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Sorbent-amended compost filter socks in grassed waterways reduce nutrient losses in surface runoff from corn fields

M.J. Shipitalo, J.V. Bonta, and L.B. Owens

Abstract: Surface runoff from row-crop fields frequently has high concentrations of sediment, nutrients, and pesticides, particularly in the first few events after tillage and agrochemical application. Compost filter socks placed in grassed waterways can further reduce sediment concentration as runoff is transmitted offsite but are generally ineffective in removing dissolved chemicals. Therefore, we investigated the effect of adding a proprietary sorbent, Nutriloxx, to filter socks filled with composted bark and wood chips on sediment, nutrient, and glyphosate concentrations in runoff. Surface runoff from one tilled and one no-till watershed planted to corn (*Zea mays* L.) was routed into two parallel, 30 m (99 ft) long, grassed waterways. Three, 46 cm (18 in) diameter filter socks filled with Nutriloxx-amended compost were placed 5 m (16.5 ft) apart across the upper half of one waterway and in the lower half of the paired waterway. Automated samplers were used to obtain samples above and below the treated waterway segments in the 2009 and 2010 crop years. The effectiveness of the grassed waterways and filter socks was highly dependent on tillage treatment and timing and size of the runoff events. In 2009, there were no sizable events during the early growing season. Consequently, erosion was minimal, and no significant effects on sediment concentration were detected. Averaged for both watersheds, however, the amended filter socks contributed to an additional 28% reduction in dissolved phosphate-phosphorus (PO_4-P) concentration compared to waterway segments without filter socks (significant at $p = 0.05$). The filter socks, however, significantly increased sulfate (SO_4) concentrations up to 20-fold in the first sampled event, but SO_4 concentrations declined rapidly with subsequent events. Similarly, the filter socks increased concentrations of calcium (Ca), potassium (K), and sodium (Na), but this was not significant in all instances. In 2010, runoff-producing rainfall occurred frequently during the growing season, and the filter socks significantly decreased sediment and PO_4-P concentrations from the tilled watershed. In addition, large reductions in ammonium-nitrogen (NH_4-N) concentrations were noted (average > 7-fold), but field observations suggested that this was due to physical trapping of eroded coated-urea fertilizer prills rather than sorption. The filter socks continued to contribute to significantly increased SO_4 concentrations from both watersheds. Filter socks can effectively reduce sediment losses when used in agricultural applications, and adding selective sorbents can increase their ability to retain nutrients. However, losses of sorbent components need to be considered.

Key words: filter socks—grassed waterways—surface runoff—water quality

Surface runoff from cropland can have high concentrations of nutrients and pesticides, particularly if runoff occurs shortly after application of these materials (Fawcett et al. 1994; Shipitalo and Owens 2006). If tillage has been used for crop production, the runoff may also contain high concentrations of eroded soil. Vegetated treatment systems and conservation buffers, such as constructed wetlands, vegetated ditches and waterways, and forested and grassed buffer strips, positioned between the runoff-generating fields and receiving bodies of water may help to reduce these concentrations and impairment of water quality (Lowrance et al. 2002; Stehle et al. 2011). These systems, however, tend to be more effective in retaining sediment than dissolved chemicals and further lose effectiveness when channelization occurs resulting in concentrated flow (Daniels and Gilliam 1996; USDA NRCS 2000; Dosskey et al. 2002; Fiener and Auerswald 2009).

One method of increasing the retention of dissolved chemicals in vegetated treatment systems and buffers is through the use of selective sorbent and flocculent materials. This can be accomplished by treating concentrated flow areas within buffers with materials that readily sorb the chemical species of concern. For example, Gallimore et al. (1999) found that alum-based water treatment residual can be successfully used to reduce dissolved phosphorus (P) in surface runoff from fields that had received applications of animal manures. This was achieved by broadcasting the water treatment residual over the entire field, but was more effective when the material was applied to buffer strips. Similarly, Leytem and Bjornberg (2005) found that dosing irrigation return flows with alum ($Al_2[SO_4]_3$) significantly reduced soluble P concentrations with reductions of up to 98% noted when alum was added at a rate of 40 mg L^{-1}.

Additional materials that can be used to remove P and other nutrients from runoff include ferric sulfate (Närvänen et al. 2008), iron slag, iron hydroxides, modified clays, limestone, gypsum, fly ash, and zeolites (Penn et al. 2007; Turtola et al. 2010). Organic polymers, such as polyacrylamides, can be used to reduce sediment concentration and turbidity (King and McLaughlin 2009). These materials can be land-applied or added to the water in retention basins and sedimentation ponds. Commercial products, such as Phoslock (lanthanum-modified bentonite clay; SePRO Corporation, Carmel, Indiana), have been specifically designed to remove dissolved P from eutrophic bodies of water (Haghseresht et al. 2009).

Martin J. Shipitalo is research soil scientist at the USDA Agricultural Research Service National Laboratory for Agriculture and the Environment in Ames, Iowa. **James V. Bonta** is a research hydraulic engineer at the USDA Agricultural Research Service National Sedimentation Laboratory, Oxford, Mississippi. **Lloyd B. Owens** is a retired USDA Agricultural Research Service research soil scientist.

