Optimizing Biofiltration Media for the Capture of Phosphate and the Support of Vegetation Growth

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Abstract

Biofiltration is a stormwater management practice designed to treat runoff for harmful contaminants. A critical component of these systems is the granular media. In this study, I investigated six different types of base media (10% leaf compost, 20% leaf compost, 10% food compost, 20% food compost, sphagnum peat, reed sedge peat) and four different amendments (spent lime, biochar, iron and sphagnum peat) in various combinations with sand to test their capacity in mitigating phosphate release and supporting the growth of Switchgrass *(Panicum virgatum)* as an indicator of potential to support vegetation. The study consisted of an outdoor mesocosm experiment over three years, with 34 events total where 30 seeded mesocosms containing various media mixes received water from the Mississippi River (near downtown Minneapolis, MN, USA) that was spiked with phosphorus to simulate stormwater inputs. Soluble reactive phosphorus and nitrate concentration, pH, Switchgrass height over time, and Switchgrass biomass at senescence was measured each year. In general, mixes containing food compost, leaf compost, biochar with compost and spent lime with compost leached phosphorus whereas mixes containing peat, iron with compost, and sand adsorbed phosphorus. The mixes that leached phosphorus supported the most plant growth. Spent lime mixes and biochar mixes had the highest effluent nitrate concentrations indicating effects on N mineralization or nitrification. The iron and leaf compost layered media mix performed the best of all the mixes tested in terms of mitigating the release of phosphate and having the potential to support vegetation. Future research is necessary to determine if it can continue preventing phosphorus leaching and support vegetative growth with a higher percentage of compost and different plant species.

Keywords: phosphate, nitrate, biofiltration, stormwater treatment, switchgrass (*Panicum virgatum)*, compost, peat, biochar, water treatment residuals, iron

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1. Introduction

Biofiltration has become a popular method of stormwater treatment aimed at improving water quality and hydro functions as urban areas continue to expand, resulting in increased impervious surface cover. Stormwater is water that results from precipitation events washing off urban impervious surfaces and can transport pathogens, heavy metals and excessive nutrients. Reducing runoff from rain events and removing the pollutants within this runoff present difficult obstacles within the field of stormwater management (Yang et al., 2022). One obstacle is designing a system that can treat all of the contaminants stormwater can carry. Biofiltration systems are depressions within the landscape that treat stormwater runoff via physical, chemical and biological processes and depending on design may have an underdrain. If no underdrain is present, stormwater leaves the system via infiltrating directly into native soils.

Biofiltration systems are often used to target the removal of excess nutrients, including phosphorus (P) and nitrate (N) from stormwater. The removal of P is critical to prevent algae blooms and eutrophication in receiving waterbodies (Carpenter, 2008). Another obstacle that presents itself within the design of biofiltration systems is the addition of organic material that may have phosphorus leaching potential (Hurley et al., 2017; Shrestha et al., 2020; Paus et al., 2014). Designing a media mix that contains organic matter to support vegetation and contains an amendment that can mitigate P leaching from the organic material is one potential solution to this obstacle.

Mesocosm experiments are enclosed and controlled outdoor experiments that are mid-sized and serve to bring laboratory science into real world settings (Kwak and An, 2016 citing Odum, 1984; Crossland and La Point, 1992; Bruckner et al., 1995). Mesocosm experiments are a popular way to test media performance and design (i.e., layered systems), media support of vegetation, and stormwater treatment (Davis et al., 2006; Henderson et al., 2007; Yang et al., 2020).

Previous studies have shown that vegetated mesocosms are more efficient in N and P removal after being flushed with stormwater than non-vegetated mesocosms and that nutrient removal may increase once vegetation has been established (Henderson et al., 2007; Lucas & Greenway, 2011). Hence, the presence of vegetation within biofiltration installations is a key component within their design. Vegetation also enhances the aesthetic appeal of biofiltration installations making them easy to incorporate along roadsides, within public open spaces and private properties (Bratieres et al., 2008).

1.1. Introduction: Base Media

Biofiltration media mixes are composed of specifically selected granular media. Sand is the primary component for granular filtration; organic matter (such as compost or peat) holds moisture and supports plant growth; and amendments add additional water quality treatment. In this study, we investigated compost and reed sedge peat as organic matter; sphagnum peat as both organic matter and amendment; and biochar, lime-based water treatment residuals (spent lime), and iron as amendments.

Compost is the product of a biological degradation process of heterogeneous solid organic material under aerobic, self-heating and controlled moisture conditions (Lobo & Dorta, 2019). Compost can vary according to its source (food, yard clippings, manure), climate where processing occurs, and time of year collected. Compost is a popular addition to biofiltration systems because it can retain moisture and support vegetation (Hurley et al. 2017). N and P in compost aid in vegetation growth but can also result in nutrient leaching. In addition, studies have shown that compost can also uptake of heavy metals such as zinc, copper, lead and cadmium (Al-Mashaqbeh & McLaughlan, 2012; Lim et al., 2015; Silvertooth & Nason, 2014; Paus et al., 2013; Paus, et al., 2014). Studies examining biofiltration systems and the use of compost have shown that compost contributes to leaching of P (Shrestha et al., 2020).

Regulations regarding the use of compost in stormwater management vary by State and local governing authority. In Minnesota, USA, certain compost sites must report to the Minnesota Pollution Control Agency (MPCA) and regularly test their products to prove that it meets certain criteria, which often includes testing the compost for phosphorus content to address leaching potential (*MPCA*, 2022). The percent of compost used within our media mixes for this study were selected based on a water quality media blend from the Minnesota Stormwater Manual which suggests the mix contains 15-30%

organic matter (*MPCA*, 2022). Our design included mixes containing 10% and 20% organic matter.

Peat is the accumulation of organic remains of plants in places where decay has been slowed due to excessively wet conditions (Monson Geerts & McCarthy, 1999). By definition, peat will vary from place to place based on the source material and decay conditions. Sphagnum peat has a porous structure allowing it to absorb dissolved contaminants including organics and heavy metals (Tirpak et al., 2021 citing Brown et al. 2000). Reed sedge peat is typically further decomposed than sphagnum peat (Evans, 2014). Peat is a relatively affordable alternative to compost and has been shown to capture heavy metal toxins such as cadmium, copper, nickel, chromium and lead (Henryk et al., 2016). Sphagnum peat has a history of use in municipal wastewater treatment and peat-packed biofilters have shown to remove nutrients from wastewater streams (Danley-Thomson et al., 2015). In a study by Zhou et al., (2003) the use of a peat filtration system in karst terrain resulted in a reduction of metal concentrations as well as removal of total suspended solids (TSS) and total volatile solids (TVS). The longevity of peat and replacement procedures in large scale applications needs further examination. A potential downside of using peat for biofiltration practices is that this material needs to be harvested from peatlands which can result in environmental disturbance and a loss of ecological services (McCarter et al., 2021, Andersen et al., 2017). Additionally, the disturbance of peatland has released significant amounts of CO_2 into the atmosphere (Knox et al., 2015).

1.2. Media Amendments

Water treatment residuals (WTR) are by-products of the drinking water treatment processes. Aluminum- and iron-based WTRs used in biofiltration media mixes have been shown to be an effective way of removing P from stormwater (O’Neill & Davis, 2012; Liu & Davis, 2014). When compared to other popular amendments such as green zeolite, peat soil and fly ash, WTR had the greatest P removal (Li et al., 2018; Zhang et al., 2018; Lucas & Greenway, 2011). Additionally, because WTR is a by-product, it is generally low cost and readily available (Xu et al., 2019). Spent lime, a waste material that results from the water softening process, is a WTR that can be used in stormwater treatment

(*MPCA*, 2021a). In a study by Shrestha et al., (2019), spent lime was shown to remove P from leachate when used as an amendment, however only leachate concentrations were measured, not influent vs. effluent. Studies using spent lime as a WTR are limited and therefore it was included in this study.

Biochar is a carbonaceous sorbent created by pyrolysis of biomass at elevated temperatures in the absence of oxygen (Tirpak et al., 2021). It has been used as a bioretention soil media (BSM) amendment because it has been shown to absorb heavy metals and nutrients (Cao et al., 2009; Reddy et al., 2014) and enhance plant biomass (Kasak et al., 2018). The effectiveness of biochar is dependent on its source and production process, and little is known about its effect on the environment (Wang & Wang, 2019). Overall, the results from the literature suggest that biochar does not reduce phosphorus leaching potential when mixed with compost but should be used when metal contamination is of concern (Iqbal et al., 2015).

Iron filings are the by-product of the milling, filing or grinding process from finished iron products (Reddy et al., 2014). The addition of iron to stormwater practices has been shown to be effective at the uptake of both orthophosphate and total phosphate in stormwater management practices (Erickson et al., 2012, Reddy et al., 2014). A study by Erickson et al., (2012) examined trenches installed along a detention basin that contained iron enhanced sand and the enhanced sand showed the potential to capture 85-90% of phosphate coming into the system. Iron filings are an effective stormwater treatment amendment because they capture phosphorus without fouling and tend to be more cost effective than materials such as steel wool via an efficient manufacturing process (Erickson et al., 2012). Media layers have also been shown to improve system performance (Yang et al., 2020). An example of a layered system may be a layer of compost to support vegetation and address pollutants such as toxic metals, and a layer of sand containing iron that will address leaching potential and aid in P removal (Paus et al., 2014).

The research described in this thesis was designed to further develop a media mix that addressed the leaching of P in particular. The results of this project will aid practitioners in the design and improved performance of biofiltration systems. To improve performance of these systems, there is a need for a media that (1) adsorbs and does not release phosphorus and (2) supports vegetation growth. By testing various mixes, the objectives of this research were to determine: (1) which mixes limit the release of phosphorus, (2) which mixes support the most vegetation growth, and (3) to investigate whether the mixes contribute to nitrate pollution. These objectives were addressed using eight common media materials in controlled outdoor mesocosms.

2. Methods and Materials

Mesocosm studies were conducted for a total of three years (Y1, Y2, and Y3) to evaluate the filtration rate, dissolved P concentration in the effluent, and ability of the media to support vegetation growth. The mesocosms were located in the decommissioned spillway adjacent to St. Anthony Falls Laboratory in Minneapolis, Minnesota. Y1 consisted of 14 simulated rainfall events from July 18 through October 24, 2019. Y2 consisted of 8 simulated rainfall events from August 21 through 2019 October 15, 2020. Y3 consisted of 12 events from July 22 until October 14, 2021.

2.1. Mesocosm Construction

The mesocosms in Y1 and Y2 consisted of 10 different media blends comprising up to three different media components. The media components included sand as the granular filter media, compost or peat as organic material, and various amendments or enhancements to increase pollutant removal. Food compost was provided by the Mulch Store in Rosemount, MN (USA). Plaisted Companies, Inc. (Elk River, MN, USA), provided the leaf compost, biochar (sourced from Royal Oak Charcoal (Roswell, GA, USA)), iron filings (d_{50} ~ 0.75mm, sourced from Connelly GPM, Inc. (Chicago, IL, USA)), sphagnum peat and reed sedge peat, and concrete sand (ASTM, 2002). Water treatment residual was collected from the St. Paul Water Treatment Facility (St. Paul, MN, USA). Plaisted Companies, Inc. also mixed all the media to produce the following mixes (by volume unless otherwise noted) that were investigated in Y1 and Y2 (see Table 1.).

Table 1: Summary of mixes for all years including mixes remaining and new mixes added for Y3

Y1 - Y2	**Y3**	**Short Name**
100% Sand	100% Sand	sand
90% sand, 10% leaf compost	*(removed)*	10% leaf
90% sand, 10% food compost	*(removed)*	10% food
80% sand, 20% leaf compost	80% sand, 20% leaf compost	20% leaf
80% sand, 20% food compost	*(removed)*	20% food
80% sand, 20% reed/sedge peat	*(removed)*	reed peat
80% sand, 20% sphagnum peat	80% sand, 20% sphagnum peat	sphagnum peat
75% sand, 20% leaf compost (by volume), 5% iron (by weight)	*(removed)*	5% iron
75% sand, 20% leaf compost, 5% spent lime	75% sand, 20% leaf compost, 5% spent lime	5% spent lime
65% sand, 20% leaf compost, 15% biochar	65% sand, 20% leaf compost, 15% biochar	biochar
N/A	100% Sand *(added)*	new sand
N/A	90% sand, 10% leaf compost *(added)*	new 10% leaf
N/A	80% sand, 10% leaf compost, 10% sphagnum peat *(added)*	10% sphag/10% leaf
N/A	Layered 90% sand & 10% leaf compost (top half) over 95% sand & 5% iron (bottom half) *(added)*	layered iron
N/A	80% sand, 10% spent lime, 10% leaf compost *(added)*	10% lime/10% leaf

The media blends were placed into thirty 83.3 L (22-gallon) cylindrical plastic containers with a top diameter of 40 cm (15.75 inches) and a height of 76.2 cm (30 inches, Fig.1). There were three replicates each of the ten mixes resulting in thirty containers total. The barrels were placed on a wooden platform that set them between 57 cm (22.5 inches) to 68.5 cm (27 inches) above the ground. A plastic bulkhead was installed by drilling a hole into the bottom of each barrel, and approximately 51 cm (20 inches) of black vinyl tubing with 1.9 cm (¾ inches) inner diameter was attached to the bulkhead. Ten centimeters of pre-washed pea size gravel was provided by Plaisted Companies, Inc. and placed into the bottom of each barrel to allow for drainage. Next, the media blend was added in approximately 11 cm (4.5 inches) lifts until a total of 46 cm (18 inches) had settled. In between lifts, a rubber mallet was used to tap the sides of the barrel to encourage gravity settling and consolidation of particles. Identical masses were added to two other replicates of the same media blend. This was repeated for all 10 media blends resulting in a total of 30 mesocosms.

