Sediment Removal by Prairie Filter Strips in Row-Cropped Ephemeral Watersheds

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Twelve small watersheds in central Iowa were used to evaluate the effectiveness of prairie filter strips (PFS) in trapping sediment from agricultural runoff. Four treatments with PFS of different size and location (100% rowcrop, 10% PFS of total watershed area at footslope, 10% PFS at footslope and in contour strips, 20% PFS at footslope and in contour strips) arranged in a balanced incomplete block design were seeded in July 2007. All watersheds were in bromegrass (*Bromus* L.) for at least 10 yr before treatment establishment. Cropped areas were managed under a no-till, 2-yr corn (*Zea mays* L.)–soybean [*Glycine max.* (L.) Merr.] rotation beginning in 2007. About 38 to 85% of the total sediment export from cropland occurred during the early growth stage of rowcrop due to wet field conditions and poor ground cover. The greatest sediment load was observed in 2008 due to the initial soil disturbance and gradually decreased thereafter. The mean annual sediment yield through 2010 was 0.36 and 8.30 Mg ha^{-1} for the watersheds with and without PFS, respectively, a 96% sediment trapping efficiency for the 4-yr study period. The amount and distribution of PFS had no significant impact on runoff and sediment yield, probably due to the relatively large width (37–78 m) of footslope PFS. The findings suggest that incorporation of PFS at the footslope position of annual rowcrop systems provides an effective approach to reducing sediment loss in runoff from agricultural watersheds under a no-till system.

SOIL EROSION BY WATER is an increasingly serious problem in agricultural landscapes, especially as growing populations intensify pressures on a fixed land area for food and energy. In addition, the impact of climate change is projected to increase the erosive force of precipitation by as much as 58% (Nearing, 2001). A mean rate of 0.64 mm soil is lost annually from the world's agricultural land, about 28 times faster than erosion rates by natural processes (Wilkinson, 2005). Loss of sediment along with sediment-bound organic matter and nutrients reduces on-farm soil productivity and sustainability (Smith et al., 2000), degrades downstream water quality (Alexander et al., 2008; Evans, 2010), and induces many off-farm social and ecological damages (Clark et al., 1985). Sediment loss is considered a major nonpoint source of pollution for surface waters (Nearing et al., 2001; Boardman and Poesen, 2006) and has been shown to increase under rowcrop agriculture (Bielders et al., 2003). Reducing sediment export from agricultural fields is particularly critical to decreasing nonpoint-source pollution in water systems in the Cornbelt region of the United States, where intensively managed rowcrop systems dominate the landscape (Nearing et al., 2001).

Although restoration of native grassland on erodible soils would reduce soil loss, this practice is not feasible across large regions where local communities depend on agriculture. One alternative strategy for erosion control and water quality improvement is the incorporation of relatively small amounts of vegetative filter strips in strategic locations within agricultural landscapes (Dosskey et al., 2002; Blanco-Canqui et al., 2006). Vegetative filter strips within crop production systems are bands of perennial vegetation established at the lower portion of the watershed or distributed upslope along the contour (Dillaha et al., 1989). They are designed to remove sediment and other pollutants from agricultural runoff by slowing flow velocity, increasing water infiltration, and promoting plant uptake of excess nutrients. In particular, through ponding of water (backwater) above the strips, vegetative filter strips promote the settlement of sediment and thereby reduce its movement and export (Hussein et al., 2007; Pan et al., 2010).

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Abbreviations: ET, evapotranspiration; NSNWR, Neal Smith National Wildlife Refuge; PFS, prairie filter strips; TSS, total suspended solids.

Numerous studies have clearly demonstrated the effectiveness of filter strips in reducing sediment and sediment-bound pollutant transport by stormwater runoff from agricultural fields. These studies typically report efficacy rates ranging from 45 to 100%, if properly installed and maintained (Dillaha et al., 1989; Robinson et al., 1996; Schmitt et al., 1999; McKergow et al., 2003; Liu et al., 2008). Vegetative filter strips are most effective under conditions of shallow, uniform flow across the filter strips but are prone to overtopping and inundation under concentrated flow conditions, rendering them less effective (Dosskey et al., 2002; Blanco-Canqui et al., 2006). Other factors also affect the efficacy of vegetative filter strips in removing sediment, including vegetation type, filter strip width, slope, soil type, and rainfall characteristics (Yuan et al., 2009; Huang et al., 2010). Although wider filter strips generally trap more sediment in surface runoff than narrower strips, the first several meters of filter strips (from the leading edge) play a dominant role in sediment removal (Dillaha et al., 1988; Robinson et al., 1996; Gharabaghi et al., 2006). For example, sediment discharge was reduced between 50 and 60, 60 and 90, and 99% for strips of 1-, 4- to 5-, and 10-m width, respectively (Van Dijk et al., 1996). Slope of vegetative filter strips is also a key factor in sediment removal. Previous studies suggested that sediment trapping efficacy of filter strips increased with increasing slope until a threshold (~10%) above which the efficacy of the vegetative filter strips decreased (Dillaha et al., 1989; Liu et al., 2008). Other studies indicated that vegetative filter strips were uniformly less effective in reducing sediment due to decreased ponding as slope increased (Hussein et al., 2007). Generally, the effectiveness of vegetative filter strips was low when rainfall intensity was greater than infiltration rate of filter strips during large storms, especially with high antecedent soil moisture. High sediment load in water runoff caused by concentrated flow also reduces the sediment trapping efficiency of vegetative filter strips (Blanco-Canqui et al., 2006).

