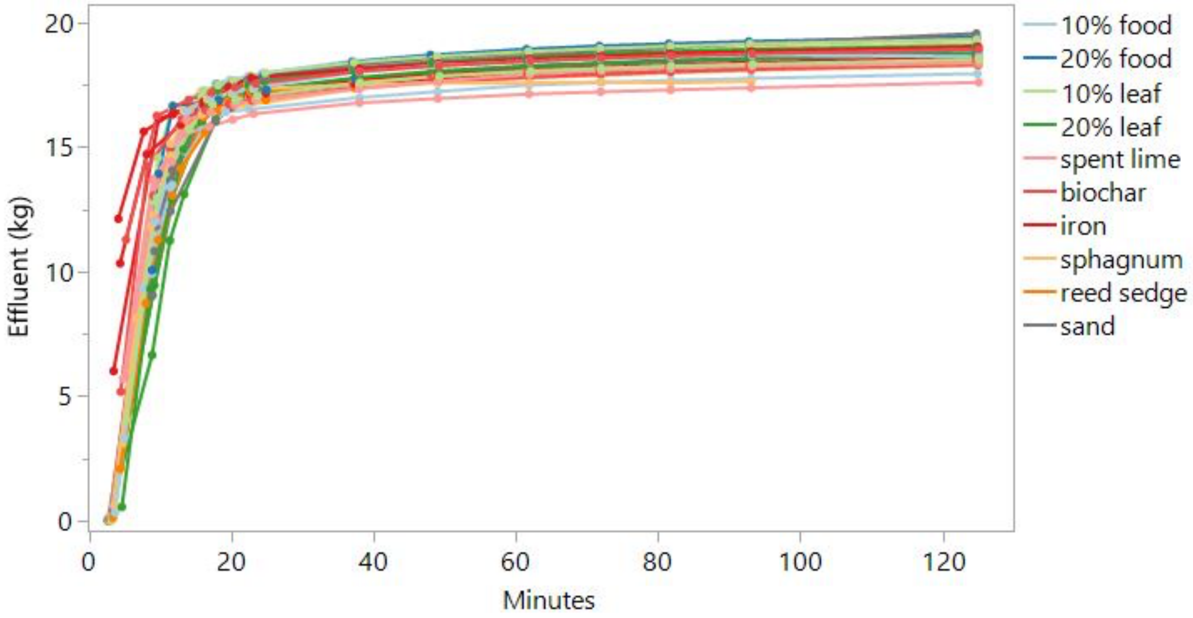


Figure 19: Example of mass of effluent water time series data from Event 8. The effluent water mass timeseries from all events followed a similar pattern.

4.1.6.2 Statistical Analyses

All statistical tests were completed in JMP (https://www.jmp.com/en_us/home.html). For data with repeat measurements (flow parameters, water chemistry, vegetation growth), a full-factorial repeated measures ANOVA analysis was conducted to evaluate the effect of event number, media treatment, and the interaction between event and media treatment. For the final biomass data, without repeat measurements through time, a one-way ANOVA was conducted. Post-hoc Tukey HSD or Dunnett's (to compare to controls, either sand or influent concentrations) were used to evaluate differences between media treatments. For all tests, alpha was set equal to 0.05. Reported averages are the arithmetic means of the results by media mix treatment.

4.2 RESULTS AND DISCUSSION

From July until October 2019, 14 simulated stormwater event experiments were conducted using the outdoor biofiltration media mesocosms (Figure 20). These events occurred approximately once a week except for the week of September 8-15, 2019 when large storm events prevented experiments. Flow through, nutrient concentrations, and vegetation growth were monitored over the course of the experiments. For all simulated stormwater events, samples were collected for water quality analysis. Samples for all events were analyzed for phosphate. Samples from four events (4,7,9, and 13) were analyzed for nitrate (Figure 20). Rainfall and air temperature over the experimental period were downloaded from the nearest weather station at the MSP airport. Plant growth was monitored over the duration of experiments until the final biomass was collected on October 11, 2019.

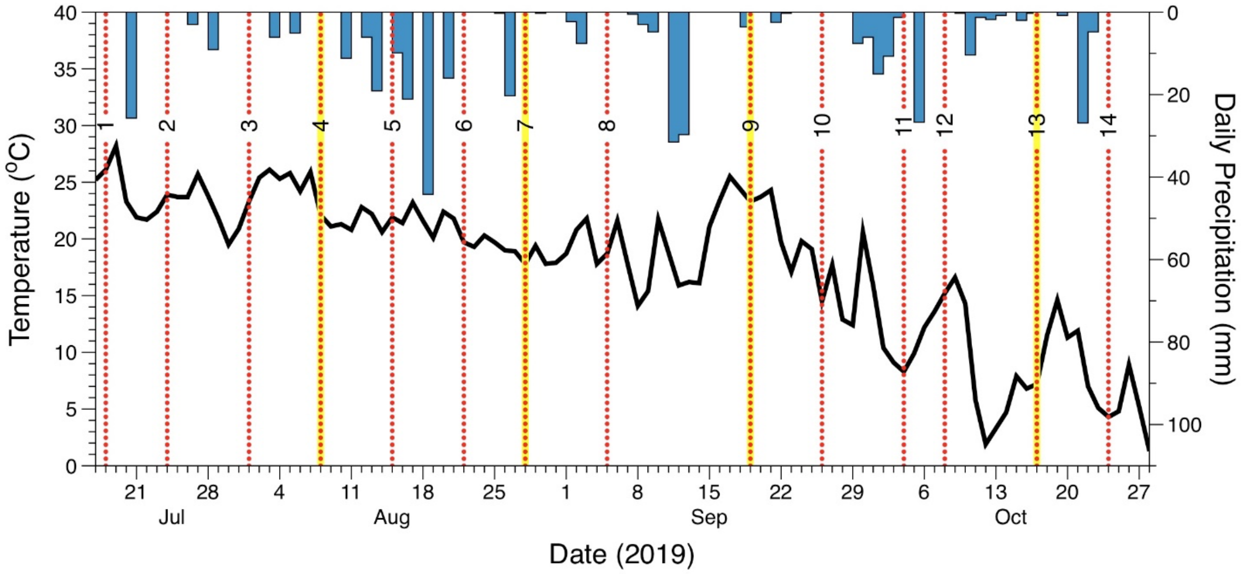


Figure 20: Average daily temperature and total daily precipitation over mesocosm testing. Simulated events are indicated by dashed red lines (analyzed for phosphate concentration and flow rate). Highlighted (yellow) events were also analyzed for nitrate concentration.

4.2.1 Flow through mesocosms

Two parameters calculated from the effluent time series, time to 50% of influent (T50) and percent of influent at 120 minutes (per120) were compared across events and treatments. To analyze T50, events 1, 6, and 10 had to be excluded because of missing data for the iron mix treatment and the biochar mix (for event 1). Missing data occurred when initial recordings were collected after 50% of the effluent was collected, or, in isolated circumstances, because of scale issues. Scale issues occurred when effluent buckets were not seated correctly, or if the bucket moved or tipped during measurement. These issues were recorded during each event and/or identified in the QA/QC analysis.

For T50, both media treatment and event were significant (p-value = 0.0002 and p-value < 0.0001, respectively). The interaction between media and event was not significant. Using Dunnett's post-hoc test, only the iron mix T50 was significantly different than 100% sand indicating that stormwater flowed through the iron mix faster than it flowed through sand. It is unknown if this effect will persist into subsequent rainy seasons. Over the course of all 14 events, for all media mix treatments, T50 increased (Figure 21) with the exception of events 5 and 6, where ponding was observed in reed sedge mix mesocosms which resulted in a longer T50.