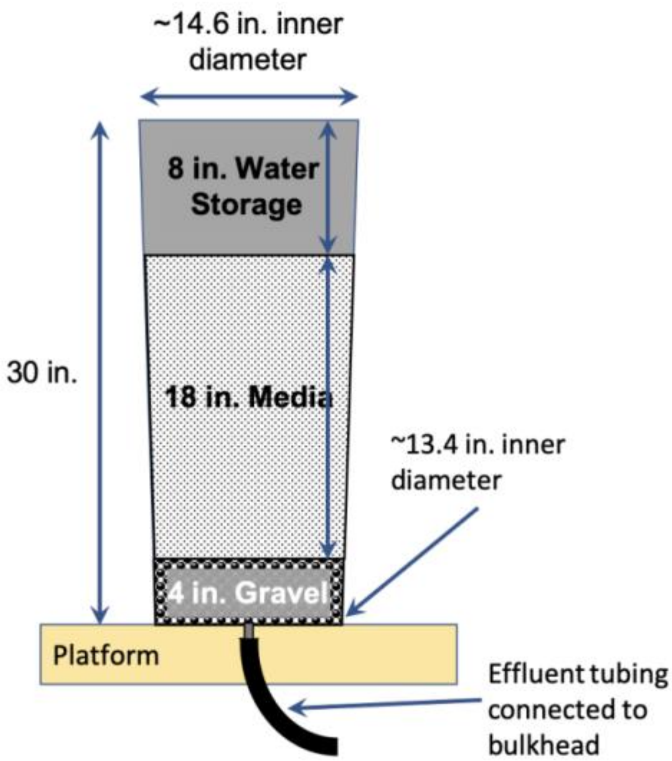

Figure 1: Mesocosm schematic with approximate dimensions (Erickson et al., 2021)

Flow dissipaters were placed on the surface of each mesocosm to prevent the media surface from scouring (Fig. 2). Each dissipater was on average 8 inches tall with a (10 cm) 4-inch diameter. Metal wire mesh was secured around the 10 cm (4 inch) PVC caps and 2.5 cm PVC pipe was placed in the middle of the dissipater to secure influent tubing during an event. The mesh was filled with pea size gravel. Wooden dowels were guided through the mesh and the gravel and were then pressed against the sides of the barrels to stabilize the dissipaters.

Figure 2: A side view (left) and aerial view (right) of installed dissipaters (Erickson et al., 2021)

Each mesocosm was seeded with 0.4 grams of pure live switchgrass seed (seeding rate = 3.7g/m^2) provided by Prairie Restorations in Princeton, Minnesota (USA). The seeds were scattered as evenly as possible across the mesocosm surface and each mesocosm was watered with 1 L of Mississippi River water, collected near downtown Minneapolis, MN, USA (henceforth called River water). The mesocosms were watered twice weekly until experiments began and they were covered with plastic in Y1 in order to prevent any rainfall from disrupting the media and encourage seed germination.

For Y3, 15 new mesocosms were constructed and select media mixes were replaced (see Table 1). The new media mixes were selected to further test whether an increase in the percent of spent lime would prevent P leaching when mixed with leaf compost and if sphagnum would mitigate P release when mixed with leaf compost. The iron layer was included because previous research has suggested testing a system containing a layer amended with iron beneath a layer of compost to address the P leaching potential of compost (Paus, et al., 2014). The new 10% leaf mix was considered the baseline and was used to assess how the new mixes performed. Once the old media was removed, the mesocosms were cleaned with phosphate free soap and rinsed with ultrapure water (Milli-Q, 18.2 MΩ·cm). All mesocosms were seeded and the mesocosms containing new media mixes were covered in plastic to prevent contamination from rainwater. Mesocosms were watered twice weekly with 1 L of Mississippi River water until experiments began.

To prepare for the events, a ~2080 Liter (550-gallon) storage tank was cleaned and scrubbed with phosphorus free soap and rinsed with River water. The tank was filled with approximately 946 Liters (250 gallons) of River water extracted with a hose and pump. During the filling process, three 50 mL samples of the River water were collected and placed in the freezer. Based on previously measured background soluble reactive phosphorus (SRP) concentration in the River water, K_2PO_4 (99.9%, J.T Baker) was added to the tank when it was approximately halfway full to achieve a target SRP concentration of 300 µg/L. Previous studies in the Twin Cities have shown average dissolved P concentrations in stormwater to be 200 µg/L and 90 µg/L (Brezonik & Stadelmann, 2002,; Janke et al. 2017, respectively). We used an elevated target concentration to increase the difference between the influent and the level of detection (10 µg/L). A kayak paddle was used to fully mix and dissolve the K_2PO_4, and then the lid was placed on the tank and it was allowed to equilibrate overnight.

In Y1, thirty scales (ACCUTECK- All-in-1 series W-820) were placed below and in front of the mesocosms on concrete tiles. Each scale was set to kilograms and tared. A wooden brace was placed on top of the scale to level and stabilize the collection buckets. The effluent buckets with their lids were placed on the scales and the black tubing from each mesocosm bulkhead was inserted into the hole within the lid. Y2 and Y3 followed a similar methodology to Y1 but load cells were installed and data were continuously recorded using a Raspberry Pi® system. This replaced the use of the scales in measuring the weight of buckets to calculate the filtration rate.

To simulate the runoff events, the influent '5-gallon' buckets were hung ~33 cm (13 inches) above the mesocosms and effluent buckets were hung below the mesocosms (Y2 and Y3, Fig. 3). Influent buckets were filled to the edge of the buckets with water pulled from the tank using a sump pump and hose system. Each mesocosm received 20.4L +/- 0.2L of the phosphorus-enhanced River water. Plastic boards were placed on top of the mesocosms and behind the mesocosms while the influent buckets were filled to prevent any water that was spilled during the filling process from entering the mesocosms. Each influent bucket was fitted with a ~28 cm (11 inch) length of black vinyl tubing (1.6 cm, 5/8 inch inner diameter) and an inline valve about ~10 cm (4 inches) from the end of the tubing. Tubing from the influent buckets were carefully placed into the PVC pipe within the dissipaters in each mesocosm. Three samples were collected while filling buckets, one at the start, one at the middle and one at the end of filling. The temperature of the tank was recorded after all the buckets were filled.

Figure 3: Photo of experiment set up

Valves were opened consecutively, the first valve to be opened was randomly selected. Once the water had drained from the influent buckets freely, the buckets were manually tipped to ensure all water had been drained completely. In Y1, effluent mass recording began as soon as possible after the valves had been opened. An example of the inflow and outflow characteristics from Y2 is shown in Fig. 4. For Y1, statistical analysis of the results indicate that filtration rate did not vary significantly between the mixes and that on average 50% of influent volume passed within 5-15 minutes and 80% of volume passed within 20 minutes (data not shown; Erickson et al., 2021).

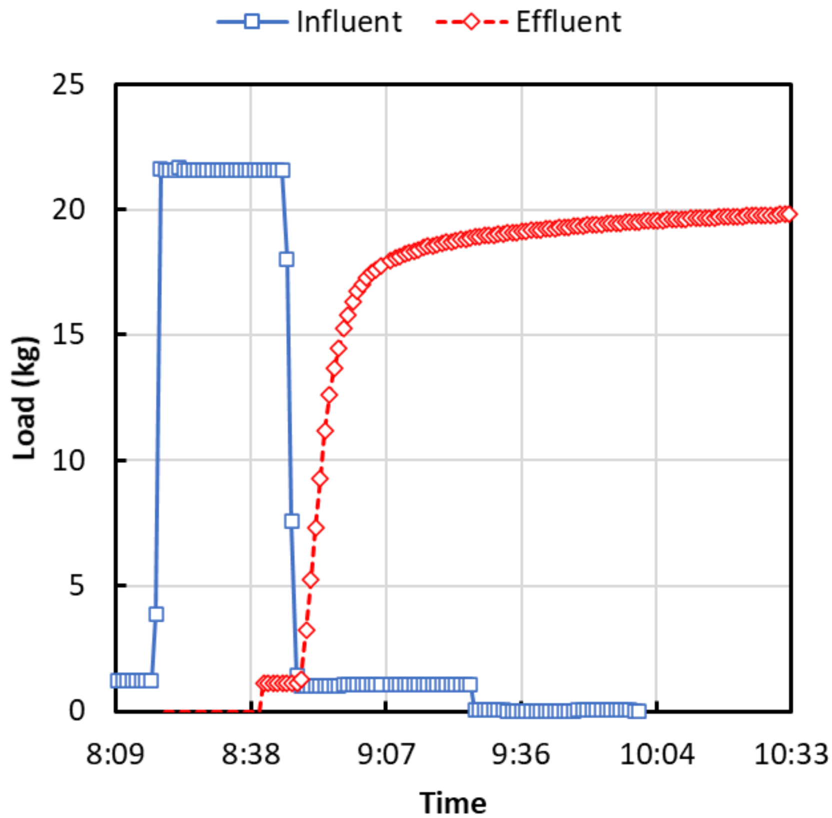

Figure 4: A graph depicting the typical flow characteristics of the mixes. The blue line represents the bucket being filled, the influent volume when full, and the quick decrease when the valve was opened. The red line represents the effluent bucket being filled over time.

The mesocosms were allowed to collect effluent for two hours and then triplicate 50 mL samples in new plastic tubes were collected from the effluent buckets. Water was collected, swirled and dumped three times before saving the final sample. The temperature of each effluent bucket was recorded. In Y3, pH and conductivity were measured in addition to temperature. After conclusion of the experiment, influent buckets were rinsed with River water, effluent buckets were washed with phosphorus free soap, rinsed with ultrapure water (Milli-Q, 18.2 MΩ·cm) and all buckets were stored on raised platforms and secured with netting until the next event.

2.2. Vegetation Assessment

Photos from above the mesocosms were taken on a weekly basis to document vegetation growth (data not shown). The height of switchgrass in each mesocosm was recorded every other week. Above ground biomass was collected at the end of each experiment season, and biomass samples were dried in an oven and weighed.

2.3. Sample Handling and Analysis Methods

During Y1, influent and effluent samples were frozen after they were collected. To prepare for analysis, they were either allowed to thaw at room temperature for approximately 12 hours or allowed to thaw in the refrigerator at 5°C for 48-72 hours. The samples were then centrifuged for 15 minutes at 2800rpm. Immediately following the centrifuge, the samples were filtered using a 10mL syringe and 0.45-micron filter. The samples were sub-sampled into 3 different 15mL conical tubes; one for phosphate, one for nitrate and one supplemental. The nitrate and supplemental samples were placed back into the freezer. The phosphate samples were then analyzed or stored at 5°C and analyzed within two days. For Y2 and Y3, the samples were centrifuged and filtered immediately following the event. The phosphate samples were then either immediately analyzed or stored at 5°C and analyzed within two days.

Phosphate concentrations were analyzed using flow injection analysis by a Lachat Instrument (Milwaukee, Wisconsin) Quick-chem model 8000, method 10-115-01-1 with a statistically determined detection limit of 5 µg P/L. Prepared phosphorus standards were used to calibrate the Lachat before analysis ranging from 0-1500 µg P/L. Check standards were run every 15 samples using the calibration standards. Analytical duplicates were run every 10 samples for quality assurance and quality control. After every check standard and every analytical duplicate, the instrument was flushed with Disodium ethylenediaminetetraacetic acid (EDTA) and ultrapure water (Milli-Q, 18.2 MΩ·cm). Calibration curves and measured concentrations were recorded digitally from the Lachat software and exported into Excel for further QA/QC and statistical analysis. A subset of effluent samples was tested for Nitrate (nitrate+nitrite, mg/L) concentration using the cadmium reduction method (Events 5,7,9 and 13 of 14 total events were sampled in Y1; events 2,4,6 and 8 of 8 total events were sampled in Y2; and events 1,3,5 and 7 of 12 total events were sampled in Y3). Media characteristics (for Y3 only) and nitrate analysis was performed by the Research Analytical Laboratory on the St. Paul campus of UMN (https://ral.cfans.umn.edu/). Media characteristic analysis included Mehlich-III P, Bray P, Olsen P, LOI, extracted nitrate, total nitrogen and total organic carbon (Table A1).

2.4. Data Exclusions and Adjustments

Following a thorough quality assurance/quality control review, some exclusions and adjustments were needed to complete the data analysis. For phosphorus analysis, the tank concentration for event 14 of Y1 was missing and therefore the tank concentration was estimated by taking the average of all other tank values measured during Y1. In Y1, events 1 and 2 were not included in analyses and in Y2 event 7 was excluded due to unreliable concentration measurements from the Lachat (i.e., poor QA/QC results). For nitrate analysis, event one from Y3 was removed from the data set due to measurements that were 2-20 times higher across treatments than measurements from the later events and other years. For vegetation biomass analysis, values less than 0.01g were assumed to be 0.01g (measurement limit of the scale) for mesocosm 8 (sand) in Y2 and Y3 and mesocosm 30 (new sand) in Y3. Mesocosm 1 (20% leaf) showed little vegetation growth and was excluded from analysis for Y1 and Y2. In Y3, mesocosms 14 (10% spent lime/10% leaf), 25 (sphagnum), 27 (10% sphagnum/10% leaf) and 29 (biochar) were removed from analysis due to a loss of vegetation before harvest. Biomass was normalized to 100 growing days by taking the biomass measurement, dividing it by the number of growing days and then multiplying that by 100. For vegetation height analysis, the average maximum height value for each mesocosm for the entire year was used to compile the data set and the data was not transformed. The pH data was not transformed. The phosphate, nitrate and biomass measurements were natural log transformed.

2.5. Statistical Techniques

A linear mixed effects model was conducted to examine the effects of media mix, events and the interaction between media mix and event for nitrate and phosphate data. Three replicate samples were collected from each mesocosm and each media mix (Table 1) had three replicate mesocosms. For each event, the replicate samples from each mesocosm were averaged to determine the average effluent P concentration for that mesocosm. The effluent N concentrations were averaged in the same manner for a subset of events. The tank concentration from all events within a year (e.g., Y1) were averaged to determine the average tank concentration for that year.

The comparison between effluent nitrate and phosphate concentrations to influent concentrations (control) were conducted using a post hoc Dunnett's test with control. The control value was the average tank (i.e., influent) concentration. A post hoc Tukey test was used to examine differences among effluent P and N concentrations for different media mixes. A one-way ANOVA and a post-hoc Tukey's HSD ($\alpha = 0.05$) test was conducted to examine differences between biomass and vegetation height between the media mixes. A multivariate multiple regression analysis of the media characteristic sample analysis, effluent P concentration, effluent N concentration, biomass and vegetation height was performed to reveal relationships between media characteristics, water quality and vegetation data for the new mixes added in Y3.

3. Results and Discussion

3.1. Phosphate in Effluent

The effluent phosphate concentration for Y1, Y2 and Y3 for all media mixes is shown in Fig. 5. The linear mixed effects model revealed the effect of media mix and the interaction between media mix and event were significant for natural log-transformed phosphate data for all years (p-values: <0.05). This revealed that the media mixes performed differently depending on the event. The effect of event was not significant in Y1 (p-value: >0.05) but was significant in Y2 and Y3 (p-values: <0.05). In Y1, event did not influence the phosphate concentrations, but in Y2 and Y3 event did influence the phosphate concentrations.

