Performance of Compost Filtration Practice for Green Infrastructure Stormwater Applications

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ABSTRACT: Urban storm water runoff poses a substantial threat of pollution to receiving surface waters. Green infrastructure, low impact development, green building ordinances, National Pollutant Discharge Elimination System (NPDES) storm water permit compliance, and Total Maximum Daily Load (TMDL) implementation strategies have become national priorities; however, designers need more sustainable, low-cost solutions to meet these goals and guidelines. The objective of this study was to determine the multiple-event removal efficiency and capacity of compost filter socks (FS) and filter socks with natural sorbents (NS) to remove soluble phosphorus, ammonium-nitrogen, nitrate-nitrogen, *E. coli, Enterococcus*, and oil from urban storm water runoff. Treatments were exposed to simulated storm water pollutant concentrations consistent with urban runoff originating from impervious surfaces, such as parking lots and roadways. Treatments were exposed to a maximum of 25 runoff events, or when removal efficiencies were $\leq$ 25%, whichever occurred first. Experiments were conducted in triplicate. The filter socks with natural sorbents removed significantly greater soluble phosphorus than the filter socks alone, removing a total of 237 mg/linear m over eight runoff events, or an average of 34%. The filter socks with natural sorbents removed 54% of ammonium-nitrogen over 25 runoff events, or 533 mg/linear m, and only 11% of nitrate-nitrogen, or 228 mg/linear m. The filter socks and filter socks with natural sorbents both removed 99% of oil over 25 runoff events, or a total load of 38,486 mg/linear m. Over 25 runoff events the filter socks with natural sorbents removed *E. coli* and *Enteroccocus* at 85% and 65%, or a total load of 3.14 CFUs x 10^8/linear m and 1.5 CFUs x 10^9/linear m, respectively; both were significantly greater than treatment by filter socks alone. Based on these experiments, this technique can be used to reduce soluble pollutants from storm water over multiple runoff events. *Water Environ. Res.*, **85,** 806 (2013).

KEYWORDS: compost filter sock, stormwater runoff, water quality, green infrastructure, pollutant filtration, low impact development.

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Introduction

According to the U.S. Environmental Protection Agency's (USEPA) national water quality assessment, 35% of U.S. streams are severely impaired and 75% of the population lives within 10 miles of an impaired surface water (USEPA, 2007). In accordance with Section 303(d) of the Clean Water Act, the USEPA designates specific stream segments for Total Maximum Daily Load (TMDL) development for particular pollutants. Between 1995 and 2007, bacterial pathogens and nutrients have been the leading causes of TMDL designations, with 5081 and 3511 listings, respectively. These pollutants are the primary (10,249 cases) and fourth (6,900 cases) leading causes, respectively, of impaired water quality in the US (USEPA 2009). Urban storm water runoff is one of the leading sources of these pollutants. Typical concentrations in urban storm water runoff, contributing to water quality impairment for total nitrogen (N) and nitrate-nitrogen, range from 0.14 mg L^{-1} to 29.0 mg L^{-1}, total phosphorus (P) from 0.24 mg L^{-1} to 3.6 mg L^{-1} (Flint and Davis 2007), oil/grease ranges from 10 mg L^{-1} to 35 mg L^{-1} (USEPA 2002), and *E. coli* levels from 1,000 to 100,000 CFU/100 mL, with an average level near 30,000 CFU/100 mL (McLellan and Sauer 2009).

Pollutants in urban stormwater typically originate from non-point sources; impervious surfaces, such as parking lots, roadways, and rooftops; and vegetated surfaces, such as golf courses, lawns, and pet recreation areas. The majority of these pollutants are typically in soluble form. According to Westermann et al. (2001), sediment-bound stormwater pollutants can become desorbed, thereby increasing soluble pollutant loads in runoff. Berg and Carter (1980) reported that soluble pollutants may exceed 80% of the total stormwater pollutant load where land surfaces have been stabilized. In some watersheds, soluble pollutants may be of greater concern due to an increased bioavailability to aquatic organisms, relative to sediment-bound pollutants. Project planners need adequate best management practices (BMP) design information to effectively reduce site stormwater pollutants and protect the water quality of receiving waters.

There is a pressing need for more low-cost green infrastructure and low impact development (LID) management practice options, to be utilized by those involved with site storm water design and maintenance, including green builders and designers, watershed managers, National Pollutant Discharge Elimination System (NPDES) storm water permit holders, storm water pollution prevention plan (SWPPP) designers, landscape architects, hydrologists, and project engineers.. Many of the options available to Municipal Separate Storm Sewer System (MS4), industrial NPDES storm water permit managers, and TMDL watershed managers are capital- and design-engineering intensive. Additionally, the on-site reduction of stormwater pollutants

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can reduce subsequent energy and infrastructure costs at off-site water, wastewater, or storm water treatment facilities.

The *USEPA NPDES Phase II National Menu of Best Management Practices (BMPs) for Construction Activity Stormwater Management* includes compost filter socks (FS) as a runoff-sediment control barrier (USEPA 2006). The University of Georgia (Faucette, Governo, Tyler, Gigley, Jordan, Lockaby, 2008), Ohio State University (Keener et al., 2007), and the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) (Faucette, Sefton, Sadeghi, Rowland, 2008) have reported positive performance results, and limited information on design criteria, in sediment control applications for the use of filter socks.