The majority of studies assessing the performance of vegetative filter strips in reducing sediment transport were conducted on a plot scale and assessments at the watershed scale are lacking (Helmers et al., 2005; Baker et al., 2006). Accounting for the heterogeneity of watersheds in topography, soils, and land use is particularly challenging. This is underscored by findings suggesting that performance of vegetative filter strips under on-farm conditions is rarely as effective as that for plot settings (McKergow et al., 2003; Blanco-Canqui et al., 2006; Verstraeten et al., 2006). This trend is largely explained by the less uniform and more concentrated flow that develops in watersheds having longer slopes compared with shorter slopes at the plot scale. Furthermore, the effectiveness of vegetative filter strips has often been investigated from simulated or natural rainfall events over relatively short periods. Soil erosion values are not very meaningful unless they are analyzed against a distribution of storm sizes and intensities (Kirkby, 2010), whereas the minimum number of recorded events needed to dilute the impacts of the largest events on mean erosion rates is between 75 and 100 (González-Hidalgo et al., 2009). Therefore, there is a critical need for multiyear data to assess the performance of vegetative filter strips with commonly adopted field operations, while accounting for variability in both climate and field conditions.

This paper presents results from the first 4 yr of a long-term field experiment testing the impacts of prairie filter strips (PFS) on sediment export in runoff from watersheds maintained under annual rowcrop systems in central Iowa. It is hypothesized that filter strips placed on a landscape scale will significantly reduce sediment loss compared with no filter strip systems. The study also tested the hypothesis that different PFS designs with varying sizes and locations perform differently in reducing sediment. Because sediment export can be reduced through either the reduction of surface runoff volume and/or sediment concentrations in runoff, the effects of PFS on both flow amount and sediment concentrations were investigated.

Materials and Methods

The study was conducted at the 3000-ha Neal Smith National Wildlife Refuge (NSNWR) (41°33′00″ N; 93°16′24″ W) in Jasper County, IA. The refuge is located in the central portion of the Walnut Creek Watershed, which is well dissected by streams and ephemeral drainages, and its terrain is moderately to steeply rolling. Created by an act of Congress in 1990, the refuge's mission is to reconstruct the presettlement vegetation on the landscape, particularly native tallgrass prairie. Portions of the refuge awaiting restoration are either leased to area farmers for crop production or maintained in perennial cover.

A total of 12 watersheds in NSNWR and within the Walnut Creek Watershed were selected to evaluate the benefits of integrating PFS in rowcrop agriculture for enhancing water quality in central Iowa (Fig. 1). A balanced incomplete block design was implemented across four blocks, each with three watersheds, with each treatment excluded once from one of the blocks. Two blocks are located at Basswood (six watersheds), one block at Interim (three watersheds), and one block at Orbweaver (three watersheds) (Fig. 1). The size of the watersheds varied from 0.5 to 3.2 ha, with average slopes ranging from 6.1 to 10.5% (Table 1). Ladoga silt loam (fine, smectitic, mesic Mollic Hapludalfs) and Otley silty clay loam (fine, smectitic, mesic Oxyaquic Argiudolls) are predominant soils in the study watersheds. The soils among these sites are similar, with preliminary sampling at the sites showing 7 to 10% sand, 63 to 68% silt, and 25 to 28% clay, with bulk densities near 1.41 g cm^{-3} (Zhou et al., 2010).

Before treatment, all watersheds were in bromegrass for at least 10 yr without fertilizer application. In August 2006, all watersheds were uniformly tilled with a mulch tiller. Basswood–1–6 and Orbweaver–1 were tilled again in spring 2007 to further level field residue. Starting in spring 2007, a 2-yr, no-till corn–soybean rotation (soybeans in 2007) was implemented along the contour in areas receiving rowcrop. Crop residues after harvest were left in the field. Standard herbicide- and fertilizer-based weed and nutrient management practices were applied in each watershed. Consistent with methods used for other prairie reconstructions at NSNWR, areas receiving PFS treatment were seeded with a diverse mixture of native prairie forbs and grasses using a broadcast seeder on 7 July 2007. The seed mixture included >20 species, dominated by Indiangrass [*Sorghastrum nutans* (L.) Nash], little bluestem [*Schizachyrium scoparium* (Michx.) Nash], and big bluestem (*Andropogon gerardii* Vitman) seeds. Multiple strips were established on contours in the larger watersheds and the distance between strips was determined to accommodate local field equipment.