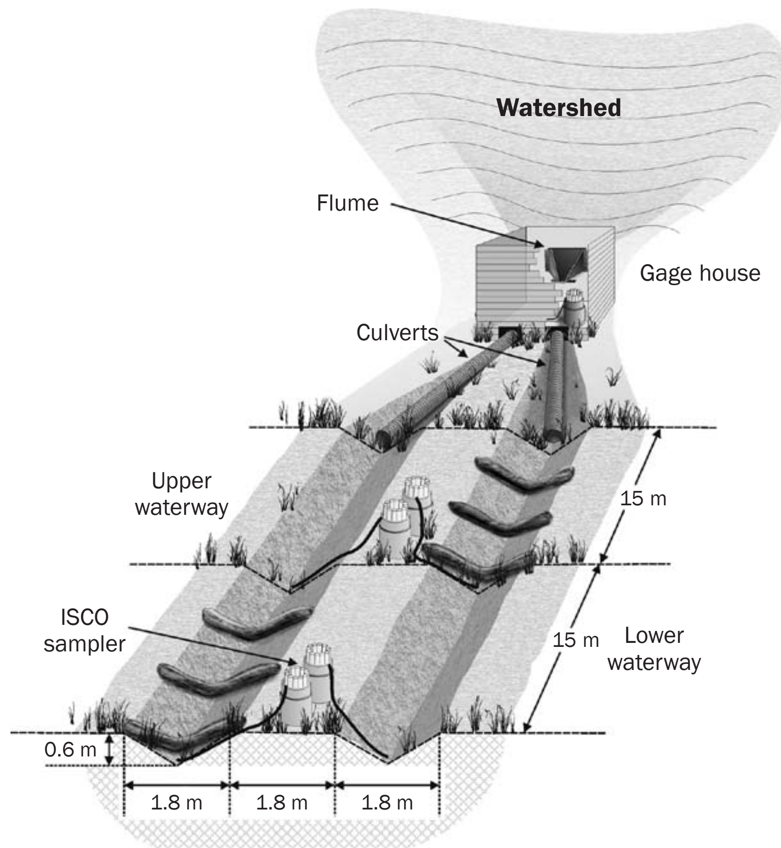
Another treatment method that has shown promise is to include sorbent materials in permeable flow-through structures placed in ditches, grassed waterways, and adjacent to tile outlets. These structures actively treat the water as it passes through them. The structures can be semipermanent, for example, filling proportions of ditches with reactive materials such as gypsum, limestone, or iron slag (Penn et al. 2007; Turtola et al. 2010). Alternatively, they can be temporary, removable structures made of fibrous materials such as straw, coir, and wood, or materials such as compost placed in open mesh tubes referred to as filter socks (USEPA 2006; Keener et al. 2007; King and McLaughlin 2009; Shipitalo et al. 2010). Once they have served their purpose, the compost used to fill the filter socks can be disposed of by spreading onsite and the mesh removed for disposal or left onsite to biodegrade if made of appropriate material (Filtrexx International 2011).

A field study on the effectiveness of compost-filled filter socks installed in grassed waterways indicated that they significantly reduced sediment concentrations, particularly when concentrations were high, and reduced the concentrations of selected herbicides up to 18% (Shipitalo et al. 2010). These reductions were attributed to a combination of particle entrapment in the filter socks, sorption by the compost, and temporary ponding behind the filter socks that reduced turbulence and increased contact time with sorptive elements in the soil, grass, and thatch in the waterways. Nutrient (chlorine [Cl], nitrate-nitrogen [NO_3-N], phosphate-phosphorus [PO_4-P], sulfate [SO_4], calcium [Ca], potassium [K], sodium [Na], and magnesium [Mg]) concentrations, however, were slightly increased, probably due to leaching of soluble forms present in the compost.

Nevertheless, laboratory-scale tests of filter socks filled with compost amended with a variety of proprietary sorbent materials and flocculants have demonstrated impressive removal efficiencies (>90%) for nutrients, bacteria, metals (cadmium [Cd], chromium [Cr], copper [Cu], nickel [Ni], lead [Pb], and zinc [Zn]), and petroleum hydrocarbons (Faucette et al. 2008, 2009a, 2009b). Stehle et al. (2011), however, excluded small-scale mesocosm studies from their meta-analysis of vegetated treatment systems arguing that this type of information is not comparable to field conditions. Furthermore, they noted a dearth of studies conducted under conditions typical of real-world farming conditions. Therefore, our objective was to field test the effectiveness of filter socks amended with a commercially available sorbent, Nutriloxx (Filtrexx International, Grafton, Ohio), in reducing the concentration and transport of nutrients, sediment, and the herbicide glyphosate (N-[phosphonomethyl] glycine) in surface runoff generated by natural rainfall on two small watersheds planted to corn (one tilled and one no-till) and diverted into grassed waterways.

Figure 1

Schematic representation (not to scale) of the layout of the watersheds, gaging station, culvert diversions, paired grassed waterways, amended filter socks, and automated water samplers. For each watershed, amended filter socks were installed 5, 10, and 15 m downstream from the culvert outlet in one grassed waterway and 20, 25, and 30 m downstream in the paired waterway.



Materials and Methods

Watershed and Waterway Management and Configuration. A two-year (2009 and 2010) field study was conducted at the North Appalachian Experimental Watershed near Coshocton, Ohio, using the same watersheds and grassed waterways used by Shipitalo et al. (2010) to investigate the effectiveness of compost-filled filter socks in 2007 and 2008. Thus, the current study represents a continuation of this research, and the materials and methods are briefly outlined below. The only major modifications of the experimental design were the use of sorbent-amended filter socks and an increase in the number of filter socks per waterway from two to three.

