



FINAL REPORT

NEIWPCC Job Code: 0356-002-001

Project Code: L-2020-090

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Project Period: December 2020 to September 2023

Date Submitted: October 6, 2023

Date Approved: July 2, 2024

EFFICACY OF THE 2017 VERMONT STORMWATER MANAGEMENT MANUAL BIORETENTION SOIL SPECIFICATION IN REMOVING POLLUTANTS AND SUPPORTING PLANT HEALTH

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This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement to NEIWPCC in partnership with the Lake Champlain Basin Program.

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Executive Summary

In 2017, the Vermont Agency of Natural Resources (ANR) updated the Vermont Stormwater Management Manual (VSMM) to reflect advances in Best Management Practice (BMP) methodologies and design. Bioretention is among the preferred BMPs for stormwater management. Bioretention systems utilize engineered soil media and vegetation to store, infiltrate, and filter pollutants from stormwater runoff. Some members of the stormwater BMP design community are concerned about the ability of this soil specification to promote vegetation growth due to its low organic matter content and water-holding capacity. Commencing in 2023, the State of Vermont has drafted revisions to the 2017 VSMM, this research can inform the forthcoming updates.

Stone Environmental, Inc. (Stone) and the University of Vermont (UVM) Plant and Soil Science Department worked in consultation with the Lake Champlain Basin Program (LCBP) to evaluate the water quality BMP design standard for bioretention soil media outlined in the 2017 VSMM, analyzing different soil media for their abilities to remove sediment, nutrients, and heavy metals, while supporting plant health. The Stone-UVM team produced a literature review of nationwide bioretention soil specifications and performance studies to provide comparison to the 2017 VSMM soil specification. Effects of bioretention media treatments on water quality and plant health were evaluated in a mesocosm study conducted in 2021 through 2023, which combined laboratory and field techniques to study environmental processes in a controlled setting. Bioretention media studied included a sand only media, a media with topsoil, topsoil plus a layer of woodchips, and topsoil mixed with aluminum-based drinking water treatment residuals (DWTR). Monitoring data were evaluated using descriptive statistics, percent removal calculations, and analysis of variance (ANOVA) tests.

Overall, reductions were seen in effluent soluble reactive phosphorus (SRP), total phosphorus (TP), and heavy metals when compared to influent concentrations in all bioretention mesocosms. On average, bioretention soil media containing woodchips resulted in the highest percent removals of nitrate (66%) among the treatments, suggesting some denitrification taking place in the woodchip layer. The DWTR treatment had the highest mean percent removal of SRP (89.6%), this result is consistent with hypothesis that DWTRs reduce SRP concentrations and load due to its high aluminum content. All treatments resulted in relatively high removals (greater than 72%) of heavy metals (copper and zinc), suggesting that the bioretention mesocosms are efficient at sorbing metals. Additionally, the low-phosphorus topsoil-containing treatments performed significantly better in terms of plant health than the sand treatment, suggesting that topsoil is a beneficial media to include in place of compost.

EFFICACY OF THE 2017 VSMM BIORETENTION SOIL SPECIFICATION IN REMOVING POLLUTANTS AND SUPPORTING PLANT HEALTH

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1. Project Synopsis

1.1. Background

In 2017, the Vermont Agency of Natural Resources (ANR) updated the Vermont Stormwater Management Manual (VSMM) to reflect advances in Best Management Practice (BMP) methodologies and design. Bioretention is among the BMPs (also known as Stormwater Control Measures) that are preferred for stormwater management. Bioretention systems utilize engineered soil media and vegetation to store, infiltrate, and filter pollutants from stormwater runoff. Nationwide, some standardized bioretention soil specifications have been found to export nutrients, particularly of dissolved forms of phosphorus and nitrogen, to the effluent rather than reducing them as intended (Cording et al. 2018, Shrestha et al. 2018, Herrera 2014, City of Redmond 2012). This export of nutrients has been attributed to the presence of compost in the soil media in quantities greater than that required for vegetation growth (sometimes making up to 40% of the bioretention soil media volume), subsequently leaching nutrients from the soil media. In response, the VSMM update included a new bioretention soil specification (Section 4.3.1.4, Bioretention Treatment) that specifies a soil very high in sand content relative to silt and clay (i.e., soil texture with sand 85-88%, silt 8-12%, clay 0-2%) and compost not exceeding 3-5% of the total bioretention soil media volume to promote stormwater infiltration and reduce nutrient leaching. However, some members of the stormwater BMP design community are concerned about the ability of this soil specification to promote vegetation growth due to its low organic matter content and water-holding capacity. Commencing in 2023, the State of Vermont has drafted revisions to the 2017 VSMM and we hope this research can inform the forthcoming updates.

1.2. Current Project

Stone Environmental, Inc. (Stone) and the University of Vermont (UVM) Plant and Soil Science Department worked in close consultation with the Lake Champlain Basin Program (LCBP) to evaluate the water quality BMP design standard for bioretention soil media outlined in the 2017 Vermont Stormwater Management Manual (VSMM), analyzing different types of soil media for their abilities to remove sediment, nutrients, and heavy metals, while supporting plant health. The bioretention media treatments were evaluated in a mesocosm study, which combines laboratory and field techniques to study environmental processes in a controlled setting.

In the first phase of this study, the Stone-UVM team produced a literature review of nationwide bioretention soil specifications and performance studies to provide comparison to the VSMM soil specification. Next, the Stone-UVM team designed, constructed, and monitored bioretention mesocosms to evaluate four bioretention soil media treatments. The experiment was established at UVM's Horticultural Research and Education Center (HREC) in South Burlington,

VT and consisted of twelve bioretention mesocosms, essentially large mesocosms filled with three replicates of each of four different soil media treatments. The four treatments evaluated included 1) sand only media, 2) a mix of sand and low-phosphorus (low-P) topsoil, 3) sand and low-P topsoil with a lower layer of woodchips to target nitrate removal and 4) sand and low-P topsoil mixed with aluminum-based drinking water treatment residuals to target P removal. Each bioretention mesocosm had an impermeable liner and perforated underdrain for effluent stormwater collection and sampling. Influent samples were composed of simulated stormwater, made in a lab of known concentrations of stormwater pollutants, and diluted with well water on site. Effluent samples were compared to influent samples for the following parameters: total nitrogen (TN), nitrite- + nitrate (NO_x), total phosphorus (TP), soluble reactive phosphorus (SRP) and heavy metals (Cu and Zn). Plant health was assessed based on plant survival, visual above-ground biomass digital surveys and plant height measurements compared for four different species of bioretention vegetation. Monitoring was conducted during the growing season in 2021 and 2022. Data analysis was completed in 2023.

1.3. Project Objectives

The overall goal of this study was to evaluate the comparative performance of the different components of bioretention soil media mixes regarding the reduction of pollutants (nutrients and heavy metals) and promotion of vegetation growth. The review and evaluation of this stormwater treatment standard is timely as Vermont is implementing many bioretention projects to reduce pollutants entering the State's waterways via stormwater and actively revising the VSMM. The results from this study may help inform the design of bioretention projects and best practices moving forward.

2. Tasks Completed

The following tasks were accomplished to meet the study objectives.

Prepare Quality Assurance Project Plan (QAPP): A QAPP addressing the monitoring and analytical phases of the project was approved on July 29, 2021. This QAPP is included as Appendix A.

Quarterly Reports: Brief quarterly reports summarizing progress made on each objective and tasks were submitted quarterly for the project's duration.

Literature Review & Report: In collaboration with UVM, a nationwide review of publications and municipal/state stormwater manuals on the performance and descriptions of bioretention specifications was completed. Findings were compared to the VSMM soil specifications. The literature review report highlighting key findings from the literature review is included as Appendix B.

Bioretention Laboratory Development: The Stone-UVM team reserved research space, obtained materials, and constructed the bioretention mesocosms used for this project in June 2021. The experimental design is described in Section 3.1.

Conduct Monitoring of Bioretention Mesocosms: A UVM graduate research assistant (UVM staff) conducted monitoring of the bioretention mesocosms in consultation with Stone staff and UVM Faculty Advisor in 2021 and 2022. Monitoring and associated analytical methods are described in Section 3.1 and Section 3.2, respectively.

Analyze Monitoring Data: UVM staff analyzed monitoring data in consultation with Stone staff and the UVM Faculty Advisor. Analysis included comparing influent and effluent concentrations of pollutants and assessing vegetation survival to evaluate the performance of various soil media. The Stone-UVM team completed this task in Spring through Summer 2023. This task is described in Section 3.3.

Conference Presentation: UVM staff presented on the study methods, results, and recommendations considered to-date at the June 2023 American Ecological Engineering Society (AEES) Annual Meeting in Tampa, Florida. The AEES Annual Meeting brought together students, industry professionals, and academic researchers to discuss emerging practices and nature-based solutions for more resilient communities.

3. Methods

3.1. Experimental Design and Sampling

3.1.1. Study Site – Location and Layout

The study field site is located at the UVM Horticulture Research and Education Center (HREC) farm in South Burlington, VT (44.43207° N, 73.20241° W). The site is surrounded by an uncultivated field for at least 25 meters on all sides. Beyond the uncultivated field there is a grape vineyard to the east, a field for parking tractors and machinery to the west, a farm equipment storage shed and wooded area to the north, and a gravel road and apple orchards to the south.

The field site is exposed to ambient weather conditions. The site receives ample sunlight, with the entire experimental footprint located in full sun. Prevailing winds at the site are from the west. The bioretention mesocosms were exposed to natural rainfall. Rainfall at the site was measured at a Network for Environment and Weather Applications (NEWA) monitoring station located at the HREC farm (available at <https://newa.cornell.edu/> at the South Burlington, VT site).

The field site was constructed on June 7 – 14, 2021. The site consisted of twelve mesocosm systems. Each system included an influent tank, bioretention mesocosm (mesocosm), and effluent tank. The mesocosms were planted on June 21, 2021. During construction, the twelve mesocosm systems were placed north to south in a randomized order (**Figure 1 and Figure 2**). The mesocosm systems were constructed into a gently sloped hillside to allow gravity flow of water from the inflow tank, through the bioretention mesocosm, and finally into the outflow collection tanks.



Figure 1. Photo of research site including twelve sets of influent tanks for mixing simulated stormwater, water distribution lines, and vegetated bioretention mesocosms.
Photo by Samantha Brewer.

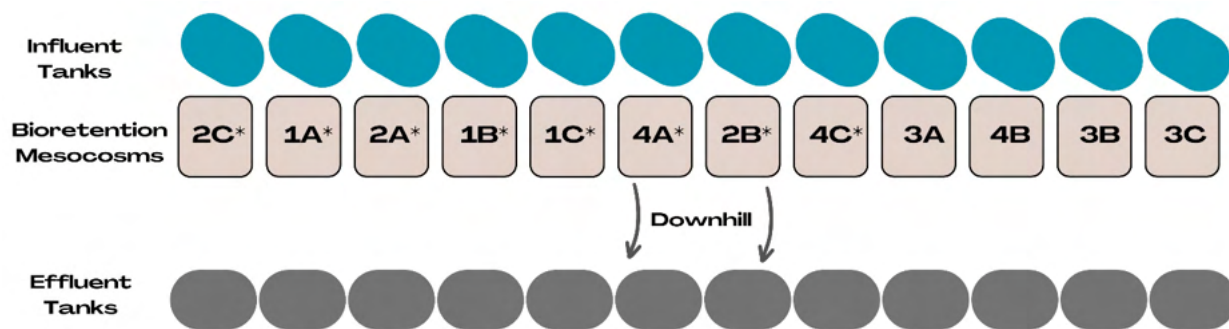


Figure 2. Plan view of the experimental design showing relative locations of the inflow tanks, bioretention mesocosms, their randomized order, and outflow collection tanks.

* Mesocosms planted with blue star flower in the second growing season (2022)

Diagram by Samantha Brewer.