Each watershed received one of four treatments (three replicates per treatment): 100% rowcrop, 10% of the watershed area
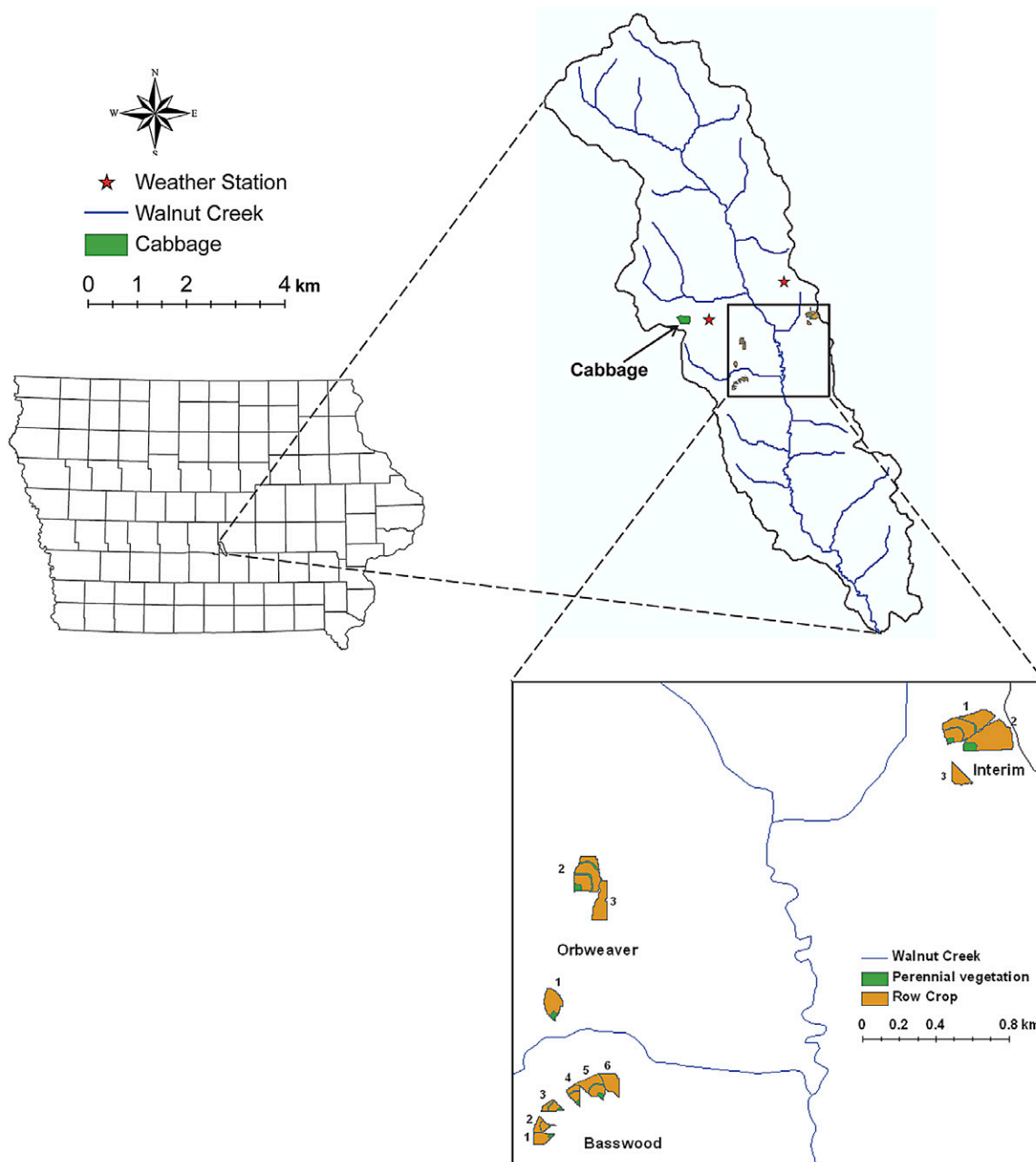
Fig. 1. Location of Walnut Creek Watershed and study watersheds.

in PFS at the footslope position, 10% of the watershed area in PFS distributed between the footslope position and in contour strips further upslope in the watershed, and 20% of the watershed area in PFS distributed between the footslope position and in contour strips further upslope in the watershed (Fig. 2). Treatments were randomly assigned to watersheds within each block. The PFS were designed based on the percentage of contributing flow area of the watershed, rather than designating widths. The width of PFS varied from 37 to 78 m at the footslope position, and 3 to 10 m on the contours (Table 1). No fertilizer was applied in the PFS areas.

A fiberglass H flume was installed at the bottom of each watershed in 2005 and early 2006, according to the Field Manual for Research in Agricultural Hydrology (Brakensiek et al., 1979). The flume size was determined based on the runoff volume and peak flow rate for a 10-yr, 24-hr storm. Runoff volume was estimated using the soil conservation service curve number method,

using the curve number for cultivated land with conservation treatment (Hann et al., 1994). Peak flow rate was estimated using the SCS–TR55 method. A total of eight 0.61-m H-flumes and four 0.76-m H-flumes were installed. Plywood wing walls (5 m at each side of a flume) were constructed at the bottom of watershed to guide surface runoff to the flumes.

ISCO 6712 automated water samplers (ISCO, Inc.) equipped with pressure transducers (720 Submerged Probe Module) were installed in 2007 at each flume to record flow rate and collect water samples. A long period of frost and snow cover with relatively small amounts of precipitation and runoff generally occurs from late November through March (Table 2); therefore, ISCO units were removed from the field during winter to avoid damage from freezing. Flow stage was measured by pressure transducers and logged every 5 min. Each ISCO autosampler contained 24 1-L bottles that were filled during storm events. Samplers took a

Table 1. Site description and experimental design.

	Size	Slope	Max. slope length	Location and percent of PFS†	Width of PFS at footslope‡	Width of PFS at upslope§
	ha	%	m		——————— m ———————	
Basswood–1	0.53	7.5	120	10% at footslope	38.2	¶
Basswood–2	0.48	6.6	113	5% at footslope and 5% at upslope	40.5	3.1
Basswood–3	0.47	6.4	110	10% at footslope and 10% at upslope	37.6	6.0
Basswood–4	0.55	8.2	118	10% at footslope and 10% at upslope	38.1	7.5
Basswood–5	1.24	8.9	144	5% at footslope and 5% at upslope	46.4	7.0
Basswood–6	0.84	10.5	140	All rowcrops	¶	¶
Interim–1	3.00	7.7	288	3.3% at footslope, 3.3% at sideslope, and 3.3% at upslope	51.0	6.0
Interim–2	3.19	6.1	284	10% at footslope	78.2	¶
Interim–3	0.73	9.3	137	All rowcrops	¶	¶
Orbweaver–1	1.18	10.3	187	10% at footslope	57.3	¶
Orbweaver–2	2.40	6.7	220	6.7% at footslope, 6.7% at sideslope, and 6.7% at upslope	52.0	9.8
Orbweaver–3	1.24	6.6	230	All rowcrops	¶	¶

† Percentage of prairie filter strips (PFS) = area of PFS per area of watershed.

