Impact of Engineered Filter Bed Substrate Composition and Plants on Stormwater Remediation within a Rain Garden System¹

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—— Abstract —

Thirty-two rain-garden-engineered filter-bed substrates (EFBS) resulting from combinations of two substrate bases (sand and slate), two organic matter amendments [composted yard waste (CYW) and pine bark (PB)], two combination methods (banding and incorporation), and four combination amounts [2.5 cm/5%, 5.1 cm/10%, 7.6 cm/15%, and 10.2 cm/20% (by vol.)] were evaluated using three plant species (*Betula nigra* L. 'Duraheat', *Monarda fistulosa* L. and *Panicum virgatum* L. 'Shenandoah'). The impact of particle size distribution, saturated hydraulic conductivity (K_{sat}), volume of effluent, evapotranspiration, EFBS composition, and plant growth on water movement within a rain garden was determined. Sand EFBS maintained a numerically lower K_{sat} compared to slate EFBS regardless of composition. Using CYW and banding reduced effluent volume and increased evapotranspiration. Each EFBS was also evaluated for its ability to support plant growth and nutrient uptake. Shoot dry weight and shoot nutrient content (nitrogen and phosphorus) trends were similar and were highest for all species when grown in sand amended with banded CYW. Higher levels of total soluble nitrogen (TSN) were in the effluent from CYW compared to PB, regardless of substrate base. Sand generally had lower concentrations of TSN and PO₄⁻³-P present in the effluent than slate.

Index words: bioretention cell; saturated hydraulic conductivity (K_{sat}); effluent volume; effluent nutrient concentration; evapotranspiration; particle size distribution; total soluble nitrogen; ortho-phosphate; nitrate; ammonium.

Species used in this study: 'Duraheat' river birch (*Betula nigra* L.); wild bee balm (*Monarda fistulosa* L.); and 'Shenandoah' switch grass (*Panicum virgatum* L.).

Significance to the Horticulture Industry

Rain gardens are commonly installed landscape features that remediate stormwater runoff. They do so via volume reduction and contaminant removal; both of which, are impacted by the engineered filter bed substrate and plant selection. For this study, three species ('Duraheat' river birch, wild bee balm, and 'Shenandoah' switch grass) were grown in two common rain-garden-engineered filter-bed substrates (sand or slate), amended with two sources of organic matter (composted yard waste or pine bark). Composted yard waste and pine bark were added to sand and slate by one of two methods, banding or incorporation,

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in varying amounts: banded at 2.5 cm (1 in), 5.1 cm (2 in), 7.6 cm (3 in), and 10.2 cm (4 in) or incorporated at 5%, 10%, 15%, or 20% (by vol.).

The addition of composted yard waste as a band within a sand or slate engineered filter bed substrate positively impacted the hydrology of a rain garden system by reducing the outflow volume and increasing the evapotranspiration. All species had enhanced shoot growth when sand was used rather than slate. Shoot growth was enhanced for all species when composted yard waste was banded as the organic matter amendment instead of pine bark. Also, shoot nitrogen and phosphorus content were higher when composted yard waste was banded as the organic matter amendment compared to pine bark. However, with the utilization of composted yard waste, concentrations of total soluble nitrogen in the effluent were higher compared to pine bark for both sand and slate while ortho-phosphate concentrations were generally not impacted by amendment.

Introduction

In urban environments, the volume of stormwater runoff has increased due to the large amounts of impervious surfaces (roads, driveways, parking lots, sidewalks, and rooftops) that prevent infiltration of the stormwater into soil. Thus, urbanized watersheds are more open to pollution, flooding, and water shortages (Li et al. 2009). Also, as stormwater runoff moves over impervious surfaces, contaminants [nitrogen (N), phosphorus (P), zinc (Zn), copper (Cu), cadmium (Cd), lead (Pb) and total suspended solids (TSS)] are carried along and can impair water quality (Davis et al. 2001, Li et al. 2009). These contaminants can lead to algal blooms and subsequent eutrophication, which degrade surface waters.

Rain gardens, also known as bioretention cells or bioinfiltration devices, are one of the most commonly utilized stormwater control measures (SCMs) in the country to help manage water quantity and improve water quality from stormwater runoff (Davis et al. 2009, Hunt et al. 2012). Rain gardens are effective SCMs for water quality and quantity management due to their adaptability for many locations, maintenance of groundwater and base flow, surface and groundwater pollutant removal, and peak flow reduction (Davis et al. 2009). Of the many SCMs (detention basins, green roofs, constructed wetlands, or rainwater harvesting systems), rain gardens can be aesthetically pleasing and can be designed and sized to fit a multitude of applications. These SCM systems are not irrigated, are planted with vegetation, and are designed to capture runoff from contaminated stormwater. They function well for remediating and controlling contaminated stormwater because of their two main components: (1) engineered filter-bed substrate (EFBS) and (2) vegetation.

The chemical and physical composition of the EFBS is critical, as stormwater runoff moves through and is stored within the EFBS (Liu et al. 2014). Sand-based EFBS are recommended due to their suitable hydraulic conductivity and permeability (Hsieh and Davis 2005). In North Carolina, EFBS are recommended to be 75 to 85% medium to coarse washed sand, 8 to 15% fines (clay and silt), and 5 to 10% (by vol.) organic matter (NCDEQ 2017). Pine bark (PB) fines are recommended (NCDEQ 2017) and often used as the organic matter source in EFBS within North Carolina. However, recommendations vary from state to state. For example, Pennsylvania and Michigan recommend an addition of compost, 20-30% and 20-40%, respectively, for the organic material (PDEP 2006, SEMCOG 2008).

The water flow characteristics (infiltration and K_{sat}) of EFBSs are influenced by particle size distribution. Kraus et al. (2014) and Turk et al. (2014) recommend grouping EFBS particle sizes as described by Drzal et al. (1999) where coarse particles are 6.3 to 2.0 mm, medium particles are 2.0 to 0.5 mm, and fine particles are 0.5 to 0.106 mm. Kraus et al. (2014) reported that a sand EFBS should have a particle size distribution of 67% fine, 30% medium, and 2% coarse, while a coarser textured slate EFBS should have a particle size distribution of 30% fine, 48% medium, and 22% coarse. Infiltration and drainage will vary considerably with different EFBS components and change with time (Turk et al. 2014).

In addition to binding pollutants and allowing water conveyance, EFBS must support plant growth and nutrient removal from the rain garden system. A reduction in the volume of water (effluent) exiting the bottom of a rain garden positively impacts remediation of stormwater runoff volume and quality. The amount of water that can be held within the EFBS impacts plant function. Low water availability may cause lower leaf area and biomass above ground for plants in a rain garden system (Sigmon et al. 2013) and may impact plant nutrient accumulation. Also, under low soil moisture conditions, plants in a rain garden

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may have decreased stomatal conductance, which would indicate a decreased transpiration rate (Sigmon et al. 2013), reducing nutrient uptake and water return to the hydrologic cycle. The process of evapotranspiration (ET) is critical in meeting long-term hydrology goals with rain gardens (Hunt et al. 2012). Hunt et al. (2006) reported that during a oneyear study, outflow volumes from rain gardens were less than 50% of the volumes entering due to ET and exfiltration into the surrounding, existing soil. Also, the amount of water held within the plant structures may have impacted outflow volumes reported by Hunt et al. (2006). Increased ET from rain garden systems may be achieved by using types of vegetation that have long root systems, increasing opportunity for storage by the substrate and for vegetation to absorb water in between events (Hunt et al. 2012). Plants within rain gardens need to maintain growth and transpiration processes to continue positively influencing water movement within a rain garden system.