3.1.2. Experimental Bioretention Mesocosm Design

An example cross-section of the bioretention mesocosm experimental design, showing the three main components (influent tank, bioretention mesocosm, and effluent tank) is provided in **Figure 3**. Rubbermaid brand “Stock Tanks” were used to create influent storage and effluent collection tanks. Each of the twelve mesocosms was connected to a 100-gallon (378.5 L) influent storage tank on its upstream end, and to a 100-gallon (378.5 L) effluent tank on its downstream end. The influent tank drain was affixed with pipe fittings to deliver synthetic stormwater to the top of the mesocosm (mesocosm) where it is distributed via a perforated pipe containing six ¼” holes (**Figure 5**). The drainage hole at the bottom of each mesocosm is attached to a buried tube that conveys water from the bioretention soil media’s underlying gravel layer to the effluent collection tank. The effluent collection tanks are 26 feet (7.9 m) downstream of and approximately 0.5 ft (15 cm) below the mesocosms bottoms. This arrangement facilitates gravity flow at ~1.5-2% slope from one structure to the other. Since monitoring samples were collected from the effluent collection tanks, the effluent collection tanks were fitted with a lid to minimize cross-contamination of the sample water from rainfall and/or sediment.

Cross section of experimental design (not to scale)

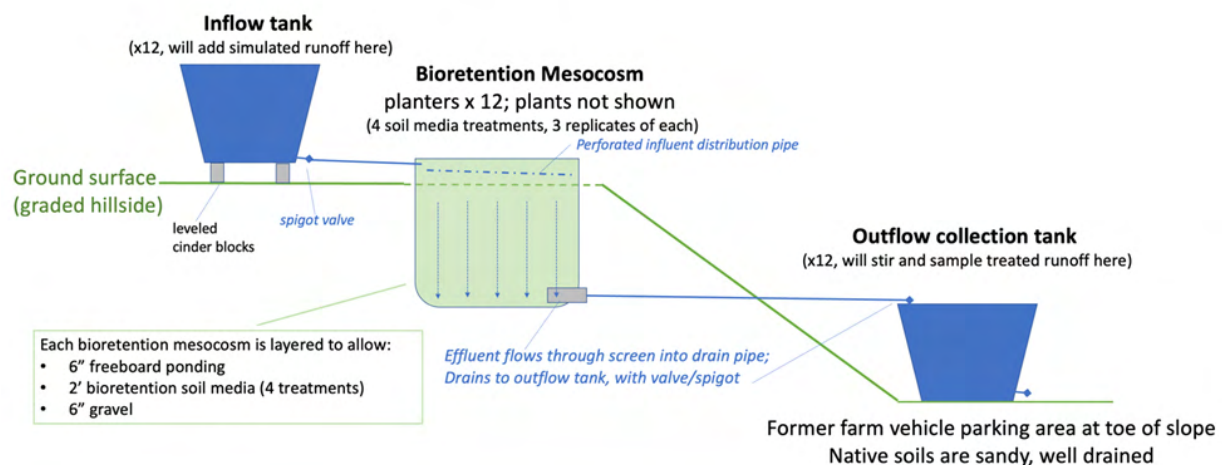


Figure 3. Cross sectional view of the experimental design showing relative locations and elevations of the inflow tank, bioretention mesocosm, and outflow collection tank.

Diagram by Stephanie Hurley.

The mesocosms were established in open-top impermeable HDPE plastic basins measuring 102 cm wide, 122 cm long, and 107 cm deep (40 x 48 x 42 inches). The basins functioned as liners (or mesocosms) separating the bioretention soil media from the surrounding ground. Each basin was thoroughly washed prior to use. The basins were sunk approximately 90 cm (35 inches) into the ground, with 15-17 cm (6-7 inches) of the liner visible aboveground. The portion of the liner aboveground acted as a barrier allowing water to pond on top of the soil media surface in each mesocosm.

Four different experimental bioretention soil media treatments were selected for this study (**Figure 4**). Bioretention mesocosms were created in triplicate for each treatment for a total of twelve mesocosms. Approximately six inches of pea gravel was installed at the bottom of each mesocosm to prevent clogging of the outlet pipe. The soil media treatments were as follows (components are listed from top to bottom, compost is not shown as a separate component in **Figure 4**):

- **Treatment 1 (control):** Medium **sand** (0.25 – 0.5 mm diameter particle size) layer with low-phosphorus (low-P) compost applied at root zone of each plant (~0.75L scoop at time of planting), followed by sand-only layer and pea gravel at the bottom.
- **Treatment 2:** low-P **topsoil** layer with low-P compost applied at root zone, followed by lower sand-only layer and pea gravel at the bottom.
- **Treatment 3:** low-P topsoil layer with low-P compost applied at root zone, followed by sand-only layer, and inclusion of **woodchips** between the sand-only layer and pea gravel at the bottom. The woodchips are hardwood; they were freshly chipped the day before installation by a local arborist, “Treeworks” and were derived from Norway Maple (*Acer platanoides*) trees.
- **Treatment 4:** low-P topsoil layer with low-P compost applied at root zone, followed by sand-only layer, and inclusion of Aluminum-based **drinking water treatment residuals (DWTR)** blended with the lower sand-only layer at a ratio of 11:2 and pea gravel at the bottom. DWTR was mixed into the sand layer, following the recommendation of Ament et al. (2021) by mixing DWTR into the sand layer to avoid clogging (reduction in hydraulic conductivity), which is more likely to occur in a solid layer.

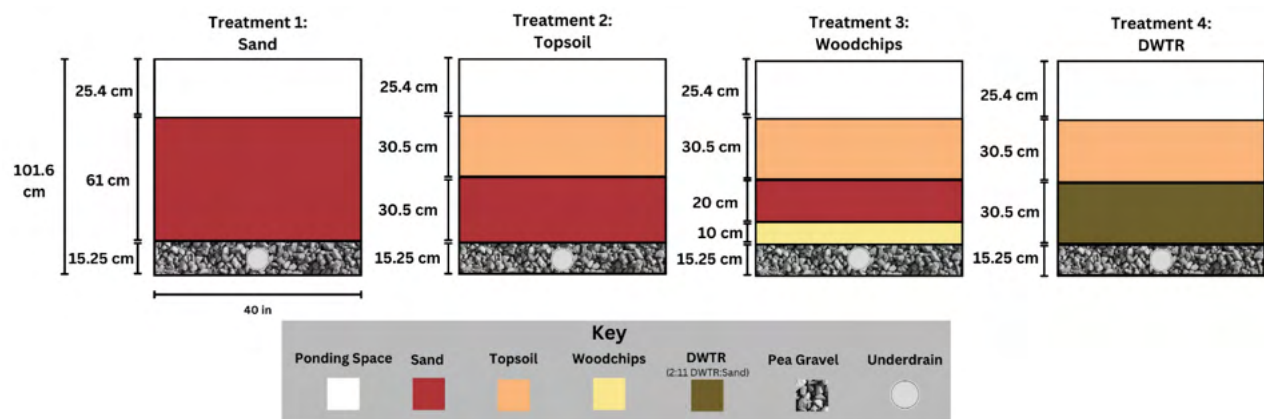


Figure 4. Four bioretention soil media treatments evaluated as part of this study. Three mesocosms were constructed for each treatment for a total of twelve mesocosms. Diagram by Samantha Brewer.

Bioretention soil media materials (i.e., topsoil, sand, and low P compost) were analyzed for background levels of target contaminants prior to installation. Samples were collected in June 2021 and sent to the Maine Soil Testing Service at the University of Maine for macro- and micronutrient analysis (**Table 1**). Soil media materials were tested for organic matter, nitrate, phosphorus, copper, and zinc. Testing confirmed a low likelihood of leaching these contaminants and the capacity for sorption of target contaminants in the bioretention mesocosms.

Table 1. Background concentrations of macro- and micro-nutrients in bioretention soil media.

	Topsoil	Sand	Low Phosphorus Compost
Organic Matter (%)	1.6	0.2	25.4
Nitrate-N (ppm)	17	2	816
Phosphorus (ppm)	8.4	0.7	117.5
Copper (ppm)	0.13	0.45	0.72
Zinc (ppm)	1.3	0.2	22

Plants for the bioretention mesocosms were selected based on the following parameters: perennials, native to New England, resilient to periods of drought and inundation, provision of pollinator habitat, aesthetics (flowering and colorful). On June 21, 2021, the bioretention mesocosms were planted with species meeting these criteria. Two plants each of Butterfly Milkweed (*Asclepias tuberosa*, also known as butterfly weed), Joe-pye Weed (*Eupatorium maculatum*), and Purple Coneflower (*Echinacea purpurea*) were planted in each mesocosm for a total of six plants per mesocosm. In all figures and tables below, these plants are nicknamed butterfly weed, joe-pye, and coneflower, respectively. Plants were placed in a randomized order with three plants on each side of the perforated pipe designed to distribute water at the top surface of each mesocosm (**Figure 5**). Plants were sourced from VT Wetland Supply Co. in Orwell, VT and transferred to the bioretention mesocosms as 4" plugs. Approximately 0.75 liters of low-phosphorus (low-P) compost was applied to the plant roots at the time of planting. The low-P compost was sourced from Casella Organics in Johnston, RI and derived from leaf litter only. The low-P compost was well-cured as it had been sitting in a covered pile for five years. The plants were watered every other day over a six-week establishment phase, except for day when there was greater than 0.25 inches of rainfall.

Approximately one year post planting, prior to the start of the 2022 sampling season, each bioretention cell was evaluated for vegetation loss over the first winter. Cells containing fewer than five of the six original plants by June 10, 2022 received one additional plant. The additional

plant species was Blue Star (*Amsonia tabernaemontana*) sourced from Gardener's Supply in Williston, VT. These additional plants came in 2.5 qt (2.3 L) containers and were added to eight of the twelve cells on June 13, 2022 (1 A, B, C; 2 A, B, C; 4 A and C, noted by asterisks in **Figure 2**). Like the original plants, the new plants were watered every other day, except for days with greater than 0.25 inches of rainfall, for a six-week establishment phase. Photographs of the plants used in the bioretention mesocosms are provided in **Figure 6**.

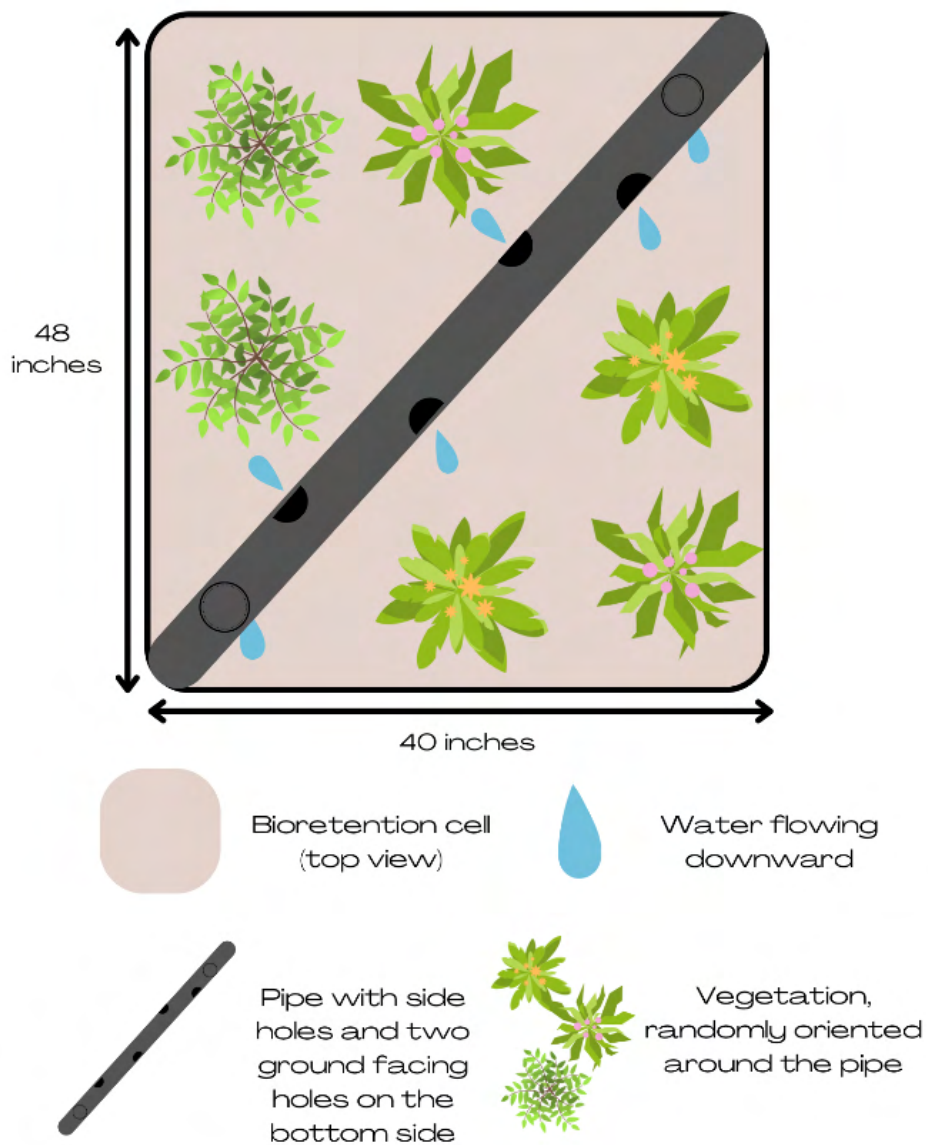


Figure 5. Example bioretention cell layout.
Diagram by Samantha Brewer.