Two watersheds (WS) were used in the study, one that was disked prior to planting of corn and cultivated between the rows during the growing season for additional weed control (WS 127, 0.67 ha [1.65 ac], average slope 9%) and another that was in no-till corn production (WS 118, 0.79 ha [1.96 ac], average slope 10%). The configuration of the watersheds, grassed waterways, and samplers is schematically depicted in figure 1. The waterways were designed by USDA Natural Resources Conservation Service personnel using standard criteria (USDA NRCS 2007) and installed under their supervision in 2005. After passing through a gage house where flow rate was measured using H-flumes and float-type water stage recorders connected to data loggers (Brakensiek et al. 1979), equal amounts of outflow from the watersheds were diverted into parallel grassed waterways (3.3% slope WS 118 and 4% slope WS 127) so that the effect of the filter socks could be assessed using a paired waterway approach. The waterways differed from standard NRCS design only in that they were installed in parallel and diversions were constructed to minimize the inflow of water not originating from the watersheds. The predominant soil series mapped on both watersheds was Coshocton silt loam, a fine-loamy, mixed, active, mesic Aquultic Hapludalf (Kelly et al. 1975).

On February 23, 2009, liquid swine manure was applied to the frozen soil on the watersheds at a rate of approximately 79,500 L ha^{-1} (8,500 gal ac^{-1}). A setback strip of 30 m (99 ft) above the gage houses received no manure. Phosphorus (77 kg ha^{-1} P_2O_5 [69 lb ac^{-1}]) and K (101 kg ha^{-1} K_2O [90 lb ac^{-1}]) fertilizer was broadcast applied to the no-till watershed (WS 118) on May 18. Both watersheds received a broadcast application of 197 kg ha^{-1} (176 lb ac^{-1}) of N as Agrotain-coated urea (Agrotain International, St. Louis, Missouri) on June 1 in the setback strips and half this rate on areas that had received swine manure in February. Glyphosate-tolerant corn was also planted on this date. Residual herbicides were used for primary weed control and were applied on June 5, and a 2-propanamine formulation of glyphosate was applied on June 23 and again on July 1 at a rate of 1.12 kg active ingredient ha^{-1} (1 lb active ingredient ac^{-1}).

Management practices for the 2010 crop year were similar to 2009 with liquid manure applied to frozen soil at the same rate on February 5, 2010. Phosphorus (103 kg ha^{-1} [92 lb ac^{-1}] P_2O_5) was broadcast applied to both watersheds on April 21 and 197 kg ha^{-1} (176 lb ac^{-1}) of N as polymer-coated ESN urea (Agrium US Inc., Denver, Colorado) was applied on May 20 to the setback areas and at half this rate to the rest of the watershed. Glyphosate-tolerant corn was planted on May 10, and residual herbicides were applied on May 20. Glyphosate was applied only once, on June 21.

Filter Sock Installation and Sampling. Filter socks filled with composted wood chips and bark amended with a proprietary sorbent, Nutriloxx, were obtained from Filtrexx International LLC and installed in the grassed waterways according to their specifications (Filtrexx International 2011) on June 5, 2009. The filter socks were nominally 46 cm (18 in) in diameter and 3 m (10 ft) long, and three socks were installed approximately 5 m (16.5 ft) apart in the upper 15 m (49.5 ft) of one of the paired waterways (figure 1). Similarly, three filter socks were placed in the lower half of the paired waterway 5 m (16.5 ft) apart, beginning at 20 m (66 ft). The socks were installed in a U-shape facing upstream and were held in place using stakes. When surface runoff occurred, samples were automatically collected at five positions using ISCO Model #3700 samplers with a 24 glass bottle configuration (Teledyne ISCO, Lincoln, Nebraska). The intake for the first sampler was just below the flume, the next two were in shallow stainless steel pans 15 m (49.5 ft) beyond the outlets of the culverts that diverted runoff into the waterways, and two were in pans 30 m (99 ft) downstream from the culverts (figure 1). The actual position of the sampler intakes was approximately 0.5 m (1.7 ft) downstream from the last filter sock in each waterway.

Because a finite depth of flow was required to submerge the sampler intakes, sampling was initiated when the depth in the flume reached 3 cm (0.1 ft). As long as the flow rate was above this threshold, samples were collected every 10 minutes until 10 samples were collected, then every 20 minutes for the next 10 samples, and every 60 minutes for the last 4 samples. The sampling system was placed in operation beginning with filter sock installation in 2009 and continued until the end of November when further sampling was precluded by temperatures below freezing. The samplers were reinstalled on May 15, 2010, and their operation was discontinued on November 30, 2010.

Sample Analysis. The runoff samples were passed through 1.5 μm pore size filter paper, and total suspended solids were determined by weighing the filter paper after drying at 105°C (220°F) as specified in Method 2540 D (Eaton et al. 2005). Ion chromatography was then used to determine the concentrations of the anions (Cl, NO_3-N, PO_4-P, and SO_4) and the cations (Ca, K, Na, ammonium-nitrogen [NH_4-N], and magnesium [Mg]) in the filtered samples. Separate samples were passed through 0.45 μm glass filters, followed by determination of glyphosate and the glyphosate metabolite aminomethylphosphonic acid (AMPA) concentrations using the high performance liquid chromatography–based US Environmental Protection Agency (USEPA) Method 547 (USEPA 1990) with a detection limit of 1 μg L^{-1}.