A permeable sand layer over a less permeable soil layer has been reported to increase stormwater retention within and enhance nutrient removal by the EFBS (Hsieh et al. 2007b). This substrate arrangement allowed nitrification in the well-aerated sand portion of the substrate and denitrification in the saturated, low permeable soil layer (Hsieh et al. 2007b). However, Hsieh et al.'s (2007b) experiments did not include plants. Roots of plants may be unable to grow in a saturated zone or may create macropore channels through the saturated zone, resulting in undesirable channeling or preferential flow. Layering of varying EFBS components has the potential to create an anaerobic zone within the rain garden system as shown by Hsieh et al. (2007b). An anaerobic zone occurs only when the oxygen consumption rate exceeds the rate at which it is supplied (Tiedje et al. 1984). This can promote the removal of N from the EFBS via denitrification (Tiedje et al. 1984). However, the anaerobic zone needs to be located near the bottom of the rain garden system to prevent detrimental effects on plants, such as root stress from anoxia or the favorable environment created for root pathogens (Tiedje et al. 1984).

The use of composted plant material as the organic matter source within an EFBS may provide many benefits, such as plant growth enhancement due to the plant-available nutrients, pollutant binding (complexes and cation exchange capacity), and microbial support. Palmer et al. (2013) reported that creating a saturation zone within the rain garden system greatly reduced nitrate-nitrogen (NO⁻₃-N) in effluent (71% compared to 33% without a saturated zone) when the EFBS consisted of a 60% sand, 15% compost, 15% finely shredded cedar bark, and 10% aluminum-based drinking water treatment residuals mix. While the same was not true for ortho-phosphate $(PO_4^{-3}-P)$, which was remediated better without a saturation zone (80%) compared to with a saturation zone (67%) (Palmer et al. 2013). However, nutrient load of the compost would be a concern if contaminants were exported out of the rain garden when compost is utilized within the EFBS. Liu et al. (2014) found low levels of contaminants exported when there was an incorporation (by vol.) of 25% yard waste compost added to an EFBS in combination with 3% aluminum-based drinkingwater-treatment residuals, 15% saprolite, and 57% sand. Liu et al. (2014) reported that with the addition of the 25% yard waste compost, N removal increased, possibly due to denitrification. The addition of compost has also been found to have high sorption capacities for Cd and Zn (Paus et al. 2014). However, these researchers found that an increasing volume of compost in a sand EFBS caused a significant export of P (Paus et al. 2014).

The second major component of a rain garden system, the planted vegetation, has been reported to improve the remediation of N and P from simulated polluted stormwater when compared to non-vegetated rain gardens (Bratieres et al. 2008, Read et al. 2008). Gautam and Greenway (2014) grew a variety of species [coast banksia (Banksia integrifolia L. f.), wallum bottlebrush (Callistemon pachyphyllus Cheel), pigface (Carpobrotus glaucescens (Haw.) Schwantes), blue flax lily (Dianella brevipedunculata R.J.F. Hend.), and fountain grass (Pennisetum alopecuroides (L.) Spreng.)] in gravel, loam, and sand EFBS. These researchers found that plants with the faster growth rates and larger biomass amounts retained greater amounts of nutrients in their roots and above ground structures (Gautam and Greenway 2014). Plant parts accounted for 2.7-4.3% of the total P and 8.7-17.7% of the total N retained in the rain garden system (Gautam and Greenway 2014). However, plant type (trees, shrubs, ornamental grasses, etc.) and species influences remediation of N and P as shown by Turk et al. (2016).

The EFBS, in combination with the appropriate planted vegetation make rain gardens functional and efficient at remediating contaminants and controlling outflow volumes. The main objectives of this study were to: 1) Determine the effect of different sources of organic matter amendments in rain garden EFBS and 2) Analyze different combination methods and amounts of organic matter amendments to EFBS for their impact on water movement, plant growth, and N and P remediation.

Materials and Methods

An experiment was conducted over two years 2012-2013 (trial 1) and 2013-2014 (trial 2). A factorial treatment arrangement of thirty-two engineered filter bed substrates (EFBS) resulted from combinations of two substrate bases (base), two organic matter amendments (amendment), two combination methods (method) and four combination amounts (amount). Trial 1 and 2 were conducted at North Carolina State University's Horticultural Field Laboratories, Raleigh, NC (longitude: 35°47'29.57"N; latitude: 78°41′56.71″W; elevation 136 m). Plastic containers [23 L]; 51 cm (20.1 in) tall, a top diameter of 27cm (10.6 in) and a bottom diameter of 23 cm (9.1 in) (Black Pecan King 1020, Haviland Plastic Products, Haviland, OH) were filled with one of the thirty-two EFBS and arranged in a randomized complete block design with eight replicates (N=256). Before addition of the EFBS to the container, a 0.03 cm (0.01 in) mesh wire screen (ADFORS, Grand Island, NY) with a length of 43.2 cm (17 in) and a width of 35.6 cm (14.0 in) was placed in the bottom to prevent the EFBS from falling through the container drainage holes. The two filter bed substrate bases were sand (80% washed

sand, 15% clay and silt fines and 5% pine bark (by vol.)] (Wade Moore Equipment Company, Louisburg, NC) and D-tank 100% expanded slate for trial 1 and MS-16 100% expanded slate for trial 2 (Permatill, Carolina Stalite Company, Salisbury, NC). The two slate products had different particle size distributions; D-tank 100% expanded slate had 39% coarse, 36% medium, and 25% fine particles, while MS-16 100% expanded slate had 29% coarse, 46% medium, and 25% fine particles. Both sand and slate were amended with two different sources of organic matter: pine bark (PB) (Parker Bark Co., Rose Hill, NC) and composted yard waste (CYW) (City of Raleigh Yard Waste Recycling Center, Raleigh, NC). Two combination methods of PB and CYW were used: banding and incorporating. The banded treatments included banding PB or CYW at four different depths: 2.5 cm (1 in), 5.1 cm (2 in), 7.6 cm (3 in), or 10.16 cm (4 in) (Fig. 1). This was accomplished by placing 10.2 cm of the base (sand or slate) in the bottom of the container; then either 2.5 to 10.2 cm bands of CYW or PB were added; finally the container was topped off with either sand or slate to within 2.5 cm from the top to allow for ponding of synthetic stormwater. For the incorporation treatments, PB or CYW were blended with the base (sand or slate) to achieve the rates of 5, 10, 15, and 20% (v/v)(Fig. 1). Approximately the same amounts of organic matter (PB or CYW) were applied for banding and incorporating.

For trial 1, eight replications (four replications for harvest 1 and four replications for harvest 2) of *Monarda fistulosa* L. (*Monarda*) and *Panicum virgatum* L. 'Shenan-doah' (*Panicum*) were planted (1 plant per container) into all substrate treatments on June 1, 2012 (N=512). For trial 2, eight replications (four replications for harvest 1 and four replications for harvest 2) of *Panicum* and *Betula nigra* L. 'Duraheat' (*Betula*) were planted (1 per container) on May 24, 2013 into all substrate treatments (N=512).