There is limited evidence that filter socks can filter urban stormwater pollutants, other than sediment (Faucette and Tyler, 2006; Faucette et al., 2006). Humus and organic matter within compost has the ability to adsorb soluble ions, such as soluble phosphorus (P) and ammonium nitrogen (N) (Brady and Weil, 1996). Single-event removal efficiencies for filter socks have been reported between 14% and 28% for soluble phosphorus, between 1% and 17% for nitrite-nitrate nitrogen (Faucette, Sefton, Sadeghi, Rowland, 2008); and between 85% and 99% for motor oil (Faucette and Tyler, 2006).

Water and storm water treatment systems have historically used sorbents to reduce pollutant concentrations. Sorbents have been used for storm water runoff turbidity reduction (Hayes et al., 2005). Soluble phosphorus concentrations in stormwater ponds have been reduced by up to 98% using sorbent agents (Leytem and Bjorneberg, 2005), while Moore (1999) and Harper et al. (1999) have reported stormwater runoff total phosphorus reductions between 75% and 90%. Soluble phosphorus runoff from fertilized soils was reduced up to 93% to 99%, and turbidity reduced up to 79% to 98%, when using sorbent agents with filter socks in bench scale watershed experiments (Faucette, Sefton, Sadeghi, Rowland, 2008). Further research evaluating filter socks, with the addition of natural (non-synthetic) sorbents to target specific stormwater pollutants, may provide a new management practice for on-site stormwater pollutant reduction in post-construction and urban retrofit applications. Additionally, relative to stormwater treatment by detention ponds, the filter socks' land-use footprint is lower, thereby increasing the potential to preserve natural landscapes, create new green space, increase development density, and allow alternative higher-value land uses.

This project sought to evaluate the capacity of filter socks, and natural sorbents (NS) added to the filter socks, for use in soluble pollutant filtration of common surface storm water runoff pollutants that negatively affect surface waters of the United States. Although this study did not address the issue of aging of these practices, the multiple-event effectiveness after repeated simulated runoff events was evaluated. Preliminary research has shown that the use of filter socks with natural sorbents can remove soluble and particulate storm water runoff pollutants under first flush, single-event conditions. This new information may assist green builders, regulators, watershed managers, urban planners, engineers, and architects in better site design, storm water management, water quality improvement, low impact development (LID), and green infrastructure site design, implementation, and management programs. These results will be used to assist regulatory agencies and green designers in determining the acceptability of filter socks as a post-construction storm water management BMP.

The objective of this study was to determine the multiple event removal efficiency and capacity of filter socks, and filter socks with natural sorbents, to remove soluble phosphorus, ammonium-nitrogen, nitrate-nitrogen, *E. coli*, *Enterococcus*, and oil from urban storm water runoff.

Materials and Methods

Experimental Design, Chamber System, and Runoff. Research was conducted at the Environmental Management Byproduct Utilization Laboratory at the USDA Agricultural Research Service (ARS), located in Beltsville, MD. The laboratory study was set up to simulate, collect, and examine runoff from box chambers, with the two different treatments installed. Four separate experiments (I-IV) were conducted to test the removal efficiency and capacity of filter socks, with and without natural sorbents, of various pollutants from synthetic runoff. Treatments were installed on a bare concrete surface to simulate impervious surfaces typically found in the urban landscape. Treatments were randomly assigned to chambers and repeated in triplicate for statistical analysis. Each experiment was designed to evaluate treatment performance on a specific group of pollutants typically found in urban runoff. Experiment I evaluated the removal of soluble phosphorus; experiment II evaluated the removal of inorganic nitrogen, as NH_4-N and NO_3-N; experiment III evaluated the removal of bacteria, specifically *Escherichia coli* and *Enterococcus faecium*; and experiment IV evaluated the removal of motor oil. All runoff was collected and analyzed after each simulated runoff event. Preliminary trials showed that all runoff and pollutants were transported and exited from the system when no treatment was installed. Therefore, bare surface treatments were not re-established for each experiment.

The chambers used in this experiment were constructed of plywood with a thickness of 15 mm, with inside dimensions of 1 m length by 360 mm width by 250 mm depth, and are described in detail in Sadeghi and Isensee (2001) (Figure 1). Chambers were prepared by packing a Hatboro silt loam (Ap horizon) soil, which was added in small increments to the chambers, and packed with a pressure of approximately 0.0015 kg mm^{-2} (2.14 psi) before each addition (Sadeghi and Isensee, 2001). The soil was packed until the chambers contained a uniform depth of 76 mm of soil. Soil surfaces were covered with a 6.4 mm concrete veneer to simulate surface conditions common to road ways and parking lots. The concrete veneer was separated from the soil surface by a thin black plastic sheet. An adjustable runoff drain and gate were positioned so the runoff drain was level with the surface. Silicone was used to seal the gate and prevent any leaks during the runoff simulation. The chambers were positioned at a 10% slope to simulate a worst-case scenario for urban impervious conditions.