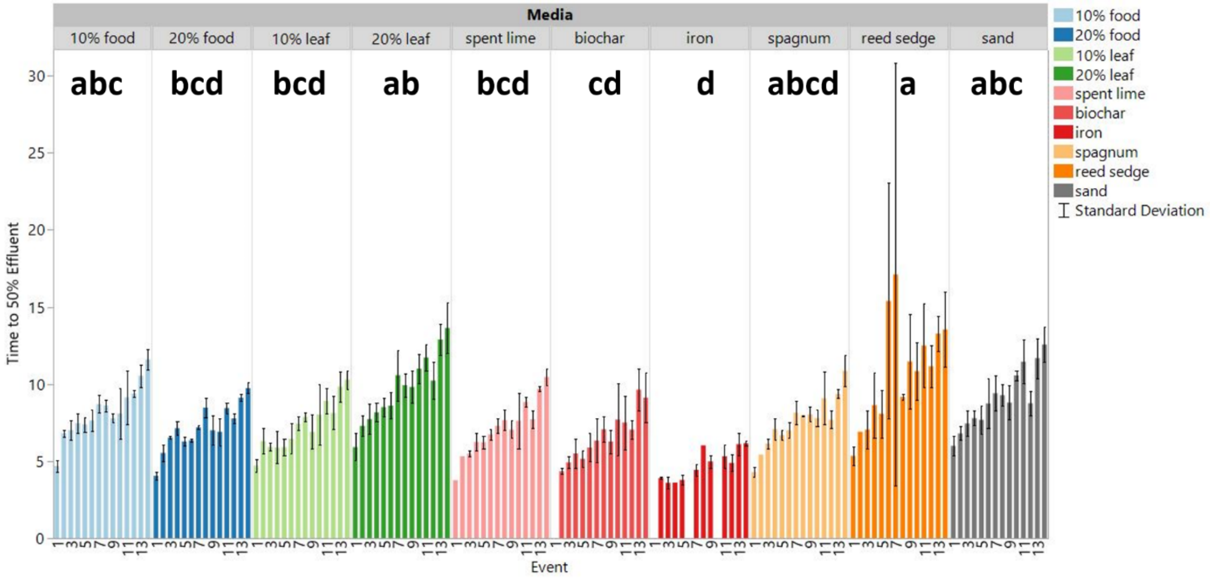


Figure 21: Time (minutes) to 50% effluent by media mix treatment over simulated stormwater events. Data are missing when the time to 50% effluent was less than the initial recording time. Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc, α = 0.05).

The percent of influent that flowed through the mesocosms at 120 minutes, per120, was arcsine transformed (Aper120 = arcsine(√(Per120/100)). This is a common transformation to account for the non-normality of percentage data. Aper120 varied by event (p-value < 0.0001) and by media mix treatment (p-value = 0.0006) but the interaction was not significant (p-value =0.1927). Comparing media mix treatments to the control (100% sand), the Aper120 of biochar, reed sedge peat, and spent lime mixes were significantly less than sand. This indicates that these mixes retained more stormwater for longer than sand (Figure 22). Reed sedge was the only treatment that was observed to have prolonged ponding (events 5 and 6 only).

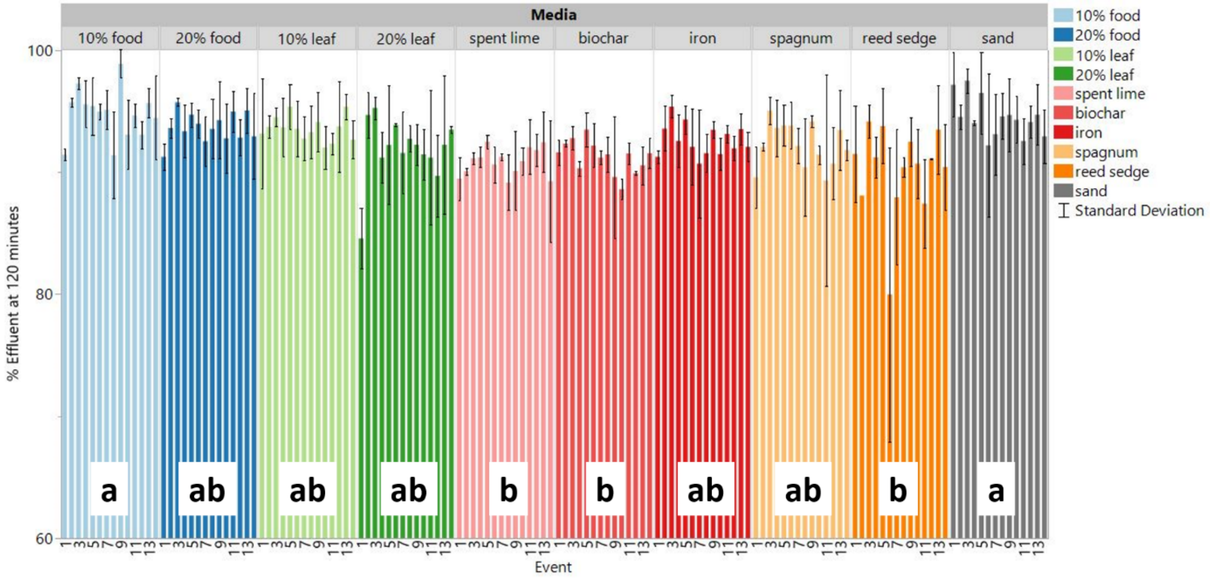


Figure 22: Percent (by mass) of stormwater influent measured in effluent at 120 minutes after experiment start. Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc, α = 0.05).

4.2.2 Nutrients in Effluent

4.2.2.1 Simulated Runoff Events

Phosphate was measured in the effluent of each mesocosm after every simulated stormwater event and in the tank prior to each event (Figure 23). For the last event, tank data are missing, therefore, the tank value was estimated as the average of the four previous tank concentrations. Because the effluent phosphate concentration data spanned more than two orders of magnitude (min = 0 µg/L; max = 2561.5 µg/L), the phosphate concentration data was transformed with the natural logarithm(ln). This reduces the strong impact of extreme large values when compared to extreme small values. The effect of media treatment and event was tested using a full-factorial repeated measures ANOVA. Results comparing effluent concentrations to control (influent) concentrations were conducted using a post-hoc Dunnett's control test; pairwise comparisons between media treatments were conducted using a post-hoc Tukey HSD test (alpha = 0.05).

For the ln-transformed data, the effect of media mix, event and the interaction between media mix and event were significant (p-values: <0.0001). The effluent phosphate concentration from the 10% and 20% food compost, 10% and 20% leaf compost, biochar, and spent lime media mix treatments was significantly greater than the influent phosphate concentration (influent tank; average P = 197 µg/L), while the iron, peat (reed sedge and sphagnum) and 100% sand mix effluent concentrations were significantly less than the influent. The 20% leaf (average P = 1643 µg/L) and biochar (average P = 1301 µg/L) produced significantly greater effluent phosphate concentration than all other mixes.

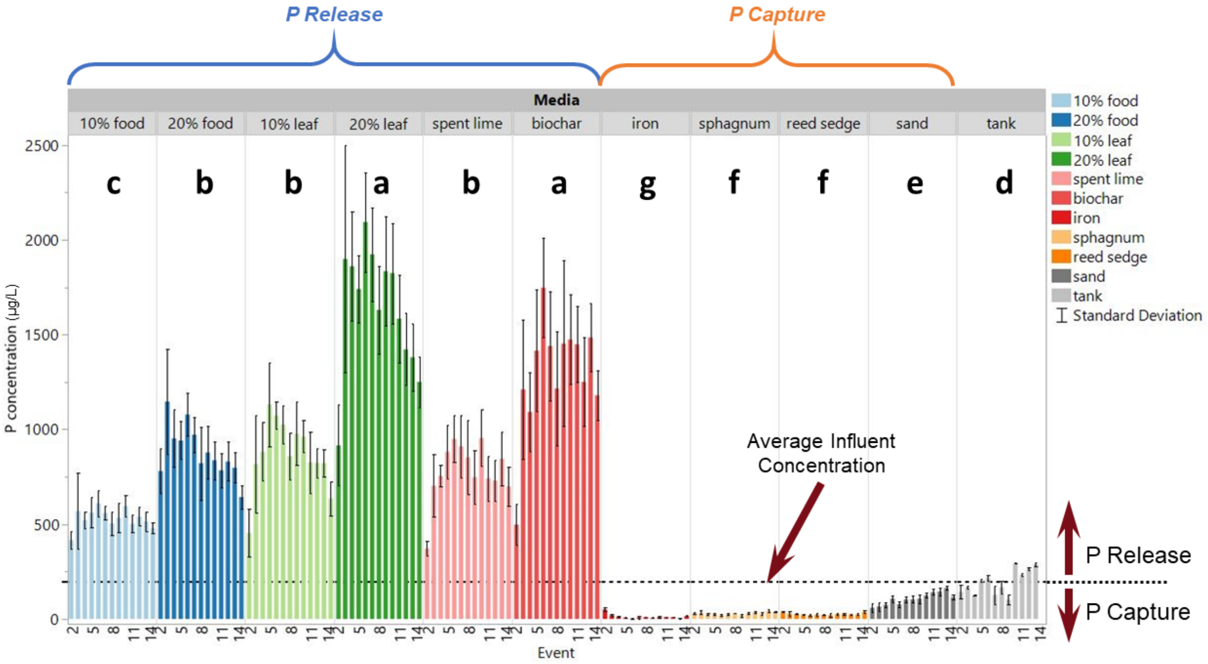


Figure 23: Phosphate as P concentration (µg/L) in effluent across events by media mix treatments and influent (tank). Dashed line indicates the average of the influent concentrations (197 µg/L). Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc on ln-transformed data, α = 0.05).