The plants were watered daily with tap water, without any additional nutrients, for the first two weeks to allow establishment. Synthetic stormwater was made by dissolving 6.8 g of diammonium phosphate 18N-20P-0K (18-46-0) and 129.3 g of ammonium sulfate 21N-0P-0K (21-0-0-24) in 18.9 L (5 gal) of hot tap water in order to apply targeted concentrations of 1.66 mg L^{-1} total N and 0.20 $mg'L^{-1}$ total P as reported to be in asphalt parking lot runoff (Passeport and Hunt 2009). However, actual simulated stormwater applications averaged 3.11 mg L^{-1} (± 2.49) of total soluble nitrogen (TSN) and 0.51 mg L⁻¹ (±0.33) of ortho-phosphate (PO₄⁻³-P) for trial 1 and 11.65 mg L⁻¹ of TSN (±5.44) and 0.85 mg L⁻¹ of PO₄⁻³-P (± 1.05) for trial 2. The difference in average TSN and PO_4^{-3} -P concentrations for trial 1 and 2 were due to failure of the injector (A30 Dosmatic, Carrollton, TX), which was replaced on April 8, 2013 with a new injector (D25F1VFII, Dosatron, Clearwater, FL). For each simulated stormwater event, 1 in³ (1.4 L) of synthetic stormwater was applied individually to each container using a low-volume spray stake that delivered 12.1 L/h (3.2 gal/h) (PC Spray Stake, Netafim, Ltd., Tel Aviv, Israel). The volume and frequency of synthetic stormwater applications were patterned after average Raleigh, North Carolina precipitation events of



Fig. 1. Schematic of different filter bed substrate combination methods and organic matter amounts. The two organic matter amendments were added as either a band in the depths of 2.5 cm, 5.1 cm, 7.6 cm, and 10.2 cm or by incorporation using approximately the same amounts of organic matter in the amounts of 5, 10, 15, and 20% (v/v). A: Placing a 2.5 cm band of CYW or PB above 10.2 cm of sand or slate with 32.6 cm of sand or slate placed above the band, B: Placing a 5.1 cm band of CYW or PB above 10.2 cm of sand or slate with 29.9 cm of sand or slate placed above the band, C: Placing a 7.6 cm band of CYW or PB above 10.2 cm of sand or slate with 27.4 cm of sand or slate placed above the band, D: Placing a 10.2 cm band of CYW or PB above 10.2 cm of sand or slate placed above the band, E: Combination method of incorporation with combination amount of 5%, F: Combination method of incorporation with combination amount of 15%, and E: Combination method of incorporation with combination amount of 15%, and E: Combination method of incorporation with combination amount of 15%, and E: Combination method of incorporation with combination amount of 15%, and E: Combination method of incorporation with combination amount of 15%, and E: Combination method of incorporation with combination amount of 20%.

25.4 mm or greater (http://www.nc-climate.ncsu.edu/). To measure volume of effluent, 4 individual containers (replications) for all treatments for both trial 1 and 2 were set into an 18.9 L (5 gal) bucket with a hole drilled in the bottom and supported above the surface of the ground by two bricks. A 30.48 cm (12 in) clear vinyl tray (WC CW1200B, Wyatt-Quarles, Garner, NC) was placed under each bucket's drainage hole during synthetic stormwater applications to collect the effluent that drained from the container. Table 1 shows application dates for synthetic stormwater treatments. Volume of effluent was measured for three replications during trial 1 (n=384) and for four replications during trial 2 (n=512). Containers drained for 2 h after synthetic stormwater applications before outflow volume was measured and samples were collected. Cumulative total outflow volumes over all sample dates were used for statistical analyses. Riley (2015) reported weather data for each month of sampling during trial 1 and 2. After collection, substrate solution pH was measured using a pH/EC meter (HI 9813-6, Hanna Instruments, Ann Arbor, MI) for three replications during Trial 1 and four replications during Trial 2. Also, substrate solution effluent samples were analyzed for PO_4^{-3} -P, NO_2^{-} -N, NO_3^{-} -N, and NH4⁺-N using an ICS-1600 ion chromatography system (Thermo Scientific, Madison, WI) equipped with a 4×250 mm (i.d. x length) AS22 anion exchange column, a 4×250 mm CS12A cation-exchange column, and an AS-AP autosampler on a 25 µL sample loop driven by an isocratic

pump. Due to the utilization of different calibration curves, for trial 1 and trial 2, nutrient concentration detection limits were $0.023 - 4.4 \text{ mg}\text{L}^{-1}$ and $0.25 - 128.0 \text{ mg}\text{L}^{-1}$, respectively. Any data points outside of the detection limits for either trial were not included in data analyses. All nitrogen species were combined [nitrite (NO₂⁻-N)+nitrate (NO₃⁻-N)+ammonium (NH₄⁺-N)] to estimate TSN. Cumulative totals were calculated by summing all sample dates and were used for statistical analyses of nutrient concentrations.

For the EFBS with organic matter incorporated only, particle size distribution was arranged as a completely randomized design and determined for three replications during trial 1 (n=48) and five replications during trial 2 (n=80). Oven dried samples of 350 g (12.4 oz) were placed in a Ro-tap Shaker (Model B, W.S. Tyler, Mentor, Ohio) fitted with 12 sieve plates: 6.3 mm (0.25 in), 4.0 mm (0.16 in), 2.8 mm (0.11 in), 2.0 mm (0.08 in) 1.4 mm (0.06 in), 1.0 mm (0.04 in), 0.71 mm (0.03 in), 0.5 mm (0.02 in), 0.36 mm (0.01 in), 0.25 mm (0.009 in), 0.18 mm (0.007 in) and 0.106 mm (0.004 in) for 5 min. The sample from each sieve was weighed, and particle size was expressed as a percentage of the total weight of the sample. Percentages of total sample were then grouped into fine (<0.5 mm), medium (0.5–2.0 mm), and coarse (>2.0 mm) fractions as described by Drzal et al. (1999) for statistical analyses.

Saturated hydraulic conductivity (K_{sat}) was determined for each treatment and trial by packing each of the EFBS

Table 1. Application dates for synthetic stormwater during Trial 1
(2012-2013) and Trial 2 (2013-2014).

Trial 1 ^z	Trial 2
June 15, 2012*+ ^y	June 11, 2013*+
June 26, 2012*+	June 25, 2013
July 3, 2012*+	July 10, 2013*+
July 10, 2012	July 24, 2013
July 17, 2012*+	August 9, 2013*+
July 26, 2012	August 21, 2013
August 2, 2012*+	September 4, $2013*+$
August 15, 2012*+	September 18, 2013
August 22, 2012	October 17, 2013
August 29, 2012*+	October 30, 2013*+
September 5, 2012	November 25. 2013*+
September 12, 2012*+	December 20, 2013*+
September 26, 2012*+	January 20, 2014*+
October 10, 2012*+	February 27, 2014*+
October 17, 2012	March 31, 2014*+
October 24, 2012+	April 17, 2014*+
November 19, 2012*+	May 5, 2014*+
December 18, 2012*+	•
January, 18 2013*+	
February 21, 2013*+	
March 21, 2013*+	
April 19, 2013*+	
May 2, 2013*+	

^zThree replications were measured during Trial 1 and four replications were measured during Trial 2.

^yApplication dates marked with an * signifies that volume of effluent measurements were made and application dates marked with an + signifies that substrate solution samples were collected for total soluble nitrogen (TSN) and phosphate (PO_4^{-3} -P) analyses.