Synthetic runoff was generated by adding pollutants to 15 L of municipal tap water, in order to generate concentrations typically found in storm water runoff. In the case of microbial pollutants, unchlorinated well water was inoculated with the fecal bacteria *E. coli* and *Enterococcus faecium*. Only one experimental pollutant (e.g., phosphorus) was added to the synthetic runoff at one time. The entire 15 L of synthetic runoff was applied to the chamber, at 1 L/min, using a sanitized watering can to disperse synthetic runoff evenly over the

Figure 1—Bench scale experimental set-up. Experimental box (micro-watershed) inside dimensions were 1 m length by 360 mm width by 250 mm depth. Treatments were 200 mm in diameter and 360 mm in length.

concrete surfaces upslope from the treatments. One application of 15 L synthetic runoff constituted one event. This volume represents the runoff amount generated for these surfaces under a 40 mm rainfall event. Each event was conducted in triplicate using three separate chambers. Runoff events were conducted until both treatments within the experiment exhibited removal efficiencies $< 25\%$, or until 25 events were completed, whichever occurred first. Experiment I blended and dissolved 10:27:5 (N:P:K as total N : P_2O_5 : K_2O) commercial fertilizer (Miracle Grow) with the prescribed runoff water volume to obtain initial influent soluble phosphorus (as P_2O_5) concentrations of 2.0 mg L^{-1} (K = as K_2O). For experiment II, 34:0:0 (N:P:K as total N) ammonium nitrate commercial fertilizer was blended and dissolved to obtain NH_4-N and NO_3-N concentrations of approximately 1.0 mg L^{-1} and 2.0 mg L^{-1}, respectively. For experiment III, fecal indicator bacteria were used. Stock cultures of generic *E. coli 3015*, resistant to 100 mg L^{-1} Rifampicin, and *Enterococcus faecium 924*, resistant to 100 mg L^{-1} penicillin (both strains from the Millner culture collection at USDA-ARS-Beltsville Agricultural Research Center), were grown at 37°C in sterile trypticase soy broth (TSB) containing the respective antibiotics. Cultures were grown for 24 to 48 hours before cells were harvested by centrifugation and washed three times in a phosphate-buffered saline with a pH of 7.2. Colony forming unit (CFU) concentrations were estimated by spectrophotometric measurements at 490 nm, followed by corresponding colony counts on TSB agar containing the respective antibiotic concentrations. Concentrations were adjusted so that the prepared inocula of each bacterium was adequate to generate15 L batches of synthetic runoff, containing approximately 300 CFU/mL (30,000 CFU/100 mL), immediately before each runoff simulation. For experiment IV, motor oil (5W30 weight) was uniformly blended with synthetic runoff to achieve concentrations of 37.5 mg L^{-1}. No sediments were added to the system. The concentrations used for each specific pollutant were approximately in the upper range of the typical concentrations in urban storm water runoff as highlighted in the introduction (Flint and Davis, 2007; McLellan and Sauer, 2009; USEPA, 1999). Spillage of runoff occurred during experiment III, so these runoff events were omitted. This occurred for event 9 for *E. coli* and events 8, 9, and 10 for *Enterococcus*. Chambers were flushed with deionized water between experiments to prevent the contamination of subsequent experiments.

Treatment Description and Installation. Compost filter socks, filled with specified compost filter media (USEPA 2006), were manufactured and donated by Filtrexx International (Grafton, Ohio). (Disclaimer: Any mention of trade names or commercial products in this report is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the authors or the U.S. Department of Agriculture.)The compost filter media was derived from land clearing and yard debris organic materials. This material adhered to USEPA specifications for compost filter media used for pollution control applications (2006). The actual particle size distribution of this compost filter media was as follows: 0%>25mm, 56%>9.5mm, 27%>2mm, and 17%<2mm. The moisture content of the compost filter media was 40%. There were no visual or physical contaminants in the compost filter media. The density of a filled compost filter sock was 20 kg/linear m (Table 1). No processing was conducted once the filter socks were received at the experimental laboratory. The compost filter media was enclosed in a tubular mesh netting material. (The manufacturer uses a mechanical auger to fill an empty

Table 1—Filter socks design characteristics.

Design diameter	200 mm
Effective height	160 mm
Hydraulic flow-through capacity	94 L/min/meter
Density	20 kg/linear meter
Pore space	20%
Experiment influent flow rate	1 L/min
Period between wet-dry	24 hours

tubular mesh net with compost filter media and seals the ends with metal clips). The mesh netting was a 5 mm photodegradable polypropylene, with 3.2 mm diamond mesh apertures. The enclosed compost filter media in the open mesh netting allowed hydraulic movement through the filter socks, while containing the filter media and potential sediment and soluble pollutants present in storm water runoff. Twenty centimeter diameter filter socks were manufactured to fit tightly to the chamber width dimension of 360 mm. The filter socks were placed at the down-slope end of the chamber and slightly compacted manually to ensure ground surface contact. Compost filter media was used to backfill both the chamber corners and the filter socks and concrete surface interface. The natural sorbents were mechanically blended with the compost filter media, prior to filling the filter socks during manufacturing. After blending, the materials were inserted into the tubular mesh sock using the auger described above. Application rates followed the manufacturer's application specifications of 460 g/linear m of filter socks (2.2% by weight). The natural sorbents were added to evaluate their potential impact on pollutant removal efficiency and capacity. These natural sorbents were similar to those which are commonly used to flocculate and chemically adsorb opposite-charged ionic pollutants, often utilized in water and storm water treatment facilities. All natural sorbents were derived from natural materials and were applied in dry granular form ($\leq$ 2mm).