Data Analysis. Flow-weighted concentrations and transport for each runoff event were calculated from flow volumes determined using the H-flumes and data loggers, and the concentrations were measured in individual samples collected just below the flumes. Flow-weighted concentrations 15 m (49.5 ft) and 30 m (99 ft) downstream in the grassed waterways were calculated using the samples collected at these positions with the assumption that the flow rates were half those measured at the flume. While infiltration in the waterways could decrease flow and rainfall on the waterways could increase flow, it was assumed that these processes were similar in the paired waterways segments. Moreover, an analysis of measured Ca and Mg concentrations in the rainfall and concentrations in the runoff collected in the waterways in a previous study (Shipitalo et al. 2010) suggested that dilution by rainfall must have been inconsequential, which was expected given the relatively small area of the waterways compared to the size of the watersheds.

The flow-weighted concentrations varied substantially among runoff events and were affected by the combined effects of the grassed waterways and the amended filter socks. In order to account for this variability and to separate out the net effect of the filter socks from that of the grassed waterways alone, the concentrations were normalized by dividing the concentrations (C) measured at a particular location by the input concentrations (C_o) to derive a ratio (i.e., C/C_o). In the case of the measurements at 15 m (49.5 ft), the input concentrations were those measured at the flume. For the measurements at 30 m (99 ft), the input concentrations were the measurements obtained at 15 m (49.5 ft) for each respective waterway. This resulted in two sets of paired, normalized concentration measurements for each runoff event for each watershed that were compared by graphing the values for the upper half of the waterway with amended filter socks against the upper half of the waterway that was only grassed. Similarly, the values for the lower half of the waterway with amended filter socks were plotted against the lower, grass-only waterway segment. In these graphs, points plotting below the 1:1 line indicate a net reduction in concentration due to the amended filter

Table 1

Number of sampled runoff events, runoff depth and volume, and transport losses of monitored constituents (sediment, chlorine [Cl], nitrate-nitrogen [NO_3-N], phosphate-phosphorus [PO_4-P], sulfate [SO_4], calcium [Ca], potassium [K], magnesium [Mg], sodium [Na], ammonium-nitrogen [NH_4-N], glyphosphate, and aminomethylphosphonic acid [AMPA]) from the no-till watershed (WS 118) and tilled watershed (WS 127) in crop years 2009 and 2010.

	Runoff			Sediment	Cl	NO_3-N	PO_4-P	SO_4	Ca	K	Mg	Na	NH_4-N	Glyphosate	AMPA
Year	Number	Depth (mm)	Volume (L)*	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(mg)	(mg)
WS 118 (no-till)															
2009	4	12.2	97,136 (7,132 to 55,874)	36	0.62	0.07	0.12	0.37	0.97	1.15	0.68	0.09	0.02	nd†	nd
2010	5	52.4	416,311 (10,169 to 153,565)	141	2.28	4.80	0.59	1.97	5.65	9.30	3.76	0.63	1.21	215	120
WS 127 (tilled)															
2009	3	16.1	107,796 (18,482 to 65,014)	131	0.35	0.54	0.08	0.91	2.07	1.54	1.21	0.14	0.01	nd	102
2010	13	97.0	666,404 (2,041 to 166,169)	6,098	1.12	7.15	0.60	3.26	10.07	8.21	5.27	1.37	10.09	2,735	623

*Total volume of runoff for all sampled events with range given in parentheses.

† nd = not detected.

socks compared to the grassed waterway alone. These values were also statistically compared using paired *t*-tests to determine if there were significant differences ($p \leq 0.05$) between mean C/C_o values for waterway segments with amended filter socks compared to segments with only grass. If a Shapiro-Wilk test at $p = 0.05$ indicated that the values used in these comparisons were not normally distributed, they were log transformed prior to performing the paired *t*-tests.

Results and Discussion

Input to the Waterways from the Watersheds. The distribution of rainfall resulted in few sampled events in 2009 with the first runoff event occurring on September 27, well after fertilizer and herbicide application to the watersheds. Consequently, the losses of sediment and nutrients were small in comparison to 2010 when the first sampled event occurred on May 22 from the tilled watershed and on June 2 from the no-till watershed (table 1). Furthermore, in 2009 no glyphosate was detected in runoff from either watershed, and the glyphosate metabolite AMPA was detected only in the first event from the tilled watershed. Glyphosate has a short half-life, is strongly sorbed to soil, and is typically not detectable in surface runoff from these watersheds more than 80 days after application (Shipitalo and Owens 2011).

In 2010, not only were there more events that produced runoff at a rate sufficient to sample earlier in the crop year, the total volume of the largest event for each watershed was more than 2.5 times that observed in 2009 (table 1). Consequently, its ability to erode soil from the watersheds was increased. As a result, the most notable difference among watersheds was the much greater sediment load delivered to the grassed waterways below the tilled watershed in 2010 when soil loss totaled 6,098 kg (13,444 lb) compared to 141 kg (311 lb) from the no-till watershed (table 1).

Figure 2

Sediment and crop residue accumulation behind the first filter sock installed in the grassed waterway downstream from the tilled watershed (WS 127) as observed on June 7, 2010. Most of this accumulation was the result of the largest sampled event of the year on June 4 (24.9 mm of runoff) and two events on the following day that eroded 1,994, 1,481, and 1,307 kg of soil, respectively.

