Evaluation of Biochar and Compost as Soil Amendments for Nutrient and Sediment Runoff Control

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Paige C Johns

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This Thesis
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Author Signature: Paige C. Johns

This Thesis has been read and approved by the examining committee:

Advisor: Teresa Culver

Committee Member: James Smith

Committee Member: Lisa Colosi Peterson

Committee Member: ______________________

Committee Member: ______________________

Committee Member: ______________________

Accepted for the School of Engineering and Applied Science:

Craig H. Benson, School of Engineering and Applied Science

May 2019

Abstract

An established Best Management Practice (BMP) for stormwater management in Virginia is the tilling of compost into roadside soils to improve soil matrix stability and porosity, encouraging infiltration and reducing runoff. An alternative soil amendment that functions similarly and may also offer additional nutrient-sorbing properties is biochar, the carbon-rich solid component of pyrolyzed organic material. Biochar has been widely studied as a soil amendment in both agricultural and stormwater-management contexts, but its properties can vary considerably depending on many factors, including soil type. This laboratory-scale soil column study compares the hydrologic performance of compost-amended, biochar-amended, and unamended soils during and after synthetic storm events, and assesses the nutrient and sediment content of effluent draining from the soil mixtures. Four differently-textured soils from throughout Virginia were tested. Both soil amendments achieved some enhanced hydrologic function in all four soil types. On average, biochar-amended soils offered the best moisture retention and resistance to compaction, while compost-amended soils demonstrated the fastest infiltration and drainage rates and also leached the least nitrogen. Unamended soils generated the effluent with the lowest phosphorus, and biochar-amended soils also removed a significant percentage of influent phosphorus, while phosphorus removal from compost-amended soils was much less substantial. Considering biochar’s advantage over compost in terms of phosphorus transport in light of specific phosphorus-restricting regulation in Virginia, biochar may offer an opportunity for more appropriate large-scale application as a roadside soil amendment throughout the state.

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1 Introduction and Background

1.1 Motivation

Stormwater run-off from impervious surfaces such as roadways and rooftops can carry a wide range of pollutants, including the nutrients nitrogen and phosphorus, to surface waters. These nutrients can contribute to degradation of aquatic health through eutrophication that promotes algal blooms, which, following die-off and decomposition of algae, create conditions of low dissolved oxygen and high turbidity. For human populations, eutrophication carries aesthetic and financial burdens (EPA, 2015), as both drinking water and recreational water resources are hindered by these conditions. While nutrient pollution is often associated primarily with agricultural sources, in some systems urban stormwater is thought to contribute a significant share of nutrient inputs to surface waters (Atasoy et al., 2006; Paul & Meyer, 2001).

Nitrogen and phosphorus are the nutrients of greatest interest in terms of controlling eutrophication. Phosphorus is often the growth-limiting nutrient for microorganisms in freshwaters, while nitrogen is generally considered the limiting nutrient in the marine environment, with estuaries often transitional areas where either nutrient may prove the rate-limiting one (Doering et al., 1995). For this reason, both nitrogen and phosphorus are of concern in coastal regions including the Chesapeake Bay watershed, which encompasses much of the state of Virginia.

In Virginia, control of pollution is managed by the state Department of Environmental Quality (DEQ). Beginning in 2005, pollution point sources such as wastewater treatment plants were assigned yearly caps on their output of nitrogen and phosphorus in order to limit eutrophication in the Chesapeake Bay (VA Administrative Code, 2005). Nonpoint pollution sources must be similarly regulated, but directly monitoring nonpoint-source nutrient mass output, as can readily be done for point sources, is not feasible. Instead, for appropriately-designed Best Management Practices (BMPs), the DEQ assigns presumed stormwater control and pollutant removal performance efficiencies (Virginia BMP Clearinghouse, 2018).

Operating the third-largest state roadway system (VDOT, 2019), the Virginia Department of Transportation is responsible for a large potential source of nonpoint-source pollution. VDOT manages runoff from its system of highways using a variety of approved BMPs designed to reduce nutrient inputs through stormwater quality and quantity control (VDOT Location and Design Division, 2002/2017). New development, including road construction, is regulated on the basis of phosphorus alone, as phosphorus is considered the "keystone" pollutant because it shares characteristics with both particulate and soluble pollutants and thus is thought to serve as a good indicator of a variety of urban pollutants (Virginia DEQ, 2013). For this reason, phosphorus-limiting BMPs may need to be prioritized in many situations.

One BMP approach is to amend soils adjacent to impervious surfaces with compost so that stormwater can infiltrate into the soil more easily, preventing direct runoff into surface waters. Tilling in compost, often in conjunction with other practices such as vegetated filter strips and grass channels, is expected to reduce runoff and nutrient mass loads by up to 50% depending on soil type (Virginia DEQ, 2011). An alternative soil amendment that shows the potential to function similarly, but has not been adopted as a BMP in Virginia, is biochar. Biochar is the solid component of pyrolyzed organic material such as wood, manure, or poultry litter, and is the subject of ongoing study regarding its potential applications in stormwater management (Mohanty et al., 2018) as well as agriculture (Atkinson et al., 2010) and even carbon sequestration (Lehmann, 2007).

This laboratory-scale soil column study seeks to evaluate the performance of both compost and biochar as prospective roadside soil amendments. The physical and hydrologic properties of soil columns and the chemical properties of the effluent they produce following application of synthetic stormwater will help determine whether either treatment shows the greater potential in terms of maintaining soil structure, improving infiltration rates, and limiting the transport of sediment and nutrients within a watershed.

1.2 Roadside Soil Amendments

Reducing contaminant runoff from impervious roadway surfaces is of critical importance in controlling nonpoint-source pollution. Devegetation and surface disturbance at the time of road construction strips away topsoil, leaving erosion-prone subsoils (Seutloali & Beckedahl, 2015). Rainfall on bare soils can cause the smallest soil particles to migrate into soil pores, creating a sealing effect that decreases the ability of subsequent rainfall to infiltrate into the soil. This directs overland flows toward grooves or rills in the soil, where they then tend to channel more deeply and accelerate sediment transport. At the same time, long-term soil compaction can further diminish hydrologic function. Amending roadside soils with porous materials has been shown to reestablish permeability, improving infiltration rates and aiding in runoff control (Pitt et al., 2002).

1.2.1 Compost

Compost is the product of the aerobic decomposition of organic material by microbes. According to the U.S. Composting Council (2018), this decomposition process is enhanced by optimizing levels of oxygen, moisture, and carbon, all required for microbial growth. As microbes grow, they give off heat, creating a period of thermophilic conditions and destroying many pathogens. This is followed by a cooler phase, which stabilizes the compost for a particular use while it continues to decompose.

Because it is high in moisture content and porosity, one such use along Virginia roadways is to deeply till compost into soil in order to stabilize the soil matrix and maintain hydraulic conductivity (Virginia DEQ, 2011). The American Association for State Highway and Transportation Officials (AASHTO) sets parameters for testing compost to ensure its suitability for this use, specifying acceptable levels of many indicators including pH, moisture content, organic matter content, and particle size, and ensures that the compost is free of physical, chemical and biological contaminants (AASHTO, 2010). Commercially-available compost bearing the Seal of Testing Assurance (STA) has been certified to adhere to the AASHTO protocol (Alexander, 2003); accordingly, VDOT regulations require STA-certified compost in roadside treatments (VDOT, 2016).

At least 32 states now use compost for stormwater runoff reduction along roadways (U.S. Composting Council, 2008). In many cases, the goal of the compost is to improve the fertility of the soil and aid in revegetation. Projects have successfully used compost to improve the results of planting grass, wildflowers, and wetland shrub species (Batjiaka, 2016). Additionally, improvements in the hydraulic properties of compost-amended soil itself, even without the long-term intended benefits from revegetation, have been studied.

In one Iowa study, both vegetated and non-vegetated compost-amended soils reduced surface runoff from a simulated hard rainfall by greater than 98%; the non-vegetated soils actually outperformed the vegetated soils in terms of erosion prevention during the same time period (Glanville, 2003). At another site in Washington, erosion reduction was observed in some compost-amended surfaces even before grass began to grow (Lewis et al., 2000). A longer-term Georgia study found that over the course of a year, compost-amended soils reduced runoff by 55% at three months and 30% at 12 months as compared to unamended soil (Faucette et al., 2005)

While these structural improvements are well-established, compost includes substantial organic matter, which may introduce unsuitable levels of the very nutrients that must be controlled (Hansen et al., 2012). Generally, the nutrients inherent in this organic matter present a net benefit for agricultural purposes, but they may pose problems for stormwater management. During rain events, soluble nitrogen and phosphorus are both capable of leaching from the soil and being transported to ground and surface waters, especially in unvegetated and minimally-vegetated settings (Bratieres et al., 2008). Both total nutrient levels in compost and their leachability may largely be a function of the source material of the compost (Hurley et al., 2017), and while AASHTO regulates compost on the basis of percent organic matter, it does not require testing for nutrient leaching rates (Alexander, 2003).

1.2.2 Biochar

Like compost, biochar is a product of the controlled decomposition of biomass. To create biochar, organic matter is pyrolyzed, or thermally separated in a limited-oxygen environment at temperatures up to 700°C (Lehmann & Joseph, 2015). This process generates products of all phases: gases, bio-oils, and biochar, which is the solid component of the source material, characterized by a rough surface with a variety of particle and pore sizes, usually giving it a very high specific surface area (Keiluweit et al., 2010).

On one level, biochar can function similarly to compost as a soil amendment in that it increases total porosity, decreases bulk density, forms macropores and improves soil matrix stability (Laird, 2009). At one experimental roadside filter strip, biochar-amended tilled soils offered 50% greater reductions in runoff volume and peak overland flow rates compared to unamended tilled soils over a series of 74 storms (Imhoff & Nakhli, 2017). Greater water holding capacity has also been shown in biochar-amended soils and is theorized to limit nutrient runoff by increasing the retention time of stormwater in the soil matrix, which allows more complete nutrient cycling (Tian, 2014).

Biochar has also shown other pollutant-remediating properties through a variety of physical and chemical mechanisms. Improved infiltration and soil matrix stability may reduce the mobility of polycyclic aromatic hydrocarbons and pesticides, allowing their eventual uptake by plants, thus preventing their transport to surface waters (Chen & Yuan, 2011). Additionally, electrostatic interactions and complexation have been shown to be the primary drivers of biochar's ability to immobilize some heavy metals in soils (Li et al., 2017), while surface adsorption is considered the most important mechanism for immobilization and transformation of organic contaminants and nutrients (Moreira, 2017). Nutrient adsorption for improved agricultural performance is the focus of considerable research, with well-demonstrated benefits in tropical and some temperate soils (Atkinson, 2010).

A high surface area is an important driver of adsorption by biochar, and tends to vary according to both source material and pyrolysis reaction conditions. Mid-range temperatures were found, for most source materials, to produce the biochar with the highest surface area (Gai et al., 2014). A high surface area also increases biochar's cation exchange capacity (Liang et al., 2006). It is through cation exchange that biochar-amended soil has been shown to effectively adsorb ammonium (NH_4^+) and thereby control total nitrogen runoff under some circumstances (Ding et al., 2010). Research has also found the addition of biochar to existing Low Impact Development (LID) designs to enhance their performance both hydraulically and by providing surfaces for microbial communities to remove some pollutants biologically (Mohanty et al., 2018).

However, age and weathering can change biochar in complex ways. New biochar was shown to have greater positive surface charge, while aged biochar formed oxygen-containing functional groups over time, providing sites for negative surface charge, which increased with continuing oxidation (Cheng et al., 2008). However, surface properties also vary with pH (Silber et al., 2010). In short, surface chemistry of biochar is dependent on many factors. Source material, pyrolysis temperature, age, soil type, and pH can all significantly affect the performance of biochar in its various applications.

Despite the lack of universality in some of the mechanisms for biochar's performance, the U.S. Biochar Initiative reports growth in sales among surveyed biochar producers as well as continued enthusiasm among surveyed biochar users (2019). Preliminary analysis of data derived from this survey indicates total domestic biochar production of approximately 45,000 tons per year (TPY), a significant increase from previous estimates of 15,000-20,000 TPY, according to the authors. Biochar producers expected to see continued growth in the market for biochar's use in runoff filtration, nutrient retention to support crop growth, and even as an addition to animal feed; commercially, the market remains mostly focused on these agricultural applications.

But survey respondents also saw potential uses for odor control, mine reclamation, and carbon sequestration. In addition to promoting biochar to farmers and gardeners for its structural and microbial benefits, some companies also cite biochar application as a carbon-negative process with possible environmental benefits on a global scale (Wakefield, 2019; Black Owl, 2019). Some companies are now marketing biochar specifically for stormwater management as well (Stormwater Biochar, 2019).

Comparative studies have examined the performance of biochar and compost for improving coal fly ash treatment processes (Belyaeva & Haynes, 2011) and reducing toxicity of pore water in soils contaminated with multiple heavy metals (Beesley, 2010). Applications for biochar to be used in conjunction with compost have also been studied. Adding biochar during compost production may diversify its microbial community (Jindo, 2012). Another study examined whether incorporating biochar into a bioretention media consisting of 75% compost by volume would reduce leaching (Iqbal et al., 2015), and found no difference in this context. Roadside tillage of compost and biochar into native soils must be studied more closely, in a variety of soil types and experimental conditions, to determine whether either product's application on a large scale emerges as a more appropriate stormwater management technique.

2 Methods

Four types of field soil were collected and prepared for testing according to three different treatment protocols: unamended, amended with biochar, and amended with compost. For each field soil type, two replicate samples of each of the three treatments were packed into vertical PVC columns, for a total of six columns per soil type and twenty-four columns in all. Columns were constructed with mesh screens covering the bases and suspended above collection beakers. Synthetic stormwater was applied to the top of each soil column to simulate rainfall and runoff entering roadside soil, and effluent was collected as it gravity-drained from the base of each column. For each storm, effluent quality and soil physical and hydrological properties were analyzed. The study consisted of six artificial storms conducted in two phases, with a repacking procedure occurring between the third and fourth storms.

2.1 Soil Collection

Soil samples were collected from four locations throughout the state of Virginia (Figure 2-1) in order to observe compost and biochar effectiveness in soils with different characteristics. The four sites were selected based on regional soil parent material as identified by the Virginia Cooperative Extension (Baker, 2000) and located on non-agricultural plots on community college campuses with no known recent application of fertilizer. All were more than 10 meters from paved surfaces and all were within 5 meters of wooded areas, but the only vegetation growing directly over the collection sites was grass. For the experiment, the samples have been identified as North, South, East, and West samples. Table 2-1 summarizes collection site attributes.

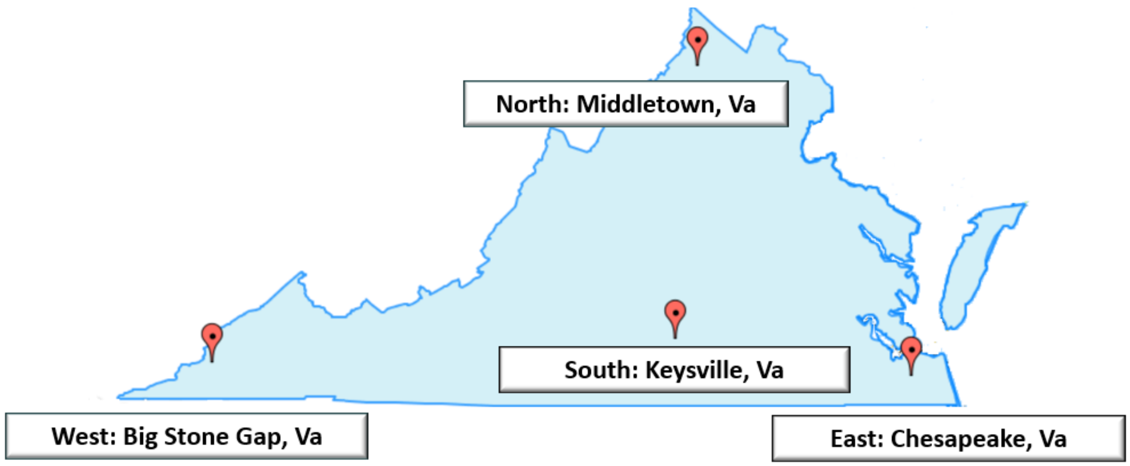


Figure 2-1: Map of regional soil collection sites

Table 2-1: Locations and dominant parent material of soil samples

Sample name	Community College	Location	Latitude	Longitude	Soil Parent Materials
North	Lord Fairfax	Middletown, VA	39.037° N	78.264° W	Limestone, dolomitic limestone, sandstone, shale
South	Southside	Keysville, VA	37.037° N	78.458° W	Aaron slate, quartz porphyr, greenstone
East	Tidewater	Chesapeake, VA	36.767° N	76.292° W	Sands, clays
West	Mountain Empire	Big Stone Gap, VA	36.853° N	82.761° W	Sandstone, shale, coal seams

At each site, an approximately three-gallon volume of soil was dug to a reasonably uniform depth of 12 inches and thoroughly mixed together in a 5-gallon bucket with a hand rake to ensure all depth zones were evenly distributed. Before storage, large aggregates were manually broken up, and stones larger than 1 inch in diameter were removed. The buckets were covered and sealed with tight-fitting lids and stored at room temperature for between 30 and 60 days before the experiment began.