Runoff Sampling and Analysis. For the phosphorus and nitrogen experiments, runoff from each chamber was collected in 19 L commercial plastic buckets. After each event, subsamples (50 ml) were collected, acidified to pH 3–5 by the addition of 5 nitric (N) sulfuric acid, then filtered through 0.45 μm membranes to remove particulates, and stored at 4°C until analysis. For experiment I, filtered samples were processed for ortho-phosphorus by flow injection analysis (Lachat QuikChem method # 10-115-01-1-A). For experiment II, concentrations of nitrate-nitrogen and ammonium-nitrogen (mg L^{-1}) were determined by automated continuous flow injection analysis (Lachat QuikChem methods # 12-107-04-1-B and # 12-107-06-2-A, respectively) using auxiliary reagent streams to produce concentration gradients. Twenty milliliter samples were prepared by filtering the sample with a 0.45 μm syringe filter (Pall IC Acrodisc, #AP-4585) prior to analysis. For experiment III, concentrations of *E. coli* (colony counts 100 mL^{-1}) in the runoff were determined by spiral plating 100 or 200 uL aliquots onto MacConkey's agar containing 100 mg L^{-1} Rifampicin; after 24 hours incubation at 44.5°C, colonies were counted. The results were calculated and reported as total cells collected per volume of runoff water collected. Concentrations of *Enterococcus faecium* in runoff were determined by spiral plating 100 or 200 uL aliquots onto Enterococcus agar (Difco, BD, Sparks, MD) containing 100 mg L^{-1} penicillin; after 48 hours incubation at 37°C, colonies were counted. Results were calculated and reported as described above for *E. coli*. Due to agar quality, there was a loss of data for runoff event 9 for *E. coli,* and runoff events 8, 9, and 10 for *Enterococcus*. For experiment IV, runoff from each chamber was collected in a 2 L separatory funnel containing 100 ml hexane. The aqueous fraction (bottom layer) was decanted slowly during the runoff events so as not to remove any hexane. Afterwards each hexane fraction (with a small amount of aqueous fraction) was decanted into a sealed glass jar. Each separatory funnel was rinsed with 100 ml hexane and the hexane rinses were added to the respective sealed jars. Subsequent aqueous fractions were carefully removed from hexane extracts, using 200 ml separatory funnels, and the aqueous fractions were re-extracted with 100 ml hexane. Hexane fractions from each event were pooled in tared 400 ml glass beakers; the hexane was then removed by evaporation in a fume hood for 16 hours at ambient temperature. The residual hexane extract (containing the motor oil) was dried for 16 to 24 hours at 40°C prior to mass determination. Equipment calibration, precision, and acceptance criteria are inclusive to the standard test methods referenced here.

Analysis of Results. Means for all pollutant concentrations and runoff volumes were determined using the three treatment replications. The runoff loads for phosphorus, nitrogen species, bacteria, and oil were determined by multiplying pollutant concentrations by runoff volume. Event removal efficiencies for all treatments in all experiments were determined by the following equation:

$$RE = 100 - [(PLE \div PLI) \times 100]$$

where RE is removal efficiency (%), PLE is pollutant load in effluent, and PLI is pollutant load in influent. Mean removal efficiencies were determined by averaging event removal efficiencies. The total load removal was determined by adding together the average load removed from each runoff event. These results have also been reported as load removed (mg) per unit length of filter (m) as mg/linear m. Statistical analyses for means separation were performed using Proc TTest, SAS Institute Ver 9.1, on the effect of filter socks and filter socks with natural sorbents on the total load removal and total removal efficiency of soluble phosphorus, ammonium-nitrogen, nitrate-nitrogen, *E. coli*, *Enterococcus*, and oil. The separation of means was determined to be significant at the $p<0.05$ level. Prior to means separation, Type 1 Error was controlled for at $<$ 0.05 level, and the resultant Pr>F values >0.05 were not deemed significant.

Results and Discussion

Phosphorus. Over eight runoff events, the average event removal efficiency for soluble phosphorus (P) by the two treatments ranged from 0% to 48%, with a mean of 9% ($\pm$9) and 34% ($\pm$10) over the entire exposure period for filter socks and filter socks with natural sorbents, respectively (Figure 1). The total load exposure of soluble phosphorus over the entire period was 240 mg (686 mg/linear m), while the total load removal for the filter socks was 22.7 ($\pm$11) mg (65 mg/linear m), and for the filter socks with natural sorbents was 83 ($\pm$14) mg (237 mg/linear m). There was a significant difference between treatments for total removal efficiency (p=0.003) and total load removal (p=0.002). Based on these results, it appears that the additive of natural sorbents increased the removal of soluble phosphorus from stormwater runoff. Although the removal capacity of the filter socks with natural sorbents was considerably reduced after eight storm events, increasing the natural sorbents inclusion rate may have a positive effect on removal efficiency and capacity. This should be explored in future studies.