(N=96) into 1029.1 cm³ (62.8 in³) cylindrical polyvinyl chloride (PVC) columns [5.1 cm (2.0 in) diameter, 50.8 cm (20 in) height]. The height of the column was used to mimic the height of the substrate in the containers. Each column filled with the EFBS treatments were placed in a

5.1 cm (2 in) flexible pipe reducer coupling (Fernco, Davison, MI). The flexible pipe reducer coupling had 16 gauge rigid screen with a mesh of 1.3 cm x 1.3 cm (0.5 in x 0.5 in) (Louis E. Page, Sterling, MA) placed in the bottom and a piece of 0.03 cm (0.01 in) mesh wire screen (ADFORS, Grand Island, NY) placed on top, both with diameters of 5.1 cm to hold the EFBS in place after it was added to the column (Fig. 2A). The flexible pipe reducer was then attached securely to a 2.5 cm (1.0 in), threaded PVC coupler with a 2.5 cm by 1.9 cm (0.75 in) reducing PVC coupler threaded into it. This reducing coupler was then threaded into a 1.9 cm PVC ball valve that was threaded into a 1.9 cm by 2.5 cm PVC coupler attached to 2.5 cm PVC pipe to allow for saturation from the bottom (Fig. 2B). Altland et al. (2010) used a similar system to determine moisture characteristic curves, however in order to determine K_{sat}, the system was modified. For the banded treatments, 10.2 cm (4 in) of either sand or slate were added to the bottom of the column, and then the 2.5 cm (1 in), 5.1 cm (2 in), 7.6 cm (3 in), or 10.2 cm (4 in) band of CYW or PB was added before the column was topped off with either sand or slate. All columns were tapped by hand three times to settle the EFBS and remove any air pockets. Columns were then slowly saturated (over approximately 2 h) from the bottom, while a constant head was maintained and were allowed to remain at saturation for 2 h. After this saturation period, water flow up through the columns and out of a 5.1 cm (2.0 in) elbow fitting placed on the top of the column was captured in a 2.4 L (0.6 gal) plastic container (300344, Encore Plastics Cooperation, Sandusky, OH) for 5 min, measured and used to calculate K_{sat} using Darcy's Law $[q=K \Delta H/L (q=flux density, K=hydraulic)$ conductivity, $\Delta H/L$ =hydraulic gradient); Hillel 2004].

During trial 2, plants (*Betula* and *Panicum*) were weighed to measure evapotranspiration (ET) for each of



Fig. 2. System utilized to measure saturated hydraulic conductivity (K_{sat}), modified based on the description provided by Atland et al. (2010). The flexible pipe reducer coupling had 16-gauge rigid screen with a mesh of 1.3 cm x 1.3 cm placed in the bottom and a piece of 0.03 cm mesh wire screen placed on top, both with diameters of 5.1 cm to hold the EFBS in place after it was added to the column (A). Columns were slowly saturated from the bottom, while a constant head was maintained and were allowed to remain at saturation for 2 h and then water flow up through the columns and out of a 5.1 cm elbow was captured for 5 min in a 2.4 L bucket, measured and used to calculate K_{sat} using Darcy's Law (B).

Table 2.Saturated hydraulic conductivity (Ksat) for sand (80% washed sand, 15% clay and silt fines and 5% pine bark v/v/v) and slate (trial 1: D-tank 100% expanded slate and trial 2: MS-16 100% expanded slate) amended with composted yard waste (CYW) or pine bark (PB) during trial 1 (2012-2013) and trial 2 (2013-2014).

Sand	K _{sat} (cm [·] h ⁻¹) Trial 1		K _{sat} (cm [·] h ⁻¹) Trial 2		K _{sat} (cm [·] h ⁻¹) Trial 1	K _{sat} (cm [·] h ⁻¹) Trial 2	
	CYW – Banded ^v	CYW - Inc	CYW - Banded	CYW - Inc	PB - Banded	PB - Inc	PB - Banded	PB - Inc
2.5cm/5% ^z	5.6	21.1	20.6	45.7	34.5	26.4	120.0	57.2
5.1cm/10%	179.0	68.2	13.9	100.1	35.3	17.3	58.1	42.4
7.6cm/15%	292.9	24.3	18.4	172.1	33.8	178.6	56.6	99.2
10.2cm/20%	170.5	35.6	21.9	104.6	32.4	86.6	49.7	159.2
Amount ^y	NS	0.0154	0.0205	0.0007	NS	<.0001	<.0001	0.0111
Linear ^x	NS	NS	NS	0.0297	NS	0.0233	0.0012	0.0044
Quadratic ^w	0.0376	NS	0.0149	0.0023	NS	NS	0.0062	NS
Slate	CYW - Banded	CYW - Inc	CYW - Banded	CYW - Inc	PB - Banded	PB - Inc	PB - Banded	PB - Inc
2.5cm/5%	270.2	348.7	141.4	48.3	232.6	972.3	205.3	232.0
5.1cm/10%	194.4	891.7	62.8	37.6	265.7	522.0	27.4	168.3
7.6cm/15%	133.4	454.7	220.4	64.2	349.1	728.6	47.5	352.3
10.2cm/20%	36.2	441.6	290.9	43.4	342.6	687.5	22.8	270.5
Amount	0.0001	0.0067	0.0049	NS	NS	NS	<.0001	NS
Linear	<.0001	NS	0.0226	NS	0.0174	NS	0.0045	NS
Quadratic	NS	NS	NS	NS	NS	NS	0.0253	NS

^zCYW and PB incorporated in sand and slate at varying amounts of 2.5 cm, 5.1 cm, 7.6 cm, 10.2 cm, or 5, 10, 15, and 20% (v/v).

^yAnalysis of variance effect of amount for each amendment (CYW and PB). NS = P > 0.05, *P*-value given otherwise.

^xRegression analyses utilized for linear trends. NS = P>0.05, P-value given otherwise.

^wRegression analyses utilized for quadratic. NS = P>0.05, P-value given otherwise.

VCYW and PB incorporated in sand and slate at varying amounts by either banding or incorporation.

the 32 EFBS. ET weights were collected the day after a simulated rainfall event (initial) and 2 weeks later, the day before the next simulated rainfall event (final). Differences between initial and final weights were calculated for statistical analyses. Weights were taken on June 12 and June 24, 2013 (sample time 1), July 25 and August 8, 2013 (sample time 2), and October 18 and October 29, 2013 (sample time 3). In the event of actual rainfall, ET weights were not utilized.

During both trials (1 and 2), plants from half of the eight replications were harvested at the end of the first summer's growth (harvest one) and the other half of the replications were harvested after growth had flushed out in the spring (harvest two). For trial 1, shoots of Monarda and Panicum were harvested from all substrate treatments on November 6, 2012 (N=128) and May 7, 2013 (N=128). For trial 2, Panicum and Betula were harvested from all substrate treatments on November 12, 2013 (N=128) and May 20, 2014 (N=128). At harvest, plants were separated into shoots (stems and leaves) and roots. Root systems were rated using a scale on if they rooted to the bottom of the container [1 (no), 2 (half way), 3 (yes)] and if they rooted out to the edges of the container [1 (no), 2 (half way), 3 (yes)]. Shoots were dried at 62 C (144F) for 5 days. After drying, shoot samples were weighed and then submitted to the North Carolina Department of Agriculture and Consumer Services, Agronomic Division (Raleigh, NC) for grinding and whole plant tissue concentration analysis of nitrogen (N) and phosphorus (P). Shoot N concentration was determined by oxygen-combustion gas chromatography with an elemental analyzer (NA 1500; CE Elantech Instruments, Lakewood, NJ) (Campbell and Plank 1992). Shoot P concentration was determined with an inductively coupled plasma (ICP) spectrometer (Donohue and Aho,

1992) (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corp., Shelton, CT) following open-vessel nitric acid digestion in a microwave digestion system (CEM Corp., Matthews, NC) (Campbell and Plank 1992). Tissue nutrient content was determined by multiplying total shoot weight by percent nutrient concentration. Betula shoot samples were too small individually, thus all replications for each treatment were grouped together for tissue analysis and averages were utilized for nutrient content calculations. During trial 2, to further investigate the impact of EFBS on plant growth, substrate temperatures were measured using a thermocouple and datalogger (U12 Outdoor/Industrial, Onset Hobo Data Loggers, Bourne, MA). A thermocouple was placed on the south side of the container, approximately 2.5 cm deep into each of the EFBS for temperature measurements for 100% slate and 100% sand EFBS controls with Panicum growing in them on September 24, 2013 from 6 am to 6 pm.