2.2 Soil Characterization

Samples of each homogenized soil type were sent for analysis at Waypoint Analytical Laboratory (Richmond, Virginia). Table 2-2 summarizes the soil properties measured by Waypoint. Estimated

Nitrogen Release was defined based on percent organic matter, and Total Phosphorus was determined using a Mehlich-3 extraction (Mehlich, 1984).

Table 2-2: Soil properties characterized by Waypoint Analytical Laboratory

Sample	Organic Matter (%)	Cation Exchange Capacity	pH	Estimated Nitrogen Release (lbs/acre)	Total Phosphorus (ppm)
North	7.9	12.0	5.6	150	10
South	6.1	5.0	5.1	150	19
East	2.1	3.7	4.8	87	10
West	5.4	3.5	5.8	150	7

Additional soil characterization was performed using sieve and hydrometer tests to determine distribution of particle size. First, soil was passed through no. 10, 30, 50, 100 and 200 sieves while being shaken for 10 minutes, and the fractional masses of each particle size were recorded. Then, a 50-g combined sample of all soil passing the no. 10 (2 mm) sieve was removed and prepared for hydrometer analysis using ASTM procedure D7928 – 17 for a 151-H hydrometer (ASTM 2007). This procedure was followed to create a smooth-fit plot of the percent of soil (by mass) finer than a series of particle diameters determined using Stokes' Law (with the simplifying assumption that soil particles are spherical).

Soil particle size at reading *m* was calculated with Equation 1-1:

$$D_m = \left(\sqrt{\frac{18\mu}{\rho_w g(G_s - 1)} \times \frac{H_m}{t_m}}\right) \times 10 \qquad \text{Equation 1-1}$$

where D_m equals the maximum diameter of particles in suspension at reading m, μ is the viscosity of water, ρ_w is the mass density of water at 20° C, g is the acceleration of gravity in cm/s^2, G_s is the dimensionless specific gravity of the soil (estimated at 2.65 for all soils), H_m is the particle fall depth in centimeters, and t_m is the elapsed time in seconds. A reference table for standard 151-H hydrometer fall depths was used for values of H_m (Liu & Evett, 2003).

Each mass percent finer at reading *m* was calculated using Equation 1-2:

$$N_m = \left(\frac{G_s}{G_s - 1}\right)\left(\frac{V_{sp}}{M_d}\right)\rho_c\left(r_m - r_{d,m}\right) \times 100 \qquad \text{Equation 1-2}$$

where V_{sp} is the volume of the solution in cm^3, M_d is the dry mass of the soil in g, r_m is the hydrometer reading and $r_{d,m}$ is the temperature-calibrated reference reading in deionized water.

From the curve, the soil texture was characterized by particle size using the Wentworth grain-size definitions of clay particles having a diameter less than .004 mm, silt particles ranging in diameter from .004 to .06 mm, and sand particles ranging from .06 to 2.0 mm (Wentworth, 1922). When a particle diameter of .004 mm fell between readings, the percent finer at that value was interpolated based on the slope of a linear approximation of the curve in that area. When a particle diameter of .06 mm fell outside the range of data collected (that is, by the time of the first reading at 1 minute, all particles larger than .06 mm had already fallen), a visual estimation of the curve's horizontal asymptote was used as an approximation of the mass percent finer than .06 mm. Hydrometer data curves are found in Appendix A.

Information about expected soil type and texture at the collection sites was also sourced from the United State Department of Agriculture's Web Soil Survey (WSS, 2018). The Web Soil Survey predicted different types than laboratory analysis for some locations; however, both the Web Soil Survey and the hydrometer tests characterized all soils as some type of loam. Hydrologic soil groups (HSG) A-D were also taken from the WSS; HSG A soils infiltrate the fastest and HSG D soils infiltrate the slowest. When two groups are listed, the first letter indicates behavior when unsaturated and the second letter indicates behavior when saturated (USDA, 2007)

Subsamples of all soils were oven-dried to determine gravimetric water content. For this procedure, a 600-700 mL subsample of each soil was weighed in its field-damp condition, then oven-dried for 24 hours at 105° Celsius and weighed again. Fractional gravimetric water content (u) was calculated with Equation 1.3.

$$u = \frac{M_w}{M_d} \qquad \text{Equation 1-3}$$

where M_w is the mass of water contained in the sample (found by subtracting the mass of dry particles from their field-damp mass) and M_d is the mass of the dry particles. The gravimetric water content of compost and biochar were also found using this method. Soil texture data and gravimetric water content is summarized in Table 2-3.

Table 2-3: Soil texture, soil group, and moisture data

	Hydrometer Test Data				*Web Soil Survey Data*		*Soil Moisture Test Data*
	Soil type	Percent Clay	Percent Sand	Percent Silt	Soil Type	Hydrologic soil group	Gravimetric Water Content (g/g)
North	Medium loam	9	42	49	Silt loam	C/D	0.25
South	Silt loam	12	32	56	Silt clay loam	B	0.19
East	Sandy loam	9	70	21	Sandy loam	A/D	0.17
West	Silt loam	15	28	57	Clay loam	B	0.19
Biochar	n/a						0.06
Compost	n/a						0.46

2.3 Column Construction and Packing

Columns were constructed from clear PVC pipe with a 2-inch inner diameter. Each column measured approximately 16 inches in height, with the bottom opening covered in fiberglass screen secured tightly with a metal hose clamp to hold soil and allow effluent water to freely drain. Previous setups used 1-inch diameter columns that narrowed to a 1/8” nozzle at the bottom for the outlet; drainage was extremely slow with this setup, and sometimes flows stopped entirely. The change to a larger diameter and a screen instead of a narrow nozzle was motivated by an interest in prioritizing conditions to encourage flow. Columns packed with soil were suspended over 250-mL beakers to collect effluent as columns drained by gravity during artificial storm events.

Six columns were constructed for each sample soil type. Two columns contained unamended soil, two contained a mixture of soil and biochar, and two contained a mixture of soil and compost.

Biochar columns were mixed with 4% Soil Reef biochar by mass. This amount was selected based on a range of 2-6% by mass biochar application rate considered feasible in the field (Imhoff & Nakhli, 2017). Compost columns were mixed with 30% STA-certified LeafGro compost by volume, based on Virginia DEQ recommendations for compost depth of 3-6" when tilling to a depth of 12", for a total compost volume ranging from 20-40% (Virginia DEQ, 2011). Each sample and its respective soil amendments were placed in a foil pan and completely mixed with a hand rake to ensure even distribution of components and to break up large aggregates. This process would mimic a rototilling process that could be used to add amendments to roadside soils in the field.

Lewis and Sjostrom's review of optimal experimental design for transport experiments using soil columns (2009) recommends no more than a 4:1 ratio of soil height to diameter, while other studies call for higher ratios around 6.25:1 (Hsieh et al., 2007) or higher. Columns for this experiment were initially filled to a depth of 12" (a 6:1 ratio) by adding a 1" depth increment, then lightly shaking and tapping the columns until the soil was level across the surface, then repeating with the next inch of soil. As initially packed, total densities of the field-damp soil columns ranged from 0.64-1.18 g/cm^3. Figure 2-2 shows the six columns filled with the three different mixtures of southern regional soil. Appendix B lists specifications of each filled column.

Figure 2-2 Column set-up for southern regional soil prior to stormwater application

2.4 Initial Saturation

The top surface of each soil column was sprinkled with calcium sulfate ($CaSO_4$) to prevent small clay particles from breaking free and clogging the outlet screen. This procedure was based on a suggested agricultural application of $CaSO_4$; sulfate binds to resident cations, forming soluble compounds that are easily flushed, while calcium takes the place of the removed cations and attaches to negatively charged clay particles, stabilizing them (Tirado-Corbala et al., 2013). As described in instructions under the trade name Gypsoil, a yearly application of 0.5-2.0 tons per acre $CaSO_4$ (dihydrous) is recommended (Gypsoil, 2018). 180 mg $CaSO_4$ (anhydrous) on the soil surface for these columns (approximately 20 cm^2) corresponds to the lowest recommended application rate. Once applied, the $CaSO_4$ was lightly mixed into the top 1 cm of soil.

Next, all columns were saturated with deionized water to allow the $CaSO_4$ to begin to incorporate throughout the length of the columns. The saturation took place over the course of 30 minutes, during which 350 mL of water was applied to each column in aliquots by syringe. Drainage from some columns was observed within the first 5 minutes of this procedure, and all columns began to drain within 20 minutes. Aliquot volumes were gradually increased and continued until every column had, at some point, displayed simultaneous drainage from the bottom and ponding on top of the soil surface; at this point, the column was considered fully saturated. However, all columns continued to receive the same influent volumes until all had reached full saturation. Then, columns were allowed to fully drain.

As soon as each column was observed to stop draining, the column mass and collected effluent volume were recorded. Volumes ranged from 185 to 250 mL, with the remainder of the 350 mL influent considered to be retained moisture. The height of the saturated soil columns, now somewhat compacted, was also measured at this time. This new soil height was used to calculate the volume and the approximate dry bulk density of the compacted soil mixtures. Each component's dry bulk density was calculated according to Equation 1-4:

$$\rho_{bulk} = \frac{M_d}{vol_c} = \frac{M_T(1-u)}{vol_c} \qquad \text{Equation 1-4}$$

based on the original mass of each type of media at the time of filling (M_T), the gravimetric water content (u), and the compacted volume (vol_c). Dry bulk densities ranged from 0.64 g/cm^3 to 1.24 g/cm^3, with the compost columns having the lowest average dry bulk density and the unamended columns having the highest.

2.5 Synthetic Stormwater Application

Synthetic stormwater was prepared with deionized water, sodium nitrate and dibasic sodium phosphate, for concentrations of 2 mg/L nitrate (NO_3-N) and 3 mg/L phosphate (PO_4-P). These nutrient concentrations correspond to stormwater as prepared for repetitive column studies developed by Hsieh and Davis (2005, 2007). Stormwater nutrient concentrations can vary considerably between storms, regions, and land uses. Over thousands of observations representing a wide range of each of these factors, the 2005 National Stormwater Quality Database (Pitt & Maestre, 2005) reported median nitrate concentrations of 0.60 mg/L and median phosphate concentrations of 0.38 mg/L, but noted that even within land uses, nutrient concentrations ranged over several orders of magnitude. An EPA study (1999) found typical total nitrogen (TN) and total phosphorus (TP) concentrations in separate stormwater sewers of 2 mg/L and 0.36 mg/L, with ranges up to 20 mg/L TN and 4.3 mg/L TP. The same study also reported the highest nitrate loads per unit area, as compared to other land uses, were from parking lots and freeways. Thus, synthetic loads for the present study were within observed concentrations of urban runoff, especially feasible for hotspot areas where concentrations tend to be 2 to 10 times higher than the typical concentrations (MDE 2009).

Each artificial storm consisted of 250 mL of synthetic stormwater applied to the soil surface of each column over the course of one hour, with 20 mL applied every 5 minutes from minute 0 to minute 55 and 10 mL applied at minute 60. This volume was determined based on direct rainfall and runoff entering a 22 m^2 roadside filter strip adjacent a 93 m^2 section of highway during an average one-hour duration, one-year frequency storm for Virginia (Hershfield, 1961). An experimental filter strip with these dimensions is the site of the ongoing field stormwater research (Nakhli et al., 2019) cited above.

The first three artificial storms took place beginning 48 hours after the initial calcium sulfate saturation procedure, with 48-60 hours between each storm. Some columns experienced no visible ponding on soil surfaces, indicating an infiltration rate that was faster than the application rate. Stormwater temporarily ponded on the surface of others, gradually infiltrating during and after the conclusion of the storm's "rainfall." By the third storm, infiltration had slowed significantly for several columns and stopped entirely for one (an unamended sandy loam from the eastern soil collection site). In order to restore flow, the soil mixtures were removed from each column and emptied into pans, allowed to air-dry for 24 hours, and repacked in columns following the same procedure as initial packing. Once repacked, columns were left for 30 days before the second set of three storms began. For this second phase—the fourth, fifth, and sixth storms—the same stormwater application procedure was followed except that the time period between storms was six days. All stormwater completely infiltrated every column during this phase, but surface ponding exceeded 6 hours for the column that had failed to fully infiltrate prior to repacking.

2.6 Soil Column and Effluent Analysis

Soil height and total column mass were recorded for all columns prior to each storm. These properties were measured again for each column as soon as all applied stormwater had infiltrated the soil surface and drainage from the bottom of the column was observed to stop. Effluent volumes were recorded every 10 minutes during the storm, then at 90 minutes, 120 minutes, 180 minutes, and hourly until drainage was complete. Volumes were recorded to the nearest 5 mL during the storm to calculate approximate drainage rates, and effluent beakers were also weighed to calculate total effluent volume after drainage had stopped. The electrical conductivity and pH of each effluent sample were tested (using a Fisher Scientific Traceable ISO 17025 Conductivity Meter probe and Fisher Scientific pH Meter, respectively). Turbidity was also tested at this time using a Hach 2100q turbidity meter.

All samples were refrigerated when drainage was complete, and nutrient testing took place within 48 hours. Other than refrigeration, samples were not preserved. For testing of anions including nitrate and phosphate, samples were filtered using a 0.45 µm PES membrane syringe filter (Thermo Scientific Titan 3) and diluted. Dilution levels were determined based on expected high concentrations of sulfate ions due to the one-time $CaSO_4$ application, which required a 1:8 dilution for the first three-storm series and a 1:3 dilution during the second series. Anions were measured by ion-chromatographic analysis using a Thermo Scientific Dionex IC system calibrated to 0.1-40 mg/L NO_3 and 0.2-80 mg/L PO_4.

Filtered samples were also analyzed using a Shimadzu TOC-L with TNM analyzer, which performs high-temperature catalytic oxidation procedures for total organic carbon (ASTM D7573-18ae1, 2018) and total nitrogen (ASTM D8083-16, 2016). Minimum detection limits were 4 µg/L for organic carbon and .05 mg/L for total nitrogen.

Total phosphorus was tested using Hach TNT-843 kits (detection range .05-1.50 mg/L PO_4-P), with unfiltered samples digested at 100°C for one hour in a Hach DRB200 test tube reactor and read with a Hach DR3900 spectrophotometer barcode program. This method converts all phosphorus to orthophosphate through digestion and uses molybdate reduction to allow the orthophosphate ions to be quantified by colorimetry (Dankowski and White, 2013). Measurements were corrected for turbidity, which can interfere with the colorimetric mechanism of these kits, by using a sample blank (Hach, 2016). This method is summarized in Appendix C.

When all nutrient testing was complete, remaining effluent was vacuum-filtered (following ASTM procedure D9977-97e1, 2013) through a pre-weighed glass microfiber filter (Whatman 934-AH), retaining the sample's suspended solids on the filter. Each filter was then oven-dried for 24 hours at 105°C and reweighed. The difference between the initial mass of the filter and the combined mass of the oven-dried filter and the retained solids was calculated to be the total mass of sediment in the sample.

2.7 Soil Nutrient Leaching Test

To determine the magnitude of resident leachable nutrients present in the soils and amendments prior to synthetic stormwater application, a nutrient leaching test of each soil mixture component was conducted using a modified procedure developed by Tian et al. (2016). Tested samples included all four regional field soils, LeafGro compost, and "fresh" Soil Reef biochar (taken directly from the container as purchased). "Aged" Soil Reef biochar, extracted from the media of a bioretention facility in Charlottesville, Virginia, was also tested for nutrient leaching behavior (Rossetti, 2019). 5% biochar was used in the media of that facility when it was retrofitted over 24 months earlier (Culver et al., 2016). Duplicate 3.0 g samples of all media were placed in 50-mL centrifuge tubes with 40 mL deionized water. Tubes were secured horizontally on a Thermo Scientific Max Q 4450 shaker platform and agitated at 150 rpm for four hours, then centrifuged at 4500 rpm for 15 minutes in a Thermo Scientific Sorval Legend XTR centrifuge.