There was no visible accumulation of sediment in the grassed waterways in 2009 other than a slight coating on the grass and on the filter socks, which was evident after the water receded as was noted in the previous study (Shipitalo et al. 2010). Similar observations were made for the waterways below the no-till watershed in 2010. In contrast, there was a large accumulation of sediment behind the first filter sock installed in the waterways below the tilled watershed in the upper 15 m (49.5 ft) waterway segment (figure 2). This accumulation probably limited the ability of this filter sock to further trap sediment or sorb nutrients in subsequent runoff events as most of the water passed over this filter sock. The efficiency of filter socks to trap sediment has been shown to decline with accumulation of sediment in or on them (Keener et

Table 2

Flow-weighted mean concentrations of monitored constituents (sediment, chlorine [Cl], nitrate-nitrogen [NO_3-N], phosphate-phosphorus [PO_4-P], sulfate [SO_4], calcium [Ca], potassium [K], magnesium [Mg], sodium [Na], ammonium-nitrogen [NH_4-N], glyphosphate, and aminomethylphosphonic acid [AMPA]) as measured at each sampling position for the tilled watershed (WS 127) for crop years 2009 and 2010.

Position	Sediment (g L^{-1})	Cl (mg L^{-1})	NO_3-N (mg L^{-1})	PO_4-P (mg L^{-1})	SO_4 (mg L^{-1})	Ca (mg L^{-1})	K (mg L^{-1})	Mg (mg L^{-1})	Na (mg L^{-1})	NH_4-N (mg L^{-1})	Glyphosate (µg L^{-1})	AMPA (µg L^{-1})
2009 (3 events, 16.1 mm)												
0 m	1.22	3.3	5.0	0.71	8.4	19.2	14.3	11.2	1.3	0.02	nd*	0.95
15 m with socks	0.95	5.1	3.9	0.27	88.5	43.1	22.1	17.3	3.9	0.04	nd	nd
15 m	1.31	3.3	4.1	0.46	9.7	20.5	13.0	10.6	1.3	0.00	nd	0.45
30 m with socks	0.44	4.0	3.1	0.17	106.1	50.8	20.3	17.6	5.1	0.04	nd	nd
30 m	0.41	4.9	3.4	0.22	79.4	39.8	19.2	15.8	3.4	0.09	nd	nd
2010 (13 events, 97.0 mm)												
0 m	9.2	1.7	10.7	0.90	4.9	15.1	12.3	7.9	2.1	15.14	4.10	0.94
15 m with socks	7.1	2.8	7.3	0.67	9.6	22.9	11.6	9.7	2.4	2.69	1.46	0.41
15 m	9.0	2.6	7.9	0.76	6.6	21.4	12.2	9.4	2.5	19.75	1.92	0.63
30 m with socks	4.3	2.2	6.9	0.62	11.1	21.0	11.6	8.7	2.1	2.25	0.92	0.42
30 m	4.5	2.9	6.6	0.61	8.4	19.5	11.5	8.8	2.4	2.48	0.92	0.35

*nd = not detected

al. 2007), and the manufacturer recommends removal of accumulated sediment and debris when it reaches half the height of the socks (Filtrexx International 2011). The remaining filter socks in this set, however, had only minimal amounts of sediment accumulated behind them and could continue to filter water and temporarily pond water. Accumulation of sediment and crop residue was also observed in the grass-only segment of the adjacent paired waterway, but this was more evenly distributed along the length of the waterway.

Effect of Grassed Waterways and Filter Socks in 2009. While the flow-weighted concentrations of sediment tended to be higher in the tilled watershed (table 2) than in the no-till watershed (table 3), the mean normalized concentrations were unaffected by the installation of filter socks in the grassed waterways (table 4). This was probably due to the minimal sediment losses observed in 2009 (table 1) and the poor ability of filter socks to trap suspended silt and clay (Faucette et al. 2009b). Likewise, NH_4-N losses were extremely low, and no glyphosate and little AMPA were detected in the runoff (table 1). Therefore, the grassed waterways and filter socks had no significant effect on the concentrations of these materials (table 4).

The statistical comparisons of the normalized mean concentrations indicated, however, that the filter socks significantly decreased the concentration of PO_4-P in the runoff from the no-till watershed as it passed down the grassed waterways by an additional 25% (i.e., C/C_o for waterway minus C/C_o for waterway with filter socks; 0.92 – 0.67 = 0.25), and in the tilled watershed, a 31% additional reduc-

Table 3

Flow-weighted mean concentrations of monitored constituents (sediment, chlorine [Cl], nitrate-nitrogen [NO_3-N], phosphate-phosphorus [PO_4-P], sulfate [SO_4], calcium [Ca], potassium [K], magnesium [Mg], sodium [Na], ammonium-nitrogen [NH_4-N], glyphosphate, and aminomethylphosphonic acid [AMPA]) as measured at each sampling position for the no-till watershed (WS 118) for crop years 2009 and 2010.

Position	Sediment (g L^{-1})	Cl (mg L^{-1})	NO_3-N (mg L^{-1})	PO_4-P (mg L^{-1})	SO_4 (mg L^{-1})	Ca (mg L^{-1})	K (mg L^{-1})	Mg (mg L^{-1})	Na (mg L^{-1})	NH_4-N (mg L^{-1})	Glyphosate (µg L^{-1})	AMPA (µg L^{-1})
2009 (4 events, 12.2 mm)												
0 m	0.37	6.4	0.7	1.26	3.8	10.0	11.9	7.0	0.9	0.23	nd*	nd
15 m with socks	0.31	7.0	0.6	0.79	24.6	19.6	16.4	8.0	2.1	0.02	nd	nd
15 m	0.35	6.5	0.7	0.97	3.8	10.7	11.4	6.8	1.2	0.17	nd	nd
30 m with socks	0.23	10.5	0.5	0.65	31.7	21.8	20.1	8.1	1.8	0.78	nd	nd
30 m	0.20	8.1	0.5	0.81	22.9	17.8	15.3	7.4	2.1	0.53	nd	nd
2010 (5 events, 52.4 mm)												
0 m	0.34	5.5	11.5	1.41	4.7	13.6	22.3	9.0	1.5	2.92	0.52	0.29
15 m with socks	0.54	6.0	9.7	1.14	7.4	19.3	22.0	9.1	2.0	2.57	0.25	0.15
15 m	0.32	5.8	10.4	1.43	5.2	14.8	23.5	9.0	1.8	3.05	0.26	0.18
30 m with socks	0.23	5.6	9.2	1.19	7.2	15.5	22.1	8.6	1.7	2.36	0.20	0.11
30 m	0.44	6.0	7.4	0.75	7.8	20.3	17.0	7.8	2.0	1.50	0.22	0.10