Nitrogen. Over 25 runoff events, the average event removal efficiency for ammonium-nitrogen by the two treatments ranged from 0% to 72%, with a mean of 31% ($\pm$19) and 54% ($\pm$19) over

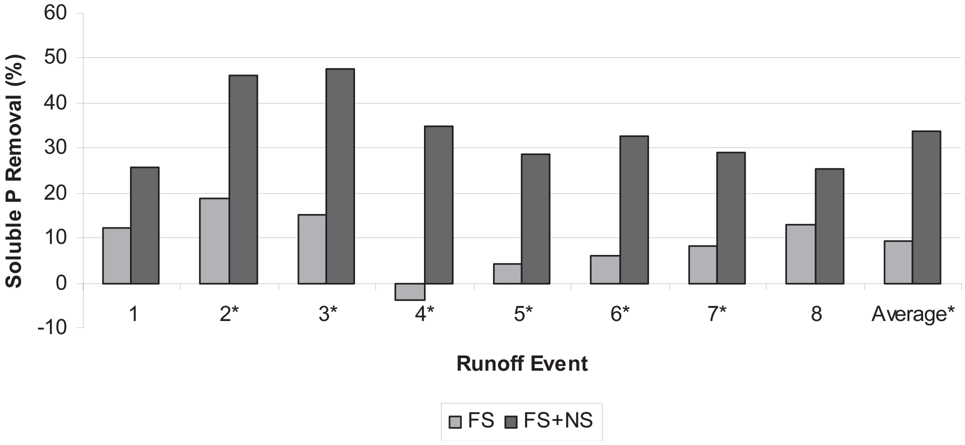

Figure 2—Soluble phosphorus removal efficiency per event for compost filter socks (FS) and compost filter socks with natural sorbent (FS+NS). After eight runoff events, removal efficiencies for both treatments were less than 25%; therefore the runoff events were discontinued. Events marked with a * had treatments that were significantly different ($p<0.05$). Total load removal for filter socks and filter socks with natural sorbents was 23 mg and 83 mg, respectively.

the entire exposure period for filter socks and filter socks with natural sorbents, respectively (Figure 2). The total load exposure of ammonium-nitrogen over the entire period was 375 mg (1071 mg/linear m), while the total load removal for the filter socks was 105.7 (±29) mg (302 mg/linear m), and 186.7 (±51) mg (533 mg/linear m) for the filter socks with natural sorbents. There was no significant difference between treatments for total removal efficiency ($p=0.068$) or total load removal ($p=0.072$). Chemical adsorption of ammonium-nitrogen by the compost and the natural sorbents is likely responsible for the removal efficiencies demonstrated in this experiment. It is possible that minor transformations to other forms of nitrogen may have occurred, but due to the rapid filtration characteristics of these experiments, the authors believe this to be minimal or non-existent. The increased removal efficiencies by the natural sorbents treatment are likely from the increased surface area and adsorption capability of the natural sorbents additive. It is likely that the removal efficiencies shown by both treatments would continue over more runoff events, due to the consistent results demonstrated over the 25-event exposure period evaluated in this study. Although not statistically significant, there was a contribution of ammonium-nitrogen from the filter socks during the first event; however, there was no contribution from the filter socks with natural sorbents. This may be the result of ammonium-nitrogen within the organic material exhibiting itself in the first flush, while the natural sorbents may have the ability to adsorb the pollutant and thus prevent its migration from the filtration system.

Over 25 runoff events, the average event removal efficiency for nitrate-nitrogen by the two treatments ranged from 2% to 17%, with a mean of 9% (±3) and 11% (±5) over the entire exposure period for filter socks and filter socks with natural sorbents, respectively. The total load exposure of nitrate-nitrogen over the entire period was 750 mg (2143 mg/linear m), while the total load removal for the filter socks was 68.9 (±13) mg (197 mg/linear m), and 79.7 (±18) mg (228 mg/linear m) for the filter socks with natural sorbents. There was no significant difference between treatments for total removal efficiency ($p=0.385$) or total load removal ($p=0.519$). Although removal efficiencies were not high for these treatments, due to the difficult nature of removing nitrate-nitrogen from storm-water without prolonged detention to induce denitrification (which requires a significant land area), these treatments may find limited application where a small treatment footprint and/or easy installation and maintenance are required. Due to low removal efficiencies, and lack of statistical significance between treatments, these results are not presented graphically.