The tank concentrations for each year are displayed in Fig. 5. as solid black lines. Effluent P concentrations that are statistically higher than the P influent (tank concentration) are considered mixes that released phosphate (post-hoc Dunnett's test). By contrast, effluent P concentrations that are statistically lower than the influent P concentrations are considered treatments that captured phosphate. Sand was not statistically different than the influent in all three years, which indicates sand does not have an impact on phosphate release or capture. In Y1 and Y2, the effluent ln(P) concentrations for 10% leaf, 20% leaf, 10% food, 20% food, biochar mix and 5% spent lime mix were statistically higher than the influent (p-value: <0.05). In Y3, new 10% leaf, 20% leaf, 10% sphagnum (sphag)/10% leaf, 10% spent lime (lime)/10% leaf, biochar mix and 5% spent lime mix were statistically higher than the influent (p-value:<0.05). All of these mixes contained compost and sand. Because sand did not influence phosphate release or capture it, can be hypothesized that compost released phosphate. Adding biochar and 5% spent lime to the mixes with compost reduced but did not prevent phosphate release. In Y1 and Y2, the effluent ln(P) concentration from iron, reed sedge and sphagnum were statistically lower than the influent (p-values: <0.05). In Y3, new sand, sphagnum, and iron layer treatment leachates were statistically lower than the influent (p-values: <0.05). Because iron was mixed or layered with compost and did not release phosphate, we can conclude that iron mitigated phosphate release from the compost within the mix. Replacing compost with reed sedge peat and sphagnum peat and using it as a base showed a capture of phosphate and therefore peat functioned as an amendment rather than a substitute for organic material.

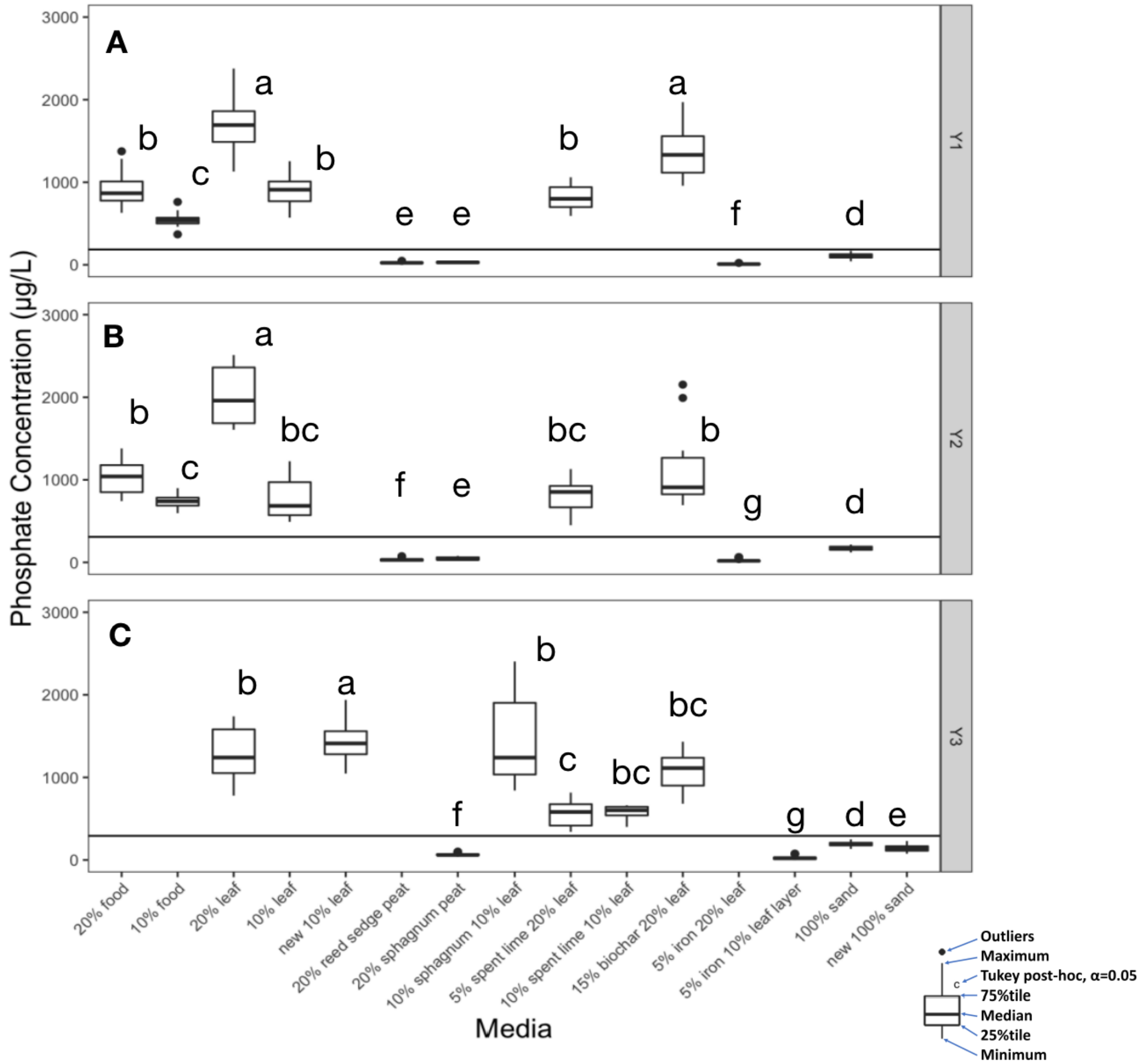

Figure 5: Effluent phosphate concentration for each media mix for Y1 (A), Y2 (B), and Y3 (C). Black lines across all media mixes depict the influent (tank) concentration for each year. Refer to data exclusions and adjustment section for omitted or adjusted data. Mixes with the same lowercase letter are not significantly different (Tukey post-hoc, α=0.05, on Ln(P) data) within each year. Statistical significance was not calculated between years.

The results of the post-hoc Tukey test are shown in Figure 5 with lowercase letters (a, b, c, etc.). In Y1 (Fig. 5A), there was no statistically significant difference in effluent ln(P) concentration between 20% leaf and biochar, and these had the highest P effluent concentration (a). Both of these mixes contained sand and 20% leaf compost, therefore adding 15% biochar mixed with 20% compost did not mitigate phosphate release. The effluent ln(P) concentration for 10% leaf, 20% food and 5% spent lime mix (b) were not statistically different from each other, but were statistically lower than 20% leaf and the biochar mix (a). Decreasing the amount of leaf compost from 20% to 10% within the mix decreased the amount of phosphate released. 20% food compost released less phosphate than 20% leaf for these experiments. 5% spent lime mixed with 20% leaf compost resulted in less phosphate release compared to 20% leaf compost, but did not prevent the release of phosphate. 10% food was statistically different from all other mixes (c). Similar to leaf compost, decreasing the food compost in the mix from 20% to 10% reduced the amount of phosphate released. Sand was statistically different from all other mixes (d). As previously stated, ln(P) from sand was not statistically different from the influent. Thus, adding compost or amendments to sand significantly affects the release or capture of phosphate. There was no statistically significant difference between reed sedge and sphagnum peat (e). Both peat mixes function in capturing phosphate. Iron (f) was statistically different than all other mixes and had the lowest P concentration. Iron was different than all other mixes containing compost and therefore mitigated phosphate release.

The trends observed in Y1 revealed that a decrease in compost (20% to 10%) resulted in a decrease in phosphate concentration; adding biochar did not affect phosphate release while adding 5% spent lime did affect phosphate release; the peat mixes were different from the compost mixes and the iron mix was different than all other mixes. Similar trends were observed in Y2 with some minor differences. In Y2 (Fig. 5B), 20% leaf (a) was statistically different than all other mixes and had the highest effluent concentration. The biochar mix (b) and 20% food (b) were statistically different than 10% food (c). As seen in Y1, reducing both food residue and leaf compost from 20% to 10% resulted in a statistically significant reduction in phosphate release. Iron had the lowest P effluent concentration.

In Y3 (Fig. 5C), within the original mixes, there was no statistically significant difference between 20% leaf (b) and the biochar mix (bc) which was also observed in Y1. There was no statistically significant difference between the biochar mix (bc) and the 5% spent lime mix (c). This supports the findings that the biochar and 5% spent lime mixes do not completely mitigate phosphate release. Sand (d) and Sphagnum (f) were statistically different than all other mixes which is consistent with previous findings.

Pertaining to the new mixes in Y3, new 10% leaf (a) served as the baseline media mix and was different than all other mixes. There was no statistical difference between the 10% lime/10% leaf (bc) and 10% sphagnum/10% leaf (b). While mixing 10% lime or 10% sphagnum with compost resulted in reduced phosphate release compared to 10% compost alone, there was still net export of phosphate from these mixes (effluent>influent). The new sand mix (e) performed similar to the original sand (d) mix, which is expected and confirms that the sand source material was consistent between the original and new mixes, with respect to phosphate. The new iron layer (g), and new sand (e) were statistically different than all other mixes and the iron layer had the lowest P concentration. The iron layered mix reinforced our previous findings that iron can mitigate phosphate release from compost.

3.2. Nitrate in Effluent

The effluent nitrate concentration for Y1, Y2 and Y3 for all media mixes is shown in Fig. 6. The linear mixed effects model revealed the effect of media mix and the effect of event were significant for natural log-transformed nitrate data for all years (p-values: <0.05). In Y1 and Y3 the interaction between media mix and event were significant (p-values: <0.05), but it was not significant in Y2 (p-value: >0.05). Thus, media mix and event were both important factors in nitrate performance for all years.

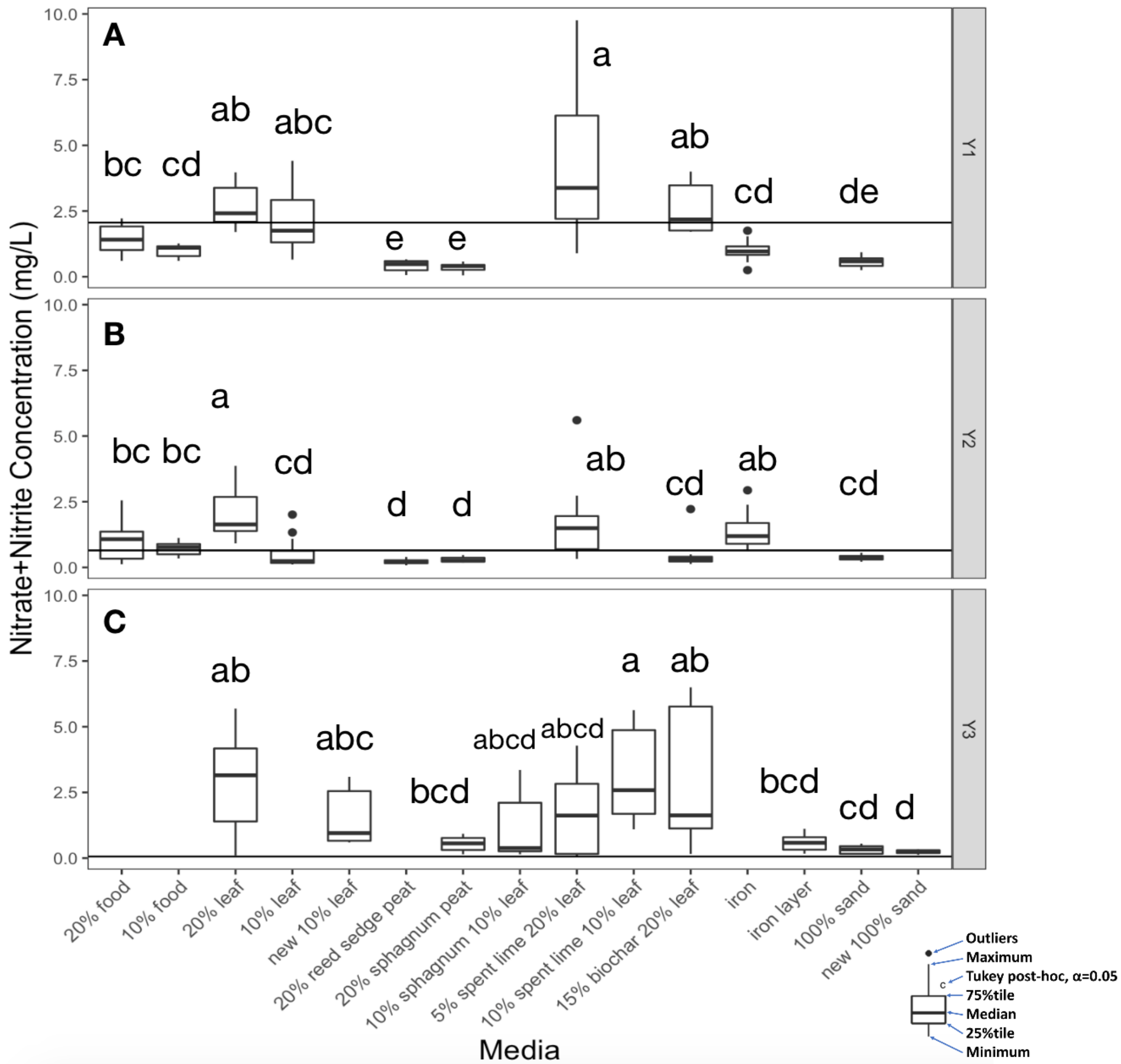

Figure 6: Nitrate concentration, mg/L for each media mix separated by Y1 (A) Y2 (B) and Y3 (C). Black lines depict the influent (tank) concentration for each year. Refer to data exclusions and adjustment section for omitted or adjusted data. Mixes with the same letter are not significantly different (Tukey post-hoc, α=0.05).

The tank N concentration for each year are displayed in Fig. 6. as solid black lines. The post-hoc Dunnett's test revealed that the effluent ln(N) concentration from sand was not statistically different from the influent ln(N) tank concentration in Y1 and Y2 (p-value >0.05) and thus did not influence the release or capture of nitrate, which is expected and similar to the phosphate results. In Y1, 10% leaf, 20% food, 20% leaf, the biochar mix and 5% spent lime mix ln(N) concentrations were significantly higher than the influent ln(N) concentration. Thus, nitrate was released from all mixes containing compost in Y1, with the exception of 10% food and 5% iron. In Y2, 20% leaf released nitrate and was the only mix that differed significantly from the influent. This suggests the nitrate within the 20% leaf mix was mobilized and this mix may have had more nitrate present. In Y1 and Y2, iron, sphagnum peat and reed sedge peat were not statistically different than the influent, and thus did not release or capture nitrate. This may be a reflection of a lower nitrate presence within the peat media. In Y3 (Fig. 6C), all mixes were significantly higher than the influent because the influent concentration from Y3 was 4.3 times lower than Y1 and 2.6 lower than Y2. The low influent nitrate concentration in Y3 may have been a result of nitrate transformation occurring within the 24 hours prior to the experiment within our supply tank that were not measured or characterized.