Each tube's supernatant was analyzed for concentration of both total phosphorus and phosphate (PO_4-P) using Hach TNT-843 kits following the same procedure as in the effluent analysis (with the PO_4-P process eliminating the steps relating to digestion so only orthophosphate would be detected). Samples were also analyzed for nitrate concentration using Hach TNT-836 kits (5.0-35.0 mg/L NO_3-N) and, if below the range for those kits, re-tested using Hach TNT-835 kits (0.23-13.5 mg/L NO_3-N). In both nitrate kits, sulfuric acid and a dimethylphenol reagent combine with nitrate to form nitrodimethylphenol, which can be quantified by absorbance. Ammonia concentration was measured with Hach TNT-830 kits (0.015-2.0 mg/L NH_3-N), which use a salicylate reagent to form absorbance-measurable indophenol in proportion to NH_3-N. For all four of these procedures, the same color correction process was followed as for the effluent total phosphorus analysis. Finally, samples were analyzed for total nitrogen using Hach Test 'N Tube persulfate digestion method 10071 (0.5-25.0 mg/L N). In this method, all nitrogen is converted to nitrate in a persulfate digestion process, and is then acidified with chromotropic acid, creating a yellow color. Calibrated nutrient concentrations (mg/L) were read on a Hach DR-3900 spectrophotometer.

Concentrations of nitrate, phosphate, and ammonium in leachate samples were also analyzed by ion chromatography using a Thermo Scientific Dionex IC system calibrated to 0.1-40 mg/L NO_3, 0.2-80 mg/L PO_4, and 0.5-50 mg/L NH_4. Nitrate results were discarded due to equipment-related malfunction, which created inaccuracies. Phosphate and ammonium results were converted to concentrations as PO_4-P and NH_4-N and averaged with the results from the corresponding kits.

The total mass of nutrients leached in each vial and the nutrient leaching rates in mg nutrient/g media were calculated based on measured concentrations, 40-mL of water, and 3 grams of media. These leaching rates (mg/g) and the mass of each media in each soil column as originally filled were then used to calculate the total expected mass of leachable nutrients available in each column.

2.8 Data and Cost Analysis

Effluent nutrient masses were calculated from measured nutrient concentrations and total volume of effluent samples; volumes were calculated from sample masses and assumed a water density of 0.999 g/mL and temperature of 20°C. Within-storm flow rates were calculated based on estimated effluent volumes as read during storms from graduated collection beakers, and can only be considered accurate to within approximately 10%. Because total effluent volumes varied, flow rates up to the first 100 mL of drainage were considered a useful representation of the most active period of drainage for all columns.

Statistical significance of comparative nutrient concentrations was calculated using the data analysis functions of Microsoft Excel (2007). Two-factor analysis of variation (ANOVA) was performed on the entire body of data for each nutrient in order to compare the relative significance of regional soil type and of soil amendment to any observed trends. Single-factor ANOVA was also performed within each region to examine the three soil treatments in relation to one another, and paired T-test analysis was performed within each region on each amendment as individually compared to unamended soils.

Cost estimates for each product are based on retail price of the compost and biochar used in this study as of March 2019. Projected field application rates for these estimates correspond with rates as applied in columns. Costs were also calculated on a per-acre-treated basis in order to compare with other, more highly-engineered BMPs for which a per-application-area estimate is not suitable. In this case, treated area was calculated using the ratio of roadway drained to surface tilled, which is approximately 4.2:1 at the Delaware site. Cost data for other BMPs currently in use in Virginia was derived from the Chesapeake Assessment Scenario Tool (CAST, 2016), a web-based nutrient and sediment estimator used for environmental planning in the Chesapeake region.

3 Results

3.1 Soil matrix physical properties

3.1.1 Moisture retention

All columns retained significant moisture within the soil matrix following initial saturation with deionized water and calcium sulfate, as measured by mass when gravity drainage from this first saturation was observed to end. Amended soils retained more moisture than unamended soils, with compost-amended soils averaging 12% greater initial moisture retention than the unamended controls in each region, and biochar-amended soils averaging 39% greater initial moisture retention than the controls (Table 3-1).

After the entire six-storm series, moisture-holding properties of all soils were diminished. In most cases, though, the relative benefits offered by the soil amendments were magnified; that is, the amended soils' moisture-holding properties, which started higher, also decreased less over time, with biochar-amended soils offering the best long-term moisture retention.

For three regions (north, south, and west), both types of amended soils retained at least 100% more moisture than the unamended soils following the observed end of drainage from the final storm application. In the east region, the soil amendments did not notably increase moisture retention as compared to the controls; the compost-amended columns actually retained 79% less moisture than the unamended columns for that soil type by the end of the series. Overall, the compost-amended soils retained an average of 20% more, and biochar-amended soils retained an average of 139% more moisture than the unamended soils at the conclusion of the study period.

Table 3-1: Average moisture retention behavior of columns

	Unamended	Biochar		Compost	
	Mass (g)	Mass (g)	% greater retention than unamended	Mass (g)	% greater retention than unamended
Retained moisture after initial saturation and drainage					
N	72.0	110.1	53%	85.3	18%
S	76.3	111.1	46%	88.6	16%
E	110.3	141.2	28%	113.5	3%
W	87.9	118.5	35%	101.3	15%
Average (all types)	86.6	120.2	39%	97.2	12%
Retained moisture after final storm application and drainage					
N	23.5	87.1	271%	49.7	112%
S	6.1	69.1	1042%	42.9	609%
E	85.7	88.8	4%	18.1	-79%
W	17.1	67.3	294%	48.7	185%
Average (all types)	33.1	78.1	136%	39.9	20%

3.1.2 Soil Compaction

Both amended soil mixtures demonstrated greater average resistance to compaction than the unamended soils. This was especially notable during the first half the experiment, when all soils compacted to some degree upon being saturated, but unamended soils continued to compact at a greater rate than both the biochar-amended and compost-amended soils. After the air-drying and repacking procedure, all soils regained some of their lost height, but the biochar-amended soils recovered the best and continued to maintain the greatest percentage of their height over the remaining storm events. By the conclusion of the series, biochar-amended columns had lost an average of 13% of their height, compost-amended columns had lost an average of 15% of their height, and unamended columns had lost an average of 17% of their height (Figure 3-1).

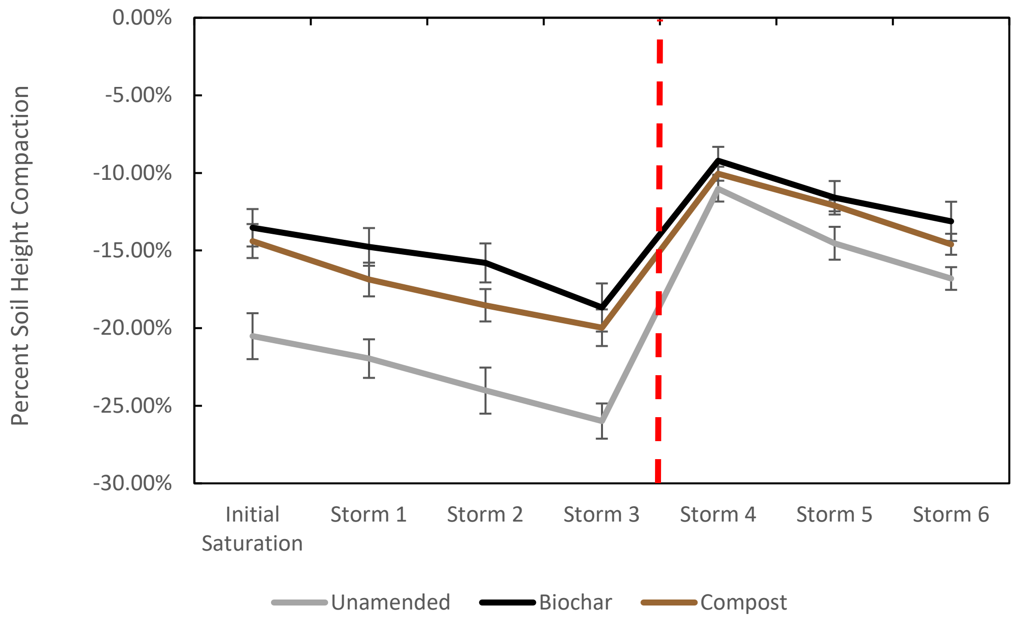


Fig 3-1: Average change in soil height from initial packed height of 30 cm, by saturation event and mixture type. Columns repacked between Storm 3 and 4. Error bars represent standard error (n=8).

3.2 Infiltration and Drainage Rates

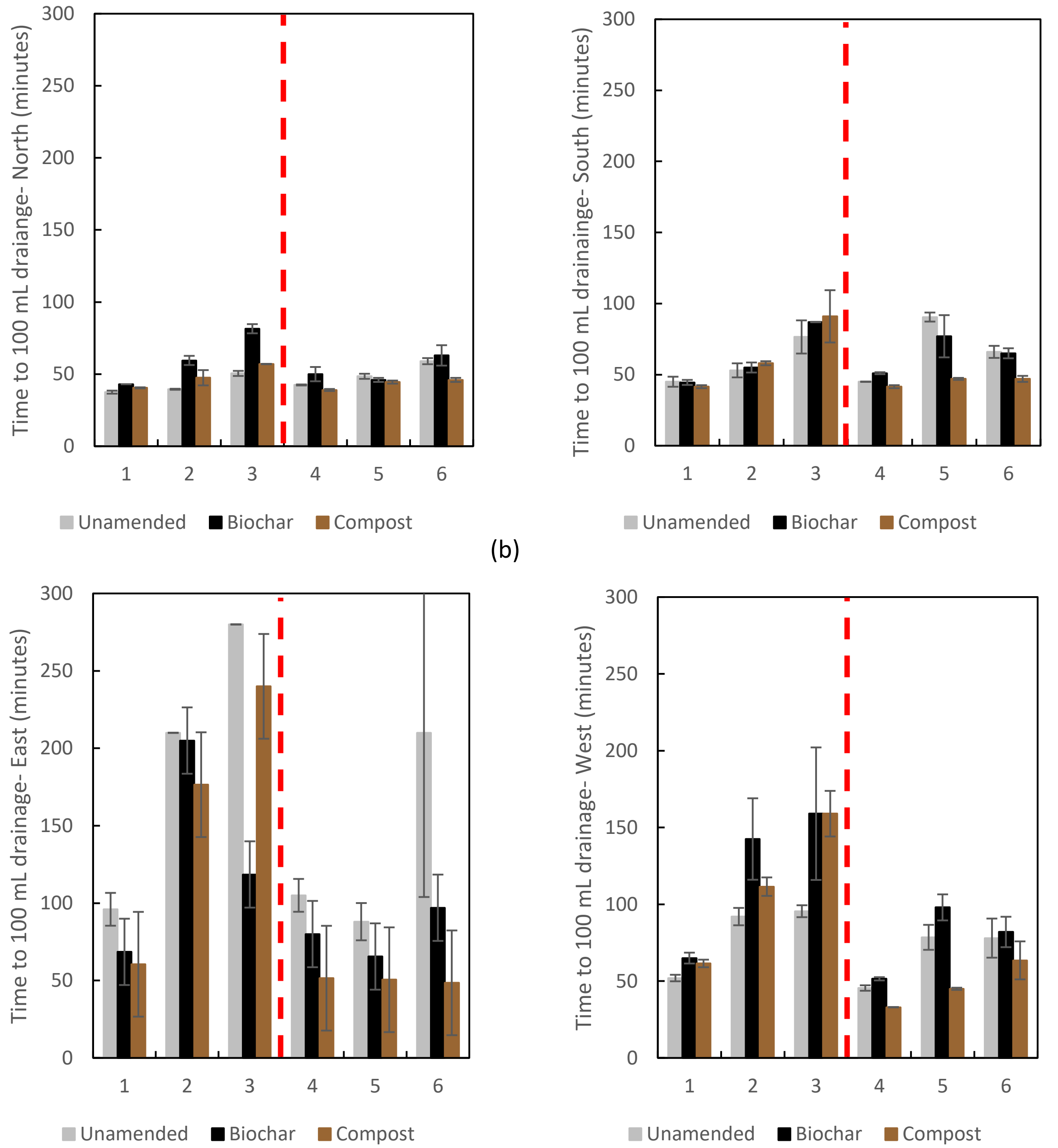
During the first artificial storm, infiltration of all columns was rapid with only minimal ponding on soil surfaces. Elapsed time from the beginning of the storm to the collection of 100 mL of effluent ranged from 36 to 111 minutes. Soil type was a significant (p=.001) predictor of this measure, but treatment type was not. Considering performance across all soil types, the treatments performed similarly, with compost-amended soils averaging 51 minutes to 100 mL of output, biochar-amended soils averaging 53 minutes, and unamended soils averaging 58 minutes.

For the first three storms, no treatment type was consistently superior in all four soil types. As the first set of three storms progressed, all columns demonstrated longer-term ponding, took longer to start draining, and increased elapsed time to drain 100 mL by between 23% and 666%. The effect was most pronounced in the eastern regional soils, where one control column stopped draining entirely.

Average time to drain 100 mL of effluent for the remaining eastern-soil columns was 213 minutes for the third storm.

Following column repacking and 30 days of air-drying between Storm 3 and Storm 4, flow was restored, and all columns allowed complete infiltration for the fourth, fifth, and sixth storms. During this second phase, there was a similar slowing trend for most columns, but not to the same extent that occurred during the first three storms (Figure 3-2).

In addition, a treatment-based trend began to emerge, as compost-amended columns became the most conducive to higher flow rates in every soil type. This trend would become more pronounced with each successive storm during Storms 4-6. By the end of the entire series, unamended soils had slowed the most, with a first-100 mL flow rate over 40% slower than observed for the first storm. Biochar-amended soils had slowed by nearly 30%, but compost-amended soils’ flow rate was virtually the same for the sixth storm as it was for the first (Figure 3-3).



(a) (b) (c) (d)

Fig 3-2: Average elapsed time from start of artificial storm to drainage of 100 mL of effluent for the (a) north, (b) south, (c) east and (d) west regional soils, by soil amendment type. Columns were re-packed between Storms 3 and 4. Error bars represent standard error (n=2 except in east region for Storms 2 and 3, in which one column did not drain 100 mL, so n=1). Columns repacked between Storm 3 and 4.

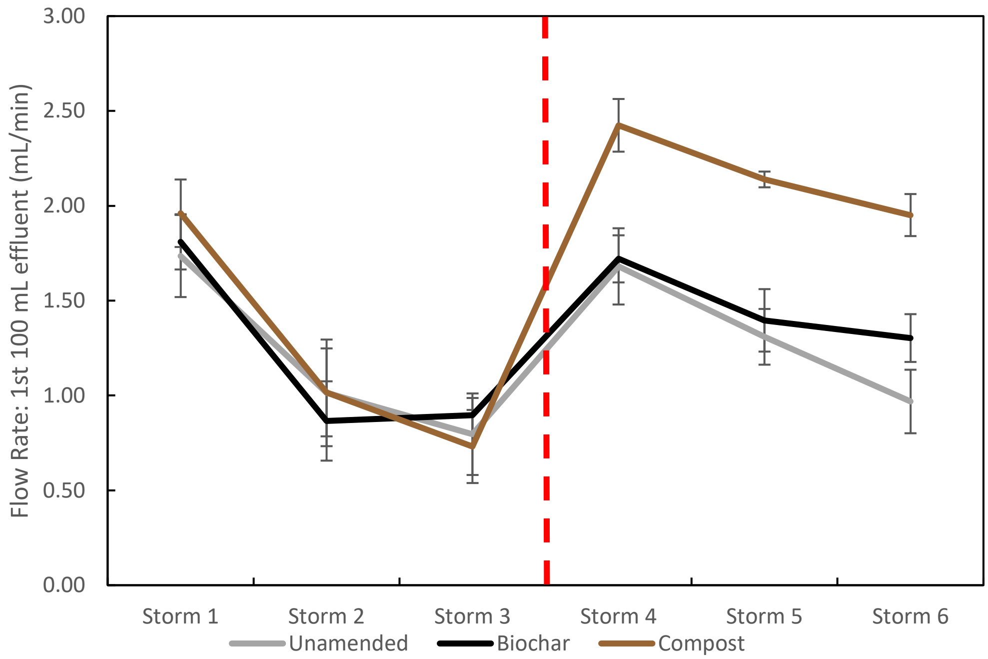


Figure 3-3: Average effluent flow rates, for all columns over entire six-storm series, by treatment type. Error bars represent standard error (n=8 except in for unamended soils in Storms 2, and 3, when one column did not produce 100 mL of effluent; for those data points, n=7). Columns repacked between Storm 3 and 4.

3.3 Nutrients

3.3.1 Nutrient Leaching Test

When agitated in a slurry of deionized water, all soils and amendments leached measurable nitrogen. Nitrate comprised the majority of the measured nitrogen in all supernatant samples (Table 3-2), though some natural soils and both the fresh and aged biochar samples also contained detectable ammonium. Phosphate and total phosphorus were also present but far less abundant than the nitrogen species in all samples. Except for the ammonium species, aged biochar leached less nutrients than fresh biochar. Aged biochar data derived from unpublished work by Rossetti (2019).