‡ Width of PFS along the primary flow pathway.

§ Average width of PFS if more than one strip at upslope.
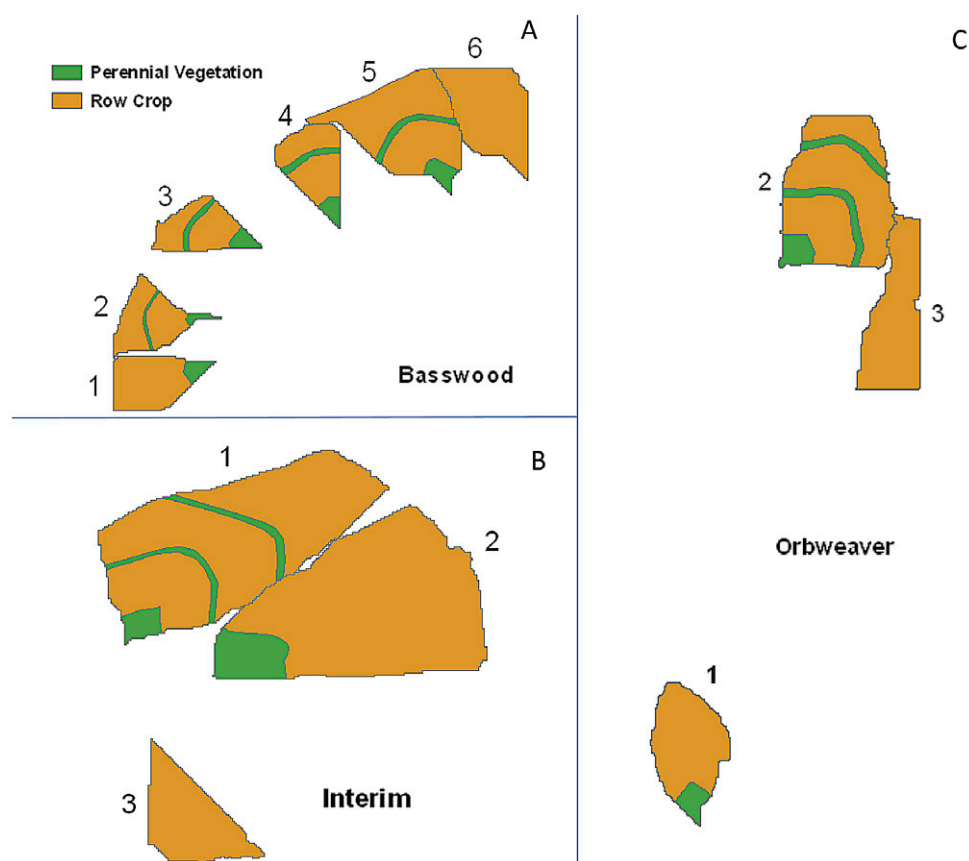
¶ Not applicable.

Fig. 2. Placement of prairie filter strips for the study watersheds at: (a) Basswood, (b) Interim, and (c) Orbweaver.

300-mL sample for every 1.024 mm runoff (Harmel et al., 2003). A total of three samples were placed in each bottle in sequential fashion. Typically, a total of eight bottles could be filled for a 2-yr storm and 14 to 15 bottles for a 10-yr storm. Several large storms occurred during the study period, causing runoff samples to fill all 24 ISCO bottles such that no additional samples could be taken until the bottles were replaced. Water samples were refrigerated at 4°C until analysis. The data (including flow stage and a record

of sample date and time) were downloaded on at least a monthly interval, using an ISCO 581 Rapid Transfer Device (ISCO, Inc.).

To help understand hydrologic response to storm events along the hillslope, shallow groundwater wells were installed at the upslope and footslope positions of each watershed in November 2004 (Zhou et al., 2010). The groundwater levels in four watersheds (Basswood–1, Interim–1, Interim–2, and Weaver–1) were

Table 2. Long-term monthly precipitation and maximum/minimum temperatures of the Neal Smith National Wildlife Refuge, Jasper County, IA.

Month	Precipitation	Max. temperature	Min. temperature
	mm	————— °C —————	
January	21.1	−2	−12
February	27.7	1	−9
March	53.8	8	−3
April	91.2	16	3
May	117.9	22	9
June	120.6	27	15
July	115.6	29	18
August	109.0	28	17
September	90.2	24	11
October	69.1	17	4
November	59.4	8	−3
December	27.9	0	−10

Table 3. Monthly precipitation during April through October in 2007 to 2010, at the Neal Smith National Wildlife Refuge, Jasper County, IA.

	2007	2008	2009	2010
	———————— mm ————————			
April	123.2	115.2	125.2	124.4
May	148.5	122.9	75.3	117.2
June	87.0	265.8	147.9	337.0
July	45.8	205.9	83.9	155.1
August	212.5	56.5	157.2	372.7
September	94.8	119.1	56.4	102.3
October	126.4	81.0	165.3	12.4
Total	838.2	966.2	811.1	1220.9

continuously monitored by a water level logger (Global Water Instrumentation, Inc.).