The results of the post-hoc Tukey test are shown in Fig. 6 with lowercase letters (a, b, c, etc.). In Y1 (Fig. 6A), there was no statistical difference between the effluent ln(N) concentration from 5% spent lime mix, 20% leaf mix, biochar mix and 10% leaf mix. The 5% spent lime mix had the highest N effluent concentration (a). These mixes contained sand and 20% leaf compost. Sand has no influence over the release or capture of N, therefore suggesting 20% leaf compost is likely the source of released nitrate. The 5% spent lime mix and biochar mix did not mitigate the release of nitrate when used as an amendment because they were not statistically different than 20% leaf compost alone. There were not many statistically significant differences among the media that contained compost, thus suggesting that compost contributes to the release of nitrate and was not mitigated by the amendments. There was no statistical difference between 10% food, iron and sand (d). This suggests iron did not function as well as mitigating N release as it did in mitigating P release. There was no statistical difference between sand, reed sedge and sphagnum and sphagnum had the lowest N concentration (e). Reed sedge and sphagnum were not different from sand because they may have had a lower presence of nitrate.

The trends in Y1 revealed little difference in how mixes containing compost performed (released nitrate). Sand, reed sedge peat and sphagnum peat did not influence the release or capture of nitrate. Similar trends applied to Y2 with some differences (Fig.

6B). The effluent ln(N) concentration from 20% leaf (a) was statistically different than 10% leaf (cd) and there was no statistical difference between 20% food, 10% food, sand, 10% leaf and the biochar mix (c). This revealed that lowering the percent of food compost from 20% to 10% did not affect the amount of nitrate released. Lowering the leaf compost from 20% to 10% did reduce the amount of nitrate released. There was no statistical difference between sand, 10% leaf, the biochar mix, sphagnum and reed sedge and reed sedge had the lowest N effluent concentration (d). In Y2, biochar and 10% leaf performed similar to sand and therefore had little influence over the capture or release of nitrate perhaps because the nitrate within the media had been taken up by vegetation in Y1 or had undergone bacterial denitrification.

In Y3 (Fig. 6C), within the old mixes similar trends suggested that mixes containing compost release nitrate and that sphagnum has no influence over the capture or release of nitrate. Within the new mixes, there were few differences between the mixes containing compost. These trends are similar to the old mixes containing compost and reveal that the new mixes containing compost performed similar to the old mixes in releasing nitrate. The iron layer and the 10% sphagnum/ 10% leaf mixes did not differ from the new sand and the new sand had the lowest N effluent concentrations. Similar to previous findings, iron and sphagnum did not influence the capture or release of nitrate and the iron layered mix and the sphagnum compost blend did not have an influence on the nitrate results.

3.3. Vegetation Biomass

The ANOVA revealed the effect of media mix was significant for natural log-transformed vegetation biomass for all three years (p-value= <0.05). This implies the media mix determined the biomass measurements for all years. The results of the post-hoc Tukey test are shown in Fig. 7 with lowercase letters (a, b, c, etc.). Similar trends in significant differences were observed in all years. In Y1 (Fig. 7A), 5% spent lime (a) was significantly different than sand (b) and iron (b). In Y2 (Fig. 7B), biochar (a) was significantly different than sand (b) and sphagnum peat (b). In Y3 (Fig. 7C), biochar (a) was significantly different than sand (c). Because 5% spent lime and biochar revealed a release of both nitrate and phosphate, we may hypothesize that this mix may have contained more bioavailable nutrients and therefore supported more plant growth. The

Ln(biomass) in the new mixes containing compost were not statistically different from one another. While there was little statistical difference in supporting plant biomass between mixes that contained compost and those that did not, biomass ranges from 0.01 grams to over 40 grams. Thus, there were observable, visible differences in the growth of the plants within the mesocosms for all years and all mixes.

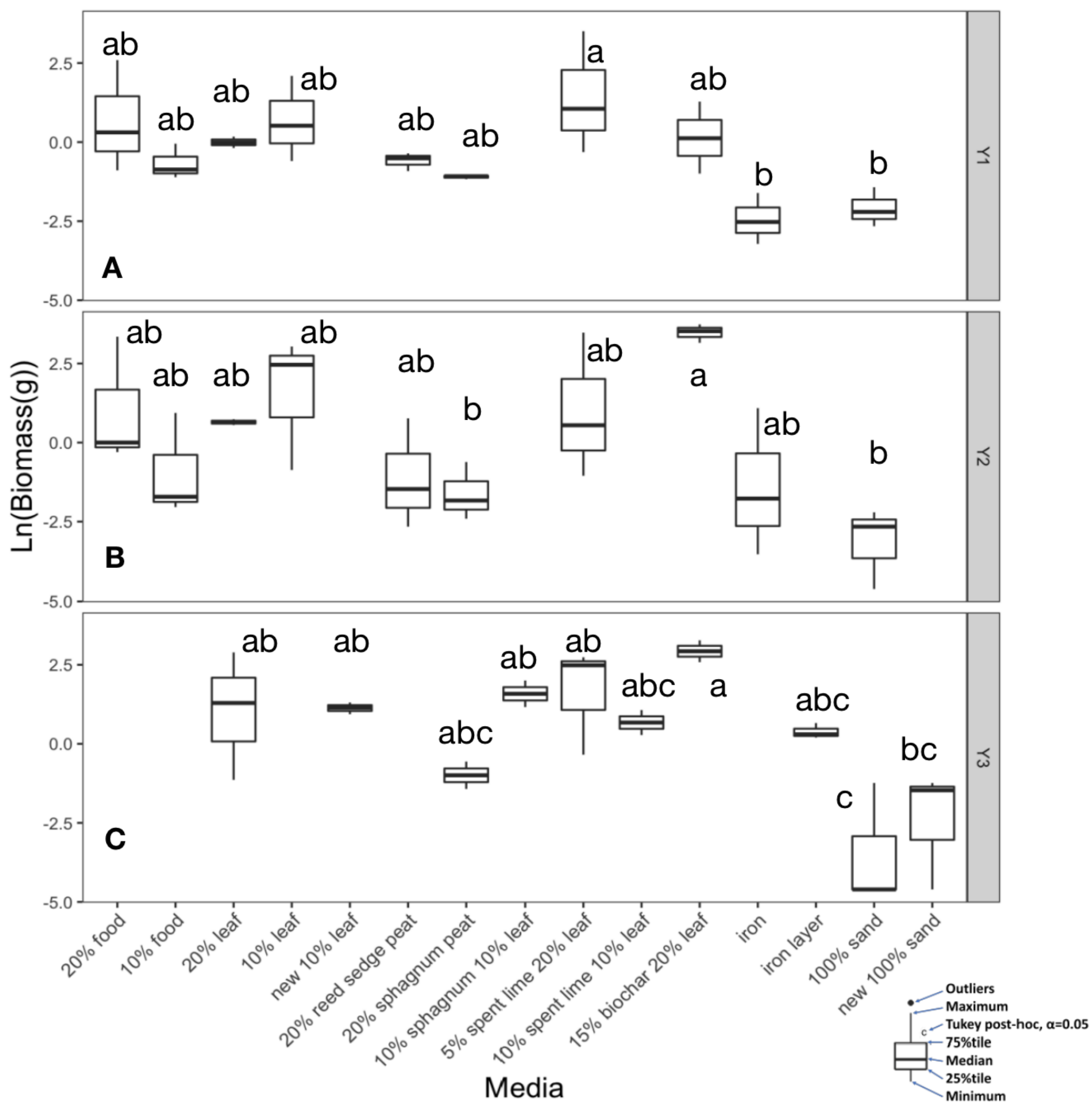

Figure 7: (Ln)Biomass (g) for each media mix separated by Y1 (A) Y2 (B) and Y3 (C). Refer to data exclusions and adjustment section for omitted or adjusted data. Mixes with the same letter are not significantly different (Tukey post-hoc, α=0.05).

3.4. Vegetation Height

The ANOVA revealed the effect of media mix for Y1 was not significant for maximum vegetation height (p-value >0.05), but it was significant for Y2 and Y3 (p-values <0.05). In Y1 the media mix did not influence the height of the switchgrass. In Y2 and Y3 the media mixes did determine the height of the switchgrass. Y2 and Y3 may have resulted in this significant relationship to media mix while Y1 did not because of a potential seed bank from Y1. In Y1 there were visually observable differences in plant heights. Taller plants may have reached maturity and may have produced more seeds, creating a seed bank that may have contributed to more taller plants in Y2 and Y3.

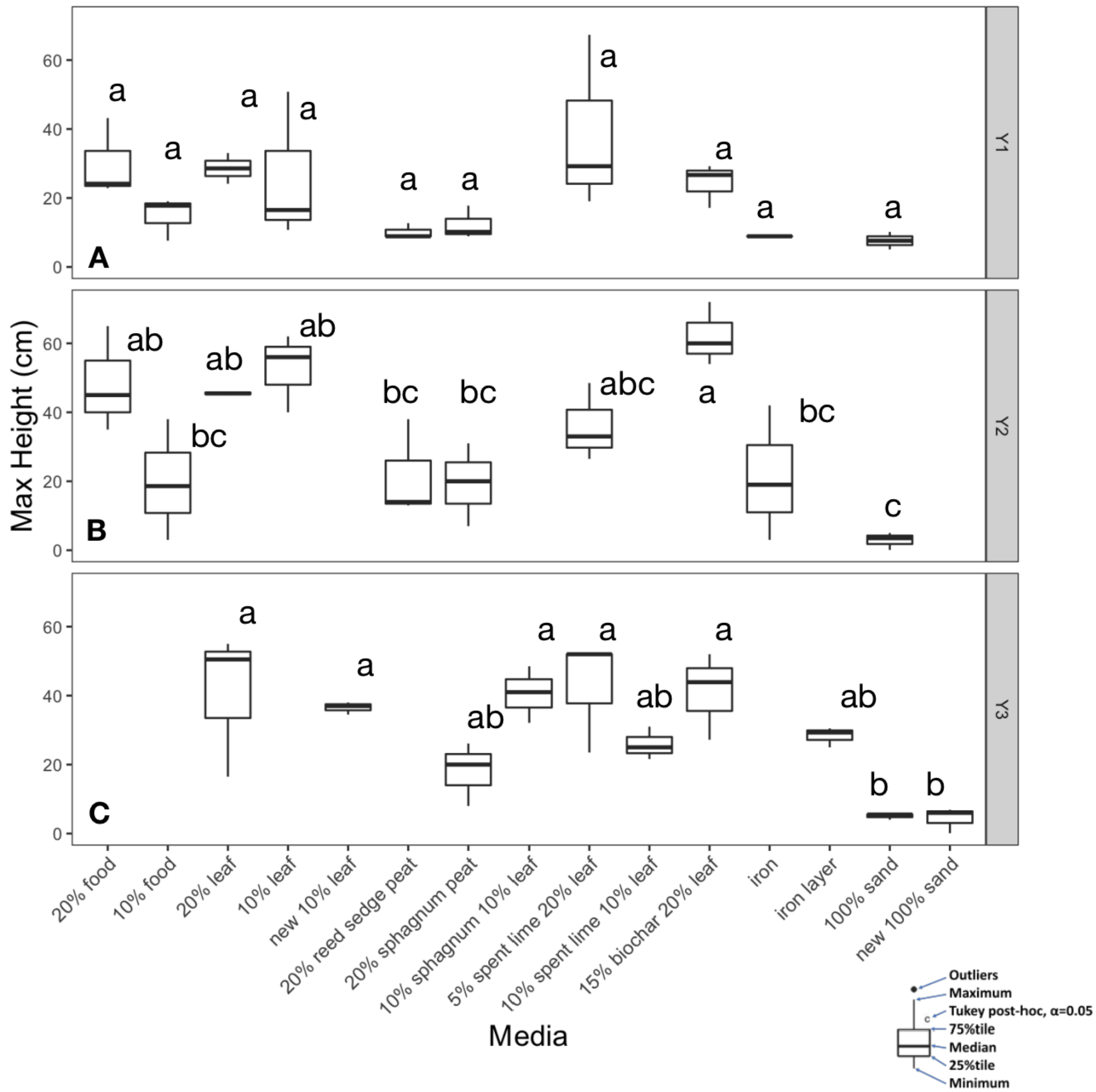

Figure 8: Vegetation maximum height (cm) for each media mix separated by Y1 (A) Y2 (B) and Y3 (C). Note: Mesocosm 1 (20% leaf) was excluded from analysis because it did not have any growth in years one and two. Mixes with the same letter are not significantly different (Tukey post-hoc, α=0.05).

The post-hoc Tukey test results are shown in Fig. 8 with lowercase letters (a, b, c, etc.). In Y1 (Fig. 8A), there were no significant differences between the mixes and vegetation height, confirming the results from the ANOVA test. Similar to the biomass results, there was little statistical difference in maximum plant height between mixes that contained compost and those that did not. Plant height ranged from 0.1 cm to over 60 cm and there were observable, visible differences in the growth of the plants within the mesocosms for all years and all mixes.

In Y2 (Fig. 8B), the biochar mix (a) was significantly different than sand (c). Similar to the biomass results, it may be hypothesized that because the biochar mix released more nitrate and phosphate overall, the mix may have contained more bioavailable nutrients. In Y3 (Fig.8C), 20% leaf, new 10% leaf, the 5% spent lime mix, 10% sphagnum/10% leaf and the biochar mix (a) were significantly different than 100% sand and 100% new sand (b). These differences suggest that these mixes may have had more nutrients present in the pore water within the media. This excess of nutrients would have been available for plant uptake thus resulting in more growth of vegetation. Similar to previous trends regarding biomass, the new mixes containing compost were not statistically different from one another.