*nd = not detected

Table 4

Comparison of arithmetic averages of C/C_o (output/input concentration) of monitored constituents (sediment, chlorine [Cl], nitrate-nitrogen [NO_3-N], phosphate-phosphorus [PO_4-P], sulfate [SO_4], calcium [Ca], potassium [K], magnesium [Mg], sodium [Na], ammonium-nitrogen [NH_4-N], glyphosphate, and aminomethylphosphonic acid [AMPA]) in paired grassed waterway segments (0 to 15 m and 15 to 30 m) with and without amended filter socks that received surface runoff from no-till and tilled watersheds. Standard deviation is given in parentheses.

	WS 118 no-till		WS 127 tilled	
Parameter	Waterway	Waterway with filter socks	Waterway	Waterway with filter socks
2009				
Sediment	0.78 (0.23)	0.84 (0.23)	0.81(0.38)	0.62 (0.51)
Cl	1.10 (0.17)	1.37 (0.43)	1.02 (0.10)	1.33 (0.51)
NO_3-N	0.87 (0.25)	1.66 (1.93)	0.88 (0.10)	0.75 (0.11)* ↓
PO_4-P	0.92 (0.13)	0.67 (0.13)** ↓	0.72 (0.20)	0.41 (0.16)** ↓
SO_4	1.01 (0.21)	5.73 † (5.22)* ↑	1.04 (0.13)	8.04 † (8.93)* ↑
Ca	1.01 (0.12)	1.73 (0.76)* ↑	1.01 (0.08)	2.06 (1.45)
K	0.96 (0.12)	1.55 (0.48)* ↑	0.90 (0.06)	1.43 (0.70)
Mg	0.95 (0.09)	1.08 (0.23)	0.94 (0.05)	1.48 (0.72)
Na	1.10 (0.32)	1.61 (0.74)* ↑	1.02 (0.11)	2.62 † (1.87)* ↑
NH_4-N	nd‡	nd	nd	nd
Glyphosate	nd	nd	nd	nd
AMPA	0.84 (0.31)	0.74 (0.20)	nd	nd
2010				
Sediment	0.91 (0.31)	1.26 (0.70)	1.71(3.89)	0.80 † (0.77)** ↓
Cl	1.07 (0.33)	1.30 (0.54)	1.52 (1.37)	1.62 (1.68)
NO_3-N	0.78 (0.18)	0.87 (0.11)	0.80 (0.28)	0.77 (0.29)
PO_4-P	0.81 (0.21)	0.81 (0.10)	0.84 (0.39)	0.65 (0.26)** ↓
SO_4	1.08 (0.16)	1.63 (0.36)** ↑	1.14 (0.41)	1.62 (0.55)*** ↑
Ca	1.05 (0.13)	1.22 (0.28)* ↑	1.09 (0.32)	1.15 (0.38)
K	0.88 (0.17)	1.07 (0.25)	1.06 (0.35)	0.91 (0.25)** ↓
Mg	0.89 (0.15)	0.98 (0.11)* ↑	1.00 (0.21)	1.02 (0.23)
Na	1.06 (0.20)	1.19 (0.38)	1.04 (0.30)	1.09 (0.52)
NH_4-N	0.90 (0.48)	0.72 (0.28)	3.37 (11.03)	0.44 † (0.29)*** ↓
Glyphosate	0.70 (0.28)	0.63 (0.19)	0.56 (0.18)	0.48 (0.35)
AMPA	0.62 (0.01)	0.58 (0.06)	0.63 (0.25)	0.43 (0.30)* ↓

*, **, *** indicate significant differences in mean C/C_o values for each parameter within watersheds at p = 0.05, 0.01, and 0.001, respectively, as indicated by paired t-tests. A down arrow is used to indicate a net decrease when a significant effect was detected, and an up arrow is used to indicate when the amended filter socks increased the concentration of a particular constituent.

†Values log transformed prior to comparison because they were not normally distributed as indicated by Shapiro-Wilk tests at p = 0.05.

‡ nd = not defined due to not being detected or a value of zero in the denominator or numerator.