Concentration of total suspended solids (TSS) in surface runoff was analyzed in the Agricultural and Biosystems Engineering Water Quality Research Laboratory at Iowa State University, according to USEPA (1999) methods. Sediment load was then calculated based on the measured TSS concentrations and total flow volume for the specific period during which the sample was collected. Flow-weighted sediment concentrations were calculated by dividing the total sediment load by the total flow volume for the period.

Meteorological data were obtained from two weather stations located within NSNWR and near study watersheds (Fig. 1): a Mesonet weather station operated by the National Weather Service and a weather station of the U.S. Climate Reference Network managed by NOAA. The Mesonet station is 1.3 to 3.6 km from the watersheds and the NOAA station is 1.1 to 3.3 km from the watersheds. The observed rainfall amount from the two weather stations was averaged to obtain daily rainfall during 2007 to 2010 to account for spatial variability in rainfall distribution. Tipping bucket rain gauges (ISCO 674, Teledyne Isco, Inc.) were also installed at three watersheds (Basswood–3, Interim–3, and Orbweaver–2) as an additional check and to provide higher-resolution rainfall data.

Sediment export was also monitored at two adjacent watersheds at Cabbage (Fig. 1), which were similarly gauged and sampled for runoff and sediment, and within 3 km of the nearest study watersheds. The two watersheds (4.2 and 5.1 ha) were under 100% native prairie reconstruction by NSNWR since 2004, as described by Tomer et al. (2010). Sediment transport from the two prairie watersheds provided a reference comparison to that from the 12 agricultural watersheds (for 2010 only).

Statistical analysis of the data was performed using the General Linear Model procedures for SAS (SAS Institute, 2003). Annual surface runoff, sediment yield, and flow-weighted sediment concentration were compared among treatments from 2007 to 2010. Due to the frequent failure of the ISCO unit in the Orbweaver–1 watershed (with 10% PFS at footslope) in 2010, this watershed was not included in the statistical analysis for 2010.

Results and Discussion

Rainfall

The entire study period (2007–2010) received higher than normal rainfall, compared with the long-term average. Total rainfall during the growing season (April–October) ranged from 811 mm in 2009 to 1221 mm in 2010 (Table 3), well above the long-term mean of 713 mm. Year 2008 had a wet June and July but a dry August. Monthly rainfall was 337 and 373 mm for June and August 2010, respectively; the total rainfall amount in these 2 mo alone was greater than the long-term mean rainfall for the entire growing season. The largest rainfall event during the monitoring period occurred 8–11 Aug. 2010, with 248 mm of rain producing 208 mm of discharge, which was ∼60% of the total flow during 2007 to 2009. This event produced record flood stages in several nearby streams and rivers. The driest month was October 2010, with only 12 mm of rainfall compared with the 67-mm average for October.

Runoff

Surface runoff exhibited a wide range of interannual variation, varying from only 32.4 mm in 2007 to 347.6 mm in 2010 (Table 4). Overall, increasing rainfall led to greater runoff with the exception of 2007, which had slightly more rainfall but much less runoff than 2009. This could, in part, be attributed to differences in seasonal rainfall distribution between the 2 yr. More rainfall occurred during August and September in 2007 than 2009, and the late-season rainfall events in 2007 may have resulted in less runoff due to greater interception by the well-developed crop canopy and high evapotranspiration (ET) during this growth stage. As expected, more runoff was observed in spring than in summer for a comparable rainfall amount due to wet field conditions and low water use by crops at their early growth stage (Fig. 3). In 2009, as an example, 125 mm rainfall in April produced 62 mm runoff, whereas 157 mm rainfall in August only produced 0.5 mm runoff.

The PFS treatments reduced surface runoff to varying extents, compared with 100% row-cropped fields. There was no significant runoff difference between watersheds in 2007 with PFS compared with 100% agricultural watersheds, which could be due to the limited vegetation cover in PFS at that time. Perennial cover percentage in PFS was estimated to be 30, 59, and 94% in the late-July to early-August periods of 2008, 2009, and 2010, respectively (Hirsh and Liebman, personal communication, 2011). Averaged over the 4 yr, runoff was reduced by 61, 29, and 28% for treatments of 10% PFS at footslope, 10% PFS at

Table 4. Annual surface runoff during growing season (April–October) for the treatments of rowcrop (100% RC) and prairie filter strips (PFS) at the Neal Smith National Wildlife Refuge, Jasper County, IA.

	100% RC	10% PFS at footslope	10% PFS at footslope and in contour strips	20% PFS at footslope and in contour strips	Mean
			———————————— mm ————————————		
2007	39.6(22.4)a†	16.2(10.8)a	32.6(24.3)a	41.2(19.3)a	32.4(9.0)
2008	254.2(47.8)a	61.1 (19.3)a	178.1(76.1)a	178.0(81.9)a	167.8(35.0)
2009	129.0(40.1)a	53.5(15.5)a	96.5(34.1)a	74.1(41.1)a	88.3(16.9)
2010	477.6(122.1)a	224.8(4.9)b	329.4(86.1)ab	358.4(109.5)ab	347.6(51.1)
Average	225.1(62.6)a	88.9(22.7)b	159.1(42.4)ab	162.9(51.1)ab	