All data were analyzed using Analysis of Variance (ANOVA) procedures in PROC GLM (SAS version 9.3, SAS Institute, Cary, NC). When applicable, means were separated with Tukey's honestly significant difference means separation test (P<0.05). Linear regression analyses were also utilized when testing the impact of amount for organic matter amendments. The data were normally distributed. To stabilize the variances, a square root transformation was done on outflow volume, K_{sat}, evapotranspiration, and shoot dry weight data prior to analyses of variance procedures.

Results and Discussion

Water flow through the rain garden system. In both trial 1 and 2, substrate base, organic matter amendment, combination method and amount of amendment generally

influenced water movement through the EFBS (Table 2). Larger amounts of coarse particles present with the increasing amounts of PB added through incorporation (Table 3) increased K_{sat} (26-86 cm h⁻¹ in trial 1 and 57-159 cm^{-h⁻¹} in trial 2) in sand (Table 2). CYW incorporated into sand had no effect on K_{sat} in trial 1 while there was a quadratic response in trial 2 with a maximum K_{sat} (172) cm^{-1}) with 15% incorporation. Sand from the same batch was used in trial 1 and 2; however, the slate was different. The slate in trial 1 had 39% coarse particles and had a nearly 2-fold greater K_{sat} than the slate in trial 2 which had 29% coarse particles. Regardless, when incorporated, the organic matter amendment and amount did not impact the particle size distribution for slate. However, organic matter amendment and amount affected the distribution of coarse, medium, and fine particle sizes in the sand EFBS. For both trials, PB and CYW had more coarse particles (Table 3) than the sand and likely explain the effects on K_{sat} (Table 2). With the addition of PB and CYW to sand, there was generally a quadratic response in the distribution of coarse and medium particles with the 15% incorporation having the greatest amount of coarse and a lower amount of medium particles (Table 3). Kraus et al. (2014) reported similar increases in coarse particles when utilizing several different compost materials (food waste, biosolid, enzyme residual, and yard waste) incorporated in a sand EFBS.

Substrates with a higher percentage of fine particles have a greater specific surface area increasing the matric potential and subsequent "drag" on water molecules, resulting in a lower K_{sat} while water moves through the rain garden system (Raviv and Lieth 2008). However, over time, the K_{sat} of an EFBS will change as settling occurs and can be influenced by plant selection. For example, when plants with fine and coarse root systems are grown together, the fine roots have a rapid turnover, contributing to high amounts of organic matter, which may facilitate soil aggregation and increase water storage capacity within the substrate, while coarse roots can potentially grow deeper into the substrate profile aiding in deeper water conductivity (Archer et al. 2002). For both trials, when sand was amended with either PB or CYW, quadratic trends in the amount of fine particles generally resulted with the 10 and 15% amendments of CYW having lower amounts of fine particles and the 5 and 20% additions of PB having greater amounts (Table 3). The particle size distribution of PB and CYW varied between trials 1 and 2, with fewer coarse particles in trial 2 than in trial 1 (Table 3). In contrast to the results of this study, Paus et al. (2014) using similar compost (derived from leaves, grass, and woody debris) added by incorporation to siliceous sand reported decreasing K_{sat} values of 183, 87, 46, and 37 $cm^{-}h^{-1}$ with compost amounts of 0, 10, 30, and 50% (by vol.), respectively. The compost used by Paus et al. (2014) had more fine particles than the siliceous sand utilized, resulting in the reduction in K_{sat}.

With banding as the method of organic matter addition, amount of PB added to sand did not impact K_{sat} in trial 1 (Table 2); however, there was a linear decrease in K_{sat} from 120-50 cm⁻¹ for the 2.5 to 10.2 cm band, respectively in trial 2. Addition of a CYW band to sand caused a quadratic trend where K_{sat} increased until 7.6 cm (293 cm^{-h-1}) and then decreased at 10.2 cm (171 cm^{-h-1}) for trial 1 but was highest with the 2.5 cm (21 cm^{-h-1}) and 10.2 cm (22 cm^{-h-1}) bands in trial 2. Water moving through the sand EFBS into the coarser textured CYW may have been slowed until the sand just above the CYW band was saturated and water was free to flow into the CYW. Apparently, the differences in coarseness of the CYW in trial 1 and 2 (Table 3) were sufficient to reverse the impacts on K_{sat} of banding in sand. Such was not the case with the PB, which was only 16% less coarse between trials 1 and 2 (Table 3). Sand banded with CYW resulted in a higher K_{sat} than incorporation during trial 1 (an average of 23% higher) but in trial 2 the opposite occurred and incorporation was on average 18% higher than banding (Table 2).

Although the particle size distribution of the CYW and PB varied by trial, they were coarse in nature with low amounts of fine particles (Table 3). As a result, the K_{sat} and particle size distribution of slate incorporated with different amounts of PB or CYW did not vary. Incorporating CYW or PB to slate resulted in an average 42% coarse, 36% medium, and 22% fine for trial 1 and 24% coarse, 45% medium, and 31% fine particle distribution for trial 2. In trial 1, when CYW was banded in slate, K_{sat} decreased linearly from 270 to 36 cm h^{-1} for the 2.5 to 10.2 cm bands, respectively while it increased from 233 to 342 cm h⁻¹ when PB was banded from 2.5 to 10.2 cm, respectively. The opposite trends occurred in trial 2; K_{sat} of slate banded with CYW increased linearly (141 to 291 cm^{-h⁻¹} for 2.5 to 10.2 cm, respectively) with increasing amendment amounts while there was a linear decrease in K_{sat} from 205 to 23 cm^{-h⁻¹} with PB at 2.5 to 10.2 cm, respectively. The differences in K_{sat} trends in slate with banding between trial 1 and 2, are most likely due to the differences in base products utilized (D-tank in trial 1 and MS-16 in trial 2). The slate and the CYW utilized in trial 2 had fewer coarse particles than in trial 1 and were very similar in particle size distribution (slate coarse = 29%, medium = 46% and fine 25%; CYW coarse = 32%, medium = 43% and fine 25%). Therefore, in trial 2 there was less of a textural difference between the particles of slate and the banded particles of CYW, which decreased K_{sat}.

Within a rain garden system, the K_{sat} of the EFBS influences the amount of retention time for stormwater runoff and therefore impacts the volume and quality of water that leaves the rain garden (Thompson et al. 2008). The K_{sat} was generally numerically slower (16% for trial 1 and 51% for trial 2) for sand than slate for both trials, regardless of amendment amount, combination method, or choice of amendment (Table 2). Turk et al. (2014) reported similar results for K_{sat} with similar sand and slate EFBS.