Spent lime (average P = 780 µg/L) had statistically similar effluent concentration as 10% leaf compost (average P = 869 µg/L) and 20% food compost (average P = 882 µg/L). These were all significantly less than 20% leaf compost (average P = 1643 µg/L). Thus, the effluent P concentration can be reduced by approximately one half with any of these three alternative mix designs: 1) replacing 20% leaf compost with 20% food compost; 2) incorporating 5% spent lime with 20% leaf compost; or 3) reducing the amount of leaf compost from 20% to 10%. Replacing leaf compost with 10% food compost (average P = 531 µg/L) further reduces the phosphate concentration, which was significantly less than the phosphate released from 10% leaf compost.

Iron, sphagnum peat, and reed-sedge peat, had effluent concentrations less than the influent concentration (tank average= 197 µg/L), as shown in Figure 24. The iron mesocosms contain 5% iron, 20% leaf compost, and 75% sand and produced an average effluent phosphate concentration of 13 µg/L. In comparison, the effluent phosphate concentration from the mesocosms with 20% leaf compost was 1643 µg/L (Figure 23). Thus, 5% iron mixed with 20% leaf compost captured soluble phosphate from the influent (197 µg/L) and from the leaf compost (1643 µg/L). In addition, the influent concentration increased from the first experiment (summer) to the last experiment (autumn) but the effluent concentration from the iron mesocosms stayed consistently below ~20 µg/L. This suggests that the iron has capacity for phosphate capture throughout the duration of these experiments. The 5% iron mix also released less soluble phosphate than 100% sand (average P = 107 µg/L).

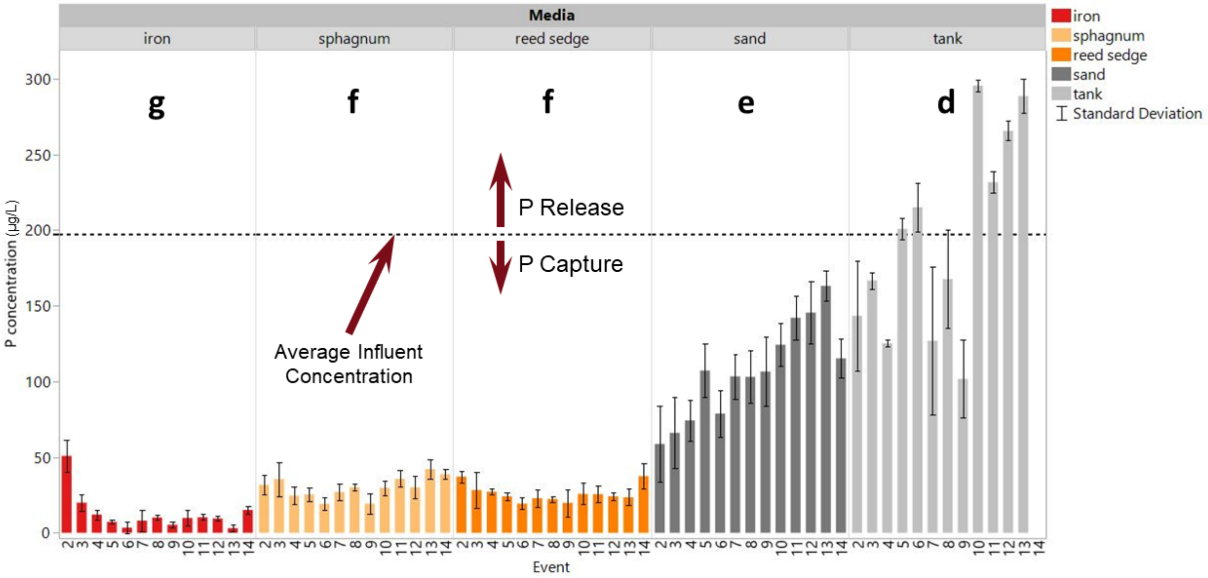


Figure 24: Phosphate as P concentration (µg/L) in effluent for iron, sphagnum peat, reed-sedge peat, 100% sand, and influent (tank). Dashed line indicates the average of the influent concentrations (197 µg/L). Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc on ln-transformed data, α = 0.05).

The effluent concentration for 20% sphagnum peat (average P = 30 µg/L) and 20% reed-sedge peat (average P = 26 µg/L) mesocosms were both significantly less than the influent (197 µg/L), the 20% leaf compost (average P = 1643 µg/L), and the 20% food residue composts (average P = 882 µg/L). Thus, sphagnum peat and reed-sedge peat release considerably less phosphate than leaf compost and food residue compost and also capture phosphate when compared to 100% sand (average P = 107 µg/L) and the influent (average P = 197 µg/L).

The effluent phosphate concentration from the 100% sand mix (average P = 107 µg/L) was statistically less than the influent (average P = 197 µg/L). Unlike the iron and peat mixes, the effluent concentration from 100% sand increased from the first (summer) to last (autumn) experiment. The tank concentration similarly increased from the first to the last experiment (with a few exceptions). This suggests that 100% sand had limited capacity to capture phosphate whereas the iron and peat mixes had capacity to capture phosphate throughout the duration of these experiments.

4.2.2.2 Rainfall Events

Effluent from the mesocosms was collected following large rainfall events and analyzed for phosphate concentrations on 8/12/2019, 8/19/2019, and 10/7/2019 as shown in Figure 25. The effluent concentrations during rain events exhibited similar magnitudes as simulated events (Figure 23). For rain events, the effect of media mix, event and the interaction between media mix and event was significant (p-values: <0.0001). The 10% and 20% food, 10% and 20% leaf, biochar, spent lime, and 100% sand media mix treatments all had significantly more phosphate in the effluent than the sampled rainwater (average rainfall P = 19.1 µg/L). The peat mixes (reed sedge and sphagnum) had no significant difference in phosphate concentration in the effluent compared to the rainwater, but the iron media mix had effluent phosphate concentration (average P = 16.4 µg/L) that was significantly lower than the sampled rainwater (Figure 26). The 100% sand media mix's effluent phosphate concentration (average P = 73.2 µg/L) was greater than the rainwater, suggesting that phosphate captured during the simulated runoff events can be released when the influent concentration is low.

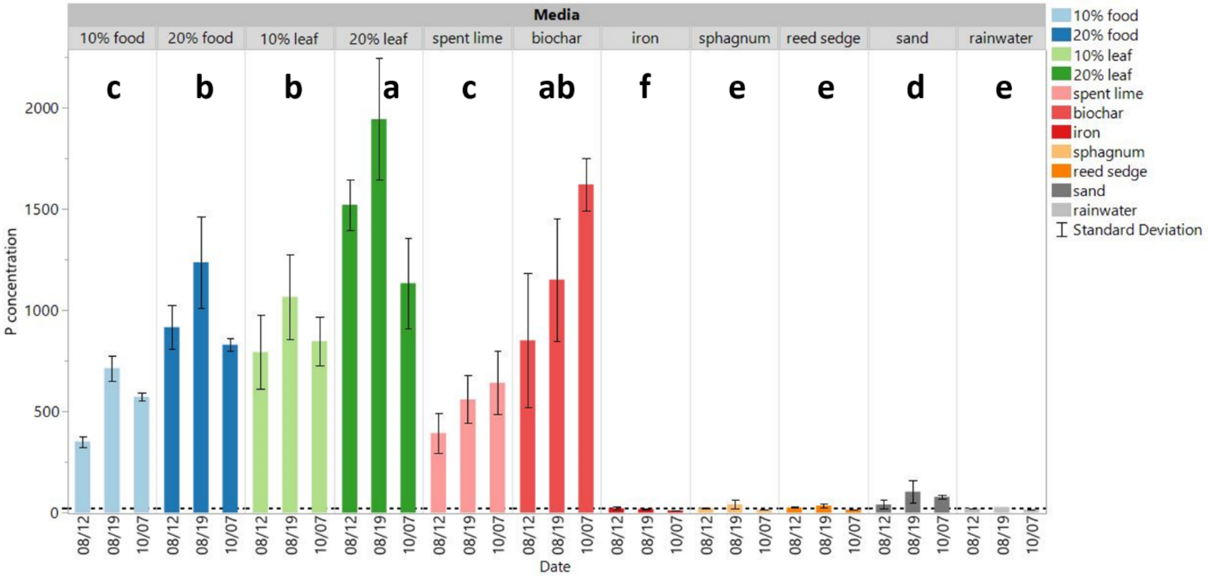


Figure 25. Phosphate as P concentration (µg/L) in effluent after three large rain events by media mix treatments and influent (rainwater). Dashed line indicates the average of rainwater concentrations (19.1 µg/L). Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc on ln-transformed data, α = 0.05).