Petroleum Hydrocarbons. Over 25 runoff events, the average event removal efficiency for oil by the two treatments ranged from 98% to 99%, with a mean of 99% (±1) for both treatments over the entire exposure period (Figure 3). The total load exposure of oil over the entire period was 14,000 mg (40,000 mg/linear m), while the total load removal for the filter socks was 14,147 (±216) mg (the slightly higher value for removal relative to exposure is due to replicate deviation from the mean) (40,008 mg/linear m); the total load removal for filter socks with natural sorbents was13,609 (±549) mg (38,486 mg/linear m). There was no significant difference between treatments for total removal efficiency ($p=0.87$) or total load removal ($p=0.152$). Based on the consistently high removal efficiencies for these treatments over the full exposure period, it is likely that they would continue to perform at or near this level under repeated exposures, and might exhibit similar results under higher concentration levels. This may also provide evidence that this management practice could be employed in oil spill clean-up projects– where concentrations can be orders of magnitude higher– in addition to the treatment of typical concentrations in oil contaminated soils, which range from 5,000 to 20,000 mg kg^{-1} (US EPA, 1998).

Bacteria. Over 25 runoff events, the average event removal efficiency for *E. coli* by the two treatments ranged from 0% to 99%, with a mean of 4% (±16) and 85% (±18) over the entire exposure period for filter socks and filter socks with natural sorbents, respectively (Figure 4). The total load exposure of *E. coli* over the entire period was 1.17×10^8 CFUs (3.34 CFUs x 10^8/linear m), while the total load removal for the filter socks was 1.8×10^7 CFUs ($\pm 1 \times 10^7$) (5.14 CFUs x 10^7/linear m) and was 1.1×10^8 CFUs ($\pm 0.04 \times 10^8$) (3.14 CFUs x 10^8/linear m) for

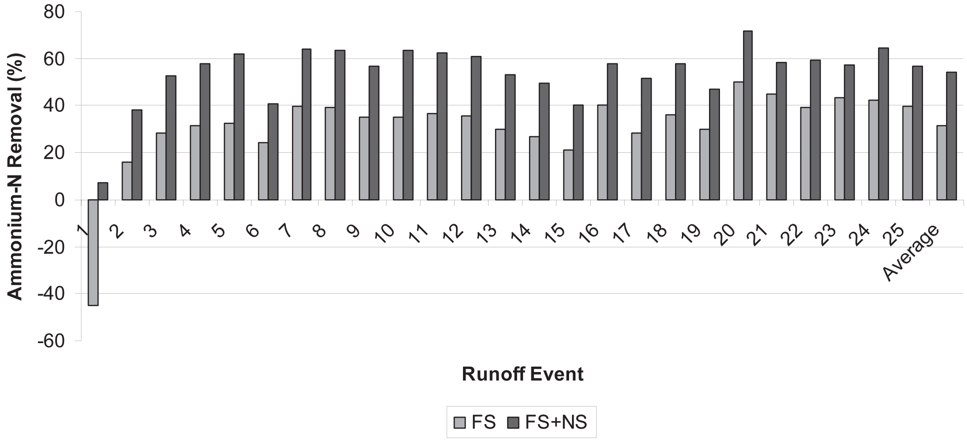

Figure 3—Ammonium-nitrogen removal efficiency per event for compost filter socks (FS) and compost filter socks with natural sorbent (FS+NS). No event treatments were significantly different ($p<0.05$). Total load removal for filter socks and filter socks with natural sorbents was 106 mg and 187 mg, respectively.

the filter socks with natural sorbents. The difference between treatments for total removal efficiency ($p<0.001$) and total load removal ($p<0.001$) was statistically significant. These results indicate a clear benefit from the natural sorbents additive in reducing *E. coli* in storm water, while there is little benefit from the filter socks alone in removing non-sediment bound *E. coli*. This benefit is likely due to the sorption or flocculation of bacteria in water. Based on the consistently high removal efficiencies for the filter socks with natural sorbents over the full exposure period, it is likely that this treatment would continue to perform at or near this level under repeated exposures and might exhibit similar results under higher concentration and load levels. This may provide evidence that this technology could be used around animal feeding operations, where *E. coli* levels are often more elevated than in urban storm water runoff.

Over 25 runoff events, the average event removal efficiency for *Enterococcus* by the two treatments ranged from 0% to 99%, with a mean of 23% (18±) and 65% (±20) over the entire exposure period for filter socks and filter socks with natural sorbents, respectively (Figure 5). The total load exposure of *Enterococcus* over the entire period was 8.44 CFUs x 10^8 (2.41 CFUs x 10^9/linear m), while the total load removal was 2.81 CFUs x 10^8 ($\pm$ 0.6 $\times$ 10^8) (8.03 CFUs x 10^8/linear m) for the filter socks and 5.25 CFUs x 10^8 ($\pm$ 0.3 $\times$ 10^8) (1.5 CFUs x 10^9/linear m) for the filter socks with natural sorbents. There was a significant difference between treatments for total removal efficiency ($p<0.001$) and total load removal ($p<0.001$). Similarly to the *E. coli* results, these results indicate a clear benefit from the natural sorbents additive in reducing *Enterococcus* in storm water, although there is some benefit from the filter socks alone in removing non-sediment-bound *Enterococcus*.