Table 3-2: Average mass of nutrients leached from 3 g. soil sample (mg)

	PO_4-P	Total P	NO_3-N	NH_3-N	Total N
Biochar	.171	.176	.315	.011	.380
Aged biochar	.041	.056	.162	.037	.250
Compost	.100	.110	.600	.000	.460
North soil	.003	.006	.763	.000	.724
South soil	.005	.008	.486	.060	.788
East soil	.000	.004	.220	.000	.622
West soil	.001	.005	.325	.104	.262

The masses of nutrients per mass of soil mixture component in Table 3-2 were then used to estimate the total leachable nutrients within in each soil column (Figure 3-4). Total leachable nitrogen ranged from 27.3 mg to 126.9 mg per column. In many cases, leachable nitrate was calculated to be higher than total nitrogen, indicating both some degree of experimental imprecision and also the likelihood that no other nitrogen species were likely to leach to a significant degree during any storm event. However, in the southern and western soils, where more ammonium was detected (up to an estimated 17 mg in one column), the possibility that ammonium would leach from the soil during synthetic storm events was considered more relevant to the interpretation of effluent nitrogen measurements.

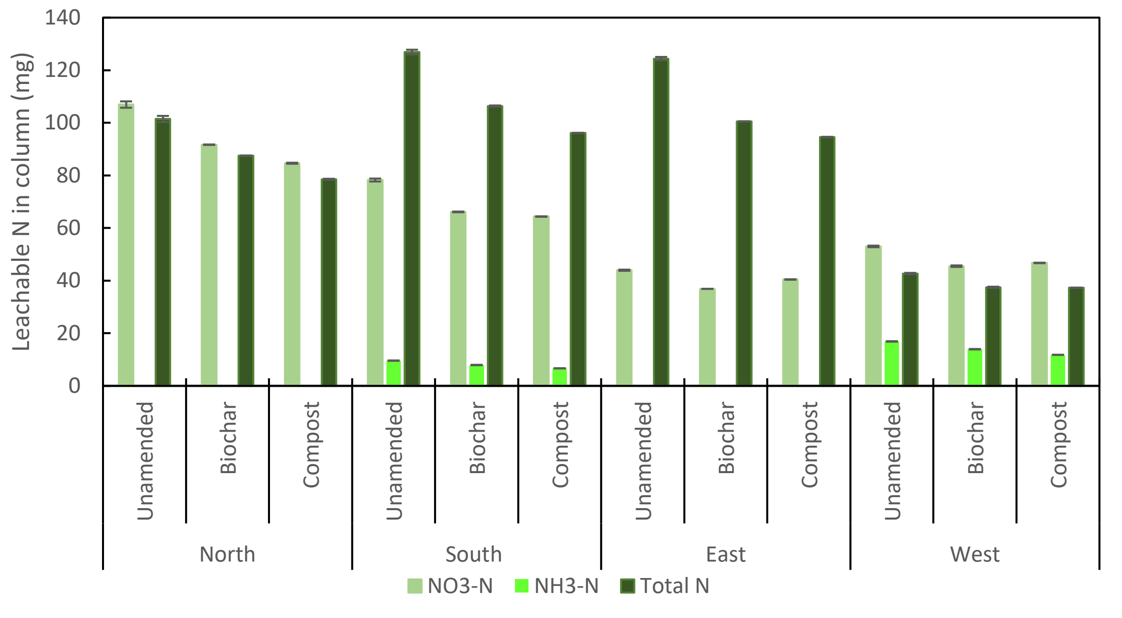


Figure 3-4: Average total mass of leachable nitrogen species in soil columns prior to storms. Error bars represent standard error (n=2).

In contrast, amended soils were calculated to contain more leachable phosphate and total phosphorus than unamended soils in all regions (Figure 3-5). While biochar leached more phosphorus than compost on a mass-per-mass basis, a greater volume of compost than biochar was incorporated into their respective columns, based on each product's different design and application specifications. Thus, total leachable phosphate was calculated to be higher in compost columns than biochar columns, which presents a notable drawback when considering regulations specifically limiting phosphorus runoff from new construction and development projects, including road construction.

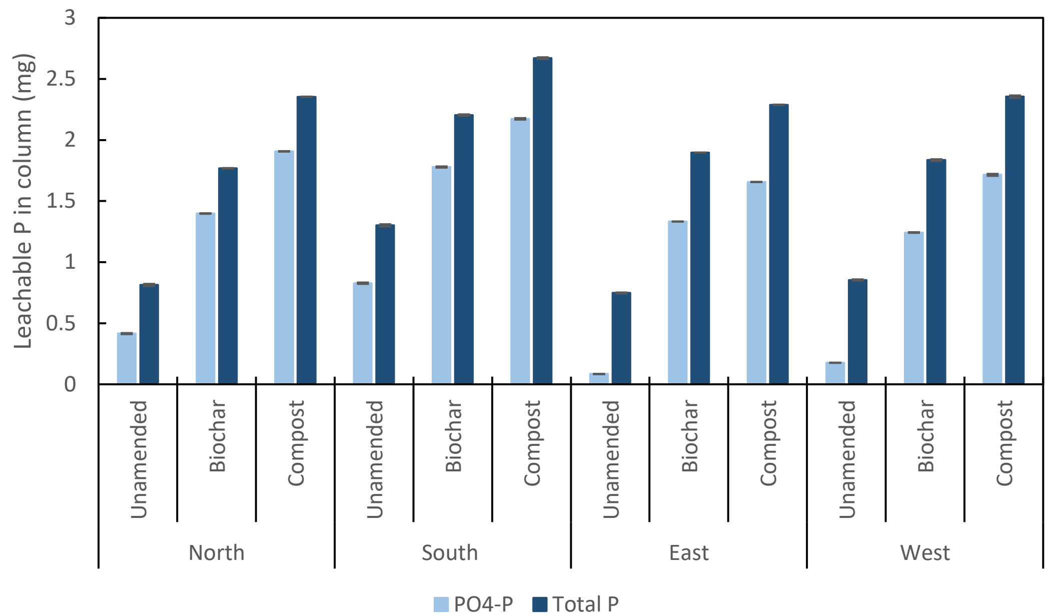


Figure 3-5: Average total mass of leachable phosphorus species in soil columns prior to storms. Error bars represent standard error (n=2).

3.3.2 Effluent nitrogen

Nearly every effluent sample, across all treatments and regions, contained higher concentrations of both nitrate and total nitrogen than the synthetic stormwater, which contained 2 mg/L NO_3-N. This indicates that the leachable nitrogen species present in the soil continued to enter the effluent stream throughout the entire six-storm series.

Among all 144 effluent samples, only 6 showed a net decrease in nitrate concentration as compared to the influent, with the lowest measuring 1.11 mg/L NO_3-N. The highest concentration among all samples was 46.6 mg/L NO_3-N, an increase of 2230%. Two-factor analysis of all samples found that trends could be statistically linked to either region (p=1.4E-05) or soil treatment type (p=1.7E-06), with unamended soils producing the greatest influent-to-effluent increase in nitrate concentration, while compost-amended soils produced effluents with the smallest average increase (Table 3-3). Paired t-test analysis comparing each treatment’s performance to unamended soils within each region revealed that the lower nitrate concentration in compost-amended soil effluent was statistically significant in the north (p=3.2E-04), south (p=4.6E-02), and east (p=4.3E-02) regions, but not in the west region. Nitrate in biochar-amended soil effluent was not significantly different from unamended soil effluent in any region. These trends correspond with the calculated leachable nitrate initially present in each soil mixture, which was also highest for unamended soils and lowest for compost soils.

Table 3-3: Average effluent NO_3-N concentration (mg/L)

	North	South	East	West	All columns
Lowest	1.3	2.5	1.1	3.5	1.1
Highest	39.7	30.0	46.6	21.3	46.6
Mean: unamended soils	25.3	13.2	14.0	12.7	16.3
Mean: biochar soils	23.8	10.4	8.9	12.0	13.8
Mean: compost soils	8.5	6.0	3.3	10.2	7.0

In most cases, nitrate concentrations in the effluent decreased over the course of the first three storms, then spiked following the repacking procedure between Storm 3 and Storm 4, before decreasing again by the sixth and final storm. Due to retention of moisture within the soil columns during and after storm events, total effluent volumes were less than the 250 mL of synthetic stormwater introduced during each event. As a result, the ratios of effluent to influent nitrate mass for each column were lower than the corresponding concentration ratios, but the trends observed were consistent: nitrate masses tended to decrease over the first three storms, increase markedly for the fourth storm following repacking, and then decrease again for the remainder of the series.

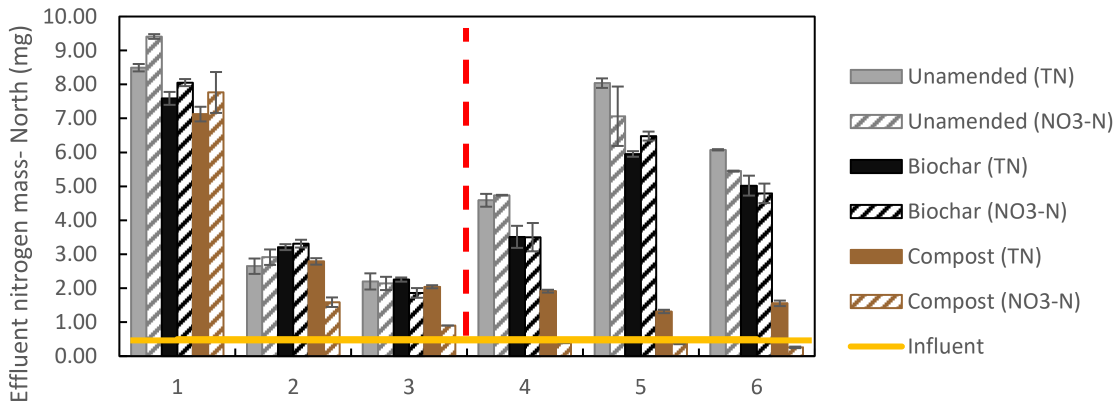
Considering the data in terms of mass, the results still show considerable leaching of nitrate from most soils. Effluent nitrate mass ranged from 0.26 mg NO_3-N (a decrease of 48.4% from each storm's influent mass of 0.5 mg) to 9.4 mg NO_3-N (an increase of 1780% from the influent mass). Unamended soil columns averaged a 540% increase in NO_3-N, while biochar-amended columns averaged a 440% increase and compost-amended columns averaged a 300% increase (Table 3-4).

Table 3-4: Average effluent NO_3-N mass (mg)

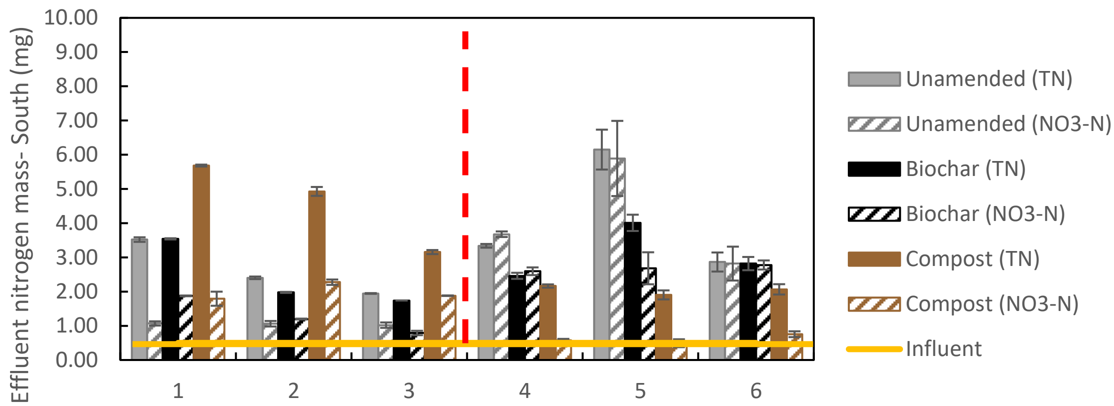
	North	South	East	West	All columns
Lowest	0.3	0.5	0.3	0.8	0.3
Highest	9.4	5.9	6.5	4.4	9.4
Mean: unamended soils	5.3	2.6	2.4	2.6	3.2
Mean: biochar soils	4.7	2.0	1.7	2.4	2.7
Mean: compost soils	1.9	1.3	0.7	2.1	1.5

Despite the nitrate-leaching tendencies of these mixtures, there were a number of cases where a net reduction in nitrate mass took place, indicating that some of the mixtures do have a capacity for nitrate immobilization. Overall, there were 17 instances out of 144 total samples in which effluent mass of nitrate was lower than influent mass of nitrate. All but one came from compost-amended soil columns. The compost-amended columns also tended to demonstrate the greatest reduction in leaching as the series progressed (Figure 3-6).

Analysis of total nitrogen (TN) in effluent samples indicates a less-clear picture of compost amendments' effectiveness in controlling nitrogen runoff. Overall trends in terms of both soil texture and storm series progression look similar to nitrate output (Figure 3-6), and two-factor analysis still finds significant differences across both soil region (p=2.8E-05) and, to a lesser degree, treatment (p=0.03). However, paired t-test analysis within each region found that compost only demonstrated a significant improvement over unamended soil in the north region (p=.003). Biochar-amended soil effluent was significantly lower in total nitrogen than unamended soil effluent in the north (p=.035), west (p=.044) and south (p=.047) regions as well. Neither treatment demonstrated statistically better performance in the east region.



(a)



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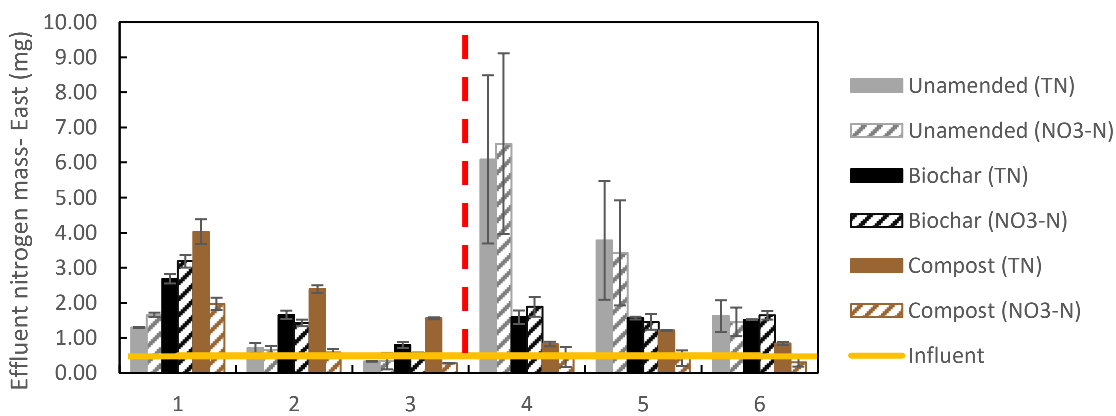
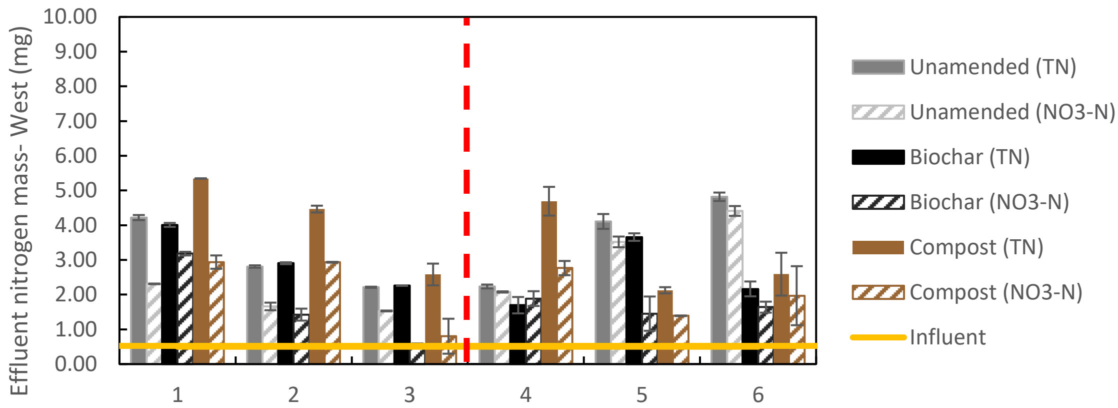


(c)

Figure 3-6: Average mass of total nitrogen in north (a), south (b), and east (c) regional soils. Error bars represent standard error (n=2 except for eastern regional soil for storm 3, where effluent volume from one column was insufficient for analysis, so n=1). Columns repacked between Storm 3 and 4.



(d)

Fig 3-6 (continued): Average mass of total nitrogen and nitrate over 6 storm events for (d) west regional soil types. Error bars represent standard error (n=2). Columns repacked between Storm 3 and 4.