† Numbers in parenthesis are standard errors. Letters after parenthesis indicate the significance test of mean difference among four treatments within each year at $p < 0.05$.
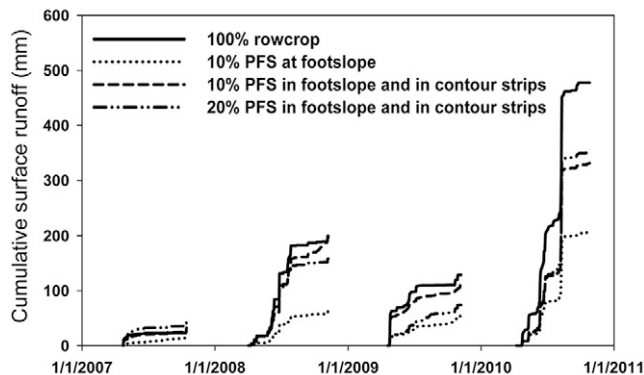

Fig. 3. Cumulative annual surface runoff during growing season (April–October) for the treatments of rowcrop and prairie filter strips (PFS).
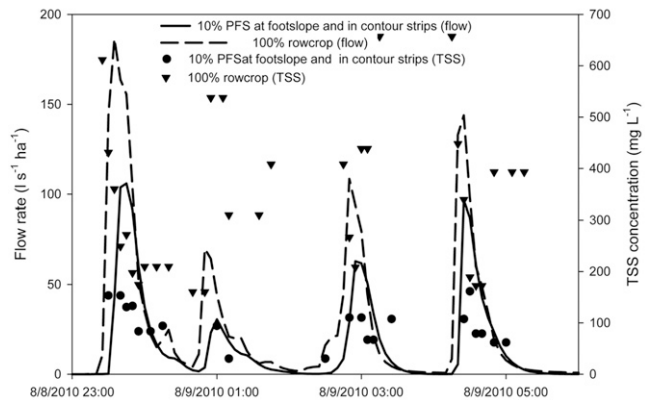

Fig. 4. Hydrographs and total suspended solids (TSS) concentrations during the storm event on 8–9 Aug. 2010, for the watersheds at Interim of the Neal Smith Wildlife Refuge, Jasper County, IA.

footslope and in contour strips, and 20% PFS at footslope and in contour strips, respectively, compared with 100% rowcrop. Only the 10% PFS at the footslope had significantly different runoff than the 100% rowcrop. The 10% PFS at the footslope treatment had the largest area in PFS at the footslope position. The PFS had the greatest infiltration capacity and since the 10% PFS at the footslope position treatment had the greatest amount of prairie vegetated area at the watershed base, runoff was reduced.

Overall, the runoff reduction was more evident at the early growth stage of rowcrop (Fig. 3), likely due in part to the higher ET and canopy interception in PFS than cropland during this period. In contrast, watersheds with 100% cropland had less runoff than watersheds with PFS during rainfall events occurring when crops were completely developed. However, other factors, including improved soil structure and infiltration, may also account for the difference in runoff amount between treatments, particularly during large storm events. During consecutive days of rainfall (248 mm) on 8–11 Aug. 2010, watersheds with PFS had 25% less runoff than watersheds with 100% row-cropped corn. Since corn had comparable ET with native prairie at this growth stage (Mateos-Remigio, personal communication, 2011), more runoff water likely infiltrated into subsurface soils under PFS. The improved soil structure and dampened flow rates under PFS could facilitate infiltration of runoff water (Rachman et al., 2004; Anderson et al., 2009). The water table at the PFS footslope was generally closer to the surface when compared with the cropland footslope (Zhou et al., 2010). Compared with 100% cropland, the time of initial runoff response and runoff peak time measured at the watershed outlets was delayed by 5 to 15 min for PFS treatments (Fig. 4), potentially allowing more time for infiltration.

Sediment

Temporal Patterns and Variability

Sediment export from the watersheds was also highly variable during the study period. Mean annual sediment yield from the 12 watersheds during the growing season ranged from 0.05 Mg ha^{-1} in 2007 to 6.0 Mg ha^{-1} in 2008 (Table 5). Notably, sediment yield did not strictly follow the trend of rainfall and runoff during the study period. Total runoff in 2008 was only 48% of that in 2010, yet total sediment yield was about 2.4 times greater than in 2010, primarily due to higher sediment concentrations in runoff in 2008. The annual flow-weighted sediment concentration in 2008 was estimated at 3578 mg L^{-1} for all treatments, approximately eight times the concentration in 2010 (Table 6). The high sediment concentrations in 2008 could be attributed to the initial soil disturbance by the tillage that occurred in 2006 and 2007, and the little PFS cover in 2008. Since 2008, sediment concentrations gradually decreased: 12,016, 1964, and 1419 mg L^{-1} in 100% cropped watersheds for 2008, 2009, and 2010, respectively (Table 6). In addition, the delayed planting due to the wet field conditions and the consecutive occurrence of extreme rainfall events likely exacerbated soil erosion in June and July of 2008 (Table 3). In contrast, 2010 had favorable field conditions for planting and the well-established crop canopy could protect soil from runoff erosion during the large storms in early August (373 mm). The decrease of sediment concentration over time could also be attributed to the increase of perennial cover percentage in PFS.

Soils were more susceptible to runoff-induced erosion during the early growth stage, especially for the first few large storms in spring. For example, sediment yield from the first large rainfall

Table 5. Annual sediment yield during growing season (April–October) for the treatments of rowcrop (100% RC) and prairie filter strips (PFS) at the Neal Smith National Wildlife Refuge, Jasper County, IA.