Plant growth and nutrient uptake in the rain garden system. Plants not only impact water movement through an EFBS, they also improve water quality of stormwater runoff. Shoot dry weights of *Panicum*, *Monarda*, and *Betula* generally responded similarly to the different substrate bases, organic amendments, addition methods, and amounts of organic amendments for both harvests in each trial. Due to the similarities in shoot dry weight responses, data will be presented for *Panicum* only. The

Table 3.	Percentage of coarse (>2.0 mm), medium $(0.5-2.0 \text{ mm})$, and fine (<0.5 mm) particle size distributions (% weight) for sand [80% washed sand, 15% clay and silt fines and 5% pine bark (by vol.)] amended with composted yard waste (CYW) and pine bark (PB) during trial 1 (2012-2013) and trial 2 (2013-2014).
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		% of Total Dry Weight							
	Trial 1				Trial 2				
Coarse	CYW		PB	_	CYW		PB		
5% ^z	17.4 ^y		19.4		12.8		12.7		
10%	18.1		19.0		14.0		13.7		
15%	19.5		28.7		15.4 13		13.9		
20%	19.7		19.5		14.2 15.		15.9		
Amount ^x	NS		0.0002		0.0084 0.0		0.0065		
Linear ^w	0.0266		NS		0.0368 0.0		0.0009		
$Quadratic^{v}$	NS	IS NS			0.0175		NS		
Medium	CYW		PB CYW			РВ			
5%	51.4		54.2		53.8		55.3		
10%	57.1	57.1 5			58.6		52.3		
15%	52.8	52.8			61.9		53.9		
20%	48.6		54.5		57.4	53.8			
Amount	<.0001	<.0001 0.0003			<.0001		0.0012		
Linear	NS	NS NS			0.0164		NS		
Quadratic	0.0003	0.0003 0.0004			<.0001		0.0117		
Fine	CYW		PB		CYW		PB		
5%	31.2		26.4		33.4		32.0		
10%	24.8		28.9		27.5		34.0		
15%	27.8		21.1		22.7		32.2		
20%	31.8		26.0		28.4 30.3		30.3		
Amount	0.0002		0.0011		<.0001 0.0307		0.0307		
Linear	NS		NS		0.0009		NS		
Quadratic	0.0002		NS		<.0001		0.0216		
	100% Sand ^u	100% CYW	100% PB	10 Sa	00% and	100% CYW	100% PB		
Coarse	20.0	48.9	68.0	1	2.9	31.9	57.3		
Medium	49.1	34.1	22.4	4	7.2	43.4	31.5		
Fine	30.9	17.0	9.6	4	0.0	24.6	11.2		

 $^z\mathrm{CYW}$ and PB incorporated in sand at varying amounts of 5, 10, 15, and 20% (v/v).

^yParticle size distribution was determined for three replications during trial 1 (N=48) and five replications during trial 2 (N=80) using a Ro-tap Shaker (Model B, W.S. Tyler, Mentor, Ohio) fitted with 12 sieve plates: 6.3 mm, 4.0 mm, 2.8 mm, 2.0 mm, 1.4 mm, 1.0 mm, 0.71 mm, 0.5 mm, 0.36 mm, 0.25 mm, 0.18 mm and 0.106 mm for 5 min. The sample from each sieve was weighed, and particle size was expressed as a percentage of the total weight of the sample. Percentages of total sample were then grouped into fine (<0.5 mm), medium (0.5–2.0 mm), and coarse (>2.0 mm) fractions.

^xAnalysis of variance effect of amount for each amendment (CYW and PB). NS = P>0.05, P-value given otherwise.

^xRegression analyses utilized for linear trends. NS = P>0.05, P-value given otherwise.

^vRegression analyses utilized for quadratic. NS = P>0.05, P-value given otherwise.

^uParticle size distribution of 100% sand, 100% CYW, and 100% PB.

exception to this was *Betula*, which had poor survival when grown in the slate EFBS, possibly due to the solar exposure and substrate heating of the black plastic containers used in this study. In order to investigate the difference in root zone temperatures, 100% slate EFBS and 100% sand with *Panicum* were measured on September 24, 2013. The 100% slate EFBS maintained higher temperatures from 9:00 am to 5:00 pm compared to 100% sand. At 12:00 pm, 100% slate had a temperature of 34 C (93 F), while sand was 31 C (87 F). In contrast, *Betula* has been reported to grow well in rain gardens (in the ground) with slate (Turk et al. 2016).

Panicum shoot growth was generally larger in sand (16.5 g) than in slate (16 g) when averaged across treatments (data not shown) and the last harvest dates for both trials (Trial 1=May 7, 2013; Trial 2=May 20, 2014), likely a result of sand retaining more water (slower K_{sat}) than slate. Liu et al. (2014) reported similar, smaller, shoot growth of tall fescue (Festuca arundinacea Schreb.) grown in an EFBS that had more coarse particles and less fine particles and presumably held less water. In this study, regardless of base and method, shoot dry weights with CYW were greater than with PB for all amounts [(Fig. 3) for slate, data not shown for sand]. Plants with larger amounts of biomass are able to retain higher amounts of nutrients from stormwater (Gautam and Greenway 2014). In this study, banding either CYW or PB resulted in more than a twofold increase in *Panicum* shoot growth than incorporation and did not inhibit root growth for any species (data not shown). Banding may have retained larger amounts of water within the band, supporting increased shoot growth.

Similar to shoot dry weight results, trends in shoot N and P contents for each species were similar, thus only Panicum data will be presented. Base, amendment, and method affected shoot N and P content. Shoot N and P content were both greatest when grown in sand and slate with CYW (Fig. 4 for N, data not shown for P) and shoot N content increased linearly as amount of CYW increased. When CYW was banded in sand, maximum shoot N content resulted with a 5.1 cm band while N content increased linearly with increasing incorporation amounts of CYW (Fig. 5). Turk et al. (2016) reported that for 16 species, EFBS did not impact the N and P plant uptake with the exception of Betula and Virginia sweet spire (Itea virginica L.) These two species had larger amounts of N and P accumulated within the plant when grown in a sand EFBS (same utilized in this study) compared to a slate EFBS (Turk et al. 2016). This study's shoot N and P content, similar to shoot dry weights, may be attributed to banding holding more water within the rain garden system than incorporation, which allowed a longer period of time for nutrient uptake by the plants.

A lab analysis of the CYW and PB utilized determined that the CYW had 8,910 mg·L⁻¹ of N present while PB had 6,370 mg·L⁻¹ (a difference of 28.5%), while the percent difference in P concentration for CYW (622 mg·L⁻¹) and PB (262 mg·L⁻¹) was higher at 57.9. The plants in CYW took up more N because more was available from the CYW than the PB amendment. This helped increase shoot and root growth initially and maintain larger plants throughout both trials.

Even though sand had a slower K_{sat} , overall ET was similar for sand and slate and was similarly affected by amendment and method for each species (data not shown). When CYW was utilized, ET was higher at each sample time than with PB (Fig. 6A for sand and data not shown for



Fig. 3. Effect of amendment [composted yard waste (CYW) and pine bark (PB)] addition to slate (100% MS-16 expanded slate) on shoot dry weights of *Panicum* during trial 2 (2013-2014) for harvest one (November 12, 2013), represented by the bars. Means between amendments with different letters are significantly different from each other based on Tukey's honestly significant difference mean separation procedures (*P*<0.05). The lines represent linear regression (*P*<0.05) of amount [2.5 cm band/5% incorporation, 5.1 cm band/10% incorporation, 7.6 cm band/15% incorporation, and 10.2 cm band/20% incorporation (by vol.)] for CYW on shoot dry weights of *Panicum* during trial 2 (2013-2014) for harvest one (November 12, 2013). Standard deviation bars represent the variation in the data.

slate). Additionally, banding generally resulted in higher ET rates [Fig. 6B for sand (P < 0.0001) and data not shown for slate]. The higher ET levels for plants grown with CYW compared to PB are likely due to the significantly larger shoots and greater retention of water by CYW. Compost materials have been reported to retain water (Carpenter and Hallam 2010), which then becomes available for ET (Barrett et al. 2013).