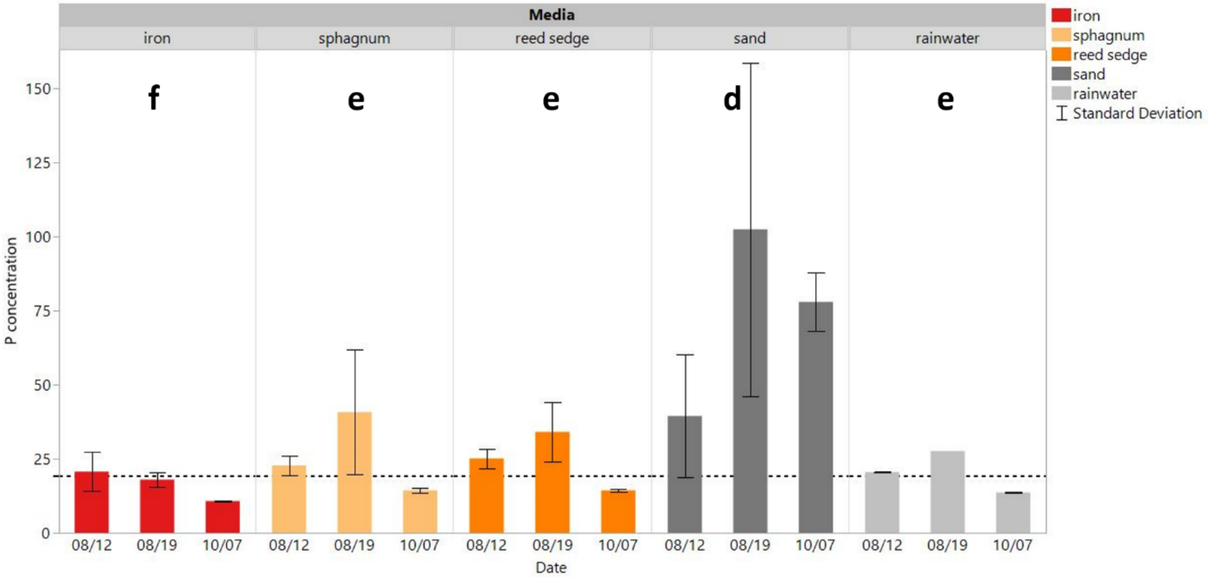


Figure 26: Phosphate as P concentration (µg/L) in effluent after three large rain events by media mix treatments and influent (rainwater). Dashed line indicates the average of rainwater concentrations (19.1 µg/L). Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc on ln-transformed data, α = 0.05).

4.2.2.3 Nitrate and pH

A similar analysis was conducted for a subset of the events to measure nitrate release (nitrate+nitrite – N). Again, the effect of media mix, event and the interaction term were significant (p-values <0.0001). 10% leaf, 20% leaf, spent lime, and biochar media mixes resulted in significantly more nitrate compared to the influent (tank). This was especially true for the spent lime mix for the fourth event which resulted in a very large (>9 mg/L) nitrate release (Figure 27).

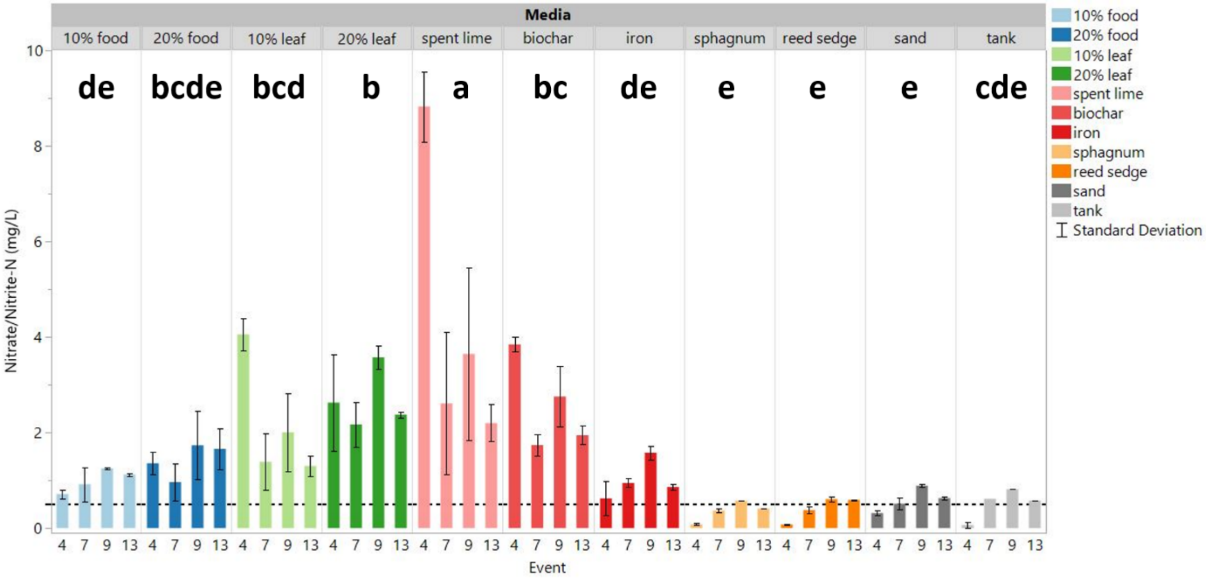


Figure 27: Nitrate + nitrite as N concentration (mg/L) across events by media mix treatments and in influent tank. Dashed line indicates average tank concentration of 0.50 mg/L. Treatments (media mix) with the same bold letter (a, b, c, etc.) are not significantly different from each other (Tukey post-hoc, α = 0.05).

The cause for the large nitrate release from spent lime in event four is unclear. To determine whether alkalinity impacts from the spent lime could contribute, pH was also measured. For statistical analysis, event 7 was excluded because the influent tank pH was not measured. For effluent pH, the effect of media mix treatment and event were significant, (p-values: <0.0001), but not the interaction between event and media mix (p-value: 0.3410) as shown in Figure 28. The 10% and 20% leaf compost, 10% and 20% food compost, and the biochar media mixes were all statistically similar to each other and to the tank pH (average pH = 8.87). The spent lime media mix pH (average = 9.16) was statistically similar to 20% leaf compost and biochar, but greater than all other media mixes, including the tank. The iron (average pH = 8.75), sphagnum peat, reed sedge peat, and 100% sand media mixes were statistically similar to each other and the tank, but less than all other media mixes.