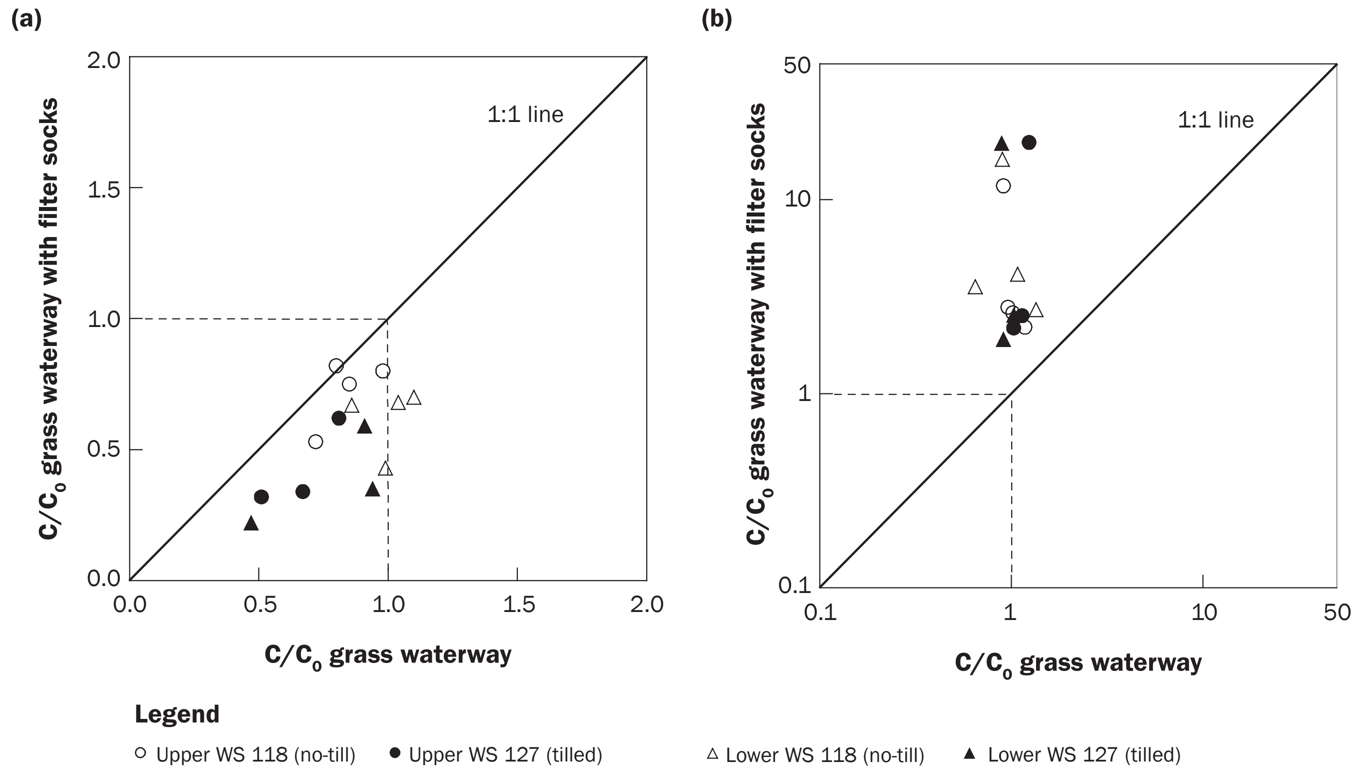
tion was noted (table 4). This reduction in PO_4-P was accompanied by a nearly 6-fold increase in mean normalized SO_4 concentration as a result of filter sock installation in grassed waterways downstream from the no-till watershed and an 8-fold increase with the tilled watershed. There were also significant increases in Ca, K, and Na concentration for the no-till watershed, whereas there was a significant increase in Na and a significant decrease in NO_3-N for the tilled watershed (table 4). The graphical comparisons of the input and output concentrations of PO_4-P and SO_4 for individual events indicated that for all events and positions except one (upper waterway of the no-till watershed) the filter socks contributed to a decrease in PO_4-P concentrations (figure 3). On the other hand, the filter socks dramatically increased SO_4 concentration in all instances with up to a 20-fold increase noted with the first sampled runoff event from the tilled watershed. For both watersheds, the SO_4 concentrations decreased with subsequent runoff events, but the filter socks contributed to elevated SO_4 levels for the remainder of the sampled events.

The source of the elevated SO_4 levels and those of Ca, K, and Na was attributed to the Nutriloxx added to the compost used to fill the socks. Nutrient sorbents produced by this manufacturer consist of proprietary blends that include aluminum sulfate (alum; $Al_2[SO_4]_3$) and/or calcium sulfate (gypsum; $CaSO_4$) (Faucette et al. 2008). The highest flow-weighted concentration of SO_4 noted was 159 mg L^{-1} in the first sampled runoff collected below the amended filter socks installed in the waterway downstream from the tilled watershed. In contrast, the flow-weighted average SO_4 concentration in 2009 for sampled events from this watershed was 8 mg L^{-1} before it entered the waterways. There are currently no enforceable standards for SO_4 in drinking water, and levels observed were well below the 250 mg L^{-1} secondary standard of the USEPA based on effects on taste and odor (USEPA 2012). Nevertheless, concentrations of the substances used to sorb nutrients should be monitored in the treated runoff to more completely assess the environmental effect of their usage. Unfortunately, we did not measure dissolved aluminum (Al) concentration in the runoff, but when Moore and Edwards (2005) applied simulated rainfall to small plots that received additions of alum-treated poultry litter, they observed no effect on soluble Al levels in runoff. Similarly, Leytem and Bjorneberg (2005) reported that alum additions to irrigation return flows did not result in Al concentrations above maximum levels established by the USEPA.