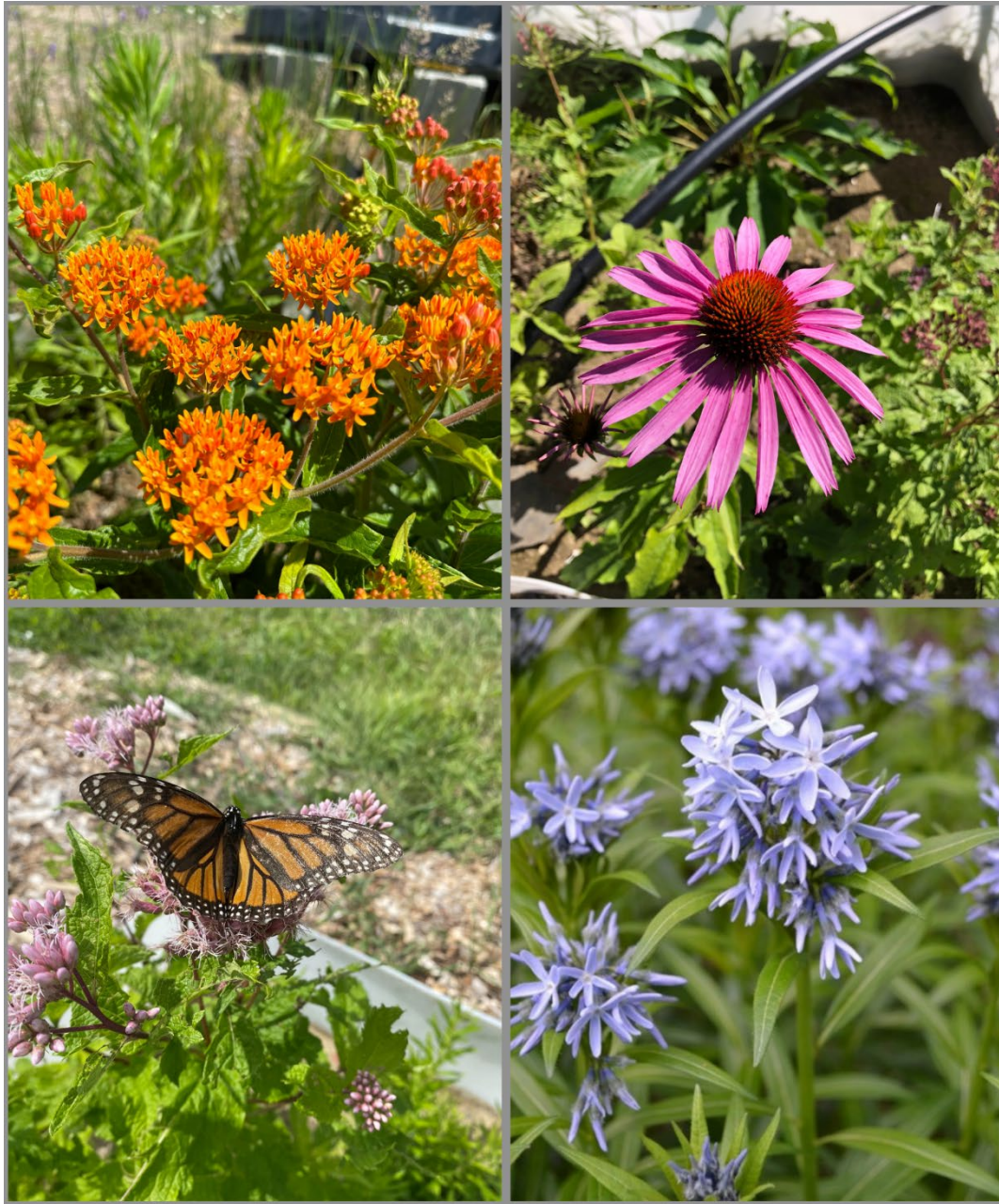


Figure 6. Vegetation planted in bioretention mesocosms.

Clockwise from top left: Butterfly milkweed (*Asclepias tuberosa*), photo by Samantha Brewer 2021; Coneflower (*Echinacea purpurea*), photo by Samantha Brewer 2021; Joe-pye Weed (*Eupatorium maculatum*), with Monarch Butterfly, photo by Bryce Carleton 2021; Blue Star flower (*Amsonia tabernaemontana*), image source: Monticello Shop.

3.1.3. Simulated Stormwater Runoff Events

Simulated stormwater runoff events were used to expose the bioretention mesocosms to a variety of storm volumes and pollution levels. Simulated stormwater events began in September 2021, following the plant establishment period starting. Well water used for irrigation at HREC was used for rinsing the influent and effluent tanks and for mixing the simulated stormwater runoff solution.

A concentrated solution of target pollutants was added to the inflow tank to achieve the desired concentrations. The concentrated solution contained potassium nitrate, potassium phosphate monobasic, copper sulfate, and zinc chloride as the sources of nitrogen, phosphorus, copper, and zinc pollutants, respectively. This solution was created in the lab and transported to the study site under ambient conditions. The HREC well water was tested for TN and TP, SRP, nitrate, total dissolved solids (TDS), pH, and electrical conductivity and values were not found to be a concern in terms of modifying the chemistry of simulated stormwater when using well-water to dilute the concentrated solution. The three concentration levels used for this study (1X, 2X, and 4X) are provided in **Table 2**.

Table 2. Background concentrations of target pollutants in HREC well water.

Season	pH	TDS (g/L)	Electrical Cond. (mS)	Nitrate (mg/L)	TN (mg/L)	SRP (mg/L)	TP (mg/L)	Cu (mg/L)	Zn (mg/L)
Season 1 (2021)	6.24	0.037	0.451	0.589	0.069	0.019	0.022	0.046	0.0275
Season 2 (2022)	6.48	0.046	0.477	ND	0.047	0.077	0.091	0.048	0.033

ND = not detected

To create a series of variable storms for the purpose of the study, three different concentrations were selected to be tested. The three concentration levels used for this study (1X, 2X, and 4X) are provided in **Table 3**. The 4X storm concentrations were only added to the experimental design in the 2022 monitoring season; at that time the QAPP was modified accordingly.

Table 3. Pollutant levels (1X, 2X, and 4X) of the simulated stormwater runoff.

Pollutant Concentration Level			
Pollutant (ppm)	1X	2X	4X
Copper from Cupric Sulfate	0.32	0.64	1.28
Zinc from zinc chloride	0.6	1.2	2.4
Nitrate from potassium nitrate	1.0	2.0	4.0
Phosphate from potassium phosphate monobasic	0.5	1.0	2.0

To create the simulated stormwater runoff, the inflow tanks were filled with 30, 60, or 90 gallons (113.5, 227, 340.7 L) of well water which correspond to approximately 0.5-inch (1.27 cm), 1.0-inch (2.54 cm), and 1.5-inch (3.81 cm) rain events falling upon a hypothetical impervious area of 97 sq ft (9 sq m) (**Table 4**). One liter of the selected concentrated solution (1X, 2X, or 4X) was fully mixed into the influent tanks. Food-grade stainless steel paddles (Wilco brand) were used to incorporate the concentrated solution into the stock tanks at the start of a simulated storm. This resulted in a virtually identical influent pollutant concentrations of the stormwater in each of the twelve inflow tanks. For each storm, two randomly selected influent tanks (of the twelve) were sampled; these influent samples were analyzed for each storm event to compare with effluent concentration among the different treatments.

Table 4. Summary of simulated stormwater runoff events completed in 2021 and 2022 monitoring seasons

Date	Influent Volume (gal)	Target Synthetic Stormwater Pollutant Level	Simulated Rainfall Depth (in)
Sept 10 2021	60	1X	0.993
Sept 24 2021	30	2X	0.496
Oct 1 2021	90	1X	1.489
Oct 15 2021	30	1X	0.496
Oct 20 2021	90	2X	1.489
Oct 22 2021	60	2X	0.993
Jun 13 2022	30	1X	0.496
June 20 2022	60	2X	0.993
June 28 2022	90	1X	1.489
July 11 2022	30	2X	0.496
July 19 2022	60	1X	0.993
July 28 2022	90	2X	1.489
Aug 2 2022	30	1X	0.496
Aug 16 2022	90	4X	1.489
Sept 21 2022	60	4X	0.993
Oct 2 2022	30	1X	0.496
Oct 12 2022	30	4X	0.496

3.1.4. Natural Rainfall Events

Four natural (ambient) rainfall events were monitored in the first season (2021) and two were monitored in the second season (2022). Ambient rain measurements were collected for storms with more than 0.5 inches of rainfall, to ensure there was enough effluent to collect for analysis. Samples were collected from each mesocosm's effluent tank to determine whether there was nutrient or metals flushing after initial planting of the vegetation and/or any leaching of nutrients or metals from media during large influxes of ambient rain.

3.1.5. Sampling

As described above in Section 3.1.3 Simulated Stormwater Runoff Events, influent grab samples were collected in one liter HDPE bottles at the start of each simulated stormwater runoff event to measure the concentration of the simulated stormwater solution in the field. This was done by taking one grab sample from two randomly selected influent tanks for a total of two influent samples for each simulated storm. Prior to sample collection, sampling personnel fully mixed the collected water using a stainless-steel paddle. To minimize the potential for cross contamination, sampling personnel wore gloves while collecting samples and rinsed the mixing paddle and hands between collection at each effluent tank.

Bioretention mesocosm effluent samples were collected following simulated stormwater runoff events and the monitored ambient (natural) rainfall events. For simulated storms, sample collection of the effluent water occurred within six hours after the beginning of the simulation, at which point all the water that is past the saturation point in the bioretention mesocosm would have filtered through to the effluent tanks. For ambient rainstorms, effluent samples were collected within eight hours of the end of a natural rainfall event (or for some nighttime rains, the following morning). Prior to sample collection, sampling personnel fully mixed the collected water using a stainless-steel paddle. To minimize the potential for cross contamination, sampling personnel wore gloves while collecting samples and rinsed the mixing paddle and hands between collection at each effluent tank. Effluent grab samples were collected into one liter HDPE bottles. One 1 L sample is collected from each effluent collection tank per event, for a total of 12 samples (i.e., 3 samples per treatment).

Following collection, water samples were immediately transported to the lab and separated into HDPE plastic scintillation vials for storage. The collected water was separated into five parts: three of the aliquots were filtered using a 0.45 micrometer pore size filter on the end of a syringe for analysis of nitrate, soluble reactive phosphorus, and heavy metals, while two of the sample aliquots were not filtered and used for total nitrogen and total phosphorus analysis. The metals aliquot was preserved using a drop of concentrated nitric acid. Nitrogen samples were acidified using a drop of sulfuric acid for preservation. All the nutrient samples were stored in the freezer until analysis, while the metal samples were stored at room temperature.