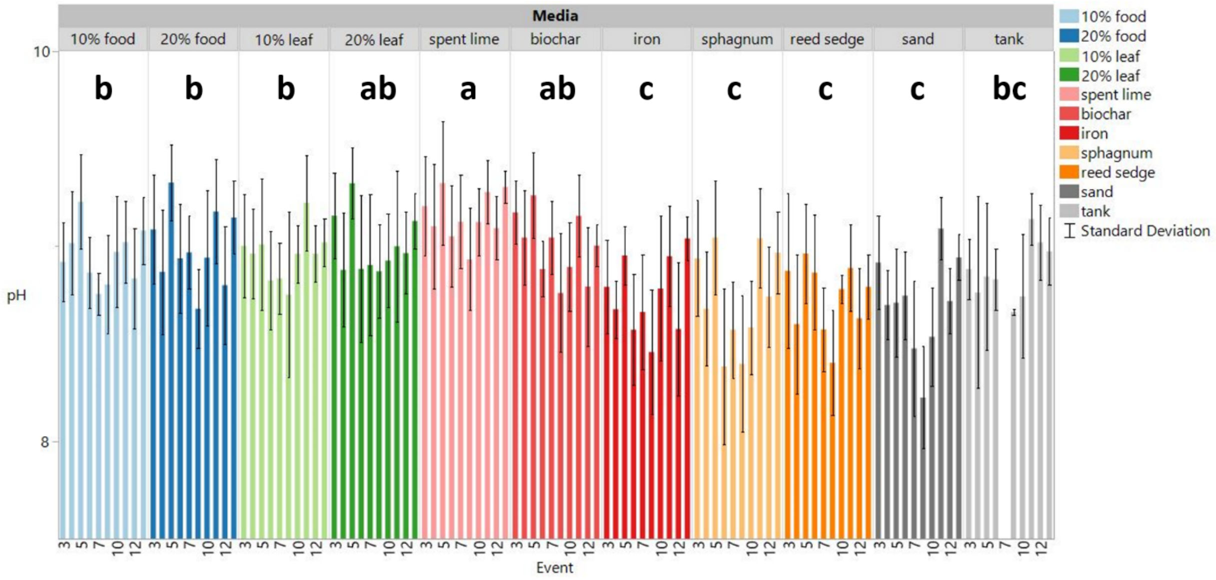


Figure 28: pH for each treatment across all events for the 2019 season. Treatments (media mix) with the same letter are not significantly different from each other (Tukey post-hoc, α = 0.05).

4.2.3 Vegetation growth and biomass

Vegetation growth over time was measured approximately weekly by counting the number of stems and recorded the maximum and minimum height. Except for mesocosm 1 (20% leaf mixture), all mesocosms had vegetation growth. For the purposes of statistical analysis, mesocosm 1 was excluded. The average maximum height for each treatment increased until approximately 50 days from seeding (Figure 29). The effect of media mix, days from seeding, and the interaction were significant (p-values: = 0.0213, <0.0001, and <0.0001, respectively. The maximum height of vegetation was greatest in the spent lime media mix and was significantly different than the maximum height in the sand mix.

For the final biomass (ln transformed), the effect of media mix treatment was significant (p-value = 0.0075) (Figure 30). The final biomass in the spent lime mixture was significantly different than the final biomass in the 100% sand mix. The final biomass in the iron mixture was also significantly less than the biomass in the spent lime mixture (Figure 30), but statistically similar to the final biomass in the sand mesocosm. The final biomass for all other treatments (food compost, leaf compost, biochar, reed-sedge peat, and sphagnum peat) were not significantly different from each other or significantly different from iron, sand, or spent lime.

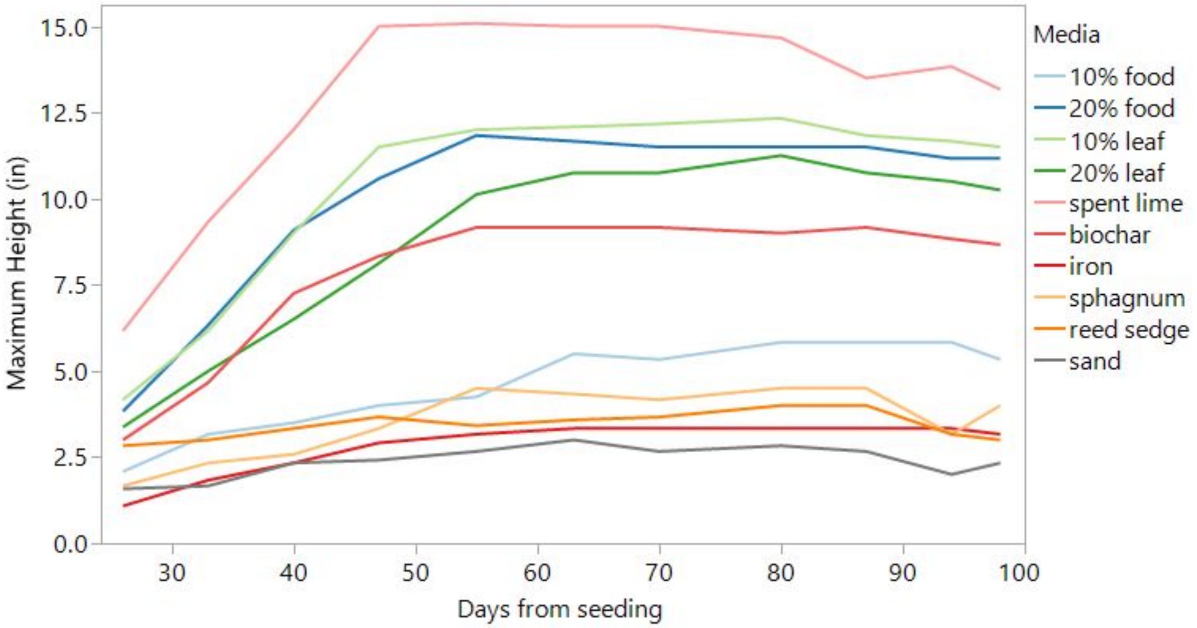


Figure 29: Average (n = 3) maximum height (inches) for each media mix treatment for switchgrass. Mesocosm 1 (20% leaf) had no vegetation and is not included in analysis.

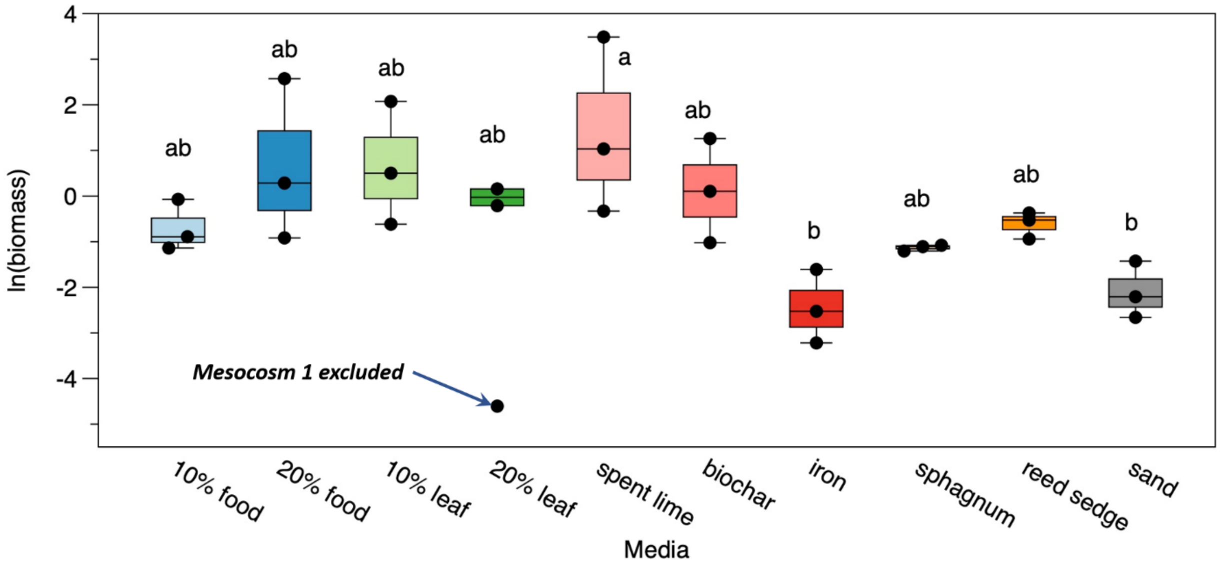


Figure 30: Ln(vegetation biomass, g) for each treatment at the end of the 2019 experimental season. Center line is the median; box boundaries represent the interquartile range (IQR); whiskers are the maximum and minimum values. Closed dots show measured data points. Mesocosm 1 (20% leaf mixture) had no vegetation growth and was excluded from statistical analysis. Treatments with the same letter are not significantly different from each other (Tukey post-hoc, α = 0.05).