The differences between total nitrogen mass and nitrate mass are particularly notable in the cases of the compost-amended soils that showed a net reduction in nitrate. In none of these cases was there a net reduction in *total* nitrogen; in fact, whenever effluent nitrate mass was reduced from the influent, this mass accounted for 50% or less of the total nitrogen mass detected (Appendix D). Thus, even though soils amended with compost show evidence in some cases of removing or immobilizing nitrate from stormwater, other transportable nitrogen species are more abundant in those same samples. However, those species are unlikely to include ammonium, as nearly all of the samples that showed a large gap between nitrate and total nitrogen came from the north and east regional soils, where no ammonium was detected in the soil leaching test.

3.3.3 Effluent Phosphorus

Effluent phosphate concentrations were lower than the influent concentration of 3 mg/L PO_4-P in the vast majority of samples, indicating moderate to high phosphate removal rates and minimal phosphate leaching. Phosphate was undetectable by ion chromatography in several of the samples in the first storm, representing 100% reduction. The highest phosphate concentration was measured as 3.5 mg/L, a 17% increase from the influent, but only three out of all 144 samples showed an increase.

All soil treatments showed an average net reduction in phosphate concentration (Table 3-5). Two-factor analysis of each soil mixture's behavior suggests that both soil region (p=4.3E-14) and treatment (p=2.1E-34) have a statistically significant bearing on the magnitude of phosphate removal. Unamended soils and biochar-amended soils both reduced average phosphate concentration by greater than 70%, while compost-amended soils showed an average phosphate reduction of 37%. Single-factor analysis for the entire data set also indicated that the unamended columns outperformed both the biochar (p=4.1E-4) and compost-amended (9.7E-14) columns to a significant degree, and that biochar significantly outperformed compost on average (p=2.9E-15).

Among the samples from unamended soils, effluent phosphate concentrations were fairly consistent across the four regions during each storm, with averages ranging from 0.62 mg/L to 0.67 mg/L regardless of texture. However, both biochar- and compost-amended soils varied more widely across the regions. Both types of amended soils from the north and south regions produced 30-60% higher effluent phosphate concentrations than those from the east and west regions (Table 3-5). These were the two regions with the most leachable phosphate present in the columns prior to the storm series.

Table 3-5: Average effluent PO_4-P concentration (mg/L)

	North	South	East	West	All columns
Lowest	0.17	0.00	0.23	0.23	0.00
Highest	3.11	3.47	1.82	1.85	3.47
Mean: unamended soils	0.67	0.66	0.62	0.66	0.65
Mean: biochar soils	0.95	0.98	0.61	0.64	0.79
Mean: compost soils	2.51	2.64	1.30	1.07	1.88

Effluent phosphate concentrations generally did not follow any notable trending pattern throughout the series of storms. After the repacking procedure between storms 3 and 4, the compost-amended soils experienced fairly sharp increases in phosphate (between 22% and 44%), while the other soil treatments did not show significantly different levels of phosphate removal after repacking.

In terms of calculated PO_4-P mass in effluent, all soils showed a net removal of phosphate, even those with the highest effluent concentrations. The greatest calculated effluent phosphate mass of 0.62 mg still represents a reduction of 17.3% compared to influent phosphate mass. Unamended and biochar-amended soils both removed approximately 80% of influent phosphate mass on average, and compost removed approximately 50% (Table 3-6). As with phosphate concentration, phosphate mass was more consistent across regions in the unamended soils than both types of amended soil.

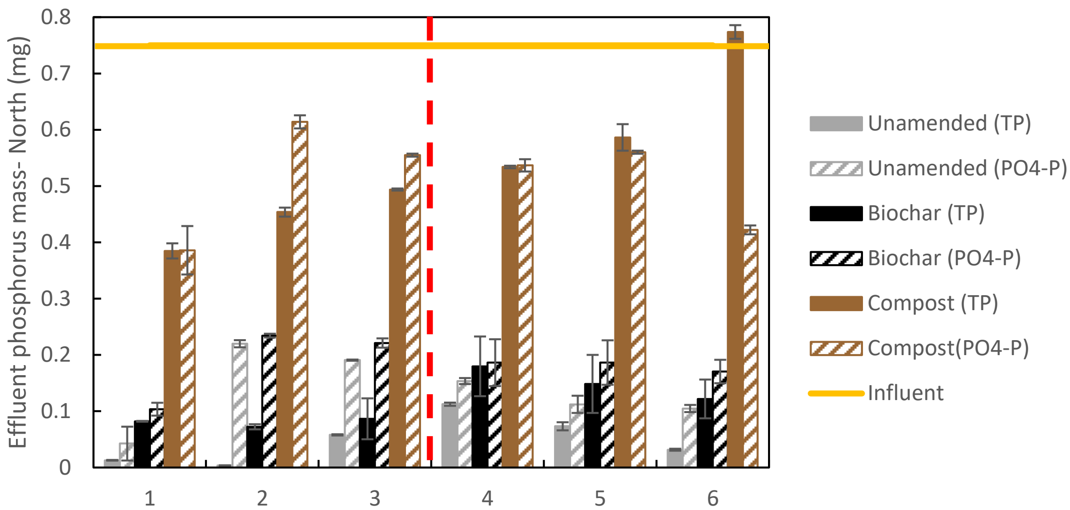
Table 3-6: Average effluent PO_4-P mass (mg)

	North	South	East	West	All columns
Lowest	0.04	0.0	0.03	0.05	0.00
Highest	0.61	0.60	0.34	0.36	0.61
Mean: unamended soils	0.14	0.13	0.11	0.14	0.13
Mean: biochar soils	0.18	0.20	0.12	0.13	0.16
Mean: compost soils	0.51	0.54	0.25	0.22	0.39

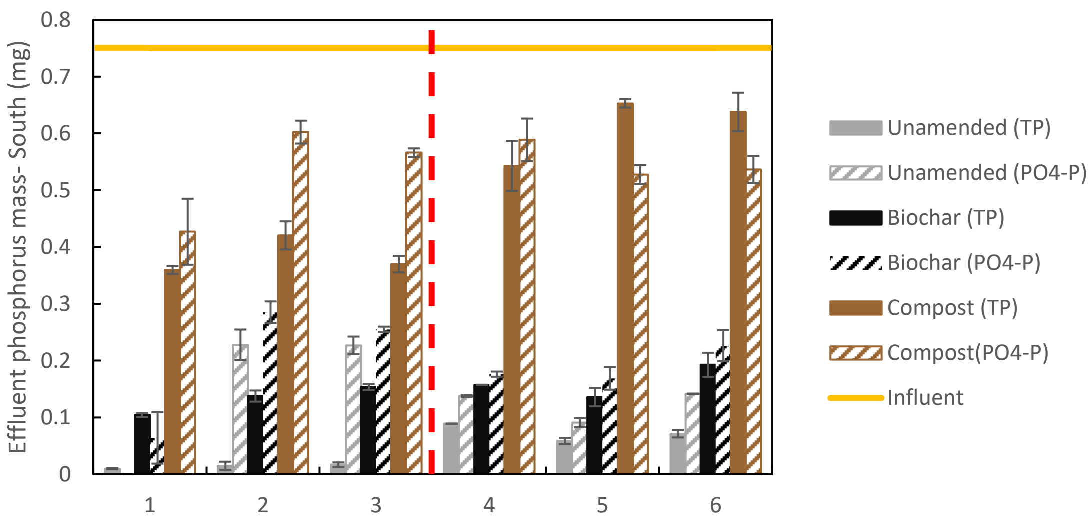
No major spike in effluent phosphate mass was exhibited following the repacking procedure after Storm 3, except in the western regional soils, where PO_4-P mass increased (as compared to the previous storm) by 33% in the compost-amended soil while decreasing in the other two soil mixtures. Effluent phosphate mass did not follow any other significant trends over the course of the storm series (Figure 3-7).

Total phosphorus output followed similar patterns to the phosphate output; effluent concentrations were lower than influent concentrations in all but 10 samples (all from compost-amended soils) out of 144 total samples. Effluent phosphorus masses were lower than influent masses in all but two samples.

Overall, when considering both the concentration and mass of all phosphorus species, the compost-amended soils consistently performed the worst, and removed less phosphorus (or leached more) on average during the second half of the series than the first. In comparison, the unamended and biochar-amended soils demonstrated significant phosphorus removal both before and after repacking procedures, with no clear indication of either improving or diminishing performance over time (Figure 3-6).

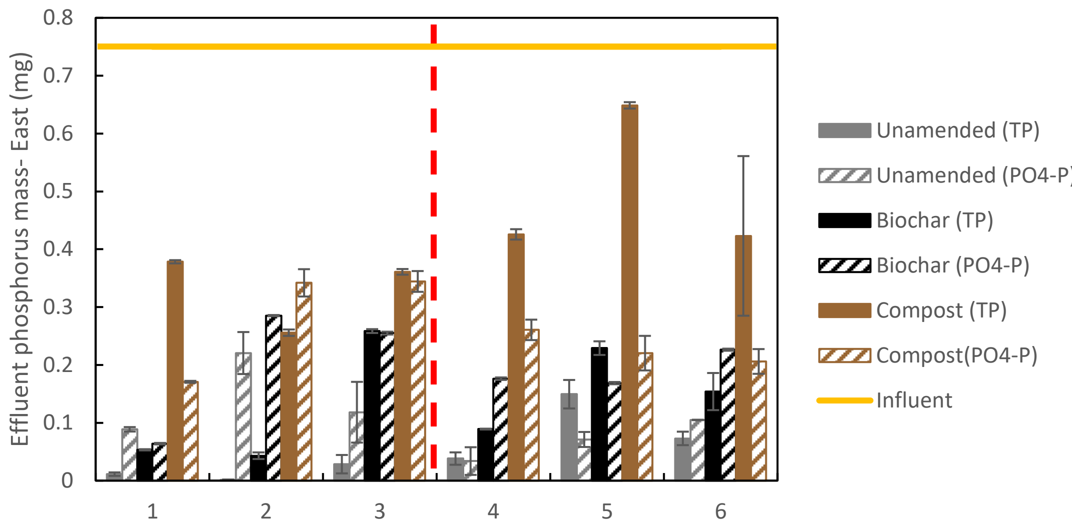


(a)

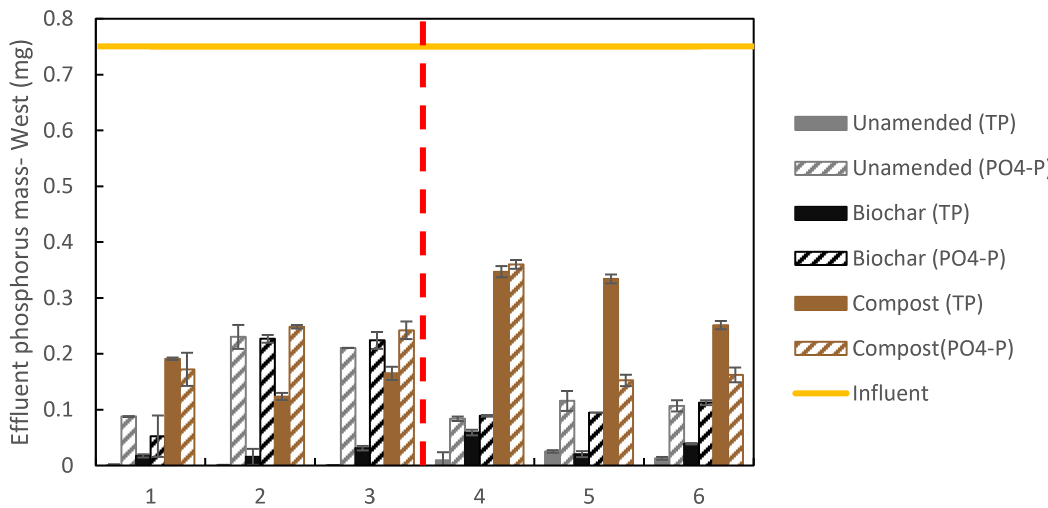


(b)

Figure 3-7: Average mass of total phosphorus and phosphate over 6 storm events for north (a) and south (b) regional soils types. Error bars represent standard error (n=2). Columns repacked between Storm 3 and 4.



(c)



(d)

Fig 3-7 (continued): Average mass of total phosphorus and phosphate over 6 storm events for (c) east and (d) west regional soil type. Error bars represent standard error (n=2). Columns repacked between Storm 3 and 4.

3.4 Organic Carbon

Effluent from unamended and biochar-amended soil columns contained less than 50 mg/L of organic carbon in all regions for all storm events. Compost-amended soil columns generated significantly more, especially during the earliest storms, when many effluent samples exceeded 200 mg/L and were as high as 359 mg/L in one case (Table 3-7). For the very first storm, unamended soils averaged 14.1 mg/L, biochar soils averaged 7.7 mg/L, and compost soils averaged 294.2 mg/L.

The organic carbon flushed out of the compost decreased rapidly over the course of the storms but still remained high compared to the other two soil mixture types. By the final storm, the compost-amended columns had decreased in organic carbon output by more than 100%, for an average output of 132.5 mg/L, while unamended- and biochar-amended columns had increased slightly but still both remained below 20 mg/L.

Table 3-7: Average effluent organic carbon concentrations (mg/L) at beginning and end of storm series

	Storm 1	Storm 6	Percent change, entire series
Unamended	14.1	17.7	+25%
Biochar	7.7	13.0	+68%
Compost	294.2	132.5	-55%

3.5 Transport of Solids

3.5.1 Turbidity

Effluent turbidity was mostly influenced by soil region (p=1.6E-34), with the northern and southern regional soils producing the least-turbid effluents and the eastern regional soil producing the most-turbid. Soil treatment also affected turbidity to a significant degree (p=2.5E-03) when considering performance across all regions; compost-amended soils produced the most turbid effluents in all regions, and single-factor analysis finds this distinction significant in the north (p=2.7E-05), south (p=4.4E-04) and west regions (p=6.0E-06). Biochar-amended and unamended soils did not have significantly different turbidity readings in any single region.

None of the soil region or treatment variations demonstrated a clear trend in increasing or decreasing turbidity over the six-storm series (Figure 3-8).

Table 3-8: Average effluent sample turbidity (NTU's)

	North	South	East	West	All columns
Lowest	4.11	3.23	51.9	2.60	2.60
Highest	59.4	88.6	880	321	880
Average: unamended soils	20.4	15.1	343	48.7	106
Average: biochar soils	18.7	18.1	527	70.3	158
Average: compost soils	42.7	57.2	625	175	225

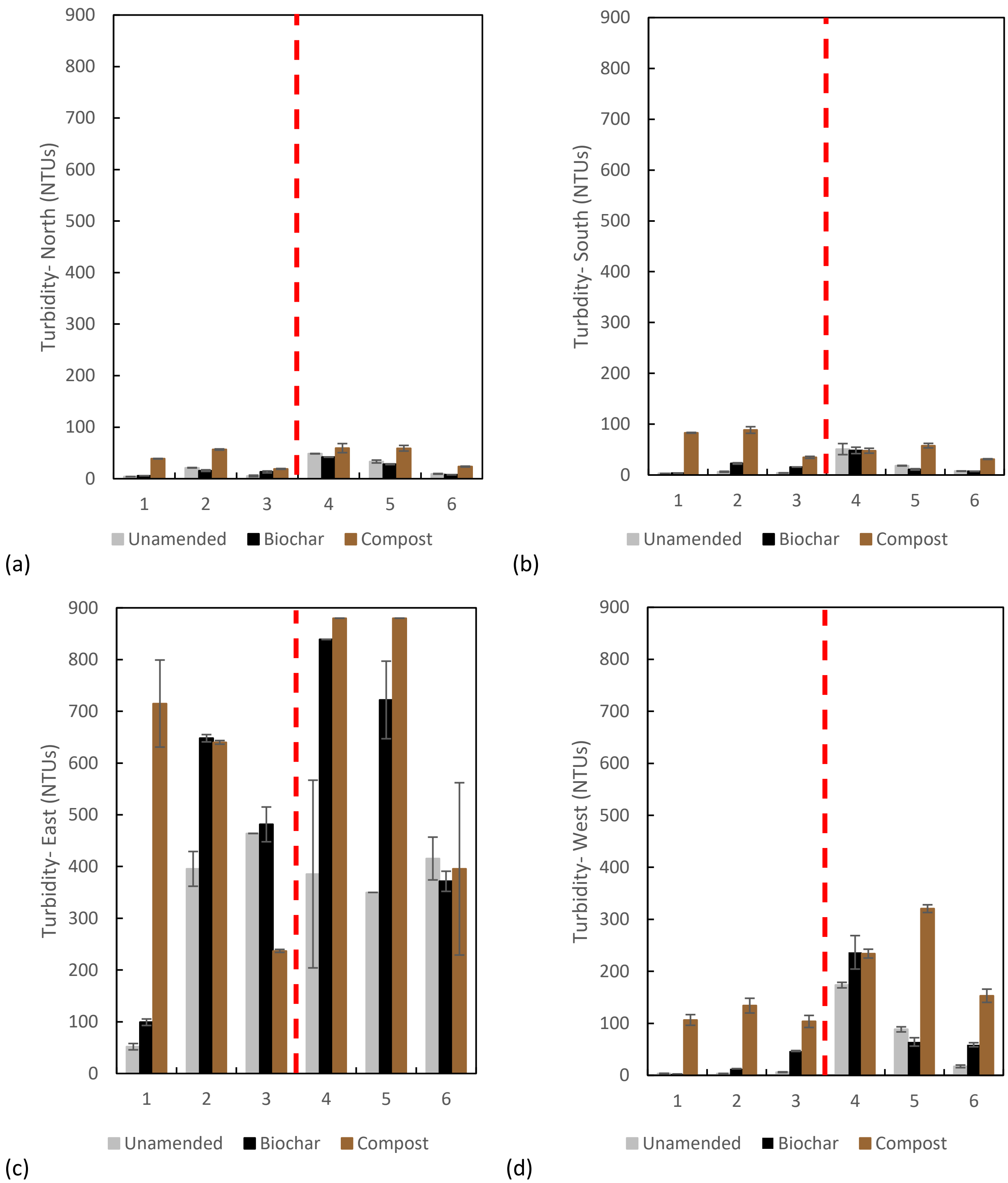


Fig 3-8: Average effluent turbidity measured in Nephelometric Turbidity Units (NTUs) over 6 storm events for (a) north, (b) south, (c) east, and (d) west regional soil types. Error bars represent standard error (n=2 except in east region, unamended soil in Storm 3, where n=1 due to one sample's effluent volume insufficient for analysis; east region, biochar and compost soil, Storm 4 and east region, unamended and compost soil, Storm 5, where n=1 due to one sample's reading exceeding the upper readable limit of the meter). Columns repacked between Storm 3 and 4.