Summary and Conclusions

These results show that these practices can be utilized effectively over many frequent rainfall-runoff events. This study did not explore how time and aging may effect these practices. From anecdotal field experiments, it appears that this practice maintains its physical integrity over many years if the netting

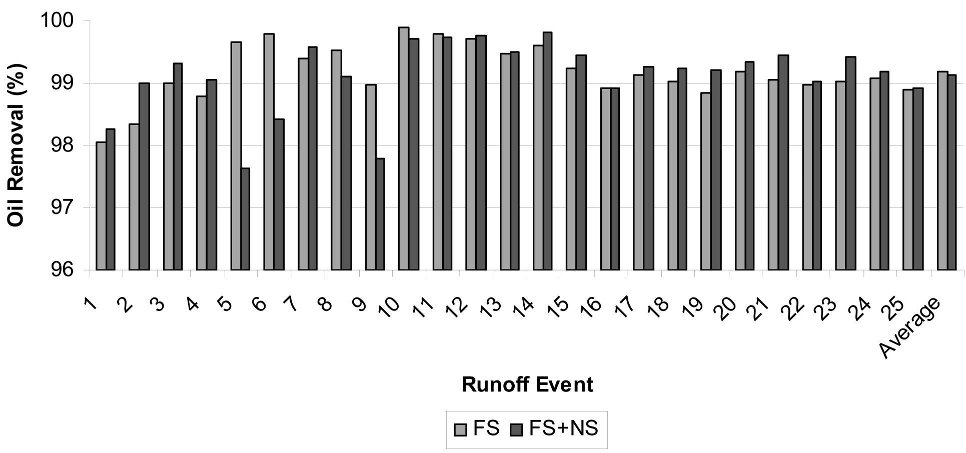

Figure 4—Oil removal efficiency per event for compost filter socks (FS) and compost filter socks with natural sorbent (FS+NS). No event treatments were significantly different ($p<0.05$). Total load removal for filter socks and filter socks with natural sorbents was 14,147 mg and 13,609 mg, respectively.

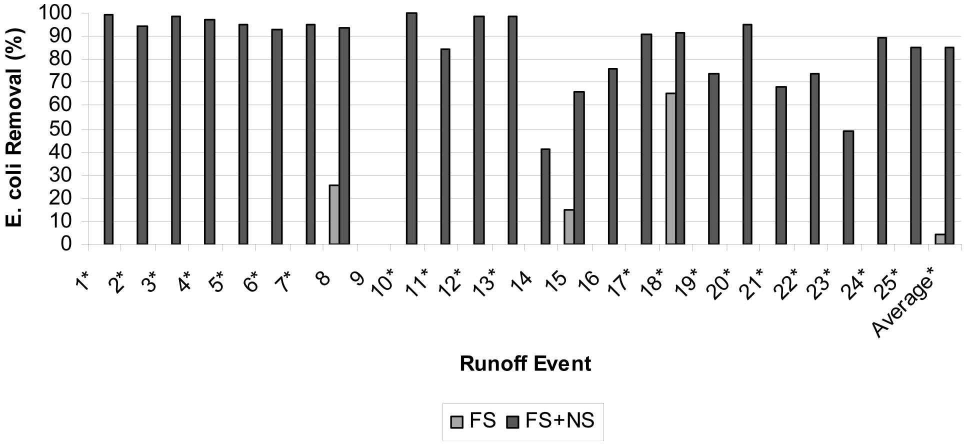

Figure 5—*E. coli* removal efficiency per event for compost filter socks (FS) and compost filter socks with natural sorbent (FS+NS). Events with * had treatments that were significantly different ($p<0.05$). Total load removal for filter socks and filter socks with natural sorbents was 1.8×10^7 CFUs and 1.1×10^8 CFUs, respectively. Event 9 was omitted due to loss from spillage.

and compost media described previously are utilized. Netting that is less durable or biodegradable, or media that is not sufficiently composted, would likely result in a loss of structural integrity and a possible reduction in performance over time. Long-term degradation and weathering would likely reduce the ability of this practice to remove pollutants from stormwater; however, this can be minimized by proper storage prior to use, and/or combining with vegetation in the field to prevent photo-degradation. It is more likely, though, that these practices will reach a pollutant-removal capacity in the field prior to actual field degradation, both because of aging due to the stability of the organic matter within the compost, and because of the slow photo-degradation rate of the netting and natural sorbents. However, a study examining this phenomenon is recommended. Additionally, this study explored the longevity and capacity of a practice based on *average* runoff events and pollutant concentrations. If pollutant concentrations or loads are increased due to site or environmental factors, thereby increasing the exposure to the practice, it would likely reduce the time in which its capacity is reached, thereby reducing its field-time longevity. At this point, the practice would need to be replaced, or a new one installed. Chemical ionic adsorption to the filter socks and natural sorbents is responsible for the majority of the removal of each pollutant, with the exception of oil, which is removed by a function of physical separation and absorption. These findings show that stronger the adsorption characteristic of the pollutant, relative to the other pollutants, the greater its removal by the treatment practice. It is possible that when multiple pollutants are present in the stormwater runoff, the capacity for specific pollutants may be reduced; however, given the different ionic adsorption characteristics of nitrogen and phosphorus, that might not be the case for these two nutrients (which are often found together in runoff). Because oil removal depends more on physical removal and absorptive characteristics, rather than chemical adsorption mechanisms, it probably does not compete for adsorption sites with the other pollutants described in this study. The bacteria and phosphorus both respond to the same ionic adsorption characteristic, and therefore high loads of one