CHAPTER 5: CONCLUSIONS

The objectives of this research were to 1) identify which local and sustainable biofiltration media are effective for filtration rate and supporting plant growth and microbial function while not releasing phosphate, and 2) document local sources, simple tests or metrics, and/or design specifications that can be used by practitioners to reliably and repeatably obtain a biofiltration practice that functions as expected. Mesocosm studies on various biofiltration media mixes were completed in the outdoor spillway adjacent to St. Anthony Falls Laboratory to evaluate the impact of media components on filtration rate, nutrient output, and vegetation growth during one rainy season. In addition to mesocosms with 100% clean washed concrete sand as baseline control, seven different biofiltration media amendments were added to clean washed concrete sand in various ratios (by volume) as follows:

- 10% food residue compost + 90% clean washed sand,
- 20% food residue compost + 80% clean washed sand,
- 10% leaf compost + 90% clean washed sand,
- 20% leaf compost + 80% clean washed sand,
- 15% biochar + 20% leaf compost + 65% clean washed sand,
- 5% spent lime + 20% leaf compost + 75% clean washed sand,
- 5% iron + 20% leaf compost + 75% clean washed sand,
- 20% sphagnum peat + 80% clean washed sand, and
- 20% reed sedge peat + 80% clean washed sand.

Fourteen simulated events each released approximately five gallons of phosphorus-enhanced water during summer and fall 2019. Flow rate through the mesocosms was measured and samples of the influent and effluent water were tested for phosphate and nitrate. In between events, settling, vegetation growth, and rainfall movement through each mesocosm were also monitored.

<u>Objective #1: Filtration Rate</u>

All media mixes passed 50% of the influent volume within 5 – 15 minutes, and 80% – 98% of influent volume passed through all media mixes at 120 minutes after the start the experiments. Compared to flow through 100% sand (baseline control), flow through all media mixes was similar except for a few isolated ponding events in the reed sedge mixture. Statistically, iron media allowed water to pass through faster than 100% sand, but otherwise all media were statistically similar to each other and to 100% sand. Based on these results, there is no clear evidence that any of these mixtures have a major advantage or disadvantage for filtration rate within the first year of use. Further testing in subsequent years will elucidate if these patterns change as the mixtures age.

<u>Objective #2: Supporting Vegetation Growth</u>

While the vegetation growth varied between media mixes, vegetation reached maximum height approximately 50 days after seeding. Spent lime had the tallest vegetation and most biomass, which were statistically greater than 100% sand. The compost-amended mixes except for those with iron (leaf compost, food compost, biochar, and spent lime) had more vegetation biomass than the iron, peat, and sand media mixes though the differences were not statistically significant due to large variation in vegetation height and biomass among mesocosms. Note that one of the 20% leaf compost mesocosms did not grow any vegetation, which was excluded from all vegetation height and biomass analysis as an outlier. The iron media mixes had statistically similar vegetation biomass as the 100% sand, which suggests that adding iron limits the vegetation support provided by compost when iron and compost are mixed together.

Objective #3: Limiting Phosphate Release

The addition of 10% or more compost (leaf or food) to the media mixes significantly increased the effluent phosphate concentration. Spent lime and biochar additions reduced this release slightly, but only the addition of iron fully mitigated phosphate release from leaf-based compost. When compost is replaced with peat, both peat mixes reduced effluent phosphate concentrations compared to the influent. The environmental cost and sustainability of using peat in biofiltration media mixes needs to be determined.

All the compost mixtures released nitrate, though 10% leaf, 20% leaf, biochar, and spent lime media mixes resulted in statistically significantly more nitrate compared to the inflow (tank). The spent lime media mix exhibited elevated nitrate release in event 4 and the mechanisms for this are unclear. The pH was also measured, and the spent lime media mix pH (average = 9.16) was statistically similar to 20% leaf compost and biochar, but greater than all other media mixes, including the tank (average pH = 8.87). The iron (average pH = 8.75), sphagnum peat, reed sedge peat, and 100% sand media mixes were statistically similar to each other and the tank, but less than all other media mixes.

Objective #4: Simple Tests or Metrics

Two at-home or in-field phosphorus test kits were investigated for use in field batch experiments, but neither could be used to adequately determine the phosphate concentration of compost mixed with clean water. Laboratory batch experiments determined that phosphate concentration increased as compost mass increases and that phosphate release varies by compost site and type (food, leaf, and blend). Solvita, Olsen P, Bray P, ICP-OES P, and Mehlich-III P were all compared to phosphate release and none were found to correlate better than $R^2 = 0.46$.

Comparison of Media Mixes

To help readers consider all the factors presented above and compare the different media mixes evaluated in this project, Table 1 below compares the different media mixes for each of the three primary objectives for the mesocosm experiments. A primary purpose for adding compost to biofiltration and bioretention practices is to support vegetation growth. In these experiments, the filtration rate was unaffected by adding 10% or 20% leaf or food residue compost. More biomass and taller vegetation were observed in the leaf and food residue compost media mixes when compared to 100% sand, but the differences were not statistically significant. It is also evident from the mesocosm data that leaf and food residue compost both release phosphate, increasing the effluent concentration throughout the first rainy season. Food residue (both 10% and 20%) released less phosphate than leaf-based compost but had statistically the same filtration rate and vegetation growth (height and biomass). While compost increased the amount of vegetation compared to 100% sand, the increase in effluent phosphate concentration is a concern for stormwater managers.

Table 3: Comparison of Media Mixes.

Media	**#1: Filtration Rate**	**#2: Supporting Vegetation Growth**	**#3: Limiting Phosphate Release**	**#3a: Nitrate Release**
10% or 20% **Leaf** Compost	= Sand[1]	> Sand[2]	> Sand[1] & > Influent[1]	> Influent[1]
10% or 20% **Food** Residue Compost	= Sand[1]	> Sand[2]	> Sand[1] & < 20% Leaf[1]	> Influent[2]
5% **Spent Lime** + 20% Leaf Compost	= Sand[1]	> Sand[1]	> Sand[1] & < 20% Leaf[1]	> Influent[1]
15% **Biochar** + 20% Leaf Compost	= Sand[1]	> Sand[2]	> Sand[1] & = 20% Leaf[1]	> Influent[1]
5% **Iron** + 20% Leaf Compost	> Sand[1]	= Sand[1]	< Sand[1] & < 20% Leaf[1]	> Influent[2]
20% **Peat** (Sphagnum or Reed Sedge)	= Sand[1]	= Sand[1]	< Sand[1] & < 20% Leaf[1]	= Influent[1]
100% **Sand**	50% of influent within 5 – 15 minutes; up to 98% of volume within 120 minutes.	Seeded with Switchgrass	< Influent[1] & < 20% Leaf[1]	= Influent[1]

[1] *Statistically Significant (alpha = 0.05)*
[2] *NOT Statistically Significant (alpha = 0.05)*

Considering amendments, spent lime (5%) mixed with 20% leaf compost produced more vegetation than 100% sand (not statistically significant) and the same amount of vegetation as the 20% leaf compost media. The filtration rate was unaffected by adding 5% spent lime when compared to 100% sand or 20% leaf compost. The spent lime mitigated some of the phosphate released from the 20% compost, but the effluent concentration was still statistically greater than 100% sand and the influent. The spent lime also increased the nitrate concentration in the effluent, which was statistically significant compared to the influent (tank). Thus, spent lime provides little overall benefit when mixed with 20% leaf compost with regards to filtration rate and limiting phosphate release. There may be minor (non-significant) effects on vegetation growth, potentially as a result of increased nitrate release.

Biochar (15%) mixed with 20% leaf compost produced more vegetation than 100% sand (not statistically significant) and the same amount of vegetation as the 20% leaf compost media. The filtration rate was unaffected when adding biochar to the media mix compared to both the 20% leaf compost and to 100% sand. The phosphate release from biochar-amended media was also statistically similar to the 20% leaf compost media, which means the biochar did not mitigate the release of phosphate from leaf compost. Thus, biochar provides little overall benefit with regards to filtration rate, vegetation growth, and limiting phosphate release.

Iron (5%) mixed with 20% leaf compost produced the same amount of vegetation as 100% sand, and significantly less vegetation than 20% leaf compost. The filtration rate through the iron media was statistically faster than through 100% sand, though all media mixes allowed >80% of the influent volume to pass within 120 minutes from the start of the experiment. The phosphate release from iron mixed with

20% leaf compost was statistically less than 20% leaf compost, 100% sand, and the influent concentration. Thus, iron mitigated not only the phosphorus released from 20% compost but also captured phosphate from the influent water as well. In summary, iron can capture phosphate and provide the same or better filtration rate compared to 100% sand but will also produce the same amount of vegetation as 100% sand, which is substantially less than 20% leaf compost. From these data it appears the 20% leaf compost when mixed with 5% iron provided no additional benefits in supporting vegetation growth compared to 100% sand.