3.5.2 Suspended solids

Region of origin was a significant (p=9.4E-04) predictor of mass of effluent suspended solids when considering all samples; the eastern soils' effluents were highest in suspended solids, with an average of 68.7 mg when considering all treatments throughout the series. Western soils averaged 54.1 mg, northern soils averaged 44.4 mg, and southern soils averaged 33.1 mg.

Soil treatment type did not produce significantly more or less suspended solids across all samples. In only one case in the southern region, a single-factor T-test found that biochar-amended soils were associated with significantly higher solids than unamended (p=1.1E-02). Otherwise, neither soil amendment demonstrated better or worse performance in terms of suspended solids in effluent samples (Table 3-9).

Table 3-9: Average mass suspended solids in effluent (mg)

	North	South	East	West	All columns
Lowest	7.05	7.40	10.9	12.1	7.05
Highest	121	80.65	122	240.5	240.5
Average: unamended soils	53.4	28.2	55.3	48.0	46.2
Average: biochar soils	37.4	35.8	68.8	38.6	45.1
Average: compost soils	42.5	35.2	82.0	75.8	58.9

Most columns sharply increased their transport of suspended solids following the repacking procedure between Storm 3 and Storm 4, but decreased again by the conclusion of the series (Figure 3-9). In fact, all samples from the northern, southern, and western regions generated less solids in Storm 6 than they did in Storm 1. All three eastern regional soils generated more solids in Storm 6 than in Storm 1.

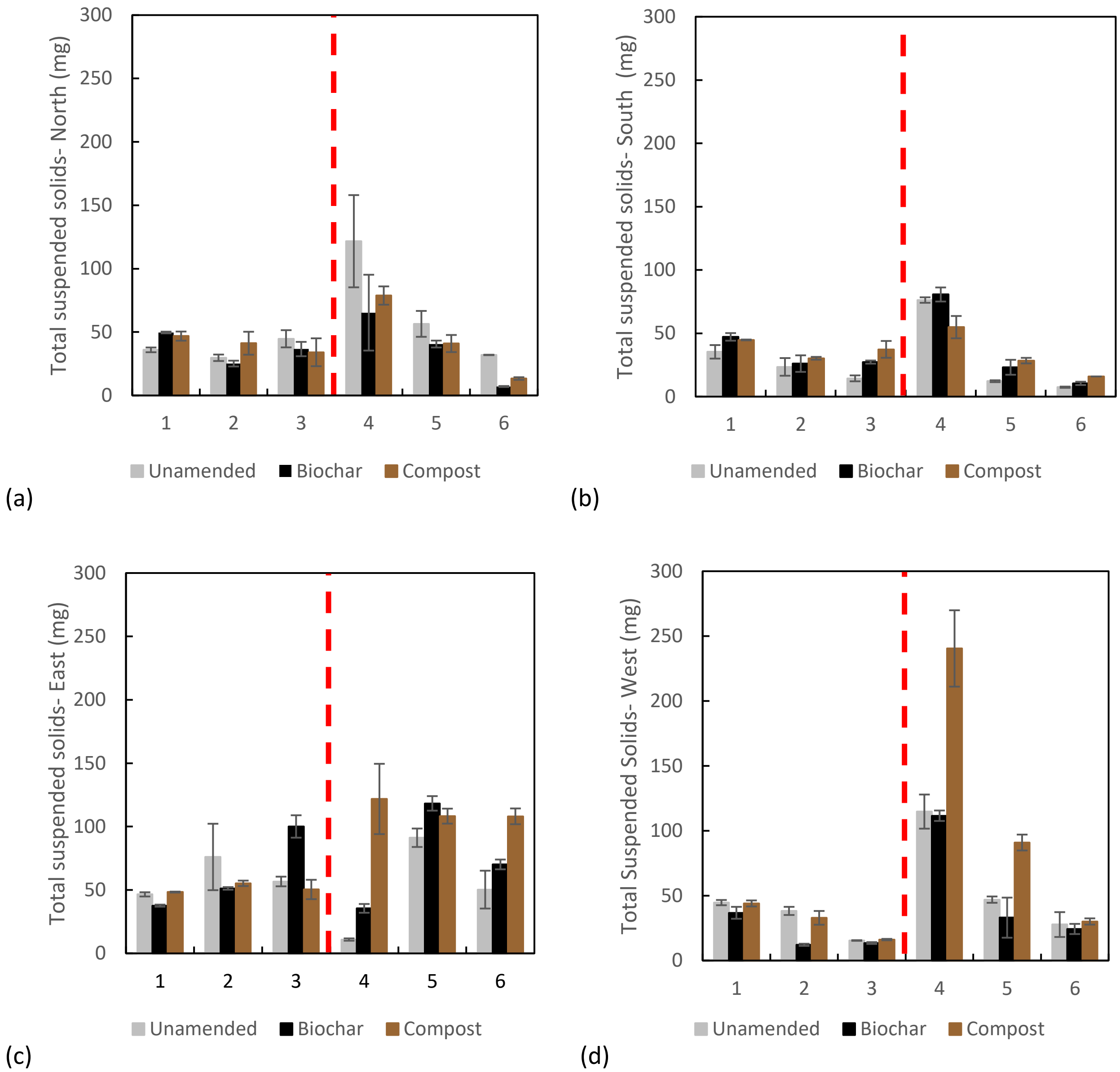


Fig 3-9: Average mass of suspended solids over 6 storm events for (a) north, (b) south, (c) east, and (d) west regional soil types. For east region (c) during Storms 2 and 3, one control column did not completely infiltrate, so filterable effluent volume was considerably less than other columns. Error bars represent standard error (n=2). Columns repacked between Storm 3 and Storm 4.

3.6 pH and Electrical Conductivity of Effluent

While the pH of the influent stormwater was measured as a slightly basic 7.43±.05, effluent pH measurements from the first storm were fairly acidic, ranging from 4.77 to 5.78, with unamended and biochar-amended soils the most acidic and compost-amended soils more neutral in all four regions for the first phase of the experiment, Storm 1-3. During this phase all treatment types became less acidic, on average, with each storm (Figure 3-10).

Repacking caused the effluent samples to return to more acidic conditions during Storm 4; the mean pH for all columns was 5.22 for this storm. However, treatment-based differences were no longer evident. For the second phase, Storm 4-6, average pH was not significantly different for any treatment type. During this phase, all columns' effluent samples again became less acidic with each storm.

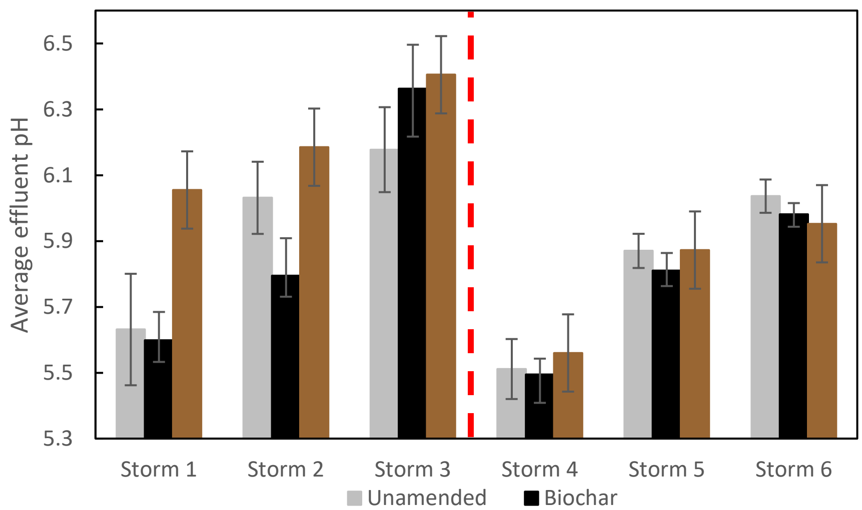


Figure 3-10: Average pH across among all soil types for six-storm series, by treatment. Columns were repacked between Storm 3 and 4. Error bars represent standard error (n=8).

Similarly, compost-amended columns demonstrated higher average electrical conductivity during the first phase, Storm 1-3, than the other two treatment types. Conductivity for the first storm ranged from approximately 400 µS to over 1000 µS, but this value decreased by at least half in all but three columns by the third storm. After repacking, no significant treatment-based difference was evident for Storm 4-6 (Figure 3-11).

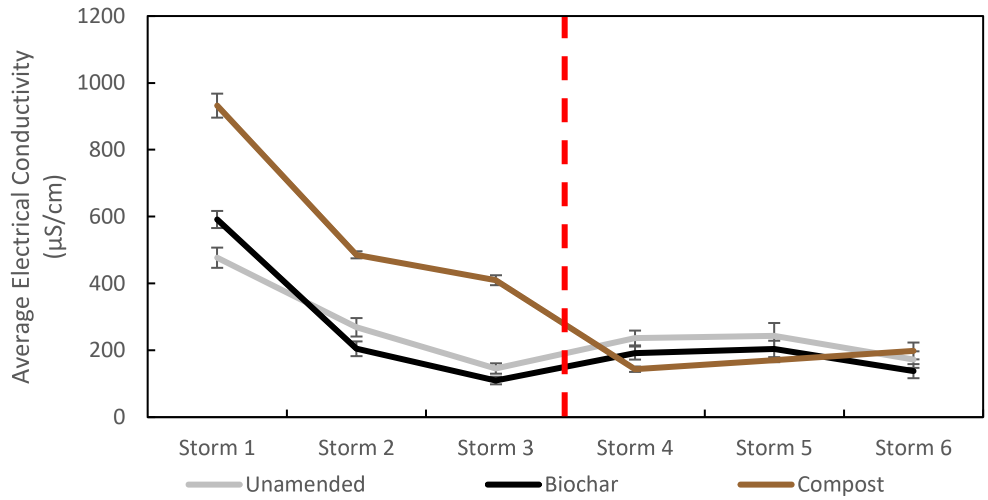


Figure 3-11: Average effluent electrical conductivity (µS/cm) among all soil types for six-storm series, by treatment. Columns were repacked between Storm 3 and 4. Error bars represent standard error (n=8).

3.7 Cost Considerations

Bulk orders of LeafGro compost are available for a retail price of $38.00 per cubic yard at a facility affiliated with its producer (RELS Landscaping, 2019), giving this product an application cost of approximately $0.42 per square foot of surface area to incorporate 30% compost by volume into the top 12” of soil.

SoilReef Biochar costs approximately $395.00 for a 2-cubic yard bulk tote (The Biochar Company, 2016). Application to the top 12” of soil at a 4% mass rate would require 3.3 pounds of biochar per square foot of surface area. With a biochar density of approximately 23.1 pounds per cubic foot, this means roughly a 14% volumetric rate, giving this treatment a cost of approximately $1.05 per square foot, about 2.5 times that of compost. Cost estimates do not include shipping or tax. See Appendix E for detailed cost estimate breakdown.

Assuming a road-to-tillage area ratio of 4.2:1 (equivalent to the dimensions of the Delaware field site referenced in this study), the cost of each amendment per treated area can also be calculated. For biochar, the initial required capital is approximately $10,800 per acre treated. Compost application would cost approximately $4,350 per acre treated. Annual maintenance costs are expected to be low for both treatments. Lifespan of compost varies depending on source material, and lifespan of biochar is uncertain.

By this measure, both soil amendments' application costs are within the range of other engineered BMPs in Virginia as catalogued by the Chesapeake Assessment Scenario Tool's cost-estimate database. CAST's estimates for initial capital required to construct stormwater BMPs in Virginia range from approximately $4,000-$30,000 per acre treated and are detailed in Table 3-10 (Chesapeake Assessment Scenario Tool, 2016).

Table 3-10: Cost estimates for developed-area BMPs as compiled by Chesapeake Assessment Scenario Tool

	Lifespan (years)	Initial capital ($/acre treated)	Annualized cost over lifetime, including maintenance and operation ($/acre treated/year)
Dry Extended Detention Ponds	50	4223.36	353.24
Filtering Practices	25	21153.22	2396.99
Filter Strip for Stormwater Treatment	10	29405.00	4481.08
Bioretention/raingardens	25	12180.62	1092.23
Bioswale	50	9912.16	892.79
Vegetated Open Channels	20	6281.00	844.15

4 Discussion

4.1 Hydrologic properties

When considering all stormwater treatment goals theorized to be achievable through the addition of compost and/or biochar to soils, the clearest indication from this data of meeting those goals is through hydrologic improvements. Biochar-amended columns retained both more moisture and more of their original soil heights than either of the other two mixture types. This offers evidence that the biochar is successfully establishing greater and more resilient porosity within the soil matrix, allowing the mixture to hold more water following complete infiltration of applied stormwater. This water-holding capacity did not diminish flow rates; on average, biochar-amended and compost-amended soils drained approximately as quickly or marginally more quickly than unamended soils. This ability for a high-volume storm to infiltrate the amended soils more readily meets a primary stormwater management goal of runoff reduction.

In one soil type, sourced from the eastern regional collection site, improving infiltration and flow rates proved to be of critical importance because of the unamended soil's extremely poor performance. Because this soil type contained the most sand—70% according to hydrometer testing and at least 45% according to the USDA profile (Web Soil Survey, 2018)—it was expected that the columns containing this soil would demonstrate superior hydraulic performance and be least likely to experience ponding prior to drainage. Instead, the eastern soil columns generally drained the slowest beginning with the first storm, and showed worsening saturated hydraulic conductivity in subsequent storms to a greater degree than the other soil types, to the extent that infiltration stopped entirely on one occasion even after being left to drain for 24 hours. These conditions were especially evident in the unamended soil. Both amended soils outperformed the unamended soils hydrologically during all six storms in the eastern soils; this was the only region where this was the case.

While hydrometer testing indicated a clay content of just 9% for this soil, USDA analysis of the soil type typically found in that location indicates a variable soil group type categorized as A/D, meaning the soil is expected to exhibit easily-infiltrated Type A characteristics when drained and poorly-infiltrated Type D characteristics when undrained (USDA, 2007). The analysis also notes the presence of a clay-sand matrix that may be inconducive to high flow rates (Web Soil Survey, 2018). At depths of 8-15 inches, the USDA reports, sand grains tend to be coated and bridged with clay. This may account for the extremely slow flows throughout the entire column, since all depth zones were homogenized prior to column packing. Clay particles may have swelled to the point of creating a damming effect in conjunction with the larger sand particles they surround.

High moisture retention for these columns may also indicate clay particle swelling. Eastern regional soils retained the most moisture by mass in all columns and all treatment types upon first being saturated. However, these columns also had the smallest degree of difference between the amended and unamended soils when it came to moisture retention. In other words, the soil itself was already trapping significantly more water than any of the other regional soils, and in this case, the retention appears to be associated with clogging of pores and disruption of hydraulic function.