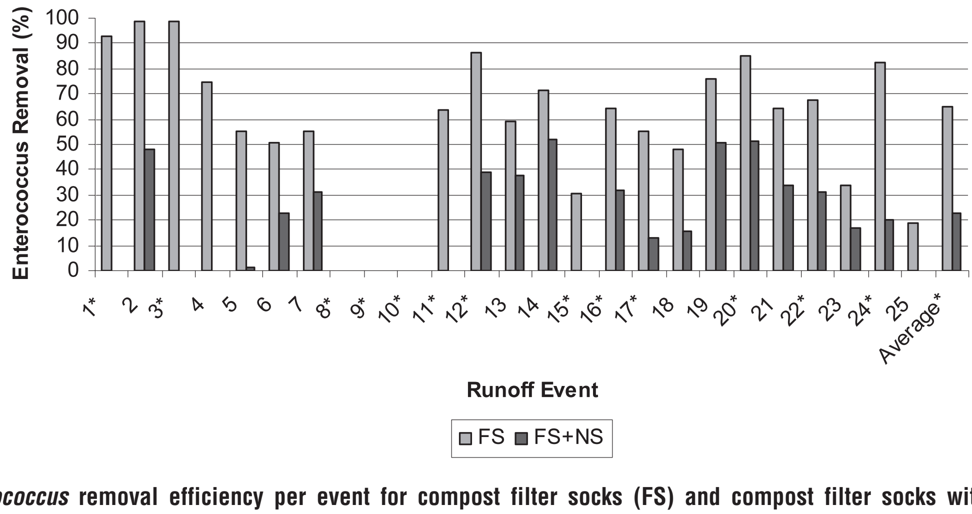

Figure 6—*Enterococcus* removal efficiency per event for compost filter socks (FS) and compost filter socks with natural sorbent (FS+NS). Events with * had treatments that were significantly different ($p<0.05$). Total load removal for filter socks and filter socks with natural sorbents was 2.81 CFUs x 10^8 and 5.25 CFUs x 10^8, respectively. Events 8, 9, and 10 were omitted due to loss from spillage.

Table 2—Experimental influent and effluent pollutant concentration means (mg L^{-1}) and typically-reported stormwater pollutant concentration values. *E. coli.* and *Enterococcus* concentrations are reported in CFU/mL.

	Influent	Effluent FS	Effluent FS+NS	Typical	Reference
Phosphorus	2.0	1.82	1.32	0.24–3.6	Flint and Davis, 2007
Ammonium-N	1.0	0.69	0.46	0.14–29.0	Flint and Davis, 2007
Nitrate-N	2.0	1.82	1.78	0.14–29.0	Flint and Davis, 2007
Oil	37.5	0.38	0.38	10–35	USEPA, 2002
E. coli	300	288	45	300	McLellan and Sauer, 2009
Enterococcus	300	231	105	300	McLellan and Sauer, 2009

may reduce the reduction of the other, if both are present in stormwater.

Urban storm water runoff poses a substantial threat of pollution to receiving surface waters. Compost filter socks (FS) and natural sorbents (NS) present a low cost, low footprint, sustainable solution to reducing on-site storm water pollutants. The objective of this study was to determine the multiple event removal efficiency and capacity of filter socks and filter socks with natural sorbents to remove soluble phosphorus, ammonium-nitrogen, nitrate-nitrogen, *E. coli, Enterococcus*, and oil from urban storm water runoff. Treatments were exposed to pollutant concentrations consistent with urban runoff originating from impervious surfaces, such as parking lots and roadways. The filter socks with natural sorbents removed significantly greater levels of soluble phosphorus than the filter socks, removing a total of 237 mg/linear m over eight runoff events, or an average of 34%. However, both treatments were only effective at removing soluble phosphorus for up to eight runoff events. The FS+NF removed 54% of ammonium-nitrogen over 25 runoff events, or 533 mg/linear m, and only 11% of nitrate-nitrogen, or 228 mg/linear m. The filter socks and filter socks with natural sorbents removed 99% of oil over 25 runoff events, or a total load of 38,486 mg/linear m. Over 25 runoff events the filter socks with natural sorbents removed significantly more *E. coli* and *Enteroccocus* at 85% and 65%, and a total load of 3.14 CFUs x 10^8/linear m and 1.5 CFUs x 10^9/linear m, respectively. Based on these results, it is clear this technique can be used to remove a variety of storm water pollutants, and for oil and bacteria this technology may be useful in more challenging applications where load exposure is much greater, such as oil spills and runoff from animal feeding operations. However, it should be understood that these results are from bench-scale conditions, and performance under field-scale conditions may be quite different due variable pollutant loading rates, pollutant concentrations, runoff flow rates, and volumetric exposure created by changing watershed conditions and rainfall characteristics.

Future studies should investigate the effects of increased inclusion rates of natural sorbents and increased pollutant exposure on the pollutant-removal efficiency and capacity of this technology. In addition, other worthwhile studies would include its performance for other persistent urban storm water pollutants such as heavy metals and pH; its performance with various pollutant exposure occurring concomitantly; and the use of this technology in other green infrastructure applications, such as bioretention systems and bioswales.

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