Laboratory studies have demonstrated removal efficiencies of soluble P as high as 99% when using sorbent-amended compost filter socks (Faucette et al. 2008). This high rate of P removal was attained for a single simulated rainfall that produced approximately 13 L (3.4 gal) of water upstream from a 20.3 cm (8 in) diameter by 35 cm (14 in) long filter sock. Under these conditions, the ratio of the volume of water to the volume of compost in the filter socks was 1.1:1, whereas the ratio for the filter socks installed in the waterways was 33:1 for the no-till watershed and 36:1 for the tilled watershed in 2009, assuming that half the total volume of sampled runoff (table 1) passed through the entire volume of the three filter socks

Figure 3

Comparison of normalized flow-weighted (a) dissolved phosphorus and (b) sulfate concentrations (i.e., output divided by input concentration [C/C_o]) for the upper (0 to 15 m) and lower (15 to 30 m) paired waterway segments for each sampled event for the no-till and tilled watersheds (WS) in 2009. C/C_o values <1 indicated phosphorus concentration was reduced compared to input concentration, and values plotting below the 1:1 line signify a net benefit of the grassed waterway with amended filter socks compared to the paired waterway segment without filter socks.



installed in each waterway. Under these more realistic conditions, the reductions in PO_4-P concentrations we noted were significant but only accounted for the removal of an estimated 0.02 to 0.03 kg (0.05 to 0.07 lb) of PO_4-P from the runoff for each watershed.

Effect of Grassed Waterways and Filter Socks in 2010. The most striking difference between 2009 and 2010 was the greatly increased sediment losses from the tilled watershed (table 1). Analysis of the normalized data (table 4) indicated that the filter socks significantly reduced the sediment concentration in runoff from the tilled watershed. The average C/C_o value of >1 for the sediment in waterway segments without filter socks (i.e., C/C_o = 1.71) was attributed to the remobilization of sediment deposited in the grassed waterways by subsequent events, not erosion of the waterway. That is, sediment that was deposited in the waterways as a result of runoff events that produced high sediment loads was resuspended and transported by subsequent events leading to apparent increases in sediment concentration compared to upstream measurements. Similarly, Stehle et al. (2011) attributed negative retention values for pesticides in vegetated treatment systems to the release of previous sorbed pesticides during high flow conditions.

The net effect of the filter socks on sediment transport can be assessed by converting the flow-weighted sediment concentrations in the waterways to loads, assuming that flow rate and sediment input was half that measured at the watershed outlet. Under this assumption, the input to the grassed waterways of 3,049 kg (6,708 lb) (i.e., half that reported the amount reported in table 1) was reduced to 2,378 kg (5,232 lb) in the socked waterway in the upper 15 m (49.5 ft) compared to 2,984 kg (6,565 lb) in the paired waterway grass-only segment. Thus, the filter socks trapped 671 kg (1,476 lb) of sediment compared to 65 kg (143 lb) in the grassed only segment, a 10-fold increase in sediment retention. This sediment retention was visually evident behind the filter sock in the upper waterway segment downstream from the tilled watershed (figure 2).

In addition to the large effect on sediment, the filter socks greatly reduced the flow-weighted (table 2) and normalized NH_4-N concentrations (table 4) in runoff from the tilled watershed. When the sediment retained by the filter socks was examined, intact prills of the polymer-coated ESN urea were observed. Moreover, these prills were also noted in some of the runoff samples collected in the grassed-only upper 15 m (49.5 ft) segment of the waterway. Thus, physical retention of the eroded fertilizer, rather than sorption by the amended filter socks, was probably the major mechanism responsible for decreased NH_4-N transport. As was done with sediment, these can be converted to transport amounts, which indicated that the 5 kg (11 lb) input to the upper waterways was reduced to 0.9 kg (2 lb) by the filter socks. The amount measured in the unamended waterway (6.6 kg [14.5 lb]) was actually slightly greater than the estimated input, probably due to partial dissolution of the prills collected in the samples prior to filtering and analysis. Ammonium-N losses from the no-till watershed were also elevated in 2010 compared to 2009, but were still approximately eight times less than from the tilled watershed (table 1). Runoff and erosion were also less than from the tilled watershed, and there was no evidence of physical transport of the fertilizer prills from the no-till watershed. This probably contributed to the lack of a significant impact on NH_4-N concentrations, although the normalized values suggested an additional 18% reduction due to amended filter sock installation (table 4).

The amended filter socks continued to significantly increase the SO_4 concentrations in the runoff from both watersheds, but only significantly decreased PO_4-P (19% additional reduction) for the tilled watershed (table 4). In addition, the amended filter socks also significantly decreased K and AMPA concentrations in runoff from the tilled watershed and increased the concentrations of Ca and Mg in runoff from the no-till watershed (table 4). There was no significant impact on glyphosate concentrations, although the concentrations tended to be lower for the amended waterways (table 4). In a previous study (Shipitalo et al. 2010), compost-only filter socks reduced glyphosate concentration by 5% compared to unamended grassed waterways. The lack of a detectable effect with the amended filter socks used in the current study was probably related to the relatively low glyphosate concentrations and losses compared to those measured in the previous study.

Summary and Conclusions

The Nutriloxx-amended filter socks installed in grassed waterways increased their effectiveness in reducing concentrations and transport of PO_4-P. When high sediment loads were encountered, the filter socks trapped significant amounts of sediment and physically retained fertilizer that was transported along with the sediment thereby reducing NH_4-N transport and concentrations. The amended filter socks, however, added significantly to the concentrations of SO_4 in the runoff. Therefore, concentrations of soluble components in selective sorbents should be measured and reported in order to more fully assess their environmental effect. Filter socks, used in conjunction with other conservation measures, can help reduce concentrations of sediment, herbicides, and nutrients in grassed waterways and other areas where concentrated flow occurs. They may be particularly useful in areas where buffer strips and other vegetated barriers cannot be readily installed because of space requirements. Nevertheless, further research and development is needed to quantify the effectiveness of adding sorbents to filter socks to increase their ability to retain solutes.

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