3.5 Nutrient, Biomass, pH and Media Characteristics Observations

Fig. 9 depicts the biomass (g) plotted as a function of P concentration (top) and N concentration (bottom). The data were observed and segments were created for low P (<400 □g/L), mid P (400-1500 □g/L), high P (>1500 □g/L) based on visual breakpoints in the data. The iron, iron layer, reed sedge, sphagnum, sand and new sand media mixes had low effluent P concentrations and less than 5g of biomass as shown in section I of Fig. 9A and illustrated in Fig. 10A. The mid-range P concentrations (~400 µg/L-1500 µg/L) corresponded to lower biomass measurements (< 5g; e.g., Fig.10B) and higher biomass measurements (> 5g, e.g., Fig.10C) as shown in section II of Fig. 9A. Above 1500 µg/L, only low biomass measurements were observed (< 5g, e.g., Fig.10D) as shown in section III of Figure 9A. Ding et al. (2021) showed that there is a reduction in vegetation growth and biomass when switchgrass experiences soluble P limitation at 620 µg/L (severe), 1860 µg/L (moderate) and 6200 µg/L (mild), which explains the low biomass growth for P < 400 µg/L in Fig. 9. Other studies have shown that an increase in phosphorus availability (i.e., concentration of phosphorus within the media) increases switchgrass biomass (Kering et al., 2012; Sawyer et al., 2019), but this is not apparent in section III of Figure 9A. where high P concentration > 1500 µg/L results in low biomass.

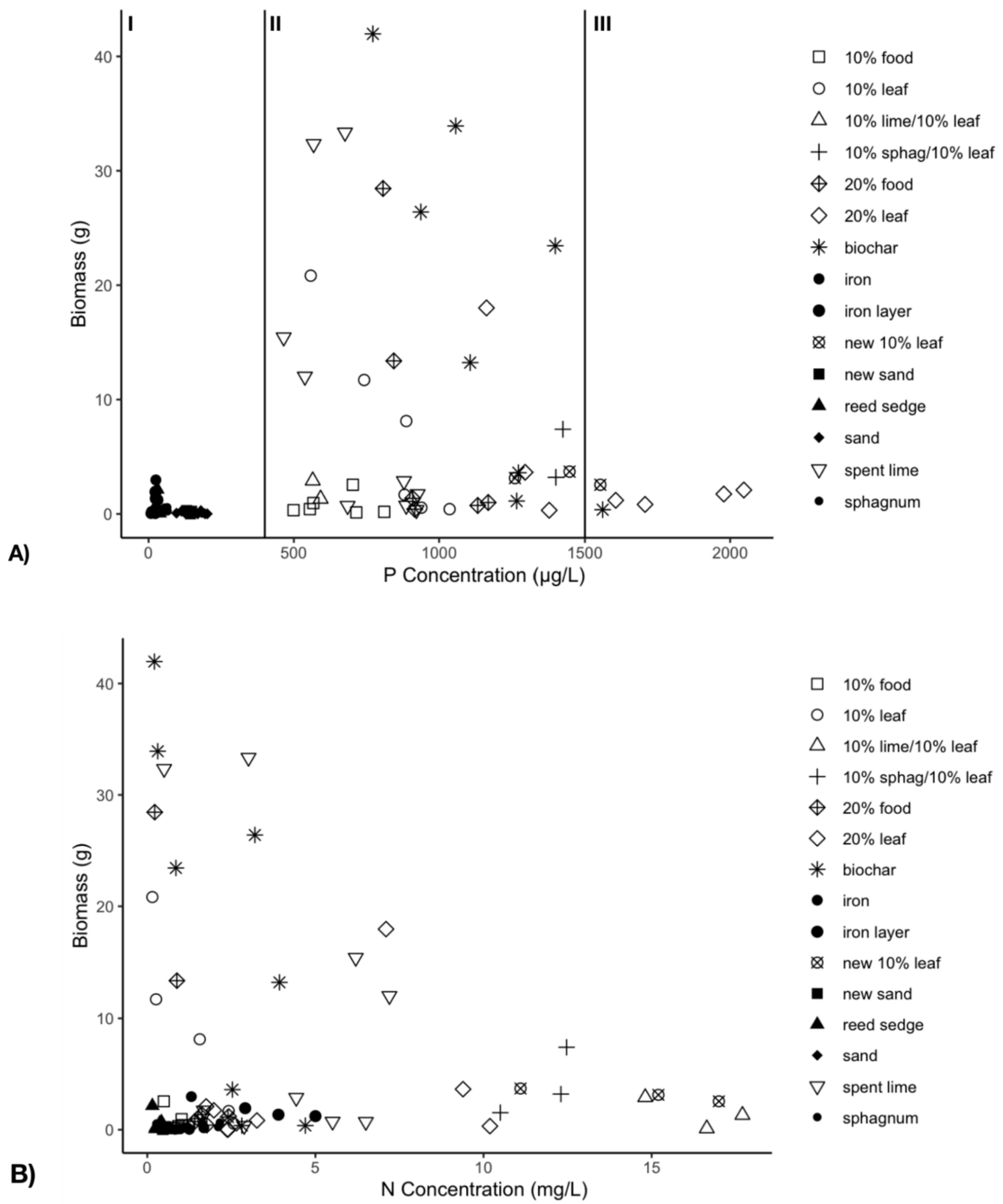

Figure 9: 9A (top) Biomass (g) vs. Effluent P Concentration (µg/L) and Figure 9B (bottom) Biomass (g) vs. N Concentration (mg/L). Media mixes are represented by shapes.

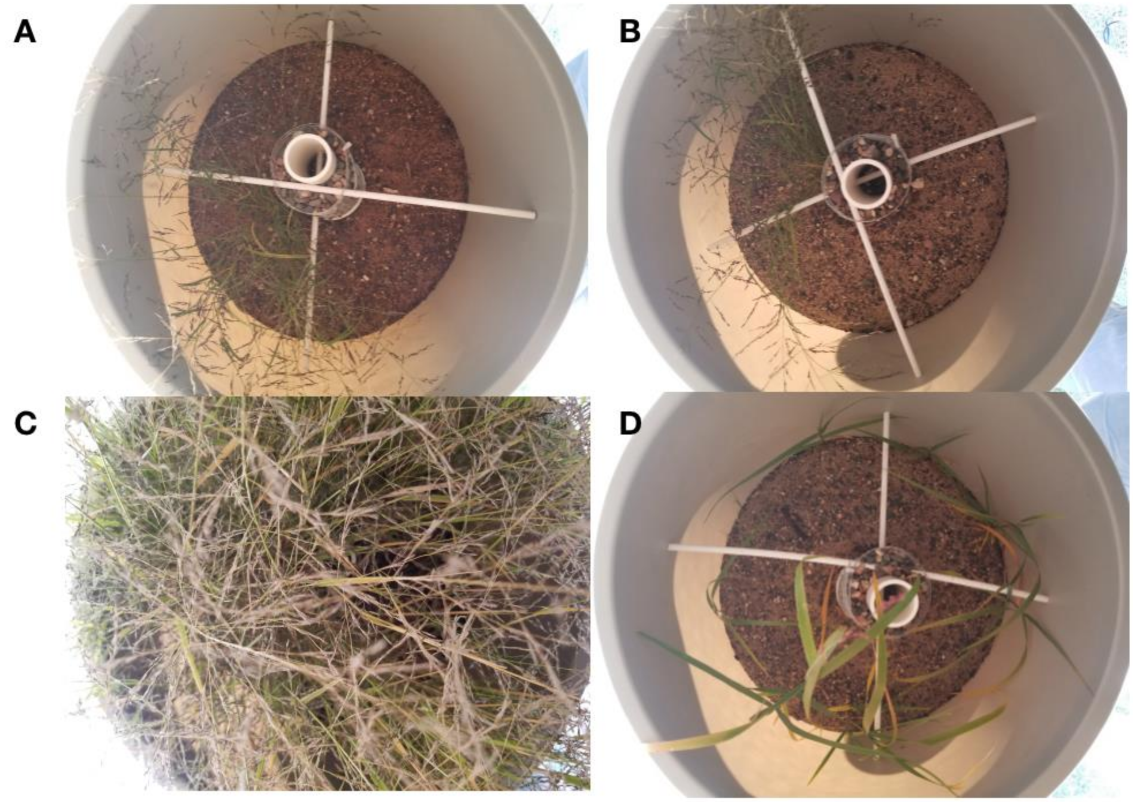

Figure 10: Photos from Y2. 107 days after seeding representing a mesocosm from the following; A is iron reflective of low P and low biomass. B is 10% food reflective of mid-range P and low biomass. C is biochar reflective of mid-range P and high biomass. D is 20% leaf reflective high P and low biomass.

Upon examining Fig. 9B, there was no clear linear relationship between biomass and effluent nitrate concentration. The mixes that had lower effluent nitrate concentrations (<5 mg/L) and lower biomass (<5g) measurements were iron, iron layer, reed sedge, sphagnum, 20% leaf, 10% food and new 10% leaf. Mixes that had low effluent nitrate concentrations but exhibited higher biomass measurements were biochar, 5% spent lime, 20% food and 10% leaf. Previous research has suggested compost increases nitrate retention efficiency and nitrate availability for plant uptake (Oladeji et al., 2020). The contradicting observation is that biochar and 20% food also exhibited low biomass at low nitrate measurements, suggesting nitrate was not bioavailable for plant growth. Because of the variation in vegetation growth, this suggests that nitrate may not have been the limiting nutrient within these mixes.

Media characteristic analysis from samples taken of the newly constructed mesocosm media in Y3 revealed that the new 10% leaf mix and the 10% sphagnum/ 10% leaf mix had initially higher levels of phosphate compared to the new sand and iron layer mixes (Fig. A1-A4, Appendix). These initially higher levels of phosphate may contribute to higher leaching potentials and may help explain why these mixes exported phosphate. The 10% leaf mix showed a lower total carbon measurement than the sphagnum and leaf and the lime and leaf mixes. If the new 10% leaf had high initial levels of phosphorus and lower levels of total carbon, we may be able to assume the 20% leaf mix in Y1 and Y2 had high initial levels of phosphorus and lower levels of carbon as well. Carbon content was not measured in food compost, but it would not be surprising if the food compost had more carbon than leaf compost. 20% leaf may have experienced low biomass measurements due to a carbon limitation or 20% leaf was an anomaly. Although the results were not statistically significant, in Y1 and Y2 10% leaf compost did have numerically higher values in biomass and height compared to 20% leaf compost.

Multivariate analysis (see Table 2.) showed that Bray P was a good predictor for higher effluent P concentrations. Bray P was selected as the main predictor for P because it is listed as the focal test for pH-neutral soils in the Minnesota Stormwater Manual (MPCA, 2021b). If there is higher initial (Bray) P concentration within the media, the mix is more likely to leach P. Bray P demonstrated the strongest linear relationship with effluent P concentration from the mesocosms (Fig. A6-A8).

The media characteristic analysis data show the new 10% leaf and 10%lime/10%leaf initially had 10-20 mg/kg of TN and NO_3 (Fig. A1 and A3). NO_3 and TN are good predictors for effluent N concentration and if there are higher N concentrations within the media initially, the media is more likely to leach N. The Bray P and total nitrate (TN) within the media were both good predictors for plant height. Bray P is a measure of bioavailable P so this is not surprising and these initially higher nutrient concentrations within the media may have contributed to vegetation support (Watson, 2007). The analysis revealed that TC, NO_3, TN were not correlated with effluent P concentration, which is expected because they are not associated with the presence or transport of P.

Table 2: Results of multivariate analysis for new media mixes added in Y3. The predictors are media characteristics, including Bray P content (mg/kg) analysis, total carbon (TC, %C), nitrate (NO_3, mg/kg) and total nitrate (TN, %N). The dependent variables are effluent P concentration (µg/L), effluent N concentration (mg/L), Biomass (In(g)) and Vegetation Height (cm). CI are the confidence intervals and estimates are the regression coefficients.

	EffluentP		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	-181.81	-521.21 – 157.59	0.260
Bray	54.50	35.61 – 73.40	**<0.001**
TC	-222.29	-795.25 – 350.67	0.408
No3	-32.33	-76.99 – 12.33	0.138
TN	1805.95	-1910.05 – 5521.94	0.304
Observations	15		
R^2 / R^2 adjusted	0.910 / 0.874		

	EffluentN		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	-0.76	-1.15 – -0.37	**0.002**
Bray	-0.01	-0.04 – 0.01	0.163
TC	0.86	0.19 – 1.53	**0.016**
No3	0.12	0.07 – 0.17	**<0.001**
TN	-7.19	-11.50 – -2.87	**0.004**
Observations	15		
R^2 / R^2 adjusted	0.938 / 0.914		

	Biomass		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.15	-2.89 – 3.18	0.916
Bray	0.09	-0.08 – 0.26	0.245
TC	-4.22	-9.34 – 0.90	0.096
No3	0.19	-0.21 – 0.59	0.313
TN	-14.95	-48.15 – 18.26	0.340
Observations	15		
R^2 / R^2 adjusted	0.449 / 0.228		

	Height		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	26.19	17.68 – 34.71	**<0.001**
Bray	0.68	0.20 – 1.15	**0.010**
TC	3.51	-10.87 – 17.88	0.599
No3	-0.59	-1.71 – 0.53	0.265
TN	-198.01	-291.26 – -104.77	**0.001**
Observations	15		
R^2 / R^2 adjusted	0.875 / 0.825		

Spent lime was expected to have a higher pH measurement due to its chemical composition of calcium hydroxide. However, the original 5% spent lime effluent pH measurements were not significantly different from the other mixes with the exception of sand and new sand. It is possible that the compost may be more influential in lowering the pH of the effluent than the spent lime. Mixes containing compost had lower effluent pH measurements than the sand with the exception of iron (Fig. A5). This suggests that adding compost lowers the pH of the effluent water. The 10% spent lime 10% leaf blend was not significantly different from sand, new sand or iron and had the fourth highest pH readings. It appears the spent lime has more influence on the pH in this 10% mix compared to the previous 5% mix. The higher pH measurements may explain why this new mix did not support as much plant growth. It is important that media containing WTR is not acidic because calcium phosphate precipitates have weak bonds and P can be re-mobilized at low pH (Shrestha et al., 2019).

4. Conclusions

4.1. Implications for Design

The objective of this study was to determine which mixes would perform best at capturing phosphorus while also supporting the growth of vegetation. It is important to emphasize that compost composition can vary by location and that other studies may have resulted in a lower leaching potential of P according to composition. Biochar, peat, and water treatment residues (WTRs) will likely vary based on source material, generation processes, and other factors. In this study, the mixes that supported the most plant biomass across all years also released phosphorus. The mesocosms with composts were among the best plant-growing media mixes in this study, but also released P concentrations that were 5 or more times larger than the influent concentration. Although the compost mixes supported the growth of switchgrass, the benefits of this vegetative support do not outweigh the costs of the leaching of phosphorus based on high effluent P concentrations as a result of this study.