Sphagnum (20%) and reed sedge (20%) peat are organic materials that have been suggested to replace compost in bioretention media mixes. The filtration rate was unaffected when replacing compost with either peat in the media mix, compared to 20% leaf compost and to 100% sand. Both peat mixes produced the same amount of vegetation as 100% sand, and less vegetation than 20% leaf compost (not statistically significant). The phosphate release from both peat mixtures was statistically less than 20% leaf compost, 100% sand, and the influent concentration. Thus, peat captured phosphate from the influent and did not release phosphate like what was observed in the 20% leaf compost mixes. In summary, peat can capture phosphate and provide the same filtration rate as 100% sand but will also produce the same amount of vegetation as 100% sand, which is less than 20% leaf compost. The environmental cost and sustainability of using peat in biofiltration media mixes also needs to be determined. From these data it appears that peat does not fulfill the purpose of replacing compost to support vegetation growth.

Cost Comparisons

It is important to consider the cost of materials when comparing media mixes. Material costs vary by location and over time and delivery costs will also vary by location and supplier. Because actual values will not be relevant beyond the publication date of this report, a relative cost was computed using the 100% sand media as the baseline cost. Thus, Relative cost = Cost of Media Mix / Cost of 100% Sand. The costs of the media used in this study were provided by a personal communication quote (Plaisted Companies, 2021) from a local Twin Cities Metropolitan Area (TCMA) supplier and used to compute the relative cost of the media mixes:

- 100% Sand: Relative Cost = 1
- 90% Sand + 10% Leaf Compost: Relative Cost = 1.6
- 80% Sand + 20% Leaf Compost: Relative Cost = 1.7
- 90% Sand + 10% Food Compost: Relative Cost = 2.1
- 80% Sand + 20% Food Compost: Relative Cost = 2.5
- 80% Sand + 20% Sphagnum Peat: Relative Cost = 2.1
- 80% Sand + 20% Reed Sedge Peat: Relative Cost = 2.3
- 75% Sand + 20% Leaf Compost + 5% Spent Lime: Relative Cost = 2.6
- 65% Sand + 20% Leaf Compost + 15% Biochar: Relative Cost = 6.8
- 75% Sand + 20% Leaf Compost + 5% Iron: Relative Cost = 14.2

Future Research

Phase II for this research effort is funded by the Minnesota Stormwater Research and Technology Transfer Program administered by the University of Minnesota Water Resources Center through an appropriation from the Clean Water Fund established by Minnesota Clean Water Land and Legacy

Amendment and from the Minnesota Stormwater Research Council with financial contributions for numerous agencies. This effort will continue the outdoor mesocosm experiments for three additional rainy seasons and reveal whether the filtration rate, nutrient release, and vegetation trends reported herein continue in subsequent years. Phase II will also investigate the impact of road salt application on media performance and expand vegetation research with a germination study of low-organic content (e.g., < 10% compost) media mixes.

CHAPTER 6: EDUCATION AND TECHNOLOGY TRANSFER PLAN

The Education and Technology Transfer Plan consists of three primary mechanisms: outdoor signage, presentations (oral and poster), and practitioner training. The current and expected outputs from these mechanisms are described in the sections below.

6.1 OUTDOOR SIGNAGE

The outdoor mesocosm experiments were performed in the reclaimed flood control channel adjacent to the Outdoor StreamLab at St. Anthony Falls Laboratory. This area is immediately adjacent to, and visible from, Water Power Park which is typically open to the public during the spring, summer, and fall. This project developed signage for display in Water Power Park to give visitors insights into urban runoff, pollution, treatment (such as biofiltration), and environmental research including the mesocosm experiments. This reaches a diverse public audience that would not typically expect to learn about urban water resources topics while visiting Water Power Park and may engage local residents that are completely unaware of the complex stormwater management system in their ultra-urban neighborhood. The signage developed for this project is shown in Figure 31.

Urban Stormwater Research

Water Resources Center
University of Minnesota

Research funded by the Minnesota Stormwater Research and Technology Transfer Program and the Minnesota Stormwater Research Council.

What happens when it rains?

When rain falls in urban and suburban areas, the water washes off the roofs, driveways, sidewalks, lawns, and streets. This water is called 'runoff' or 'stormwater' and carries with it many harmful pollutants from our urban landscapes. These pollutants include sediment, phosphorus, nitrogen, metals (cadmium, copper, zinc, etc.), hydrocarbons, chloride from road salt, and bacteria and pathogens, among others. Stormwater carries these pollutants down the gutters and into storm drains, which connect to a network of underground pipes called the storm sewer. Storm sewer pipes carry the stormwater and pollutants to nearby surface waters such as lakes, rivers and streams.

Stormwater runoff enters the storm sewer.
Photo Credit: Andy Erickson

Pollutants can have a huge impact on our water resources

Phosphorus can cause harmful algal blooms in Minnesota freshwater lakes; bacteria and pathogens can cause outbreaks and result in beach closings. To combat these problems, stormwater managers design and install stormwater treatment practices to treat stormwater runoff before it goes to lakes, rivers, and streams. Stormwater treatment practices come in a variety of types, shapes, and sizes and you likely have some in your neighborhood or near your workplace.

Lakes can accumulate excessive algae, duckweed, and aquatic vegetation due to stormwater pollution. Photo Credit: Yini Taguchi

Excessive algae and aquatic vegetation can limit recreation and be dangerous for swimmers and pets. Photo Credit: Yini Taguchi

To learn more about stormwater research at the University of Minnesota, please visit stormwater.safl.umn.edu and z.umn.edu/stormwaterprojects.

What can researchers do to reduce pollution?

University of Minnesota faculty, staff, and students are working hard to increase our understanding of stormwater runoff and pollutants, improve existing stormwater treatment practices, and develop new and innovative methods for treating stormwater. The results have improved how we manage pollutants such as phosphate, nitrate, chloride, polycyclic aromatic hydrocarbons (PAHs), and metals.

Graduate Research Assistant Brooke Asleson records data from field experiments. Photo Credit: Brooke Asleson

An iron-enhanced sand filter is one stormwater treatment practice specifically designed to capture soluble phosphorus.
Photo Credit: Andy Erickson

What related research has happened here?

An experiment uses 5-gallon buckets and trash cans with varying compositions of biofiltration media to test their efficiency at removing pollutants. Photo Credit: Tasha Spencer

Research staff and students have been performing outdoor experiments in this natural area using mesocosms (meso- or 'medium' and -cosm 'world'), which examines natural environmental processes under controlled conditions. These mesocosms were designed to replicate biofiltration practices (aka, rain gardens) in which water passes through sandy media mixed with other 'enhancements' to improve the capture of pollutants from stormwater runoff. These experiments will tell stormwater managers and designers which enhancements to use in rain gardens to reduce pollution.