3.1.6. Vegetation Monitoring

Three different metrics were used to assess plant health. The first was an assessment of vegetation coverage among the various experimental treatments. This was done using a mobile app called Canopeo (© 2022 Canopeo App, Stillwater, OK) which calculates the portion of green color in a photo (Patrignani & Ochsner, 2015). A photo is taken of every mesocosm in the Canopeo mobile application from a height of 49.5 inches above the surface of the ground outside the buried bioretention mesocosm. This height is maintained by resting the elbow of the camera holding arm on top of a wooden rod, set 12 inches away from the north side of each bioretention system, when taking the photos. This application is used to determine the percent of green cover in each of the plots throughout the growing seasons, a minimum of four times each season, at intervals of approximately three weeks. Looking at overall plant cover as opposed to considering

species by species, these data can give an idea on the overall growth of the vegetation in each soil media treatment.

The second vegetation metric evaluated was plant height. Plant height was used as a surrogate for plant health. Measurements were taken on the same day percent green cover was measured. This metric allowed us to track growth of vegetation over a season and show any differences in plant height within the same species but across the different soil media between treatments. Heights for each species in each treatment were compared for the three individual species (plus a fourth in the second season) planted in the mesocosms. Heights were recorded by measuring from the base of the plant to the apical meristem.

For the third metric of vegetation health, plant survival counts were conducted in season 2 (2022) to determine the ratio of surviving vegetation after the first winter since their establishment. An additional plant survival count was conducted in August 2023 to determine plant survival after the second overwintering for Butterfly weed, Coneflower, and Joe-Pye Weed, as well as to show the survival of Blue star flower after its first overwintering, as that fourth species was added in season 2 (2022).

3.2. Analytical Methods

Samples from the stormwater effluent and influent were analyzed at the University of Vermont Agriculture and Environmental Testing Lab (AETL). All collected effluent samples and influent grab samples for each simulated and ambient storm were analyzed on the Lachat Instruments QuickChem8000 flow injection analyzer (Hach Company, Loveland, Colorado) for nitrate, soluble reactive phosphorus (SRP), total nitrogen (TN), and total phosphorus (TP). TP, post digestion with potassium persulfate, and SRP are analyzed using the ammonium molybdate colorimetric method. TN, digested similarly as TP, and nitrate are determined using the cadmium reduction method. Heavy metals (Cu and Zn) analyses were completed on the inductively-coupled-plasma optical emission spectrometer (ICP-OES) (PerkinElmer, Inc. Shelton, Connecticut). Dilutions were made as necessary to fit within the instruments' linear ranges of calibration standards. For quality assurance, spike recoveries were run every 10 samples for all tests done on the Lachat and ICP-OES instruments and each analysis included a lab duplicate.

3.3. Data Analysis and Statistical Methods

Our experimental design allowed for several different comparisons of the four soil media treatments. Datasets were evaluated using descriptive statistics, percent removal calculations, and ANOVA and Tukey HSD Post Hoc tests.

For percent green cover measurements of the vegetation data, a repeated measures ANOVA was used for plants of the same species using one factor: the treatment type. An additional repeated measures ANOVA was completed for the plants' heights data. The heights of plants for one species cannot be compared to plants of another species, as there is natural variation in plant genetics that override any effects of treatment. However, growth of individuals of the same

species can be compared across the various treatments. Plant survival between the 2021 and 2022 sampling seasons was reported in numeric counts of the surviving plants for each species type within a mesocosm type.

For evaluating the performance of the mesocosms in terms of pollutant filtration and supporting plant health, the topsoil mesocosm (2) can be compared to each of the other three mesocosms: sand (1); woodchips (3); and DWTR (4) (**Figure 7**). Woodchips (3) and DWTR (4) are not compared against the sand treatment, nor each other, as outlined in **Figure 7**. The sand mesocosm acts as a negative control, meaning there is no application of a variable from the study (the inclusion of topsoil, woodchips, or DWTR). The purpose of the sand mesocosm as a negative control is to ensure that a notable result from the study (measurements of water quality and vegetative health) is due to variables controlled in the study (soil media), not from external factors. The negative control is only statistically compared to the positive control, not the treatments. The topsoil-only mesocosm is a positive (standard treatment) control, varying from each of the other three mesocosms by only one variable: not having topsoil (sand mesocosm), the inclusion of woodchips, and the inclusion of DWTR. Therefore, the positive control (topsoil mesocosm) *can* be compared to the treatments (woodchips and DWTR) as well as the negative control (sand).

All statistical analysis was completed using the statistical analysis packages available in RStudio and evaluated at a significant level of $p < 0.05$.

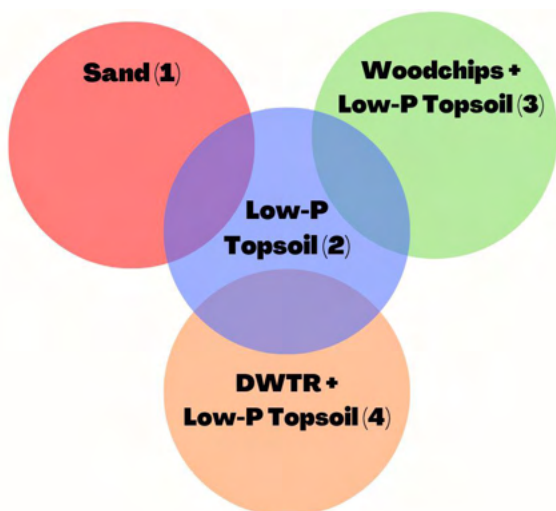


Figure 7. Diagram showing statistically comparable treatments.

3.3.1. Percent removal Calculations

Percent removal calculations were made for simulated storm events, totaling seventeen events over the two-year study. Pollutant removal efficiencies were calculated for each mesocosm to determine the change in pollutant concentration from influent to effluent. This was done for simulated storm events, totaling seventeen events over the two-year study. This comparison

was not possible for the ambient (natural) rainfall events due to the lack of influent concentration data. The following equation was used to calculate the percent removal:

$$\% \text{ removal} = (\text{influent concentration} - \text{effluent concentration}) / (\text{influent concentration}) * 100$$

3.3.2. Descriptive Statistics

The descriptive statistics calculated included the minimum (min), maximum (max), mean, and standard deviation (SD) of the water quality parameter and vegetation health results. For water quality, the descriptive statistics were calculated by combining the two seasons of effluent data by treatment. A statistics summary was also completed to determine the min, max, mean, and SD of the calculated percent removal for each treatment.

For vegetation health, descriptive statistics were calculated separately for the two seasons. The min, max, mean, and SD of plant heights were determined for each plant species. Additionally, the min, max, mean, and SD were calculated for the mesocosms' percent green cover. Plant survival over the monitored growing seasons was reported as a percentage of plants in each treatment surviving the first growing season (measured one year post planting in June 2022, and again at the end of the study in Aug 2022). An extra plant count was done to assess plant in August 2023 and is reported similarly.

3.3.3. ANOVA and Tukey HSD Post Hoc Test

Analysis of variance (ANOVA) tests were used for nitrate, SRP, the metals, TN and TP. A three-way analysis of variance test ANOVA was used to evaluate if there were statistically significant differences for nitrate, SRP, TN, TP, and the metals between treatments for the three factors at play in this study: bioretention media, pollutant concentration of the synthetic stormwater, and the size of the simulated storm.

For measurements of ambient (natural) rainfall, in which rain fell directly on the mesocosm surface rather than from influent tanks, only the effluent concentrations were evaluated; a two-way ANOVA test was used, with factors of treatment type and precipitation depth, based on weather station data.

For percent green cover measurements of the vegetation data, a one-way ANOVA was run for plants of the same species using one factor: the treatment type. An additional one-way ANOVA was done regarding the plants' heights. The heights of plants for one species cannot be compared to plants of another species.

For ANOVAs with a $p < 0.05$ (determined to be significant), a Tukey HSD test was done to determine which of the bioretention media treatment types are significantly different from one another. Once again, $p < 0.05$ is the significance level used to determine a significant difference between treatment types for the Tukey HSD test.

3.4. Challenges Encountered

In the field, two of the valves on the influent stock tanks had to be replaced at the start of the second season (2022) as they had cracked and were leaking water during storm simulations. Regarding challenges faced in lab, the nitrate and total nitrogen samples for the 2021 (first) season were not properly acidified and therefore the data from those samples was excluded from the report and data analyses. In a deviation from the QAPP, there was no biomass/destructive sampling done on the vegetation from the bioretention mesocosms; we determined that the other vegetation metrics were adequate to evaluate plant survival, coverage, and health (height by species) across the different soil media treatment, which was the stated research objective.

4. Quality Assurance Tasks Completed

The project data-quality objective was to collect, assemble, and analyze valid environmental data. Data quality was measured in terms of accuracy and precision, representativeness, comparability, and completeness. Field quality assurance measures included adherence to the QAPP, Version 1, approved July 29, 2021 (Appendix A). Training was provided by the UVM Principal Investigator and/or UVM Researcher to ensure that all sampling personnel were familiar with and followed sample collection procedures. No additional specialized training or certifications were necessary to perform the project tasks. The training completed is outlined in **Table 5**.

Table 5. Summary of sampling and laboratory personnel training.

Procedure	Description of Training	Training provided by	Training provided to	Date Completed	Location of Training
Vegetation planting and health measurements	Vegetation height, percent green cover, and survival	PI: Stephanie Hurley Post-doc researcher: Paliza Shrestha	Grad level researcher: Samantha Brewer Undergrad researcher: Bryce Carleton	06/21/21	UVM Horticultural Research and Education Center (HREC)
Inflow and outflow sample analysis	laboratory analytical procedures for nutrients and heavy metals	Post-doc researcher: Paliza Shrestha Lab manager: Daniel Needham	Grad level researcher: Samantha Brewer Undergrad researcher: Bryce Carleton	08/26/21	Agricultural and Environmental Testing Lab (AETL)
Inflow and outflow sampling	Water sample collection using EPA method 1669 (Appendix A)	PI: Stephanie Hurley Post-doc researcher: Paliza Shrestha	Grad level researcher: Samantha Brewer Undergrad researcher: Bryce Carleton	09/10/21	UVM Horticultural Research and Education Center (HREC)

The analytical laboratory for the water samples was AETL. Sample analyses by AETL were conducted according to the laboratory's established procedures and following methods outlined in Method Reference: Standard Methods for the Examination of Water and Wastewater; 21st Ed. 2005. EPA SW-846, 3rd Edition. The laboratory's procedures identify the relevant data quality objectives, assessment procedures, and reporting limits applied.

Data reviews were completed for each year of monitoring data. A summary of the data reviews completed is included in **Table 6**.

Table 6. Summary of annual monitoring data reviews

Review	Dates	Completed by
Season 1 (2021) Data	Feb 2022	Hisashi Kominami, Stone Environmental
Season 2 (2022) Data	Feb 2023	Micayla Schambura, University of Vermont

The professional judgment of the UVM Principal Investigator and Project Manager was relied upon in evaluating results. Reasons for rejecting certain sample results were determination that the results were not representative due to an adverse field condition or an evident analytical error. Censored data are summarized in **Table 7**.

Table 7. Summary of censored data.

Affected	Dates	Censored data	Comment
Influent	09/10/21 and 09/24/23	Influent samples	Influent grab samples not taken for these first dates
All mesocosms	All of Season 1 (2021)	Nitrate and TN results invalid	Samples not acidified prior to storage
Influent	06/20/23	Influent sample 2	Bottle broke, only one influent sample for this date

5. Results and Discussion

A total of seventeen events were monitored over two field seasons for twelve bioretention mesocosms, yielding 204 total effluent grab samples. In 2021 effluent from the bioretention mesocosms was sampled for six simulated stormwater events and four ambient rainfall events. In 2022 effluents were sampled for eleven simulated and two ambient events.

Tables 8-10 show the influent and effluent pollutant concentrations associated with each bioretention soil media treatment for nitrogen, phosphorus, and heavy metals. Note that for influent concentrations, the means shown represent the averages of all the simulated storms, but the six ambient (natural) rain event influent concentrations were not measured. **Tables 11-13** summarize percent removal (percent change in concentration from influent to effluent) for each pollutant respectively.