Biochar in this study supported vegetation but also exhibited P release due to the compost within the mix. Biochar provided minimal benefit as an amendment over all three years. The biochar mix had statistically significantly higher effluent P and N concentrations than the influent for each year. In all years, biochar leached phosphorus and did not perform better than the 20% leaf compost. Additionally, the biochar did not differ significantly from the 20% leaf compost in plant biomass or maximum height for all three seasons. This suggests that the biochar used in this study did not help to limit phosphate and therefore does not offer any benefit as an amendment for P capture. Other studies support the results of this study in discovering that blending biochar with compost did not reduce leaching of N or P (Iqbal et al., 2015). Further research is necessary to determine if biochar sources affect P capture or if results would differ if it was not blended with compost.

This study included a calcium-based spent lime WTR that also exhibited P release, likely due to the compost within the mix. Increasing the spent lime concentration from 5% to 10% and blending it with 10% leaf compost (decreased from 20% compost) did not differ significantly in effluent P concentration from the original 20% leaf/5% spent lime blend in Y3. It is possible that WTRs containing iron or aluminum or another biochar may have resulted in a lower P leaching. 5% Spent lime mix had highest effluent N concentrations in Y1 and Y3 and the 10%leaf/10% lime mix had the highest N effluent measurement overall. Calcium-based water treatment residuals are an attractive amendment because they are a low-cost waste product, but spent lime may not be as effective as other WTR's at mitigating P release from compost.

Sphagnum (20%) and reed/sedge peat were statistically lower in effluent P concentration than the influent for all years and did not differ significantly from one another in P or N concentrations, plant biomass or plant height. Both were effective at capturing phosphorus from the influent when compared to the mixes containing compost for all years. The effluent P concentration of the 10% sphagnum 10% leaf mix was unexpectedly statistically higher than the 10% leaf effluent in Y3. Peat will vary based on the source and it is possible that the new sphagnum peat (Y3) is different than the original peat (Y1-Y3) which could also explain the difference in P captured between these mixes. Although the original peat mixes showed capture of phosphorus, it is unclear whether other sources of peat would perform similarly.

The iron (5%) P effluent was significantly lower than the influent concentration for all years and the P effluent for the iron layer treatment was statistically lower than influent concentration for Y3. Thus, iron was efficient at capturing phosphorus in both a fully mixed design and a layered design. In Y1 and Y2, N concentrations from iron-amended media were higher that the tank suggesting that iron is not as effective at limiting nitrate release. Iron and sand did not differ significantly in supporting vegetation in all years. In Y3, the iron layer did not differ statistically in vegetation height from any of the mixes suggesting it has better potential for supporting plant growth than the 5% iron fully mixed with compost. A performance summary of all media tested is shown below in Table 3.

Table 3: Summary of mixes and their performance regarding P release, N release and the support of vegetation. Nitrate and phosphate boxes are marked with (↑) where nutrient export occurred (compared to influent concentration). Boxes are marked with (↓) where nutrient capture occurred (compared to influent). Nutrient results were based on Dunnett's test results. Plant biomass and height are marked with a (↑) where growth was significantly different from sand and a (—) where mixes did not differ from sand.

	100% Sand	100% New Sand	5% Iron 20% Leaf	5% Iron 10% Leaf Layer	20% Reed Sedge	20% Sphagnum	15% Biochar 20% Leaf	5% Spent Lime 20% Leaf	10% Leaf Compost	New 10% Leaf	20% Leaf	10% Food Compost	20% Food Compost	10% Sphagnum 10% Leaf	10% Spent Lime 10% Leaf
Nitrate (mg/L)	–	–	↑	↑	–	–	↑	↑	↑	↑	↑	↑	↑	↑	↑
Phosphate (µg/L)	↓	↓	↓	↓	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑
Plant Biomass (g)	–	–	–	–	–	–	↑	↑	↑	↑	↑	↑	↑	↑	–
Plant Height (cm)	–	–	–	–	–	–	↑	↑	↑	↑	↑	↑	↑	↑	–

4.2. Main Takeaways

The following conclusions have been drawn based on the results and observations of phosphate, nitrate, vegetation biomass and vegetation height within this study:

- Mixes containing compost released phosphorus with the exception of the mix containing iron. Mixes with compost had higher nitrate effluent concentrations than mixes that did not contain compost. Mixes containing compost should not be considered when designing a biofiltration system with the purpose of mitigating P release unless iron is included in the mix.

- Reed sedge peat and sphagnum peat captured phosphorus from the influent. These mixes had lower nitrate effluent concentrations. Disturbing and degrading peatlands results in a loss of ecological services and releases CO_2 into the atmosphere. Iron mixed or layered with compost should be considered before using peat as an amendment or as replacement for compost.
- Media mixes that released phosphorus supported more plant growth than media mixes that captured phosphorus. Further studies that incorporate plants other than Switchgrass are necessary to determine if there is a species that exhibits more growth in a system that captures phosphorus.
- The iron layer media mix met the objectives of the study in mitigating the release of phosphate and supporting some growth of vegetation but more research is necessary to determine whether or not it will continue to meet the objectives if compost volume is increased or if the volume of stormwater added to the mesocosm is increased.

5. Future Research

Of all the media mixes tested, the layered iron mix may have the most potential in addressing the objectives of the study to find a media that would (1) limit the release of phosphate and (2) support the growth of vegetation. Because the iron layer has a dedicated growth layer, or a layer of potentially nutrient rich compost, there is more potential for an increase in biomass in subsequent years. Further research is necessary to determine if it would continue to meet the objectives with a higher percentage of compost which could potentially provide vegetation with more nutrients and result in more vegetation support. Future research should incorporate other vegetation species to determine if these media mixes could support other species of vegetation and if those species would exhibit higher biomass and height measurements than Switchgrass. This would increase the biodiversity and aesthetic appeal of the designs. Furthermore, other species could potentially increase the uptake of N and P and incorporate it into the above ground biomass.

Media characteristic measurements should be taken when mesocosms are constructed so that variation among mixes can be statistically analyzed and nutrient content can be examined before and after the experiment. This will help determine which mixes have leaching potential based on their initial composition and help determine which nutrients might be limiting the growth of vegetation within the different media mixes. This study showed a strong relationship between nutrient presence within the media and P and N release and vegetation height. The initial simulated stormwater event should be closely monitored for potential flushing of P and N. If levels of P and N are higher in the effluent after this first event, it may be an indication of when an installed biofiltration system should be more closely monitored and if the systems experience a first flush of pollutants after a winter dormancy. A longer study is necessary to test the performance of aged media and this might include treating the media with larger volumes of stormwater to further test media performance. This may also help determine the longevity of the systems.

6. References

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7. Appendix

Table A1. Results from soil sample analysis of Y3 new mixes. Two separate samples were analyzed for the iron layered mix, one of just the iron and the other of just the compost.

Media Mix	Bray (mg/kg soil)	Olsen P (mg/kg soil)	LOI OM (%)	NO_3-N (mg/kg soil)	Total Nitrogen (% N)	Total Carbon (% C)	Total Organic C (% C)	Melich (mg/kg soil)
New Sand	2	1	0.2	0.6625	0.12375	0.2295	0.044	1.977
New Sand	4	1	0.25	0.5875	0.12375	0.352	0.044	2.159
New Sand	2.5	1	0.2	0.4775	0.12375	0.188	0.044	2.004
New 10% Leaf	35	20	0.85	11.715	0.06875	0.9075	0.413	76.668
New 10% Leaf	32.5	15	0.8	12.605	0.03975	0.6525	0.344	43.504
New 10% Leaf	41.5	21.25	0.9	10.4	0.04625	0.785	0.366	71.978
10% lime/10% leaf	27	20	1.2	13.19	0.064	1.0265	0.668	45.869
10% lime/10% leaf	31.25	24	1.275	14.655	0.0695	1.1835	0.569	47.364
10% lime/10% leaf	22	19	1.05	11.57	0.05525	1.3195	0.434	49.426
10% sphag/10% leaf	33.5	17.5	1.7	8.25	0.0595	1.2515	0.831	48.648
10% sphag/10% leaf	35	18	1.55	8.155	0.058	1.117	0.763	63.922
10% sphag/10% leaf	40	16.5	1.7	5.845	0.0725	1.3855	0.717	48.893
Iron Layer	3	1	0.2	0.025	0.0225	0.3035	0.091	1.393
Iron Layer	3	0.75	0.2	0.025	0.0225	0.2295	0.072	1.749
Iron Layer	3	1	0.2	0.025	0.0225	0.325	0.081	1.679
Iron Layer Compost	24	16	0.55	10.78	0.0225	0.61	0.3815	28.603
Iron Layer Compost	25	16	0.6	11.59	0.0225	0.845	0.417	34.710
Iron Layer Compost	41	24	0.55	1.43	0.047	0.672	0.759	58.122

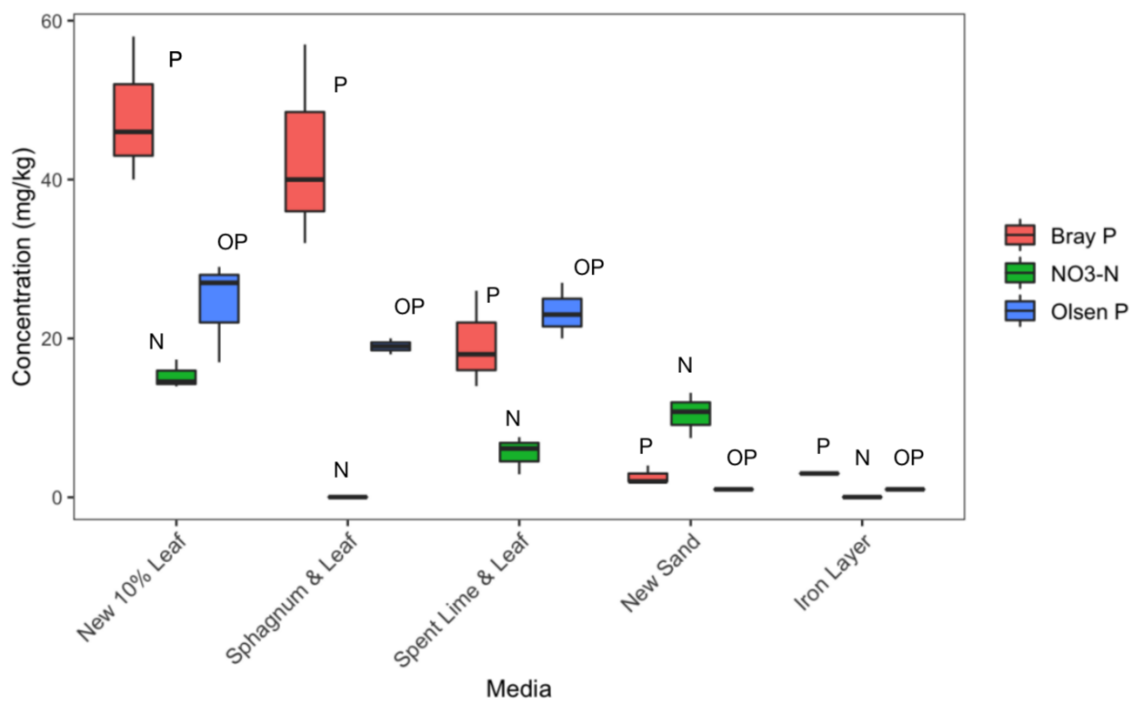

Figure A1. Media sample analysis from the initial sample batch displaying media concentrations from Bray (B) and Olsen (O) tests (phosphorus mg/kg) and NO_3 (N, nitrate mg/kg).

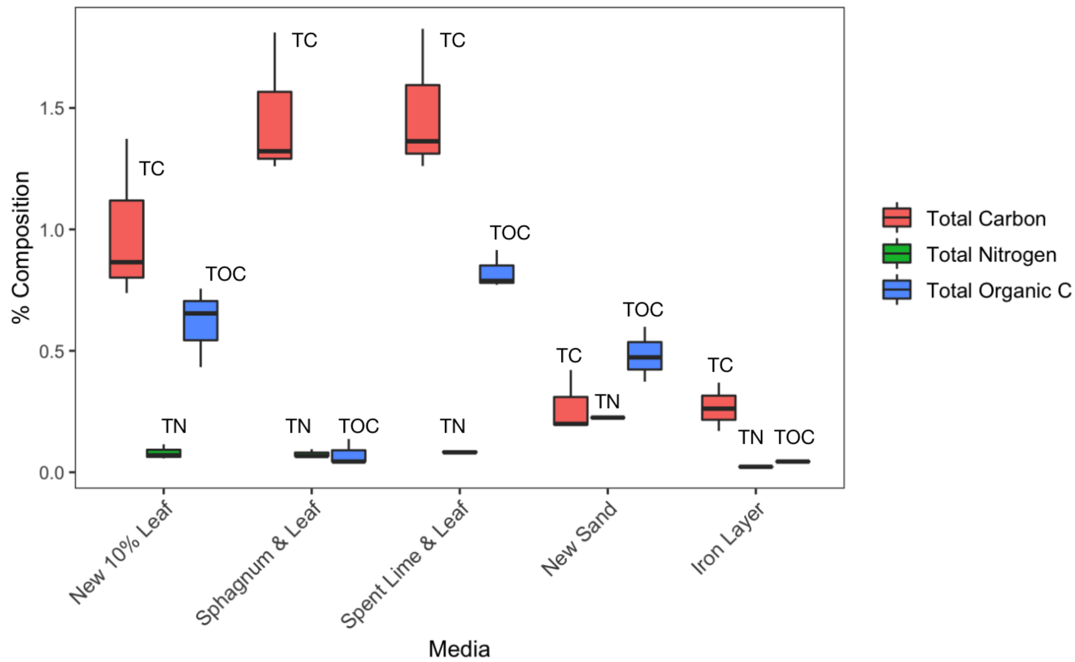

Figure A2. Media sample analysis from the initial sample batch displaying media concentrations for total nitrate (TN), total carbon (TC) and total organic carbon (TOC).