Water that exfiltrates from a rain garden is discharged towards a water supply and is no longer available to the plants in a rain garden for uptake. DeBusk and Wynn (2011) showed that a rain garden, which received an inflow of 108,461 L of stormwater, had 2,805 L that exfiltrated out of the sides of the rain garden through cracks in the surrounding soils, a 97% reduction in outflow volume. While the optimal desired export of water (effluent) from a



Fig. 4. Effect of amendment [composted yard waste (CYW) and pine bark (PB)] addition to slate (100% MS-16 expanded slate) on shoot nitrogen content for *Panicum* during trial 2 (2013-2014) for harvest two (May 20, 2014), represented by the bars. Means between amendments with different letters are significantly different from each other based on Tukey's honestly significant difference mean separation procedures (P < 0.05). The lines represent linear regression (P < 0.05) of amount [2.5 cm band/5% incorporation, 5.1 cm band/10% incorporation, 7.6 cm band/15% incorporation, and 10.2 cm band/20% incorporation (by vol.)] for CYW on shoot dry weights of *Panicum* during trial 2 (2013-2014) for harvest two (May 20, 2014). Standard deviation bars represent the variation in the data.



Fig. 5. Effect of method [banded (Band) or incorporated (Inc)] for adding composted yard waste (CYW) to sand [80% washed sand, 15% clay and silt fines and 5% pine bark (by vol.)] on shoot nitrogen content for *Panicum* during trial 2 (2013-2014) for harvest two (May 20, 2014), represented by the bars. Means between methods for each amount with different letters are significantly different from each other based on Tukey's honestly significant difference mean separation procedures (P<0.05). The lines represent the effect of amount [2.5 cm band/5% Inc, 5.1 cm band/10% Inc, 7.6 cm band/15% Inc, and 10.2 cm band/20% Inc (by vol.)] of either CYW added to sand on shoot nitrogen contents for *Panicum* during trial 2 (2013-2014) for harvest two (May 20, 2014), utilizing regression (P<0.05). Standard deviation bars represent the variation in the data.</p>

rain garden is not known, low volumes and low concentrations of nutrients in the effluent are desired for water quality protection. In this study, similar to K_{sat} , the specific effects of amendment, method, and amount varied in their impacts on the volume of effluent for each base depending on the particle size characteristics of the amendment. Additionally, the trends in effluent volume between species growing in the different combinations of base, amendment, and method were similar, so only *Panicum* is shown. In general, due to the slower K_{sat} and

greater plant growth in sand, total volume of effluent was lowest from the sand (cumulative total average = 5,731 mL) and greatest from slate (cumulative total average = 7,032 mL). Additionally, incorporation tended to increase total effluent volume compared to banding regardless of the amount (Fig. 7). Also, when *Panicum* was grown in slate with CYW, the total volume of effluent (8,429 mL) was lower (*P*=0.001) than with PB (10,277 mL). *Panicum* grown in sand with a 10.2 cm band of CYW reduced the effluent volume by 70%, while a 10.2 cm band of PB



Fig. 6. Effect of amendment [composted yard waste (CYW) or pine bark (PB) – A] and effect of method [banding (Band) or incorporation (Inc) – B] in sand [80% washed sand, 15% clay and silt fines and 5% pine bark (by vol.)] on evapotranspiration during trial 2 (2013-2014) for sample time 1 (12 June and 24 June 2013), sample time 2 (25 July and 8 August 2013), and sample time 3 (18 October and 29 October 2013). Means between amendments and methods with different letters are significantly different from each other based on Tukey's honestly significant difference mean separation procedures (P<0.05).</p>



Fig. 7. Effect of method [banding (Band) or incorporation (Inc)] with varying amounts of 2.5 cm/5%, 5.1 cm/10%, 7.6 cm/15%, or 10.2 cm/20% (v/ v) on cumulative total volume of effluent with *Panicum* during trial 2 (2013-2014). Means between methods with different letters are significantly different from each other based on Tukey's honestly significant difference mean separation procedures (P<0.05). The cumulative total volume of influent was 16,310 mL.

reduced it by 67%. Amount of amendment had a more varied impact on volume of effluent. There was a quadratic response in the outflow volume for increasing amounts of amendment in slate while this quadratic response was not significant for *Panicum* grown in sand (Fig. 8). The 5.1 cm/ 10% and 7.6 cm/15% amounts of amendment resulted in the lowest effluent volumes when *Panicum* was grown in slate. Similarly, the 7.6 cm band of either PB or CYW in slate slowed K_{sat} . Thus, when utilizing slate there may not be a benefit of adding 10.2 cm or 20% of CYW or PB for effluent reduction. Carpenter and Hallam (2010) reported that a 100% compost mix had a porosity of 0.59 with a field capacity of 115.3%, meaning that the compost could retain

approximately 115% of its weight in water. In this study, the ability of compost to retain a large amount of water may be part of the reason that when CYW was utilized as an amendment, generally, effluent volume was reduced compared to PB.

Volume of effluent also varied by time of the year as growth increased and ET changed with the season (Fig. 9A-D). Similar to growth and ET data, *Panicum* grown with CYW withdrew more water from the substrate than plants with PB as shown by the cumulative effluent volumes (Trial 1: CYW = 6,981 mL, PB = 8,381 mL; Trial 2: CYW = 4,815 mL, PB = 5,351 mL). Newly planted plants did not remove much water from the substrate and



Fig. 8. Effect of sand [80% washed sand, 15% clay and silt fines and 5% pine bark (by vol.)] or slate (100% MS-16 expanded slate) base with varying amounts of 2.5 cm/5%, 5.1 cm/10%, 7.6 cm/15%, or 10.2 cm/20% (v/v) on cumulative total volume of effluent with *Panicum* during trial 2 (2013-2014). Regression analyses were utilized for linear (L), quadratic (Q), and non-significant (NS) responses (*P*<0.05). The cumulative total volume of influent was 16,310 mL.



Fig. 9. Volume of effluent for *Panicum* grown in sand [80% washed sand, 15% clay and silt fines and 5% pine bark (by vol.)] amended with composted yard waste (CYW) banded (A) or incorporated (B) and slate (MS-16 100% expanded slate) amended with CYW banded (C) or incorporated (D) with varying amounts (banded at 2.5, 5.1, 7.6, and 10.2 cm and incorporated at 5, 10, 15, and 20%) for all sample dates during trial 2 (2013-2014). The cumulative total volume of influent was 16,310 mL.

larger volumes of effluent resulted initially (Fig. 9A-D). Panicum growing in sand with CYW banded at least 2-in retained nearly all the applied stormwater runoff in the rain garden system (zero effluent) from July through October with the exception of the September sample time due to a large rain event (6 cm) that occurred three days before stormwater application (Fig. 9A). As the Panicum plants (an ornamental grass) began to go dormant for the winter, effluent volumes increased. Effluent volume from Panicum grown in slate with CYW both banded and incorporated approached zero from July through November (Fig. 9C-D) possibly due to greater root growth in the more coarse slate compared to the sand EFBS. When larger pores are present within the substrate, roots are more able to penetrate through the system (Raviv and Lieth 2008) potentially allowing for more water uptake.