5.1. Summary of Water Quality Data Results

Measured influent and effluent nitrogen concentrations are summarized in **Table 8**. The mean influent nitrate concentration across all simulated stormwater events was 0.248 mg/L. Effluent concentrations across all treatments and events ranged from a minimum of 0.00731 mg/L for the woodchip treatment to a maximum of 1.33 mg/L, also for the woodchip treatment. The mean effluent concentration of nitrate was higher than the mean influent concentration for all treatments except woodchips. Other than the minimum effluent value for the sand treatment, all other effluent data showed that total nitrogen was greater in the effluent than influent. One possible reason for this is release of nitrate from the low-phosphorus compost that was applied at the plant roots in all of the mesocosms. The compost was tested for nitrate-N and reported to be 816 ppm (**Table 1**), which was higher than the topsoil (17 ppm) and sand (2 ppm) soil components, so it is the most likely source. Betz et al. (2023) reported export of nitrate-N in all of their bioretention cells, including DWTR amended ones, likely due to compost leaching.

The descriptive statistical analysis for phosphorus (SRP and TP) indicates that the mean effluent concentrations were lower than influent concentrations for all four study treatments (**Table 9**). The greatest range in effluent concentrations was observed in the woodchips treatment for both SRP and TP. While phosphorus was successfully being reduced by sorbing to the soil media, in the mesocosms containing woodchips, the variation in effectiveness of removal was the greatest, suggesting that the woodchips could be the cause of this variation.

The descriptive statistical analysis for metals (Zn and Cu) indicates that the mean effluent concentrations were lower than influent concentrations for both Zn and Cu for all four study treatments (**Table 10**). Additionally, the mean Zn and Cu effluent concentrations were comparable across all treatments.

Table 8. Descriptive statistical summary of measured influent and effluent nitrogen concentrations.

Treatment	Nitrate (mg/L)					TN (mg/L)				
	Influent	Effluent				Influent	Effluent			
	Mean	Min	Max	Mean	SD	Mean	Min	Max	Mean	SD
Sand	0.248	0.116	0.841	0.318	0.203	0.185	0.143	0.530	0.262	0.101
Topsoil		0.0497	0.929	0.317	0.248		0.217	0.788	0.417	0.154
Woodchips		0.00731	1.33	0.177	0.247		0.268	1.07	0.498	0.197
DWTR		0.0308	0.649	0.266	0.211		0.211	0.771	0.392	0.128

Table 9. Descriptive statistical summary of measured influent and effluent SRP and TP concentrations.

Treatment	Soluble Reactive Phosphorus (mg/L)					Total Phosphorus (mg/L)				
	Influent	Effluent				Influent	Effluent			
	Mean	Min	Max	Mean	SD	Mean	Min	Max	Mean	SD
Sand	0.104	0.00223	0.0165	0.00854	0.00276	0.301	0.000	0.0374	0.0204	0.00749
Topsoil		0.00304	0.0135	0.00780	0.00229		0.00818	0.0605	0.0238	0.00840
Woodchips		0.00295	0.332	0.0294	0.0571		0.0189	0.861	0.123	0.143
DWTR		0.00113	0.0197	0.00641	0.00317		0.0104	0.0455	0.0249	0.00866

Table 10. Descriptive statistical summary of measured influent and effluent heavy metals concentrations.

Treatment	Copper (mg/L)					Zinc (mg/L)				
	Influent	Effluent				Influent	Effluent			
	Mean	Min	Max	Mean	SD	Mean	Min	Max	Mean	SD
Sand	0.26	0.043	0.23	0.063	0.041	0.66	0.023	0.24	0.044	0.044
Topsoil		0.047	0.14	0.063	0.015		0.023	0.12	0.036	0.014
Woodchips		0.046	0.23	0.062	0.027		0.025	0.21	0.043	0.031
DWTR		0.043	0.24	0.062	0.037		0.023	0.20	0.041	0.035

5.2. Bioretention Mesocosm Water Quality Performance

Percent removal was calculated for the target pollutants following the methods outlined in Section 3.3.1 of this report. Positive percent removals presented in the results indicated a decrease in concentration from the influent to effluent, and negative percent removals indicate an increase in concentration from the influent to the effluent.

5.2.1. Nitrate and Total Nitrogen

Overall, the mean percent removal of nitrate ranged from 14.6% percent for the topsoil treatment to 65.4% for the woodchips treatment for simulated storms in 2022 (2021 nitrate and nitrogen data was excluded from analysis) (**Table 11**). An average removal of 27% for the sand treatment mesocosms indicates poor performance. Sarazen et. al (2022) reported their sand-only bioretention systems to export nitrate from the media and attributed it to nitrification happening during dry periods between storms. The topsoil treatment results also indicate poor performance (14.6% mean nitrate removal). The topsoil results differ from the hypothesis that the sand treatments would perform the poorest for nitrate removal. Sand, having large particle sizes and low-water holding capacity is expected to perform poorly for nitrate reduction as it is not a material that provides anoxic conditions necessary for denitrifying microbes (Chen et. al., 2013). Woodchips and DWTR performed better than the topsoil and sand treatments, with mean nitrate removals of 65.4% and 41.3%, respectively.

In a three-way ANOVA using factors of treatment, storm size, and pollutant level it was found that nitrate removals were significant between treatments as well as pollutant levels (**Appendix D**). For nitrate, the Tukey HSD Post Hoc Test indicated that the significant differences were between the performance of the woodchip and topsoil treatments ($p < 0.05$) (**Figure 8**), suggesting that the woodchips succeeded at their intended purpose of providing a space for anaerobic microbes to convert nitrogen out of a water-soluble form.

Table 11. Summary of percent removal results (percent change in concentration from influent to effluent) for nitrogen for all simulated stormwater events. Note that negative removal values indicate greater concentrations in effluent compared to influent.

Treatment	Nitrate (% Removal)				Total Nitrogen (% Removal)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Sand	-29	62	27	19	-32	52	15	25
Topsoil	-346	79	15	100	-253	38	-44	69
Woodchips	-103	97	66	40	-402	42	-77	102
DWTR	-107	87	41	47	-127	47	-34	50

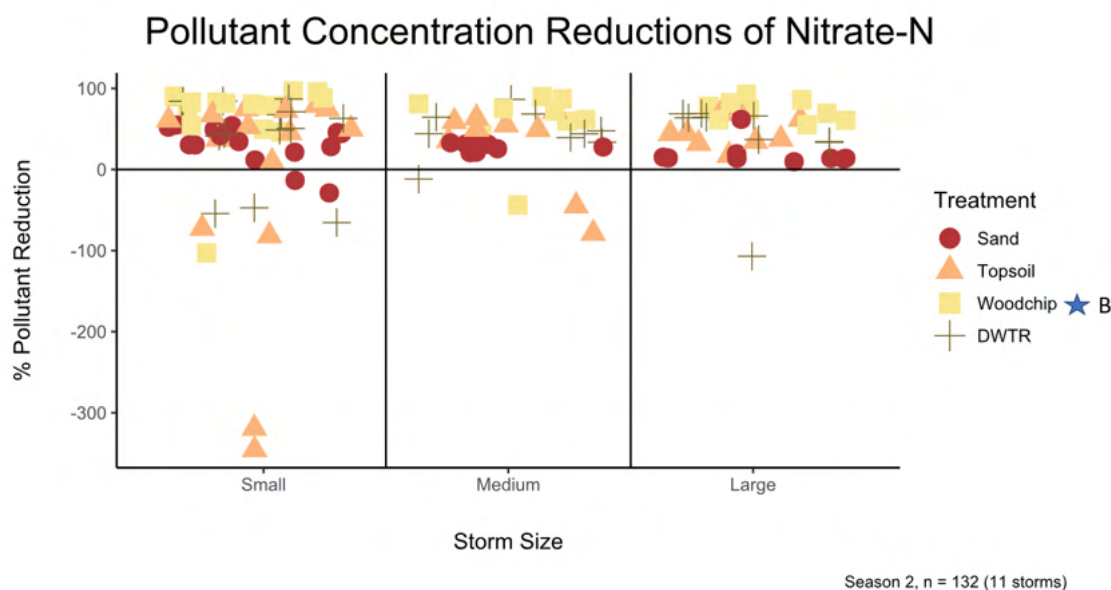


Figure 8. Pollutant concentration reductions of nitrate-N by treatment and clustered by storm size for all simulated storms in monitoring season 2 (2022). “A” indicates a significant difference ($p\text{-value} \leq 0.05$) comparing between Sand (Treatment 1) and Topsoil (Treatment 2), “B” indicates a significant difference comparing between Topsoil (Treatment 2) and Woodchips (Treatment 3), and “C” indicates a significant difference comparing between Topsoil (Treatment 2) and DWTR (Treatment 4). Stars (★) denote the direction that the significance is favoring.

Negative TN percent removals were measured for all treatments except for the sand treatment (**Table 11**). The sand treatment had a mean TN removal of 14.5%, while mean removals for the other treatments were -43.9%, -77.2%, and -34.3% for the topsoil, woodchips, and DWTR, respectively (**Table 11**).

Similar to nitrate, the three-way ANOVA results indicate significant differences ($p\text{-value} < 0.05$) between treatments and pollutant levels for TN (**Appendix D**). Specifically, the Tukey HSD Post Hoc Test indicated that the significant differences ($p\text{-value} < 0.05$) in percent TN removal existed between the topsoil and sand treatments (**Figure 9**).

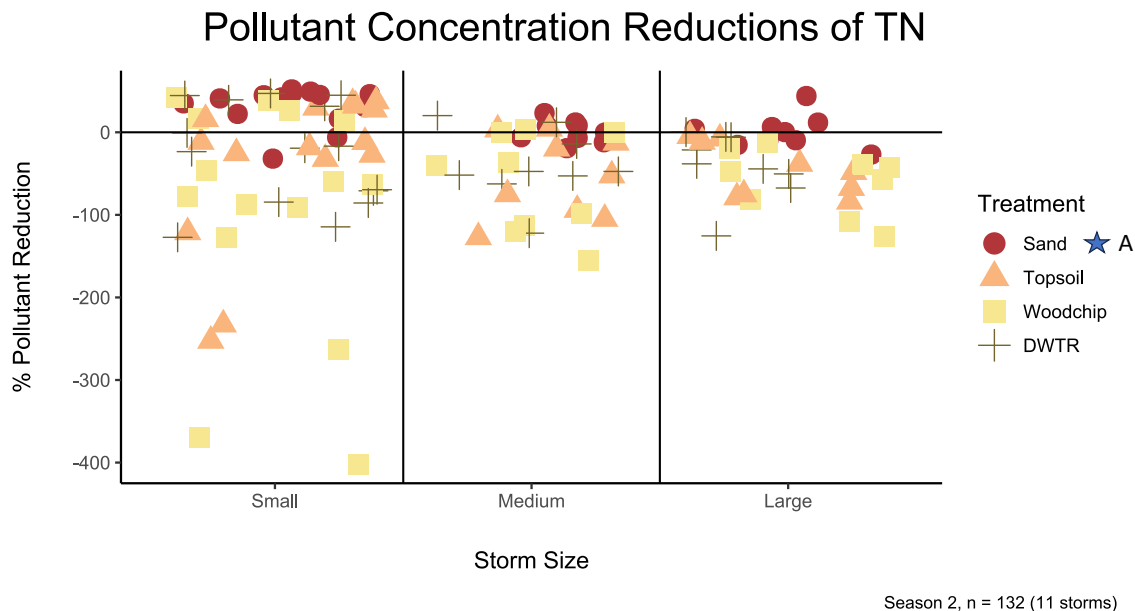


Figure 9. Pollutant concentration reductions of TN shown by treatment and clustered by storm size for all simulated storms in monitoring season 1 (2021). “A” indicates a significant difference ($p\text{-value} \leq 0.05$) comparing between Sand (Treatment 1) and Topsoil (Treatment 2), “B” indicates a significant difference comparing between Topsoil (Treatment 2) and Woodchips (Treatment 3), and “C” indicates a significant difference comparing between Topsoil (Treatment 2) and DWTR (Treatment 4). Stars (★) denote the direction that the significance is favoring.