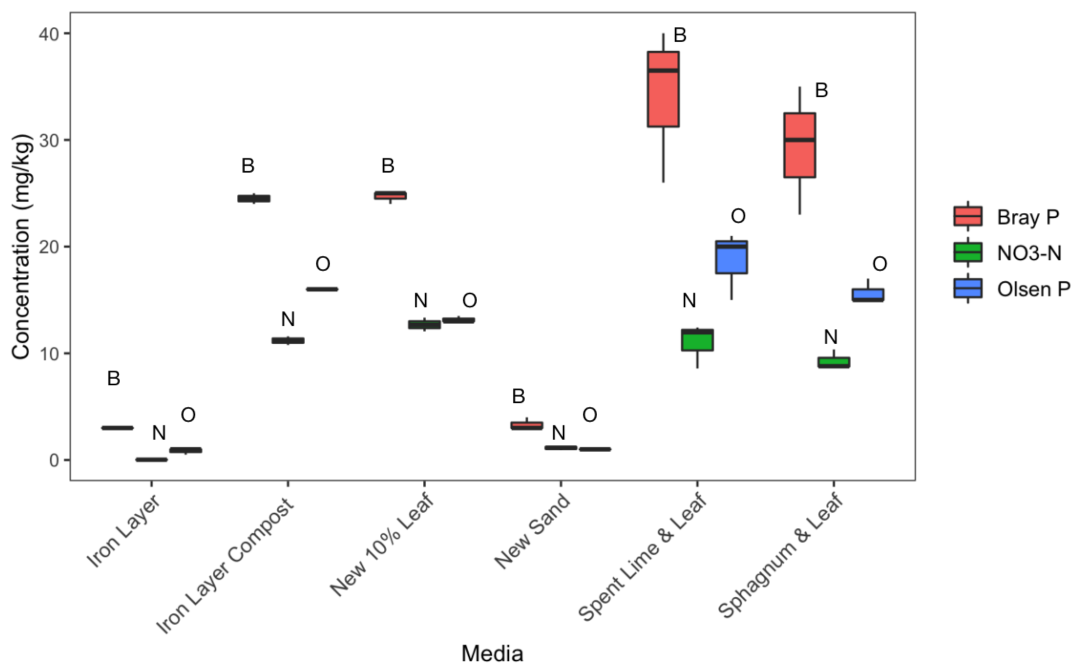

Figure A3. Media sample analysis from the second sample batch displaying media concentrations from Bray (B) and Olsen (O) tests (phosphorus mg/kg) and NO_3 (N, nitrate mg/kg).

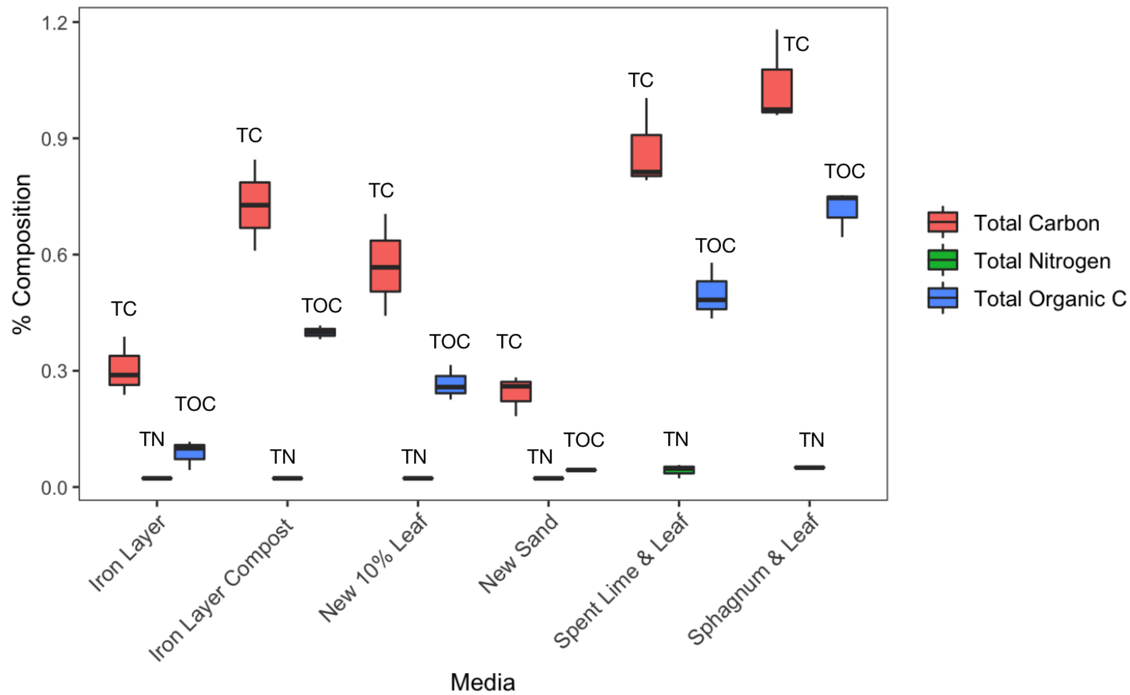

Figure A4. Media sample analysis from the second sample batch displaying media concentrations for total nitrate (TN), total carbon (TC) and total organic carbon (TOC).

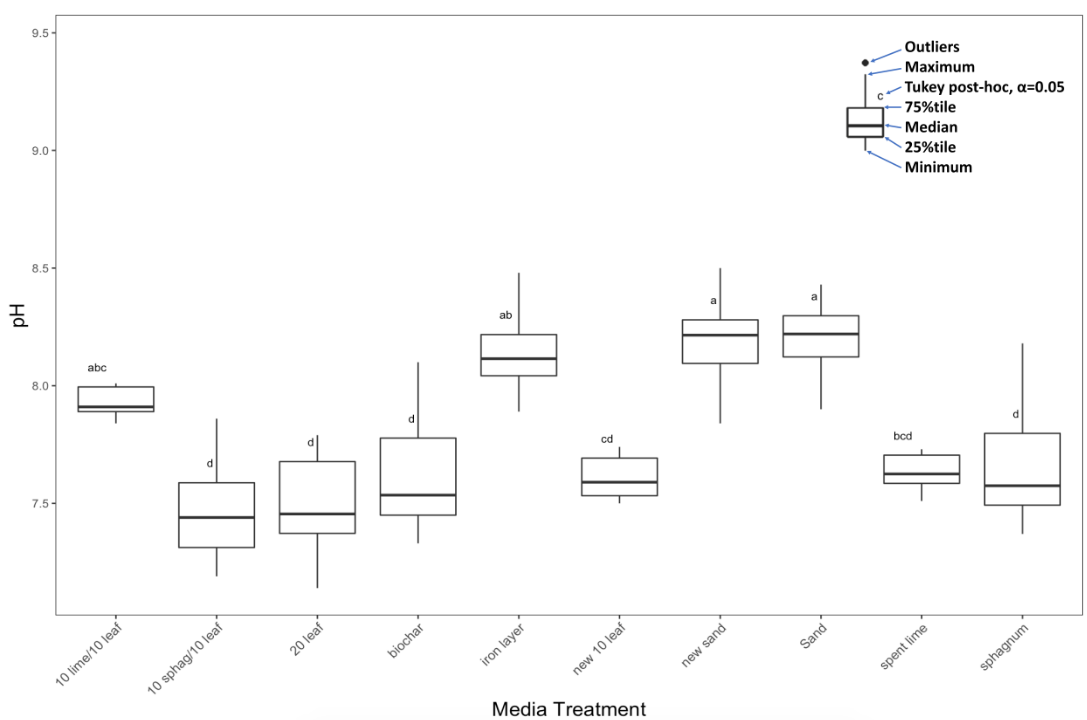

Figure A5. pH for each media mix for* Y3*. Mixes with the same letter are not significantly different (Tukey post-hoc, α=0.05).

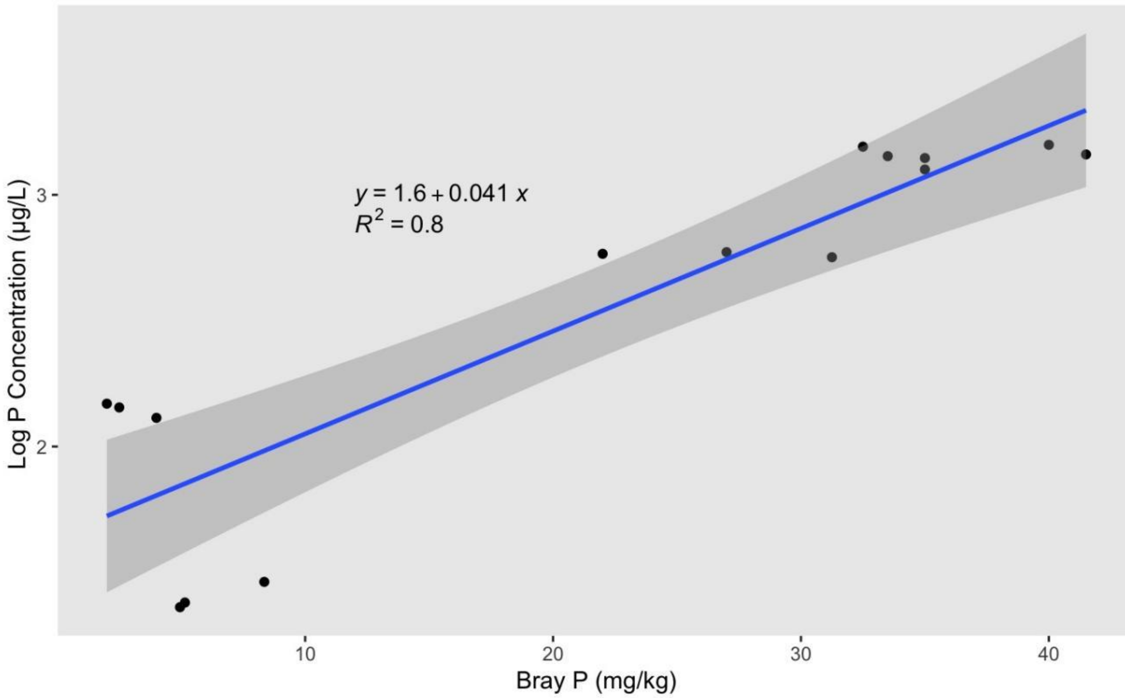

Figure A6. Log P Concentration (µg/L) effluent measurements vs. Bray P (mg/kg) soil measurements for Y3 media mixes. The grey band represents the 95% confidence interval.

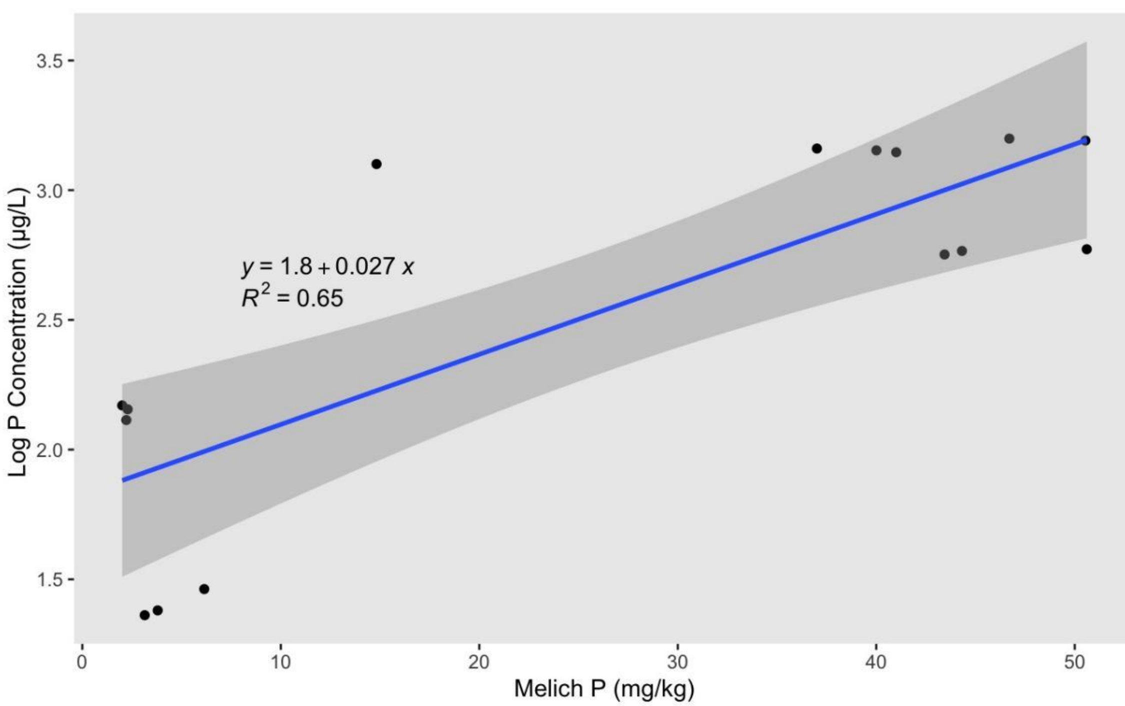

Figure A7. Log P Concentration (µg/L) effluent measurements vs. Mehlich-III P (mg/kg) soil measurements for Y3 media mixes. The grey band represents the 95% confidence interval.

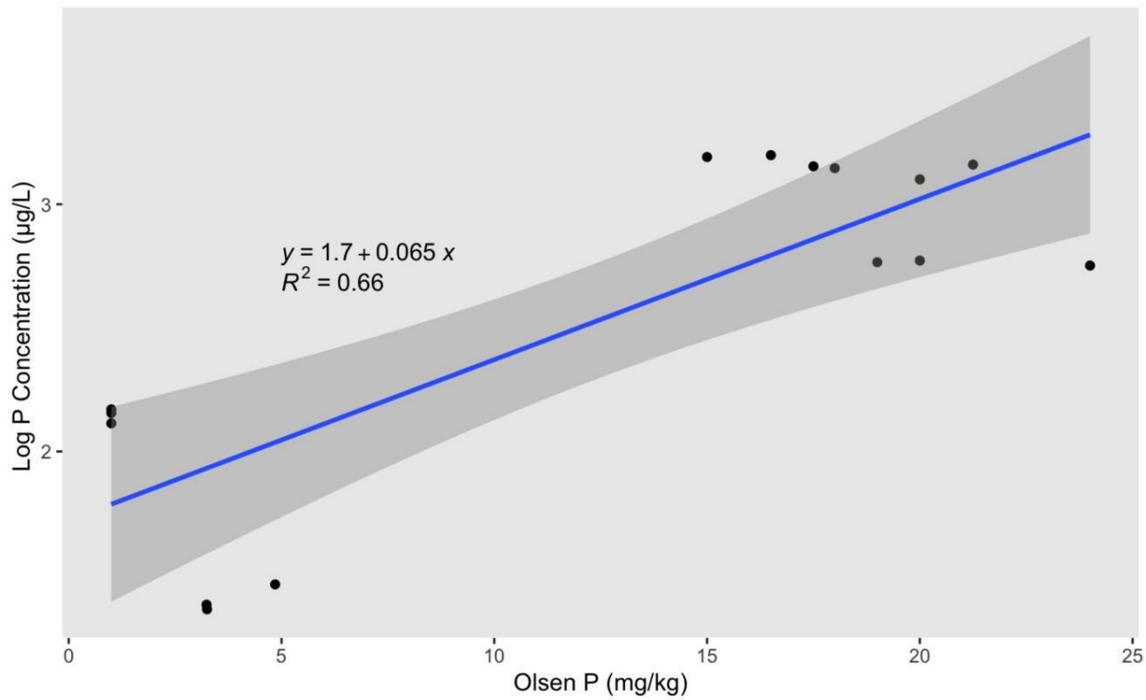

Figure A8. Log P Concentration (µg/L) effluent measurements vs. Olsen P (mg/kg) soil measurements for Y3 media mixes. The grey band represents the 95% confidence interval.