Nutrient remediation from the rain garden system.

Removal of nutrients from stormwater is affected by both the EFBS's ability to retain water and nutrients, and the water and nutrient uptake of the plants growing in the rain garden system. For trial 1, TSN (NO₂⁻-N+NO₃⁻-N+NH₄⁺-N) effluent concentrations had a base by amendment by method by amount interaction (*P*=0.02) and trial 2 had a base by amendment by method interaction (*P*=0.04). For both trials, effluent PO₄⁻³-P concentrations were also impacted by base, amendment, method and amount. Even though the influent TSN and PO₄⁻³-P concentrations for trials 1 and 2 were different (3.11 mgL⁻¹ of TSN and 0.51 mgL⁻¹ of PO₄⁻³-P for trial 1 and 11.65 mg·L⁻¹ of TSN and 0.85 mg·L⁻¹ of PO₄⁻³-P for trial 2), the general impacts of amendment, method and amount were similar for both sand and slate over both trials.

With CYW, cumulative concentrations of TSN in the effluent were higher compared to PB for both sand and slate (Fig. 10); whereas, the concentration of cumulative PO_4^{-3} -P in the effluent was generally not impacted by amendment (data not shown). Also, sand generally had numerically lower effluent concentrations of TSN and PO_4^{-3} -P than slate regardless of amendment, method or amount (data not shown). In contrast, Turk et al. (2014) reported that a slate EFBS [80% expanded slate and 20% pine bark fines (by vol.)] had better remediation of N (86% initially and 99% after 426 days) when compared to sand [80% washed sand, 15% clay and silt fines, and 5% pine bark (by vol.)]. There are several possible explanations why slate had a larger amount of TSN in the effluent, in this project, than sand: 1) slate maintained higher substrate solution pH levels (8.4) than sand (5.3) amended with CYW and nitrification is enhanced at higher pH levels, 2) slate EFBS have been reported to have a higher cation exchange capacity than sand (Turk et al. 2014), which retains more NH₄⁺-N for nitrification, and 3) growth of Panicum was greatest when grown in sand compared to slate, thus plants likely absorbed more N. Utilization of banding resulted in lower TSN (data not shown) and PO_4^{-3} -P (Fig. 11 for sand, data not shown for slate) concentrations in the effluent than incorporation regardless



Fig. 10. Effect of amendment [composted yard waste (CYW) and pine bark (PB)] addition to sand [80% washed sand, 15% clay and silt fines and 5% pine bark (by vol.)] and slate (100% MS-16 expanded slate) on cumulative total soluble nitrogen (TSN; NO₂⁻N+NO₃⁻N+NH₄⁺-N) effluent concentrations for *Panicum* during trial 2 (2013-2014). Means between amendments within each base with different letters are significantly different from each other based on Tukey's honestly significant difference mean separation procedures (*P*<0.05). Standard deviation bars represent the variation in the data.

of the amendment utilized (P=0.0005). This again may be attributed to larger shoot dry weights for *Panicum* when grown with banding instead of incorporation. Hsieh et al. (2007a) found similar results with unplanted bioretention columns for total P removal when using a less permeable soil layer below a permeable sand layer, with removal rates that ranged from 67 to >98% with effluent P concentrations equal to 1.2 to <0.55 mg·L⁻¹.

Even though ammonium sulfate was the N source in the influent, nitrification was occurring in the slate (data not shown) and sand amended with both CYW and PB as both

 NH_4^+ -N and NO_3^- -N were in the effluent (Fig. 12A-D). In bioretention cells with an EFBS of 86-89% sand, 8-10% silt, and 3-4% clay, organic nitrogen was converted into NO_3^- -N within the aerobic EFBS, and lead to an export of NO_3^- -N (Brown et al. 2013). In this study, when sand was amended with CYW banded, initially the amount of NO_3^- -N (June – November) was numerically higher than when sand was banded with PB, especially with the 7.6 and 10.2 cm bands. However, effluent NO_3^- -N concentrations from CYW were comparable to PB towards the end of the study (December-May) regardless of amount (Fig. 12A&B). Generally, when



Fig. 11. Effect of method [banding (Band) or incorporation (Inc)] for amendment addition to sand [80% washed sand, 15% clay and silt fines and 5% pine bark (by vol.)] on cumulative PO_4^{-3} -P effluent concentrations for *Panicum* during trial 1 (2012-2013). Means between methods with different letters are significantly different from each other based on Tukey's honestly significant difference mean separation procedures (*P*<0.05). Standard deviation bars represent the variation in the data.



Sand PB Banded

В

sand was amended with PB banded, the amount of NO₃⁻-N in the effluent stayed consistent throughout the study, regardless of the amount (Fig. 12B).

11.Dec

Sand CYW Banded

A

11.SeP

11-200

1.0°t

11.0ct

11.1004

N.SeP

17-AUS

2 (2013-2014).

1. MON 1, Dec

Sand CYW Banded

11.Feb

11-121

17.1021

17.Mar

11.Feb

11-120

1.4

1.2

1.0 8.0

0.6 0.4 0.2 0.0

17-34 17.34

3.0

2.5 2.0 1.5 1.0 05 0.0

17-34

Fig. 12.

 NH_4 ⁺-N (mg₁L⁻¹)

С

NO₂--N (mg₁L₋₁)

In conclusion, rain garden EFBS composition and vegetation are both important for removal of nutrients from stormwater and return of water to the hydrologic cycle of a site. Varying EFBS compositions impacted water movement into and through the EFBS, shoot growth, ET, shoot nutrient uptake, and effluent concentrations. Water flow through sand was much slower than through slate. Depending on the expected volume of water moving into the rain garden system, use of sand and slate provide different benefits. A slate EFBS is able to convey water through the system more quickly than a sand EFBS and may be helpful in an area expected to have higher inflow rates. Evaluating the K_{sat} and particle size distribution alone did not provide a clear picture in regards to water movement within the rain garden system; however, combining these results with ET and volume of effluent were more definitive. The addition of CYW and banding within a sand or slate EFBS positively impacted the hydrology of the rain garden system by reducing the volume of effluent and increasing the ET. Shoot dry weights for Panicum, Monarda, and Betula for all harvests and both trials were larger in sand than slate. Also, plant growth and nutrient uptake were supported best with CYW compared to PB and banding compared to incorporation. Banding may be an easier and more economical option for adding organic matter to an EFBS for rain gardens than

between water retention within and nutrient export out of a rain garden system. The cumulative effluent TSN concentrations were typically higher when CYW was utilized; however, NO3-N was numerically similar for CYW and PB midway through the study. The average TSN concentration in effluent from slate banded with CYW was 1.2 mg L^{-1} and from sand banded was 0.92 mg L^{-1} . CYW can have variable physical and chemical properties from source to source and thus it is important to have it tested initially before utilization. It is also important to evaluate the contaminants in need of remediation for particular sites. Plants within a rain garden located in a site with expected low N influent, such as runoff from a parking lot with no surrounding fertilized vegetation would benefit from the additional nutrients supplied by CYW, potentially with minimal NO₃⁻N export. Further research is needed to examine different sources of CYW for utilization within rain garden systems. Also, CYW needs to be evaluated within a rain garden system for a longer period to examine function over time.

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