When effluent eventually did drain from these soils, it tended to carry more solids than the other soils. Turbidity for these effluent samples was significantly higher than for any other region. This may simply be a function of the added residence time of water in the column, allowing more time for small soil particles to break away as stormwater passed through. Or, it may be more directly related to the positioning of the clay particles between grains of sand. Swelling of these particles may have caused many of them to become dislodged as others filled gaps in the soil matrix. While those that remained in place likely reinforced the clay-sand bridging that hindered the hydrological performance of the column, a portion of them possibly became displaced in the process, causing the high turbidity of the effluent.

All of these factors indicate easily disrupted structural stability of the soil from this location. However, both soil amendments offer some promise of preserving that stability over a series of storm events. By the sixth storm, the compost-amended eastern soil columns were one of just three mixtures with 100-mL flow times under 50 minutes (the other two with this distinction were also compost-amended, in the north and south regions). And, while the unamended and biochar-amended eastern soils demonstrated worsening hydrologic performance over both the first and second phases of the experiment, drainage from the compost-amended eastern soils did not slow down over the course of Storms 4-6. These soils were generally the most turbid, but they also showed the greatest reduction in turbidity during the two phases; they decreased dramatically from Storm 1-3 and then again following repacking, from Storm 4-6.

It appears from these results that amending this soil type with compost and/or biochar offers measurable benefits to the structural properties of the soil matrix. For this clay-bridged sand, then, the media itself and the act of tilling it into the soil may interrupt the tendency of clay particles to bind to one another or detach from the matrix entirely when stormwater causes them to swell.

While both soil amendments improved flow times on average in the eastern-region soils, only compost demonstrated this advantage in the other three regions, and by a much less significant margin. Still, it can be reasonably concluded that these results confirm that the presence of a low-density soil amendment can aid in maintaining soil matrix stability, encouraging infiltration and improving hydrologic function in soils of varying textures, which could offer particular benefits for soils with clay-sand bridging. Since compost is also a lower-cost product and outperformed biochar in this soil type, it appears to be a more appropriate treatment in this specific context, where improved infiltration must be prioritized.

4.2 Effluent nutrients

Assessing the nutrient-reduction potential of these two soil amendments is complicated by the demonstrated tendency of the natural soils themselves to leach nutrients, in particular nitrogen. In several cases, total nitrogen concentration in the effluent was as much as twenty times as high as the influent stormwater's concentration. For this reason, evaluation of biochar and compost on the basis of preventing nutrient runoff is limited to the relative performance of the amended soils as compared to the unamended soils, and as compared to their calculated leachable resident nutrient content.

Within this framework, both amendments demonstrate better outcomes in terms of total effluent nitrogen; unamended soils produced effluents with the greatest average mass of nitrogen, when considering all six storms, for every soil texture. By this same measure, compost soils produced effluents with the least average nitrogen mass.

These results are consistent with the leaching test conducted on the raw soils and the soil amendments. In every regional soil type, the compost and biochar columns were both calculated to contain less leachable nitrate than the unamended soil columns. It is important to note that this is partially a function of the lower density of these soil amendments, and by extension, the lower total dry bulk density of the soil mixtures that contain them. That is, even though the compost and biochar samples leached more nutrients than some of the field soils on a nutrient mass per media *mass* basis, they can be expected to leach less than those same field soils on a nutrient mass per media *volume* basis. Because the columns were packed to have equivalent soil heights and thus equivalent volumes, this means that the lower bulk density of the amended soils also influences the total mass of leachable nutrients present in each column, partially as a result of more of the soil column volume consisting of pore space in the amended soil mixtures.

However, comparing the results of the leaching study to the cumulative mass of effluent nitrate over the entire series of storms reveals that the compost-amended soils also tended to leach a smaller share of the total leachable nitrate that they were expected to contain (Figure 4-1). In other words, not only did the compost-amended soils contain less leachable nitrate on a nutrient mass-per-volume basis, but they also leached that resident nitrate at a lower rate than the unamended soils in the north, south, and east regions. Appendix F contains data detailing the total masses of nutrients detected in the effluent of each column over the entire course of storms.

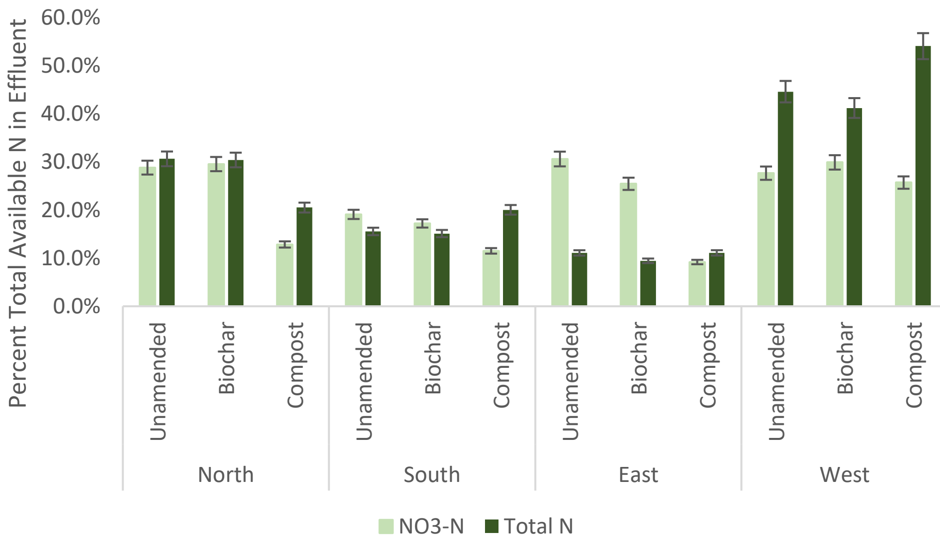


Figure 4-1: Average percent of calculated available N, including leachable and influent N, detected in effluent over six storms (cumulative)

This did not hold true for total nitrogen, however. In that case, compost-amended soils only offered better performance in the north region, while biochar-amended soils leached a somewhat smaller share of their available TN than compost in the south, east, and west regions. This shows evidence of some adsorptive mechanism on the part of the biochar that is perhaps easily disrupted by the agitation of the leaching test but more readily maintained under normal, gravity-draining conditions. In agricultural studies of biochar and soil mixtures, biochar has been found to reduce leaching of both ammonium and nitrate from the natural soils into which it is incorporated (Zheng et al., 2013). Whether the addition of biochar helps immobilize these N species in unvegetated soils is less clear.

Strictly in terms of net change in nitrate mass between the influent and effluent, the compost columns in this study generated the lowest average masses of nitrate over the entire body of data. This is particularly notable due to its large content of organic matter, presumably including nitrifying organisms, and would be expected to leach both organic nitrogen and nitrate. The earliest storms in the series fall in line with this expectation. In the south, east, and west regions, the compost-amended columns generated the highest nitrogen and nitrate masses for the first storm. In the north region, where the natural soil had the highest amount of organic matter to begin with, the unamended columns generated the most.

As the series progressed, though, the relative nitrate outputs shifted considerably. While all columns' effluents decreased in nitrate mass over the next several storms, the compost columns generally decreased the most. Then, after the columns were repacked following storm 3, most columns saw a spike in nitrate output. This phenomenon is consistent with a similar nitrate spike in other work that employed a "destructive sampling" methodology, in which soil was removed from columns, air-dried, repacked and rewetted periodically (Laird et al., 2010). Researchers theorized that this repacking action caused a burst in microbial activity leading to a sharp increase in the mineralization of organic nitrogen to ammonium, followed by nitrification to easily-leached NO_3^-.

Such a spike in nitrate did not occur in most of the compost-amended columns, though. In those effluents, nitrate concentrations generally continued to decline even after repacking. At the same time, organic carbon in the effluent decreased over the first three storms but generally stayed consistently higher in the compost columns than in the other mixtures. These conditions may indicate a high carbon-to-nitrogen (C/N) ratio, which is thought to decrease the availability of nitrogen to nitrifying bacteria (Bottomley & Myrold, 2012; Joye & Anderson, 2008). The importance of the C/N ratio is based on the idea that heterotrophic soil bacteria are nitrogen-limited at high C/N ratios and carbon-limited at low C/N ratios. At higher C/N ratios, then, nitrogen may be readily immobilized by certain heterotrophic bacteria, and thus be unavailable to autotrophic nitrifiers (Tate, 2000).

Other research has found a more complicated relationship, wherein the particular features of a soil's microbial community are an additional, perhaps more significant, factor in the rate of nitrogen immobilization in soil (Bengtson et al., 2003). Still, it may be the case that in the compost-amended columns, the repacking process accelerated immobilization by heterotrophs rather than nitrification by autotrophs. In the non-compost columns, effluent organic carbon was considerably lower than in the compost columns, indicating a likelihood of a much lower C/N ratio in the soil mixtures of those columns, and more of an opportunity for autotrophic nitrifiers to access any newly-mineralized ammonium and convert it to nitrate.

Other aspects of the nitrogen cycle become more significant under anoxic conditions. Columns that stayed saturated for the longest periods of time, including most notably the eastern regional soils, may have experienced conditions in which NO_3^- was reduced to NH_4^+ through dissimilatory reduction to ammonium (DNRA), another process by which less-mobile mineralized N species increase in fractional abundance as compared to easily-leached NO_3^-, and which is also expected to be favored at higher C/N ratios (Rutting et al., 2011). Some of the lowest effluent nitrate concentrations in this experiment occurred in the eastern regional soil during storms where drainage was the slowest and soils remained waterlogged long after other soils had completely drained. This may have led to the anoxic conditions that allow the DNRA pathway to proceed.

Prior studies of biochar's nutrient-removal capacity have found that the biochar itself may leach ammonium and/or nitrate (Mukherjee & Zimmerman, 2013), or increase leaching from native soils depending on texture and biochar preparation treatment (Borchard et al., 2012), resulting in poor total nitrogen removal. However, leaching tendencies appear to depend greatly on source material and pyrolysis temperature (Yao, 2012). Additionally, it is thought that as biochar field-ages, its ion exchange capacity increases; one study noted the sorption of both positively- and negatively-charged functional groups at various stages of biochar aging (Cheng, 2008).

Higher CEC in aged biochar increases ammonia sorption, and this tendency may prove to be significant in the western regional soils, which contained the most leachable ammonia. For these columns, biochar-amended soils' effluents contained the lowest average total nitrogen masses for all but one storm, but the length of the study was not sufficient to observe a trend towards improved or diminished performance.

Leaching test data confirmed that field-aged biochar extracted from a bioretention facility leached significantly less nitrate and total nitrogen, but more ammonia, than fresh biochar (Rossetti, 2019). It also leached less phosphate and total phosphorus. Ongoing study of these soil columns, over a longer term to simulate the effects of field aging, could reveal whether the biochar-amended soils demonstrate less leaching over time as a result of improved ion exchange capacity or other adsorptive and absorptive properties.

Phosphate and total phosphorus removal rates from synthetic stormwater show no clear evidence of improved performance in amended soils. Compost-amended columns contained the most leachable phosphorus per column and also tended to transport a larger percentage of total available phosphorus—including leachable and influent phosphorus—over the course of the entire series (Figure 4-2). Biochar-amended columns leached phosphorus species at rates statistically comparable to unamended soils.

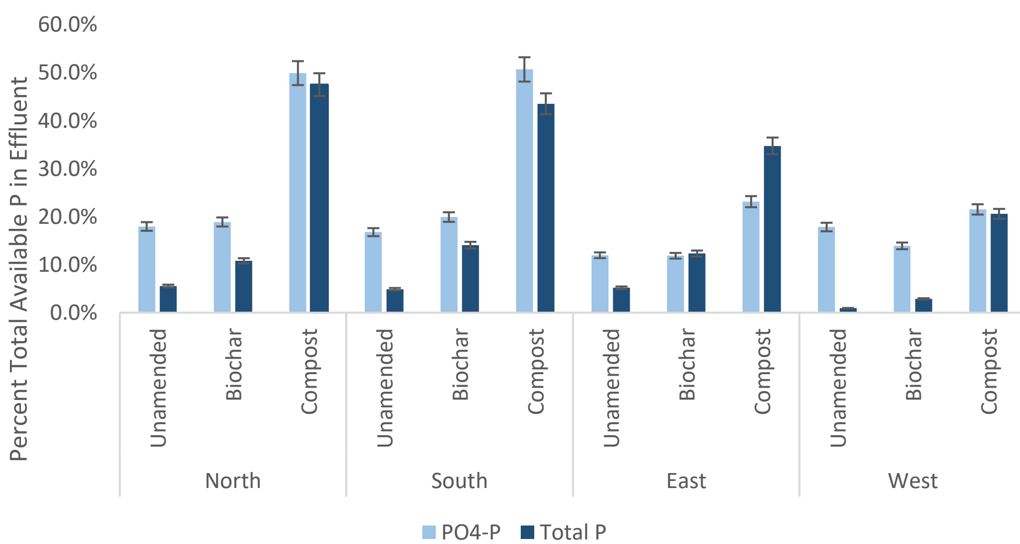


Figure 4-2: Average percent of calculated available P, including leachable and influent P, detected in effluent over six storms (cumulative)

In contrast to effluent nitrogen data, leachable resident phosphorus comprises a much smaller relative share of the total phosphorus available to enter the stormwater flows. There is evidence, though, that regional soil type has some bearing on the degree to which phosphate leaches from both biochar and compost. While the unamended soils produced nearly-equivalent phosphate outputs regardless of region of origin, the biochar- and compost-amended mixtures from the more organic-rich soils (the north and south regions) transported more phosphorus than the equivalent mixtures from the other regions. This seems to indicate that interactions between organic matter in natural soils and both amendments cause a greater share of phosphorus—from the influent and/or the soil mixture—to be transported through the effluent.

At the same time, there is no discernible downward trend in phosphorus output over time that would indicate a “flushing out” process of removing resident phosphorus from the soil. In fact, the compost-amended soils appear to have the opposite tendency, as they removed less phosphorus during the second half of the storm series in all four regions. Since phosphorus is the “keystone” nutrient regulated by the DEQ, this pattern of diminishing performance may preclude large-scale application of compost for this purpose.

There do appear to be more experimental uncertainties for the data regarding phosphorus, though. In several cases, mass of PO_4-P was measured by ion chromatography to be significantly higher than mass of total phosphorus measured by colorimetry. There are several possible causes of this uncertainty. For the ion chromatographic phosphate analysis, all anions were measured by the same process using the same calibration standards. Because of the large amount of nitrate known to be present, the calibration curve was created to cover a range up to 50 ppm. Calibration points were included below 1 ppm, but the fit of the curve is much less accurate at that low range, where most of the phosphate concentrations were read. See Appendix G for data regarding instrument calibration and verification of known standard concentrations for all nutrient tests.

Also, because the turbidity of the effluent was sometimes high, it may have interfered with the colorimetric process of the total phosphorus measurement (which used unfiltered sample). While a baseline color correction calculation was employed to adjust for color saturation prior to the molybdate reduction giving the characteristic blue color, these data for these samples could be considered less accurate than for less-turbid samples.

Filtering samples prior to analysis may introduce further uncertainty, because the mechanism for phosphate control by biochar and is thought to be chiefly through soil stability and the prevention of detachment of phosphate-containing colloidal material (Soinne, 2014). Measuring effluent samples with some colloidal material removed by filtering could produce artificially low results. Since some experimental methods required filtering and others did not, a portion of the effluent phosphorus may have gone unmeasured.

In general, neither TSS nor turbidity data indicates a clear relationship to original soil texture or soil treatment. However, when considering the regulatory goals of stormwater management, the presence of sediment in effluent that has gravity-drained as in this experiment does not necessarily indicate poor performance. While stormwater, once it has infiltrated, may subsequently enter pathways that can eventually affect overall watershed health, the immediate goal of reducing surface runoff is more significant to surface water quality in the direct vicinity of an impervious surface. By this measure, the structural improvements offered by roadside soil amendments such as biochar and compost, which encourage infiltration and may immobilize nutrients under certain conditions, are promising.

5 Conclusions and Future Work

These results indicate clear stormwater-management benefits derived from tilling in low-density soil amendments. Neither biochar nor compost demonstrates superior performance in all treatment goals across the four soil textures tested, but each treatment showed significant advantages depending on the context. On average, biochar-amended soils retained the most moisture and were least susceptible to compaction over time, and while they transported slightly more phosphorus than unamended soils, they transported far less than compost-amended soils. Compost-amended soils demonstrated the highest flow rates and transported the least nitrogen of any of the treatments, including unamended soils.

These results did not tend to differ widely by soil texture, though some textures showed the need for one treatment goal to be prioritized. For instance, the unamended sand-clay matrix found in the eastern regional soil showed the greatest tendency to lose hydraulic conductivity within just the first three storms. For this soil, compost-amending offered real improvement in this crucial stormwater management goal by draining the fastest during the second phase of the study. Since compost-amended soils also leached the least nitrogen and caused moderate net phosphorus removal, this technique appears to be a good strategy for this soil type.