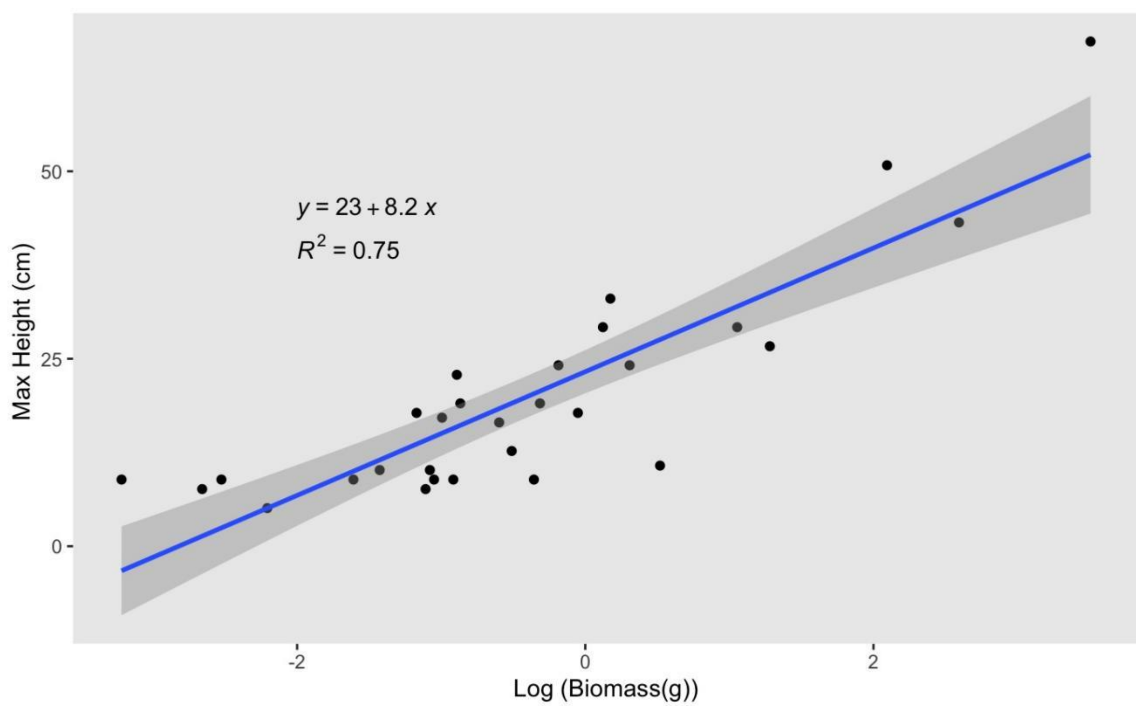

Figure A9. Log Biomass (g) measurements vs. Max Height (cm) measurements for Y1. The grey band represents the 95% confidence interval.

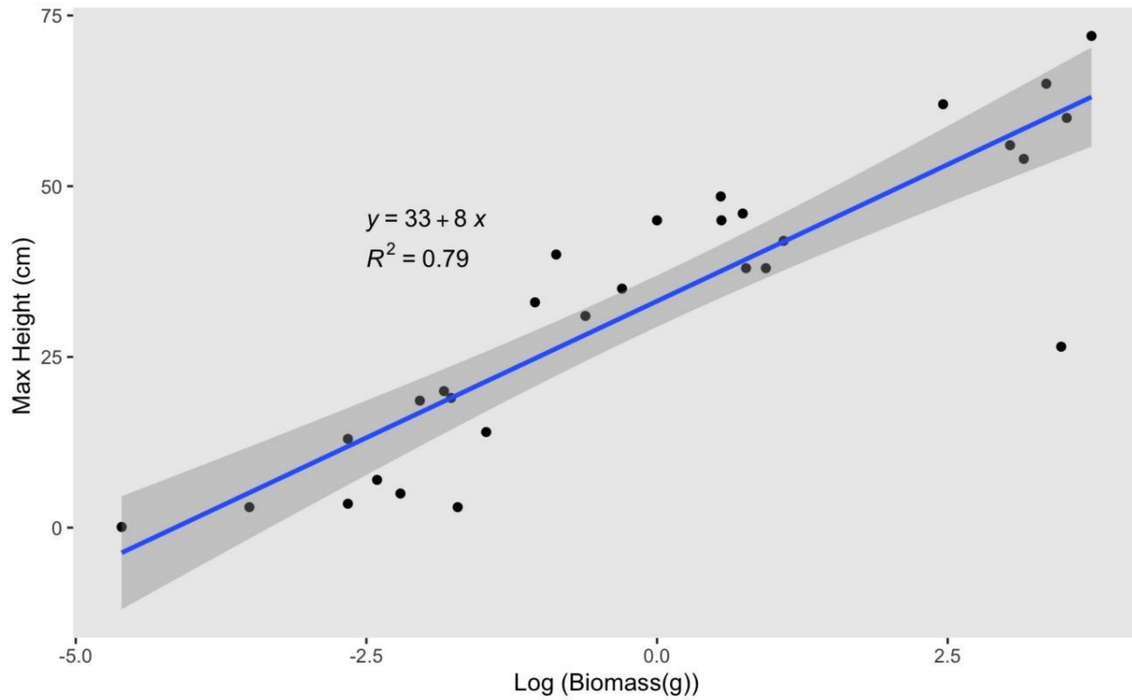

Figure A10. Log Biomass (g) measurements vs. Max Height (cm) measurements for Y2. The grey band represents the 95% confidence interval.

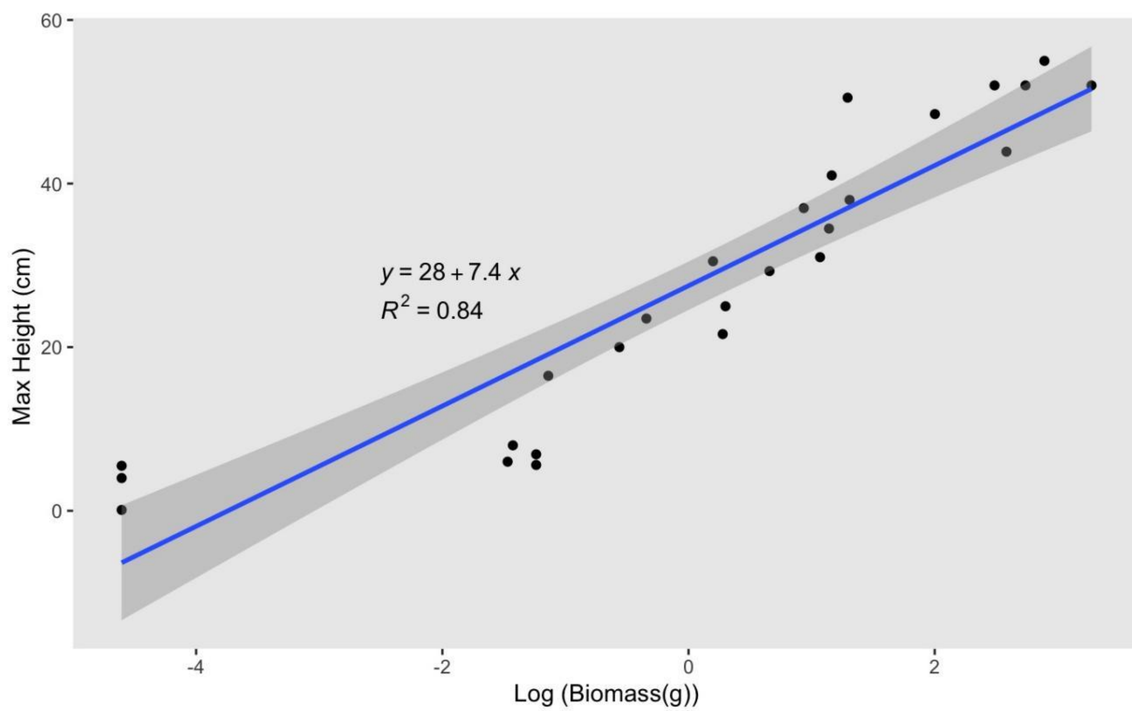

Figure A11. Log Biomass (g) measurements vs. Max Height (cm) measurements for Y3. The grey band represents the 95% confidence interval.

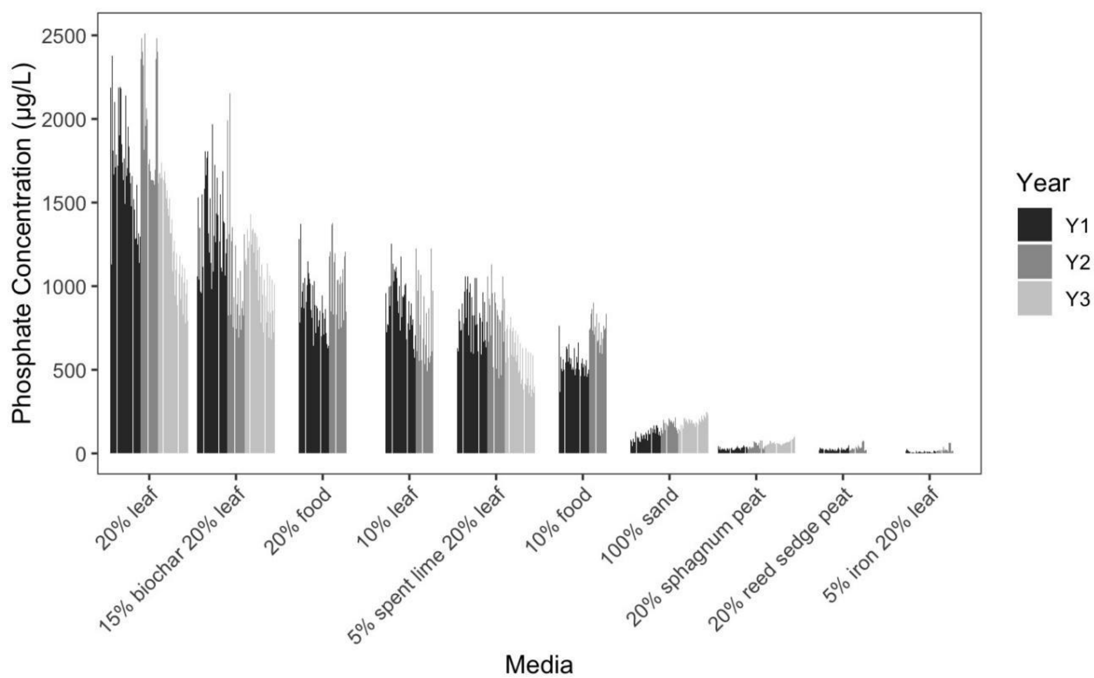

Figure A12. Phosphate concentration measurements (µg/L) in effluent from new media mixes as events progressed in Y1, Y2, and Y3.

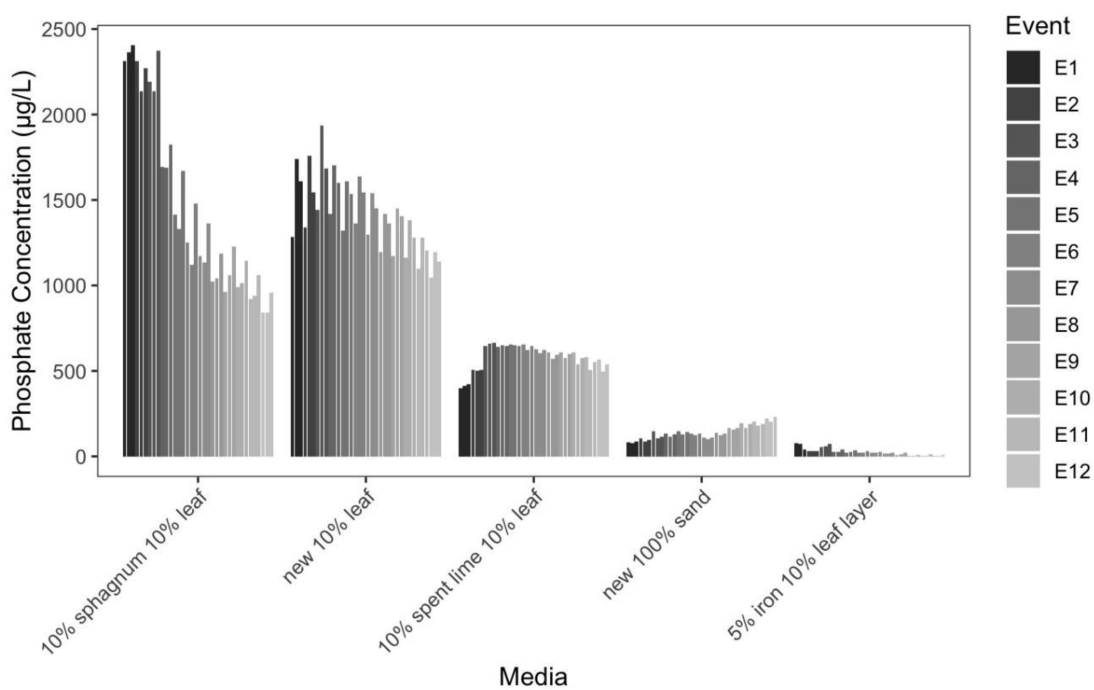

Figure A13. Phosphate concentration measurements (µg/L) in effluent from new media mixes as events progressed in Y3.