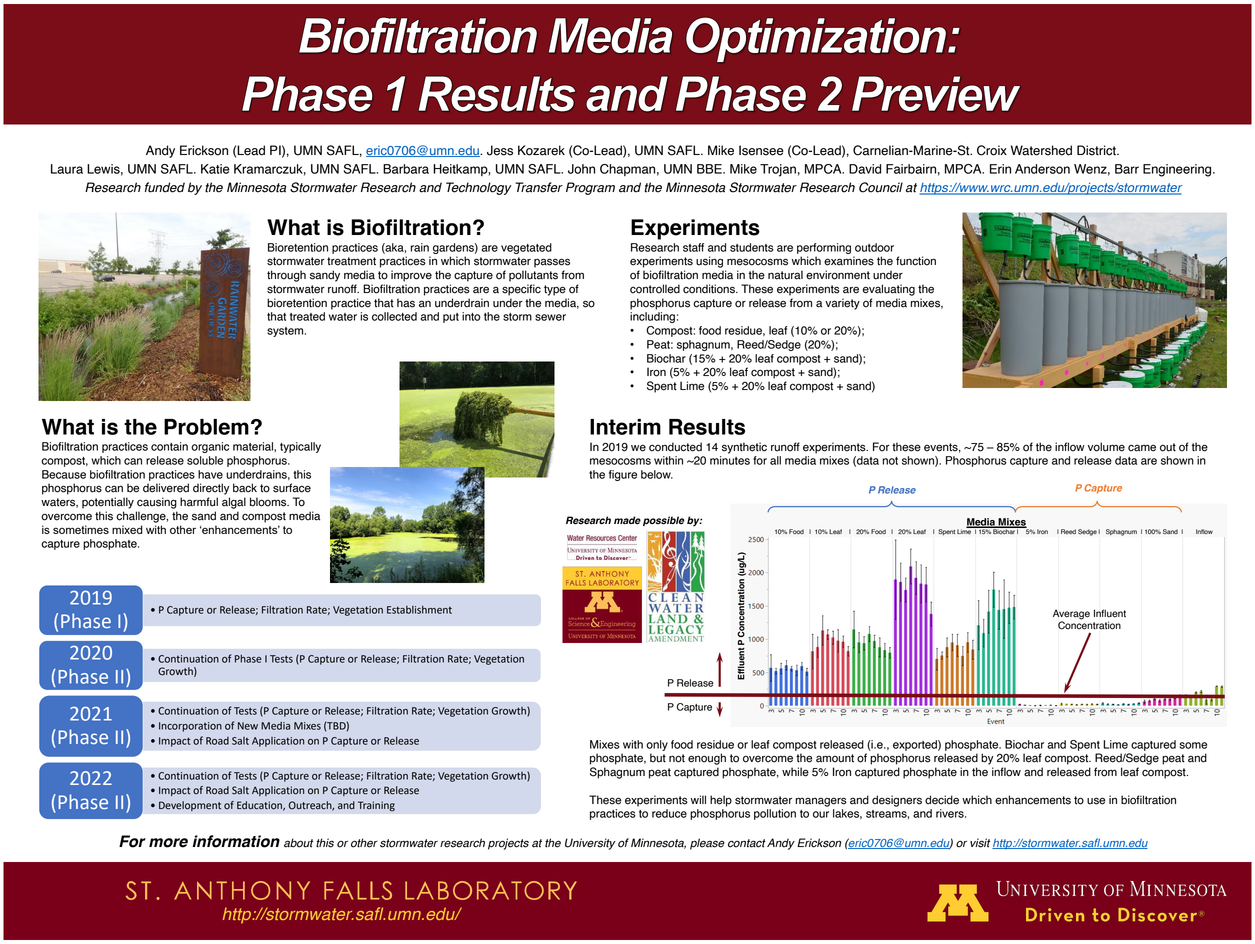
Figure 31: Signage developed for display at Water Power Park, Minneapolis, MN.

6.2 PRESENTATIONS

Several presentations have been given to individuals and practitioners in Minnesota and beyond, and are listed below:

- October 20, 2019. A.J. Erickson presented "Biofiltration Media Optimization: Phase I Results and Phase II Preview." Poster Presentation. Minnesota Water Resources Conference 2020. Virtual.
- September 28, 2020. A.J. Erickson invited to present "Urban Stormwater Runoff Research: Innovating Practice to Improve Water Quality." Recorded Oral Presentation. Michigan Technological University Environmental Graduate Student Seminar. Virtual.
- May 6, 2020. A.J. Erickson invited to present "Biofiltration Media Optimization." Oral Presentation. MPCA Updates on engineered (bioretention) media. Virtual.
- July 18, 2019. A.J. Erickson invited to present "Biofiltration Media Optimization." Oral Presentation. Minnesota Stormwater Research Council Annual Meeting. Minneapolis, MN.
- April 17, 2019. A.J. Erickson invited to present "Biofiltration Media Optimization." Oral Presentation. Minnesota Composting Council Operator Training. Chaska, MN.

The poster that was presented at the 2020 Minnesota Water Resources Conference is shown in Figure 32.



Biofiltration Media Optimization:
Phase 1 Results and Phase 2 Preview

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Laura Lewis, UMN SAFL. Katie Kramarczuk, UMN SAFL. Barbara Heitkamp, UMN SAFL. John Chapman, UMN BBE. Mike Trojan, MPCA. David Fairbairn, MPCA. Erin Anderson Wenz, Barr Engineering.
Research funded by the Minnesota Stormwater Research and Technology Transfer Program and the Minnesota Stormwater Research Council at https://www.wrc.umn.edu/projects/stormwater

What is Biofiltration?

Bioretention practices (aka, rain gardens) are vegetated stormwater treatment practices in which stormwater passes through sandy media to improve the capture of pollutants from stormwater runoff. Biofiltration practices are a specific type of bioretention practice that has an underdrain under the media, so that treated water is collected and put into the storm sewer system.

Experiments

Research staff and students are performing outdoor experiments using mesocosms which examines the function of biofiltration media in the natural environment under controlled conditions. These experiments are evaluating the phosphorus capture or release from a variety of media mixes, including:

- Compost: food residue, leaf (10% or 20%);
- Peat: sphagnum, Reed/Sedge (20%);
- Biochar (15% + 20% leaf compost + sand);
- Iron (5% + 20% leaf compost + sand);
- Spent Lime (5% + 20% leaf compost + sand)

What is the Problem?

Biofiltration practices contain organic material, typically compost, which can release soluble phosphorus. Because biofiltration practices have underdrains, this phosphorus can be delivered directly back to surface waters, potentially causing harmful algal blooms. To overcome this challenge, the sand and compost media is sometimes mixed with other 'enhancements' to capture phosphate.

2019 (Phase I)	• P Capture or Release; Filtration Rate; Vegetation Establishment
2020 (Phase II)	• Continuation of Phase I Tests (P Capture or Release; Filtration Rate; Vegetation Growth)
2021 (Phase II)	• Continuation of Tests (P Capture or Release; Filtration Rate; Vegetation Growth) • Incorporation of New Media Mixes (TBD) • Impact of Road Salt Application on P Capture or Release
2022 (Phase II)	• Continuation of Tests (P Capture or Release; Filtration Rate; Vegetation Growth) • Impact of Road Salt Application on P Capture or Release • Development of Education, Outreach, and Training

Interim Results

In 2019 we conducted 14 synthetic runoff experiments. For these events, ~75 – 85% of the inflow volume came out of the mesocosms within ~20 minutes for all media mixes (data not shown). Phosphorus capture and release data are shown in the figure below.

Research made possible by:

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St. Anthony Falls Laboratory
College of Science & Engineering
University of Minnesota
Clean Water Land & Legacy Amendment

Mixes with only food residue or leaf compost released (i.e., exported) phosphate. Biochar and Spent Lime captured some phosphate, but not enough to overcome the amount of phosphorus released by 20% leaf compost. Reed/Sedge peat and Sphagnum peat captured phosphate, while 5% Iron captured phosphate in the inflow and released from leaf compost.

These experiments will help stormwater managers and designers decide which enhancements to use in biofiltration practices to reduce phosphorus pollution to our lakes, streams, and rivers.

For more information *about this or other stormwater research projects at the University of Minnesota, please contact Andy Erickson (eric0706@umn.edu) or visit http://stormwater.safl.umn.edu*

ST. ANTHONY FALLS LABORATORY
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Figure 32: Poster presented at the 2020 Minnesota Water Resources Conference.

6.3 PRACTITIONER TRAINING

The results of this research are expected to be incorporated into future training in collaboration with the University of Minnesota Erosion and Stormwater Management Certification Program (https://www.erosion.umn.edu/) and the Minnesota Pollution Control Agency (https://stormwater.pca.state.mn.us/index.php?title=Stormwater_Manual_webinars). An example course into which this information could be directly implemented is the Design of Construction SWPPP Recertification course (https://www.erosion.umn.edu/certification-courses/rd3501-course-description). This course has several emphasis sections; one of which is infiltration designs. This would be an obvious section to include the research findings from the current study. This course has planned current events in 2021, but the details are not yet finalized. The audience for this course are stormwater practitioners and professionals. A version of this course is offered online, and the research findings could be added into this online version as well. The online class could use a video summary, which could also be provided outside of the class structure to anyone.

In addition to the past presentation given as a webinar in partnership with the Minnesota Pollution Control Agency (MPCA), the project team intends to give additional webinars on the results of this research. A webinar like this would include data and recommendations from this report. The audience for this training would include stormwater practitioners and citizen scientists. In addition, pertinent results and recommendations may be included in the Minnesota Stormwater Manual (e.g., https://stormwater.pca.state.mn.us/index.php/Design_criteria_for_bioretention) pending approval by MPCA staff.

Finally, the results and recommendations from this research will continue to be presented at local and national conferences and via webinars to practitioners and interested parties. A summary newsletter article will also be developed and disseminated via UPDATES, the University of Minnesota stormwater research e-newsletter distributed to over 2000 email subscribers. The results will also be submitted for inclusion in other e-news lists and distribution channels such as the MPCA and Water resources Center email lists.

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