On the other hand, for a soil such as the silty loam from the western region, infiltration may be less of a concern, as none of the mixtures demonstrated long-term ponding or resistance to flow. Greater attention to nutrient removal from infiltrated stormwater is warranted in this case, especially because this was the region with the most leachable ammonia present in the soil. In this case, biochar alone appears to perform a beneficial ammonia-reducing function, leading to lower total effluent nitrogen. While the short-term nature of this study makes it difficult to determine longer-term trends, this appears to be a soil in which biochar may offer the most essential improvement.

Feasibility and cost of application in the field also influence the choice of a soil amendment for stormwater management. The price of biochar, currently about 2.5 times higher than that of compost, could decrease considerably if the market grows as producers expect. And while compost can be expected to degrade over time, possibly diminishing its structural stability, biochar shows some evidence of developing higher ion exchange capacity over time, enhancing one of its proposed mechanisms for nutrient control rather than hindering it.

Because the regulatory framework for stormwater treatment prioritizes phosphorus removal, meeting this standard puts greater scrutiny on the high phosphorus output from compost. This factor alone may warrant strong consideration of biochar as an alternative to compost, especially if economic conditions move towards a smaller price disparity as industry partners predict. In addition, consideration of the cost of biochar application as compared to other existing BMPs in Virginia indicates that the initial capital investment required for biochar application is within the range of currently-used treatments; the annualized cost of biochar application would be considerably lower if it proves to be a truly one-time-application alternative. In that case, periodic deep tillage would be the only maintenance required.

To further analyze these potential benefits of biochar—improving long-term performance and lower annualized costs—additional research is necessary and should more closely approximate field conditions. First, subsequent column studies will better reflect real-world performance if columns are packed to the same bulk density as would be found along roadways. Second, testing all effluent samples for ammonia in addition to nitrate and total nitrogen will more fully illuminate aspects of the nitrogen cycle at work in the soil samples. Since few significant differences across varying soil textures were demonstrated in this study, future work could eliminate this variable entirely or perhaps limit the variation to one high-clay and one low-clay sample. Finally, using pumps rather than syringe-applied aliquots to deliver synthetic stormwater would provide a more consistent basis for calculating infiltration and drainage rates.

Further study of this nature will help determine the long-term suitability of biochar for large-scale application in Virginia as a relatively low-maintenance, minimally-engineered stormwater management strategy. For large non-point pollution sources such as Virginia's statewide network of roadways, identifying further options for treatment that can be effectively deployed in a variety of soil textures could make a significant positive impact on limiting nutrient and sediment transport to vulnerable surface waters.

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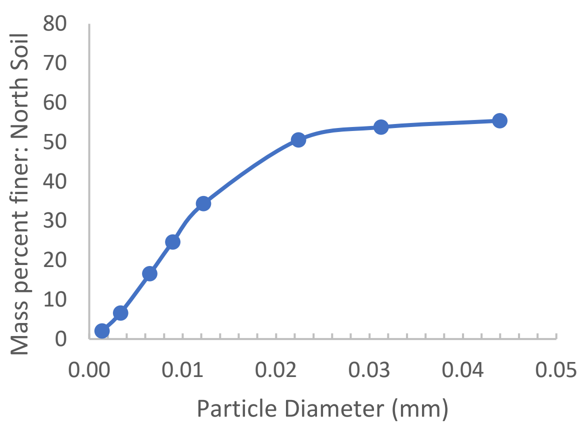
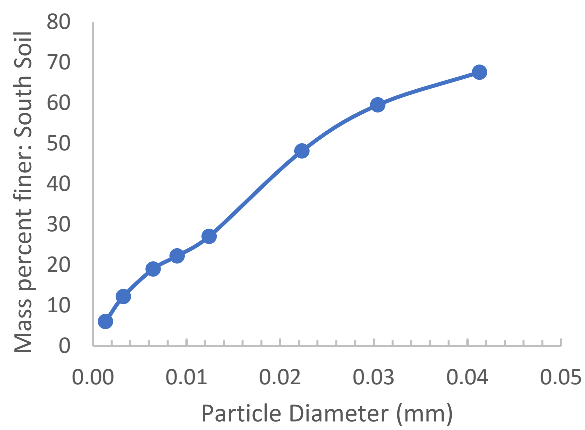
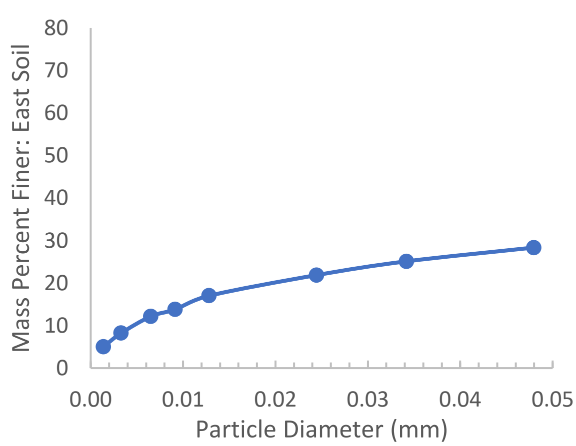
Appendices

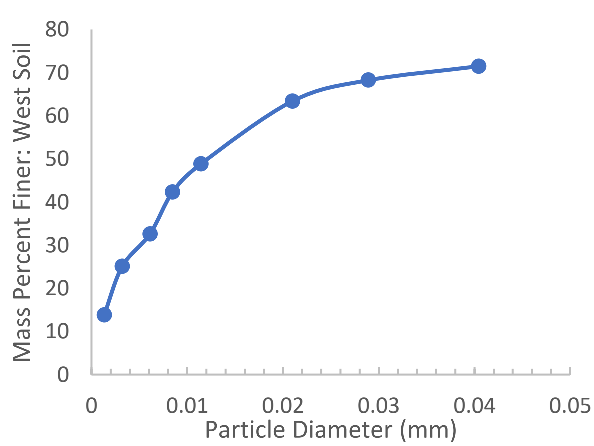
Appendix A: Hydrometer Data Curves

	North		South		East		West	
Time (m)	Particle Size (mm)	Percent Finer	Particle Size (mm)	Percent Finer	Particle Size (mm)	Percent Finer	Particle Size (mm)	Percent Finer
1	0.0440	55.38	0.0413	67.60	0.0480	28.35	0.0405	71.48
2	0.0312	53.76	0.0304	59.50	0.0342	25.11	0.0289	68.24
4	0.0224	50.53	0.0223	48.17	0.0244	21.87	0.0210	63.38
15	0.0122	34.33	0.0124	27.12	0.0128	17.02	0.0114	48.81
30	0.0089	24.62	0.0090	22.26	0.0091	13.78	0.0085	42.33
60	0.0065	16.52	0.0064	19.02	0.0065	12.16	0.0061	32.62
240	0.0033	6.60	0.0033	12.27	0.0033	8.22	0.0032	25.09
1440	0.0014	2.02	0.0013	6.07	0.0014	4.98	0.0013	13.82









Appendix B: Column Filling Specifications

		Soil Mixture Component Masses (g)		
Source	Mixture	dry mass soil	dry mass biochar	dry mass compost
North	Control	413.8	0	0
		427.8	0	0
	Biochar	352.3	18.4	0
		353.3	18.5	0
	Compost	295.7	0	48.7
		293.4	0	48.7
South	Control	487.9	0	0
		478.2	0	0
	Biochar	396.8	19.5	0
		394.6	19.3	0
	Compost	338.3	0	48.3
		337.9	0	47.8
East	Control	604.6	0	0
		595.6	0	0
	Biochar	471.8	22.3	0
		471.1	22.3	0
	Compost	421.3	0	48.2
		419.9	0	48.1
West	Control	493.0	0	0
		485.1	0	0
	Biochar	404.8	19.4	0
		397.4	19.3	0
	Compost	342.1	0	47.6
		343.4	0	48.3

Appendix C: Phosphate Color Correction

Each sample was read twice after the digestion period: once before and once after the addition of the reagent giving phosphorus the blue color detected by the spectrophotometer. The pre-reagent reading established baseline levels of coloration for each sample, which was compared to a reading of DI water taken at the same time. The difference between the two—the degree of coloration of the sample as compared to the blank before any reaction took place— was determined to be the necessary turbidity offset for each sample. This offset value was then subtracted from the final post-reagent reading in order to determine the final concentration of total phosphorus (that is, the level of coloration attributable to the phosphorus reaction as opposed to the baseline color).

Appendix D: Cost Calculations

<u>Site specifications</u>

Depth of tillage: 1 ft

Volume of soil treated per surface square foot: 1 ft^3

Assumed density of soil: 83.03 lb/ft^3

Mass of soil treated per surface square foot: 83.03 lb

Area of Delaware field site: 236.8 ft^2

	Compost	Biochar
Application rate	0.3 ft^3/ft^3	0.04 lb/lb
Unit area application weight (lb/ft^2)	N/A	3.32
Density (lb/ft^3)	N/A	23.10
Unit area application volume (ft^3/ft^2)	0.3	0.14
Bulk price as sold ($\$/yd^3$)	$38.00	$395.00
Bulk price per cubic foot ($\$/ft^3$)	$1.41	$7.31
Bulk price to apply per unit area ($\$/ft^2$)	$0.42	$1.05
Bulk price for DE site	$100.17	$248.88
Cost per acre treated	$4358.81	$10,829.99

Appendix E: Effluent NO_3-N mass as percentage of total effluent N mass

	Storm 1		Storm 2		Storm 3		Storm 4		Storm 5		Storm 6	
	Mass NO3-N (mg)	NO3-N as % of TN	Mass NO3-N (mg)	NO3-N as % of TN	Mass NO3-N (mg)	NO3-N as % of TN	Mass NO3-N (mg)	NO3-N as % of TN	Mass NO3-N (mg)	NO3-N as % of TN	Mass NO3-N (mg)	NO3-N as % of N
North control	9.31	108%	3.24	109%	2.42	95%	4.72	97%	5.83	71%	5.46	90%
	9.51	114%	2.59	111%	1.86	100%	4.75	110%	8.30	106%	5.43	90%
North biochar	7.91	108%	3.15	102%	1.66	77%	4.09	103%	6.67	114%	4.51	98%
	8.20	104%	3.47	104%	2.06	88%	2.91	95%	6.29	104%	5.08	93%
North compost	6.91	101%	1.39	52%	0.91	43%	0.38	20%	0.39	28%	0.28	17%
	8.62	116%	1.79	61%	0.90	45%	0.40	20%	0.34	28%	0.24	16%
South control	1.16	32%	1.17	48%	1.13	58%	3.56	109%	4.34	81%	3.31	102%
	0.98	29%	0.95	40%	0.91	47%	3.79	111%	7.44	107%	2.32	94%
South biochar	1.89	54%	1.21	61%	0.88	51%	2.43	104%	3.34	77%	2.64	104%
	1.86	52%	1.18	60%	0.70	40%	2.75	106%	2.02	55%	2.91	94%
South compost	2.08	36%	2.39	50%	1.89	58%	0.52	25%	0.33	19%	0.67	36%
	1.50	27%	2.16	42%	1.87	61%	0.63	28%	0.65	31%	0.84	37%
East control	1.75	133%	0.48	97%	*	*	10.18	107%	5.54	90%	1.86	83%
	1.56	123%	0.82	89%	0.67	103%	2.89	107%	1.30	94%	1.04	106%
East biochar	2.93	117%	1.56	105%	0.57	85%	1.48	113%	1.14	76%	1.76	117%
	3.43	120%	1.29	71%	0.58	64%	2.29	123%	1.76	109%	1.52	99%
East compost	2.16	48%	0.68	27%	0.44	29%	0.36	49%	0.41	33%	0.21	23%
	1.78	50%	0.48	21%	0.10	7%	0.55	60%	0.43	36%	0.39	50%
West control	2.30	53%	1.81	66%	1.55	71%	2.10	97%	3.30	87%	4.55	91%
	2.32	56%	1.51	53%	1.51	68%	2.05	89%	3.74	85%	4.27	92%
West biochar	2.86	73%	2.62	91%	1.64	73%	1.56	114%	2.85	81%	1.98	106%
	3.01	74%	2.13	72%	1.69	75%	2.16	106%	4.25	111%	2.30	93%
West compost	2.67	50%	2.92	63%	1.52	50%	2.48	60%	1.38	61%	1.12	65%
	3.21	60%	2.95	68%	0.09	4%	3.06	58%	1.40	70%	2.82	81%

Mass NO_3-N in effluent < 0.5 mg (net reduction in nitrate)

NO_3-N accounts for 50% or less of total N in effluent; other N species predominate

* Influent never fully infiltrated soil column; effluent mass invalid

Appendix F: Single-Storm and Cumulative Effluent Nutrient Content for Each Treatment

				Effluent NO_3-N (mg)						
		Leachable NO_3-N in column (mg)	Column NO_3-N + total influent NO_3-N (mg)	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6	Cumulative (entire series)
North	Unamended	106.95	109.95	9.41	2.91	2.14	4.74	7.06	5.45	31.71
	Biochar	91.68	94.68	8.05	3.31	1.86	3.50	6.48	4.79	28.00
	Compost	84.64	87.64	7.76	1.59	0.90	0.39	0.37	0.26	11.27
South	Unamended	78.26	81.26	1.07	1.06	1.02	3.68	5.89	2.82	15.53
	Biochar	66.13	69.13	1.87	1.20	0.79	2.59	2.68	2.78	11.91
	Compost	64.37	67.37	1.79	2.27	1.88	0.58	0.49	0.75	7.77
East	Unamended	43.96	46.96	1.65	0.65	0.67	6.54	3.42	1.45	14.39
	Biochar	36.88	39.88	3.18	1.42	0.58	1.89	1.45	1.64	10.16
	Compost	40.44	43.44	1.97	0.58	0.27	0.46	0.42	0.30	4.00
West	Unamended	53.01	56.01	2.31	1.66	1.53	2.08	3.52	4.41	15.51
	Biochar	45.50	48.50	2.94	2.37	1.66	1.86	3.55	2.14	14.52
	Compost	46.73	49.73	2.94	2.93	0.80	2.77	1.39	1.97	12.80

				Effluent PO4-P (mg)						
		Available PO_4-P in column (mg)	Column PO_4-P + total input (mg)	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6	Cumulative (entire series)
North	Unamended	0.08	4.58	0.04	0.22	0.19	0.15	0.11	0.10	0.82
	Biochar	1.33	5.83	0.10	0.23	0.22	0.19	0.19	0.17	1.10
	Compost	1.66	6.16	0.39	0.61	0.55	0.54	0.56	0.42	3.07
South	Unamended	0.41	4.91	0.00	0.23	0.23	0.14	0.09	0.14	0.82
	Biochar	1.40	5.90	0.06	0.29	0.25	0.18	0.17	0.23	1.18
	Compost	1.91	6.41	0.43	0.60	0.57	0.59	0.53	0.54	3.25
East	Unamended	0.83	5.33	0.09	0.22	0.12	0.03	0.07	0.10	0.64
	Biochar	1.78	6.28	0.07	0.22	0.21	0.08	0.05	0.12	0.74
	Compost	2.17	6.67	0.17	0.34	0.34	0.26	0.22	0.21	1.54
West	Unamended	0.18	4.68	0.09	0.23	0.21	0.08	0.12	0.11	0.83
	Biochar	1.24	5.74	0.05	0.23	0.22	0.09	0.09	0.11	0.80
	Compost	1.71	6.21	0.17	0.25	0.24	0.36	0.15	0.16	1.34

Appendix G: Calibration and Verification of Standards for Nutrient Tests

		Measured Values					
	Known value	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Total Phosphorus Kits (mg/L P)							
Deionized water	0.000	-0.008	0.002	0.005	-0.016	-0.003	-0.003
Influent diluted x2	1.500	1.481	1.561	1.433	1.478	1.459	1.449
Influent diluted x3	1.000	1.013	0.989	0.965	0.988	1.001	0.955
Total Nitrogen Analyzer (mg/L N)							
Deionized water	0.00	0.00	0.00	0.00	0.07	0.00	0.00
Influent	2.00	2.46	2.10	1.86	1.65	1.60	0.00
High-range standard	10.00	10.36	9.71	9.59	9.19	9.38	10.83
Ion Chromatography (mg/L NO_3 and PO_4 as ions)							
Deionized water: NO_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Deionized water: PO_4	0.00	0.28	0.35	0.29	0.40	0.39	0.37
Influent: NO_3	8.80	8.25	7.81	7.88	8.00	7.76	8.96
Influent: PO_4	9.00	8.86	9.23	8.36	8.90	9.23	8.93
Low-range standard: NO_3	0.50	0.40	0.21	0.14	0.43	0.81	0.61
Low-range standard: PO_4	1.00	0.89	1.14	1.10	1.13	1.30	1.35
High-range standard: NO_3	10.00	10.79	10.16	10.23	10.00	11.27	9.52
High-range standard: PO_4	20.00	19.97	19.54	19.51	18.13	20.19	17.77