	100% RC	10% PFS at footslope	10% PFS at footslope and in contour strips	20% PFS at footslope and in contour strips	Mean
	Mg ha^{-1}				
2007	0.06(0.04)b†	0.02(0.01)b	0.04(0.04)b	0.10(0.06)a	0.05(0.02)
2008	21.34(9.2)a	0.64(0.35)b	0.93(0.22)b	1.05(0.67)b	6.00(3.31)
2009	2.89(1.51)a	0.09(0.04)b	0.15(0.07)b	0.14(0.10)b	0.82(0.58)
2010	8.91(2.53)a	0.18(0.09)b	0.36(0.11)b	0.59(0.33)b	2.51(1.24)
Average	8.30(3.21)a	0.23(0.11)b	0.37(0.13)b	0.47(0.21)b	

† Numbers in parenthesis are standard errors. Letters after parenthesis indicate the significance test of mean difference among four treatments within each year at $p < 0.05$.

Table 6. Annual flow-weighted sediment concentration in surface runoff during growing season (April–October) for the treatments of rowcrop (100% RC) and prairie filter strips (PFS) at the Neal Smith National Wildlife Refuge, Jasper County, IA.

	100% RC	10% PFS at footslope	10% PFS at footslope and in contour strips	20% PFS at footslope and in contour strips	Mean
	mg L^{-1}				
2007	125.4b†	77.8b	90.6b	263.0a	139.2 (30.7)
2008	12016.3a	818.3b	790.6b	686.7b	3578.0 (1682.0)
2009	1963.8a	129.3b	74.7b	183.1b	587.7 (337.3)
2010	1419.4a	176.3b	90.5b	138.9b	456.3 (203.1)
Average	3881.2(1776.2)a	300.4(151.7)b	261.6(143.1)b	317.9(99.0)b	

† Numbers in parenthesis are standard errors. Letters after parenthesis indicate the significance test of mean difference among four treatments within each year at $p < 0.05$.

event (25–27Apr.) in 2009 was 2.3 Mg ha^{-1} for the 100% cropped watersheds, ~80% of the total sediment export for the entire year (April–October), whereas the rainfall and runoff during the same period accounted for only 10 and 45% of the corresponding annual amount (Fig. 5). The relatively poor ground cover during the early growth stage of rowcrop resulted in less protection of the soil surface from the force of raindrops and flowing water, compared with later growth stages. The storms during 8–11 Aug. 2010 produced 44% of annual runoff and only 12% of annual sediment, whereas the storms in June 2010 produced 26% of annual runoff but 60% of annual sediment (Fig. 3 and 5). The relatively greater contribution of the largest events to total sediment export was also concluded from an analysis of the Universal Soil Loss Equation database, indicating that the top 10% of total daily events produced a mean of 50% of eroded soil (González-Hidalgo et al., 2009).

Benefits of PFS

It is important to note that no-tillage alone did not prevent soil loss on these 6 to 10% slopes from approaching or even exceeding the annual tolerable soil loss rate of 11.2 Mg ha^{-1} during wet years in 2008 and 2010; however, the combination of no-tillage and PFS was highly effective and kept average sediment export to <1.1 Mg ha^{-1} during the crop season (April–October) in those years. Watersheds with 100% rowcrop had significantly higher sediment concentrations in runoff and total sediment yield than watersheds with PFS (Table 5 and 6). For example, the annual sediment concentration was reduced from 12,016 mg L^{-1} in 100% cropped watersheds to 687 to 818 mg L^{-1} in PFS watersheds in 2008. Similarly, the total measured sediment export from the watersheds without PFS was 21.3 Mg ha^{-1} in 2008, compared with only 0.64 to 1.05 Mg ha^{-1} from watersheds with PFS (Table 5). Overall, watersheds receiving PFS treatments had a mean sediment trapping efficacy of

96% during the study period, primarily attributed to a reduction of sediment concentration in runoff water. It is encouraging from this study that PFS could be effective in reducing sediment transport at the watershed scale. The efficiency of PFS in sediment trapping could be even higher for more intensive tillage systems (such as chisel plow), compared with the no-till adopted in this study (Zhou et al., 2009).

In spite of the relatively large scale of study area and occurrence of some extremely large storms during the study period, the sediment trapping efficacies were comparable with values reported in previous research where studies were generally conducted on a plot scale (Dillaha et al., 1989; Helmers et al., 2005; Pan et al., 2010), possibly due to the relatively greater width of the PFS (37–78 m) in this study, compared with most other studies (0.5–20 m). The mean flow-weighted annual sediment concentration over the 4 yr was 3881 mg L^{-1} for the 100% cropped watersheds, compared with only 293 mg L^{-1} for the PFS watersheds.
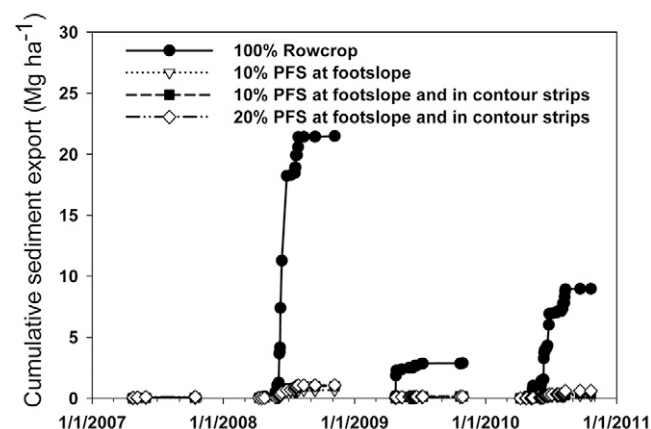

Fig. 5. Cumulative annual sediment export during growing season (April–October) for the treatments of cropland and prairie filter strips (PFS).