5.2.1. Soluble Reactive Phosphorus and Total Phosphorus

Percent removals for SRP and TP are summarized in **Table 12**. The highest mean percent removal of SRP was recorded for the DWTR treatment (89.6%), this result is consistent with hypothesis that DWTRs reduce SRP concentrations and load (Ament et al., 2022; Liu et al., 2014; Lucas and Greenway, 2011; O'Neill and Davis, 2012; Yan et al., 2017). Results indicate that the sand and topsoil treatments were also efficient at sorbing SRP, with mean percent removals of 87.7% and 88.3%, respectively. These P removal results are similar as to what was seen in Ament et al.'s 2022 study with the control bioretention systems performing in the 80% range for retention during their 2-year monitoring of bioretention field sites.

The three-way ANOVA identified significant differences in the percent removal of SRP were based on treatment, but not on storm size or pollutant level (**Appendix D**). The Tukey HSD Post Hoc Test indicated a significant difference between the woodchip and topsoil treatments (**Figure 10**). These results, combined with the relatively low mean SRP removal for the woodchips treatment (53.8%), suggest that woodchips could be a driving factor behind this lower percent removal. Hsieh and Davis (2005) found that organic matter complexes that are expected to sorb P, can be in dissolved forms which contribute to the leaching of P.

Table 12. Summary for the percent removal of phosphorus (percent change in concentration from influent to effluent) across all simulated stormwater events. Note that negative removal values indicate greater concentrations in effluent compared to influent.

Treatment	SRP (% Removal)				TP (% Removal)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Sand	41	99	88	14	77	100	92	5
Topsoil	55	99	88	13	81	98	91	5
Woodchips	-516	98	54	100	-428	95	45	85
DWTR	41	99	90	13	76	98	90	6

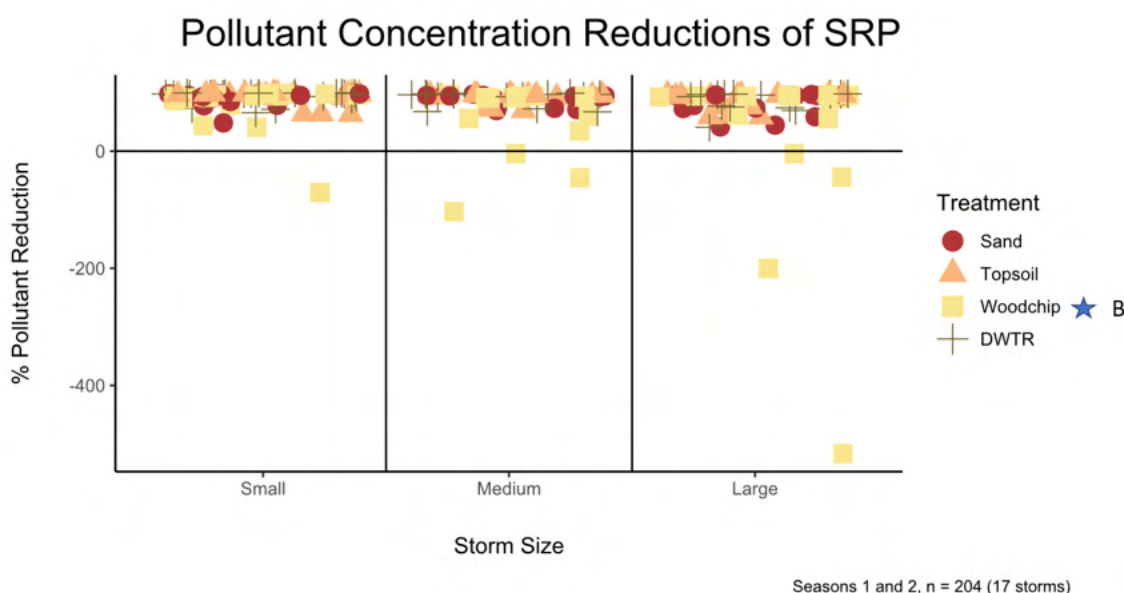


Figure 10. Pollutant concentration reductions of SRP shown by treatment and clustered by storm size for all simulated storms in monitoring season 1 (2021) and season 2 (2022). “A” indicates a significant difference ($p\text{-value} \leq 0.05$) comparing between Sand (Treatment 1) and Topsoil (Treatment 2), “B” indicates a significant difference comparing between Topsoil (Treatment 2) and Woodchips (Treatment 3), and “C” indicates a significant difference comparing between Topsoil (Treatment 2) and DWTR (Treatment 4). Stars (★) denote the direction that the significance is favoring.

High mean removals for TP of 91.8%, 90.7%, and 90.0% were seen for the sand, topsoil, and DWTR treatments, respectively (**Table 12**). Similar to SRP, the three-way ANOVA results indicate that significant differences in TP removal between treatments were driven by treatment differences, not the storm size or influent pollutant level (**Appendix D**). Additionally, the Tukey HSD Post Hoc Test indicated a significant difference between the woodchip and topsoil treatments (**Figure 11**). Like the SRP results, mean TP removal was lowest for the woodchip

treatment (44.9%), again suggesting that woodchips could be a driving factor behind this lower percent removal.

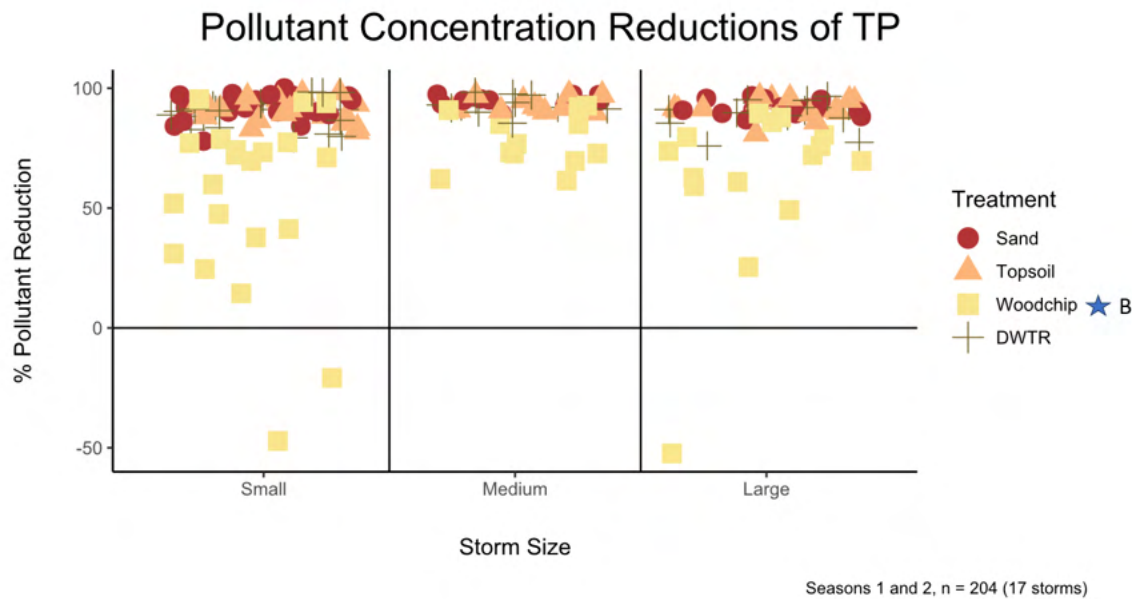


Figure 11. Pollutant concentration reductions of TP shown by treatment and clustered by storm size for all simulated storms in monitoring season 1 (2021) and season 2 (2022). “A” indicates a significant difference (p -value ≤ 0.05) comparing between Sand (Treatment 1) and Topsoil (Treatment 2), “B” indicates a significant difference comparing between Topsoil (Treatment 2) and Woodchips (Treatment 3), and “C” indicates a significant difference comparing between Topsoil (Treatment 2) and DWTR (Treatment 4). Stars (★) denote the direction that the significance is favoring.

5.2.2. Metals

The heavy metals sampled, copper and zinc, yielded high mean removals—above 75 and 92%, respectively (**Table 13**), for all treatments. This suggests that the materials used in the bioretention mesocosms, are efficient at sorbing metals. Blecken et al. (2009) in a column study of sand materials with and without a saturated zone yielded removals of 95.2% (with saturated zone) and 88% (without saturation zone) for copper and 97.4% removal in both for zinc. Additionally, in a 2011 column study, Blecken et al. Reported 24-66% removal for Cu and 99% for zinc in sand biofilters amended with topsoil. Dissolved metals are primarily removed by adsorption to the soil media and plant uptake, but plant uptake only makes up a fraction of the removal; Muthanna et al., 2012, reported plant uptake making up only 2-8% of the metal retention while Sun and Davis (2007) reported even lower values at 0.5–3.3% of metals being accumulated in plants. Metals sorb most effectively to media containing organic matter, so it is interesting that the sand-only mesocosms are performing at a similar level as the topsoil-containing mesocosms, but this could possibly be in part attributed to the spot applied low-phosphorus compost at the plant roots. While the percent removal results (**Table 13**) suggest a decrease in Cu and Zn concentrations from the influent to the effluent, three-way ANOVAs for copper and zinc yielded no significant difference for any of the three factors: treatments, storm size, or pollutant levels (**Appendix D**). These results indicate that there may not be significant

differences among treatments in metals reductions due to the bioretention soil media, and that a variety of media may perform well for reducing Cu and Zn concentrations. Shrestha et al. (2018) experienced similar low/nearly undetectable levels of metals in the effluent from their study's bioretention systems. Due to the lack of significance in the three-way ANOVA (**Figures 12** and **13**), additional statistical tests were not completed.

Table 13. Descriptive statistics summary for percent removal of metals results (percent change in concentration from influent to effluent) across all simulated stormwater events. Note that negative removal values indicate greater concentrations in effluent compared to influent.

Treatment	Copper (% Removal)				Zinc (% Removal)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Sand	-16	92	76	21	30	99	92	11
Topsoil	53	91	77	9	81	99	94	4
Woodchips	-5	91	77	15	34	99	93	9
DWTR	-2	92	77	14	36	99	93	9

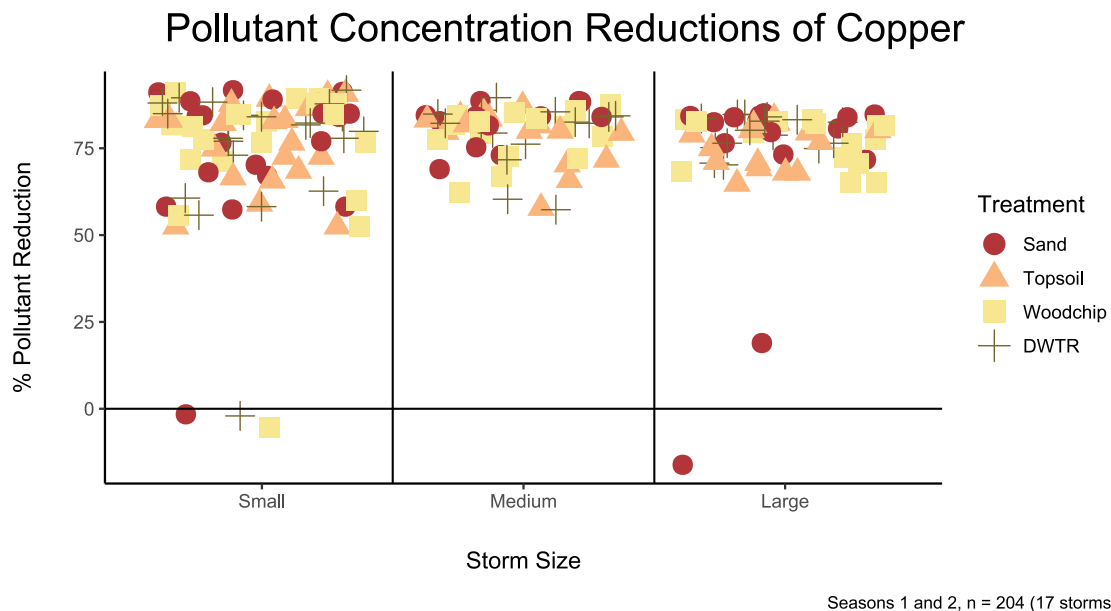


Figure 12. Pollutant concentration reductions of Cu shown by treatment and clustered by storm size for all simulated storms in monitoring season 1 (2021) and season 2 (2022).