Consistent with the results for runoff, watersheds with PFS did not show obvious benefits in sediment reduction, compared with watersheds without PFS in 2007, the first year after treatment implementation. Native prairie species were seeded in July 2007, and therefore, PFS likely were not well established and fully functional for most of 2007. Watersheds with 10% PFS at footslope had the lowest sediment export in 2007.

The performance of PFS in trapping sediment generally decreased when soils became saturated. The sediment trapping efficacy decreased to 87% for the extreme events in early August 2010. During that period, the shallow groundwater table at footslope positions was observed to be only 0.18 m below the ground surface. Cropland showed disproportionately greater increases in sediment concentration in response to high flow rates than PFS, as illustrated by the storm events in August 2010 (Fig. 4). Generally, sediment concentrations in the watersheds with PFS were consistently low during the period of the entire storm; moreover, there were no obvious spikes in sediment concentration with flow peaks as observed in the 100% cropped watersheds. The reduction in flow velocity in filter strips caused by the abrupt roughness change often produces a backwater area, leading to deposition of incoming sediment immediately upstream of the grass area (Dosskey et al., 2002; Hussein et al., 2007), which would be expected to reduce the peak sediment concentration. From visual observations in the field, there was substantial deposition of sediment at the leading edge of PFS. Moreover, concentrated flow often develops on fields with long slopes and results in the appearance of ephemeral concentrated flow paths, which could be a major sediment source on hillslopes, especially during large events (Ludwig et al., 1995; Kimoto et al., 2006). Perennial vegetative area at the watershed footslope position could be efficient in dispersing concentrated flow and preventing channelization and associated erosion (Ritchie et al., 1997). From visual observations of the watersheds, there was little, if any, ephemeral gully formation within the PFS areas, whereas there was significant gully formation in the 100% rowcrop watersheds near the footslope position.

Effects of PFS Amount and Distribution

When compared with the 100% rowcrop watersheds, total sediment export over the 4-yr study period was reduced by 98, 96, and 93% for 10% PFS at footslope, 10% PFS at footslope and in contour strips, and 20% PFS at footslope and in contour strips, respectively. The upslope strips were established to reduce the impact of long slopes that lead to concentrated flow and were expected to further reduce sediment loss. Surprisingly, no significant difference was observed in sediment concentration and export among PFS treatments, which might be because of the rather wide PFS at all footslope positions. Regardless of PFS treatment, the width of PFS along the primary flow pathway at the footslope in the present study ranged between 37 and 78 m, since they were established based on the size of the contributing area. As a result, additional placement of PFS at upslope might not be expected to increase PFS efficacy. Other studies indicated that a 20-m vegetative buffer on a 10% slope would remove almost all the sediment from runoff (Zhang et al., 2010). From the practical perspective, converting 10% of cropland to PFS at the bottom of the field would be more convenient for field operations while taking relatively smaller amounts of land out of pro-

duction. A greater proportion of the watershed area might need to be covered to PFS for conditions associated with higher soil erosion potential (e.g., highly erodible soil, steep slope, aggressive tillage, intensive flush storms) or need multiple PFS for narrow and long hillslopes. The addition of multiple strips may reduce sediment delivery to the footslope PFS.

Native Prairie Watersheds

The average annual sediment export from the two 100% prairie watersheds was 0.24 Mg ha^{-1} in 2010, which is close to or slightly lower than the sediment export in the watersheds with PFS (0.23–0.47 Mg ha^{-1}), with both much lower than the 8.3 Mg ha^{-1} in the 100% cropped watershed, further corroborating that small amount of PFS within agricultural landscapes with no-till can protect soils from water erosion similar to prairie systems. The average annual runoff from the two native prairie watersheds was 152.5 mm in 2010, ~50% lower than the runoff in the watersheds with PFS, suggesting that hydrologic functions related to flow regulation are not restored to as great of an extent as sediment retention through PFS establishment. Improved soil structure and soil hydraulic properties would be expected as PFS becomes better established (Rachman et al., 2004). The total runoff and sediment export in the native prairie watersheds during the 8–11 Aug. 2010 event was 60 and 98% lower than that in the 100% cropped watersheds, respectively. The 100% prairie watersheds were subject to a controlled burn in spring 2010, and the largest runoff events closely followed that burn.

Conclusions

Significant reduction in sediment load was observed with PFS and the reductions were similar to that observed with plot studies. The 4-yr study suggests that an appropriately placed PFS at the watershed scale could effectively reduce sediment transport as has been observed at the plot scale. The percentage of the watershed devoted to PFS and distribution of PFS in the watershed showed no significant impact on runoff and sediment yield, likely due to the relatively large width of footslope PFS in this study. This suggests that for the systems and setting studied, converting 10% of agricultural cropping systems to perennial systems at the bottom of a watershed could effectively control runoff and sediment loss from the cropped area at the small watershed scale while being convenient for field operations.

There is the potential that over time the response of the treatments with PFS and the 100% rowcrop treatment will not be as dramatic due to soil surface conditions associated with the no-till system, evolving and becoming more favorable for infiltration and more resistant to soil erosion. As such, while the response over the first 4 yr of treatment implementation is useful in assessing initial impacts of integrating PFS, there is a need for continued evaluation of these systems. This would be important for not only assessing changes that may occur as the no-till crop area changes but also as PFS systems mature.

Acknowledgments

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