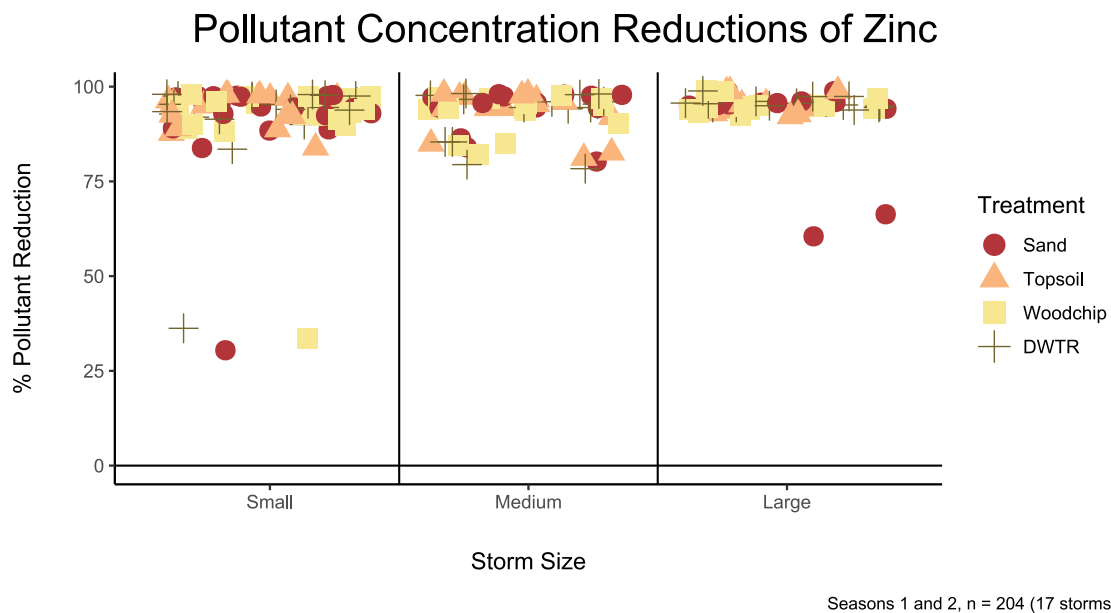


Figure 13. Pollutant concentration reductions of Zn shown by treatment and clustered by storm size for all simulated storms in monitoring season 1 (2021) and season 2 (2022).

5.3. Summary of Vegetation Monitoring Results

A total of eight measurement events were monitored over two field seasons: four measurements in each season for plant height and percent green cover.

Plant height measurements from seasons 1 and 2 are summarized in **Table 14** and **Table 15**. **Table 16** shows the calculated percent green cover for each mesocosm by treatment type.

Visual representations of vegetation health are shown in **Figure 14** which displays the color and size difference of plants grown in the sand versus topsoil-containing treatments.

Plant survival was determined at the end of season 2 (2022) as well as at the end of a third growing season, with final plant survival calculated one month ago in August (2023), as reported in **Table 17**.

Table 14. Season 1 (2021) Plant Heights Descriptive Statistics Summary

Treatment	Species	Min (cm)	Max (cm)	Mean (cm)	SD (cm)	n
Sand	Butterfly Weed	10.0	30.5	21.3	5.1	24
	Coneflower	10.0	23.0	17.8	3.8	24
	Joe-Pye	25.0	64.0	45.8	11.6	24
Topsoil	Butterfly Weed	11.5	41.0	27.4	9.0	24
	Coneflower	11.5	44.0	23.5	8.7	24
	Joe-Pye	30.5	78.5	58.8	15.2	24
Woodchips	Butterfly Weed	8.5	50.5	27.2	10.1	24
	Coneflower	10.5	80.5	27.9	18.9	24
	Joe-Pye	24.5	75.0	55.2	16.2	24
DWTR	Butterfly Weed	14.0	44.0	30.1	9.9	24
	Coneflower	8.0	85.0	25.6	16.2	24
	Joe-Pye	24.0	85.0	59.4	18.3	24

Table 15. Season 2 (2022) Plant Heights Descriptive Statistics Summary

Treatment	Species	Min (cm)	Max (cm)	Mean (cm)	SD (cm)	n
Sand	Butterfly Weed	25.5	52.0	38.1	7.0	24
	Coneflower	1.0	102.0	26.6	28.8	22
	Joe-Pye	2.0	50.0	22.6	14.7	15
	Blue Star	22.5	46.0	35.6	7.9	12
Topsoil	Butterfly Weed	38.0	67.0	53.2	7.9	24
	Coneflower	3.0	96.5	30.1	31.3	10
	Joe-Pye	16.5	131.5	84.2	42.6	24
	Blue Star	29.0	62.5	47.7	11.6	12
Woodchips	Butterfly Weed	24.0	69.5	49.9	10.8	24
	Coneflower	13.0	131.5	92.9	34.4	20
	Joe-Pye	28.0	153.0	102.2	37.3	24
DWTR	Butterfly Weed	44.0	89.0	62.4	11.6	24
	Coneflower	3.0	120.0	79.5	40.2	12
	Joe-Pye	21.5	155.5	92.0	44.3	19
	Blue Star	34.5	63.0	49.3	10.2	12

Table 16. Mesocosm Percent Green Cover Descriptive Statistics Summary

Treatment	Percent Green Cover, Season 1 (2021)				Percent Green Cover, Season 2 (2022)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Sand	4	15	10	3	6	22	13	5
Topsoil	9	52	29	13	25	78	52	21
Woodchip	9	38	25	11	34	68	54	11
DWTR	9	49	30	14	22	72	49	19

In addition to the plant height and percent green cover measurements, visual assessments provided information on plant health. For example, the sand treatment mesocosms performed poorly and had consistently yellowed leaves, minimal flowers, and short and stunted vegetation growth (**Figure 14**). While the plants in the topsoil treatment mesocosms generally appeared to be healthier, with green leaves and a greater number of flowers.



Figure 14. From left to right: Vegetation in Sand Mesocosm and Topsoil Mesocosm, Season 2 (2022)
Photos by Samantha Brewer 2022.

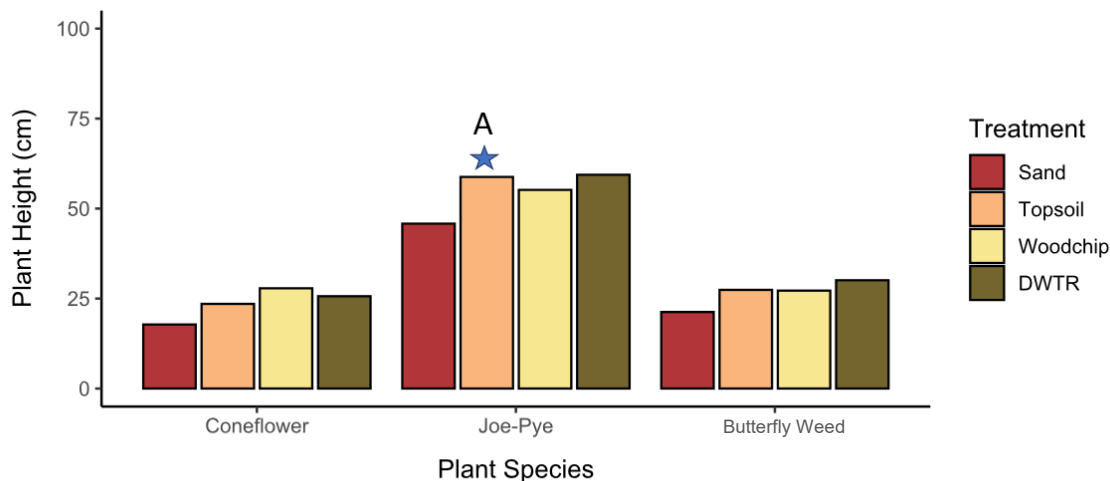
5.4. Bioretention Mesocosm Vegetation Health

5.4.1. Vegetation Heights

Plant height measurements for each species are compared across treatments for season 1 in **Figure 15**. While plant heights appeared to be lower in the topsoil treatment, there was no statistically significant difference in plant height among treatments for coneflower or butterfly

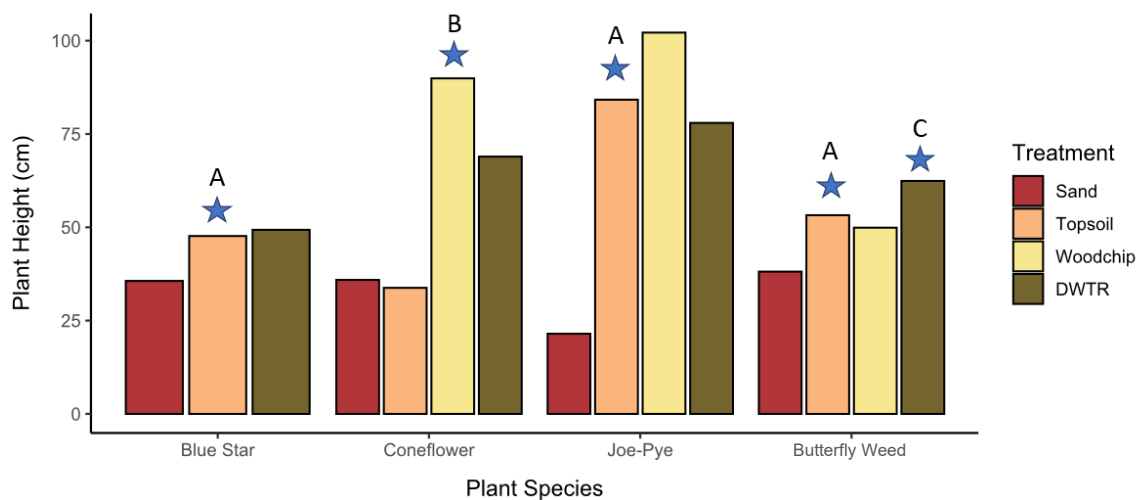
weed. There was a significant difference seen in plant height between the sand and topsoil treatments for joe-pye weed ($p < 0.05$) (**Figure 15**).

Notably, season 2 revealed more vegetation differences than season 1 (**Figures 15 and 16**). This suggests that a period longer than the one growing season is necessary to determine differences in plant health when comparing bioretention soil media types. Butterfly weed heights were significantly different between topsoil and DWTR treatments, with DWTR having the taller vegetation, as well as sand and topsoil treatments at significance levels of 0.01 and 0.0001, respectively. It is unclear whether the DWTR mesocosms' vegetation will maintain the tallest plant heights in future growing seasons; future studies could evaluate if there is a relationship between plant health and the use of DWTR in soil media. Joe-pye weed plants were found to have significantly different heights ($p\text{-value} < 0.001$) between the sand and topsoil treatments with sand being consistently the shorter of the two. Coneflower had significantly different heights comparing the topsoil (taller of the two) and woodchip treatments, but this could be attributed to the large loss of total coneflower plants in the topsoil treatment, shown in **Table 17**, rather than a direct result of vegetation performing better because of the inclusion of woodchips at the bottom of the soil profile. Blue star flower, planted in season 2 of this study, grew taller in the sand treatments than topsoil, which had a significant difference in plant heights between the two treatments at a significance level of 0.05. While height is generally an indicator of plant health, in the case of the blue star flower in the sand treatments, the leaves were more yellow and spotted with indications of nutrient deficiencies that their topsoil counterparts did not have.



July 13 to October 4, 2021

Figure 15. Vegetation Heights by Species for each Mesocosm Treatment, Season 1 (2021). "A" indicates a significant difference ($p\text{-value} \leq 0.05$) comparing between Sand (Treatment 1) and Topsoil (Treatment 2), "B" indicates a significant difference comparing between Topsoil (Treatment 2) and Woodchips (Treatment 3), and "C" indicates a significant difference comparing between Topsoil (Treatment 2) and DWTR (Treatment 4). Stars (★) denote the direction that the significance is favoring.



June 13 to September 15, 2022

Figure 16. Vegetation Heights by Species for each Mesocosm Treatment, Season 2 (2022). "A" indicates a significant difference (p -value ≤ 0.05) comparing between Sand (Treatment 1) and Topsoil (Treatment 2), "B" indicates a significant difference comparing between Topsoil (Treatment 2) and Woodchips (Treatment 3), and "C" indicates a significant difference comparing between Topsoil (Treatment 2) and DWTR (Treatment 4). Stars (★) denote the direction that the significance is favoring.

5.4.2. Percent Green Cover

The only detected significant difference in percent green cover was between the topsoil and the sand treatments in both seasons 1 and 2 (**Figure 17**), with the topsoil treatments having significantly higher percent green cover than sand. This suggests that the use of topsoil could be the defining factor in plant health (as topsoil was also a component of both woodchip and DWTR treatments (**Figure 4**) but excluded from the sand treatment). These results suggest that inclusion of woodchips low in the bioretention system and DWTR in the soil media profile do not impact the health of vegetation in bioretention systems.

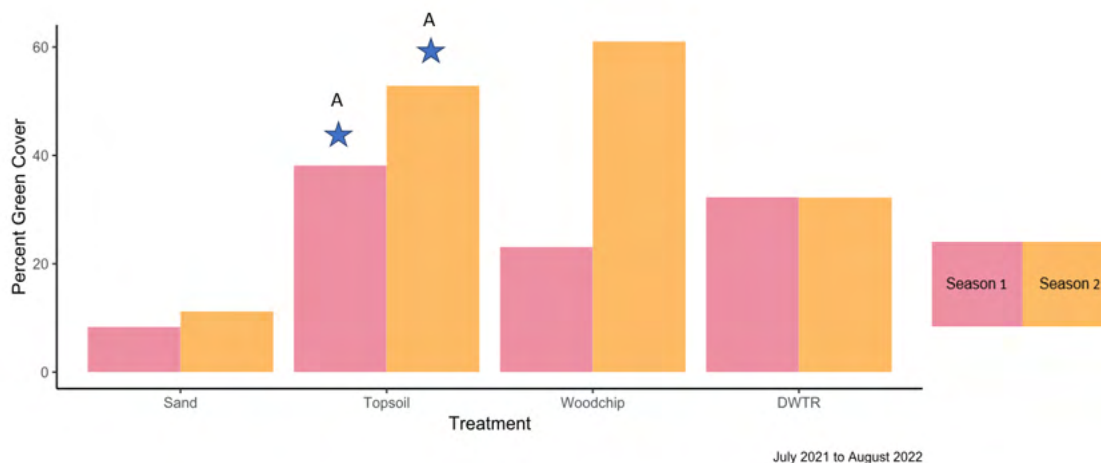


Figure 17. Percent Green Cover of Mesocosms for Seasons 1 (2021) and 2 (2022). “A” indicates a significant difference ($p\text{-value} \leq 0.05$) comparing between Sand (Treatment 1) and Topsoil (Treatment 2), “B” indicates a significant difference comparing between Topsoil (Treatment 2) and Woodchips (Treatment 3), and “C” indicates a significant difference comparing between Topsoil (Treatment 2) and DWTR (Treatment 4). Stars (★) denote the direction that the significance is favoring.

5.4.3. Survival

There was no loss of Butterfly weed during the course of the study (**Table 17**), suggesting they are resilient in stormwater conditions and can be a great choice of vegetation for bioretention systems.

All treatments lost at least two of the six total Coneflower plants. There was notable loss between seasons 1 and 2 for Coneflower in the topsoil treatment with 2/3 of the plants not surviving that first over wintering. The DWTR treatments lost half of their coneflower plants between the first and second growing season. The sand and woodchip treatments experienced a loss of two of the original six coneflower plants. In the woodchips treatment, there was additional loss of three coneflower plants between the second and third growing season. These losses suggest that coneflower might not be the best choice of plant in this design of bioretention systems.

Joe-pye weed was initially thought to have a loss of about 1/3 of plants over the first winter in the sand treatment, but interestingly was visible and alive in the third growing season, perhaps remaining dormant over that second growing season, or self-seeding from a prior year. The only other loss of joe-pye weed was seen in the DWTR treatment between the second and third growing season, with a loss of two of the six original plants.

Blue star flower, like Butterfly weed, experienced no loss during its first over-winter.

Table 17. Plant survival in percentage, reported at the end of growing season 2 (August 2022) and in August 2023

Species	Growing Season	Sand	Topsoil	Woodchips	DWTR
Butterfly weed	Season 2	100	100	100	100
	Aug 2023	100	100	100	100
Coneflower	Season 2	83	33	83	50
	Aug 2023	100	33	33	50
Joe-Pye Weed	Season 2	67	100	100	100
	Aug 2023	100	100	100	83
Blue Star	Aug 2023	100	100	NA	100

Note: Blue star was added in the second growing season to eight of the mesocosms (Indicated with * in Figure 2); no blue star was added to the woodchip treatments.

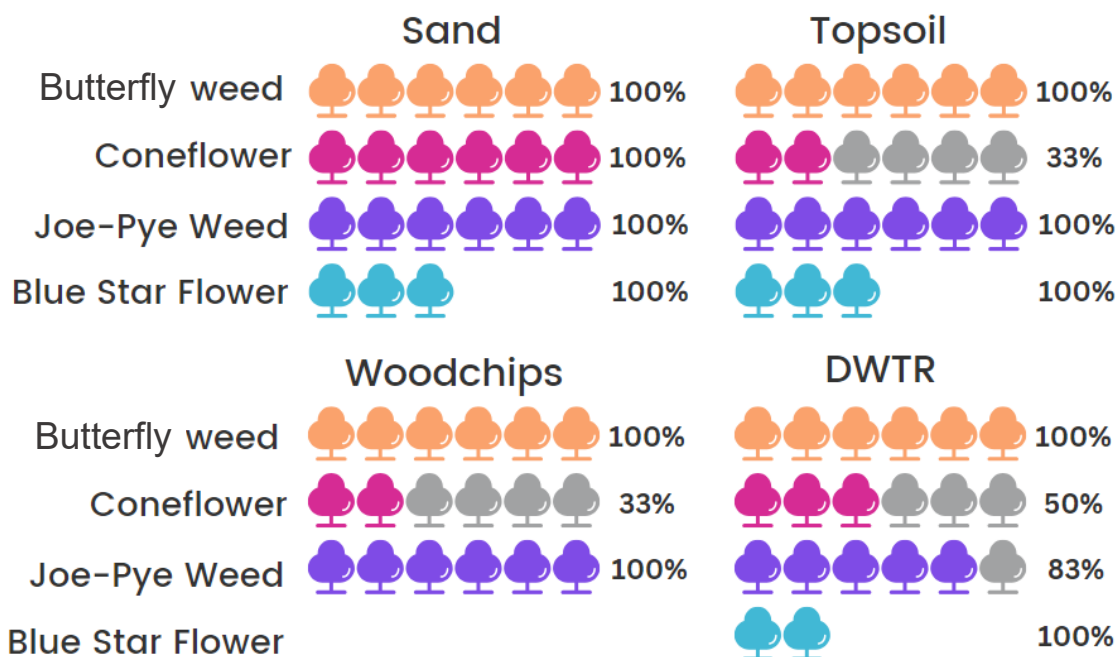


Figure 18. Plant survival percentage, reported at the end of August 2023, 26 months since planting. Each 'tree' represents a single plant, with a total number of 6 plants each of Butterfly weed, Coneflower, and Joe-Pye Weed. Blue Star Flower was only added to eight of the mesocosms (Indicated with * in Figure 2); no Blue Star was added to the woodchips treatments, hence the variable number of total plants for that species.

6. Conclusions & Recommendations

Bioretention systems have the potential to reduce the concentrations and loads of pollutants commonly found in stormwater runoff. The mesocosm study completed as part of this project provided the unique opportunity to evaluate the effectiveness of bioretention systems under a semi-controlled environment, with samples collected from both simulated stormwater runoff events and ambient (natural) rainfall events. Overall, water quality improvements were seen in effluent SRP, TP, and heavy metal concentrations when compared to the influent concentrations.

Based on the results of this study, the following should be considered for designing bioretention soil media.

1. Stormwater designers should consider using low-phosphorus topsoil as the primary form of organic matter for supporting vegetation health in bioretention systems. Vigorous vegetation growth was seen in all bioretention mesocosms where low-P topsoil was included in the soil media, alongside a small amount of low-P compost incorporated at plant roots at time of planting; aesthetics and pollinator habitat both benefit from a healthy vegetation community. Regardless of all mesocosm treatments in this study having the localized inclusion of low-phosphorus compost at planting, the low-P topsoil-containing treatment performed significantly better in terms of plant health than the sand treatment.
2. While the inclusion of woodchips showed reductions in nitrate in bioretention effluent, more research needs to be done on the possible release of phosphorus from woodchips before they are recommended as a material in bioretention systems. This should include additional research regarding the use of other hardwood species (not only the Norway maple used in this study); application of woodchips that are dried (rather than fresh); as well as efficacy of woodchips placed at different locations and/or different saturation levels within the bioretention soil profile in terms of maximizing denitrification.
3. In this study, there was no significant difference between the inclusion of DWTR in the sand layer of the systems compared to those without. Other studies have shown both that sand-based bioretention media performs poorly for P removal, particularly for SRP and that DWTR can be effective at sorbing P in bioretention media, so the lack of statistical difference here this could be attributed to the other media materials having not yet reaching their phosphorus holding capacity and subsequent studies on systems installed beyond two years might give better insight into this.
4. Nitrate performance was not consistent among any of the bioretention soil media treatments and for places where N is a pollutant of concern, additional study of ways to reduce N in bioretention systems' effluent is essential.
5. Heavy metals removal is comparable to other studies' column and field experiments with the effluent concentration values being low and nearly undetectable. There was no

significant difference in the performance of the media noted between treatments, they all performed well for copper and zinc removal, but this trend could be attributed to the age of the system (only undergoing two monitoring seasons), and future studies could continue to monitor metal removal.

7. Deliverables Completed

The Stone-UVM team developed a QAPP that was approved in July 2021.

The Stone-UVM team prepared quarterly progress reports within 10 days following the end of each calendar quarter. These quarterly reports provided updates on the progress of each task and described any problems encountered.

The Stone-UVM team completed a final draft of a nationwide literature review report in May 2022. Minor updates to the final draft of the literature review were made in 2023. This literature review report is included as Appendix B.

The bioretention mesocosms were constructed in June 2021, and photographs and schematics of the design are included in this report.

Monitoring datasets were submitted electronically at the end of each monitoring year in 2021 and 2022.

Interim statistical analysis results, included tables and figures, were submitted electronically in August 2023.

This final report includes methods and results of the bioretention soil media evaluation.

UVM presented aspects of the bioretention study as follows:

- Samantha Brewer “Woodchips and drinking water treatment residuals in vegetated bioretention systems: how do they perform against conventional soil recommendations in treating stormwater runoff?” University of Vermont Student Research Conference. Burlington, VT. April 19, 2023.
- Samantha Brewer “Exploring the performance of woodchips and drinking water treatment residuals in bioretention systems for treating stormwater runoff.” American Ecological Engineering Society Annual Meeting, Tampa, FL. June 6, 2023
- Stephanie Hurley “Recent Research on Soil Media Design for Bioretention” *New England Interstate Water Pollution Control Commission (NEIWPCC)*. Invited Presentation at State and EPA Stormwater Staff Meeting. September 21, 2023.
- Stephanie Hurley “Recent Research on Bioretention Soil Media” *New England Water Environment Association (NEWEA), Stormwater Conference*. Framingham, MA. May 10, 2023.

This final report will be presented to the LCBP TAC on November 1, 2023.

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