Grass Barrier and Vegetative Filter Strip Effectiveness in Reducing Runoff, Sediment, Nitrogen, and Phosphorus Loss

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ABSTRACT

Addition of switchgrass (*Panicum virgatum*) barriers to vegetative filter strips (FS) shows potential as conservation practice. This study evaluates the comparative effectiveness of three conservation practices in reducing runoff, sediment, N, and P losses from 1.5- by 16-m plots on an Aeric Epiaqualf. Three practices compared are a traditional fescue (*Festuca arundinacea*) filter strip (Fescue-FS), a switchgrass barrier in combination with the Fescue-FS (B-Fescue-FS) and a switchgrass barrier in combination with a native grass and forbs species filter strip (B-Native-FS). This study also predicts transport of sediment, N, and P in Fescue-FS and B-Fescue-FS. Fescue-FS and B-Fescue-FS of equal widths (0.7 m) significantly reduced runoff and sediment transport as compared with a continuous cultivated fallow (CCF) treatment, but B-Fescue-FS was more effective for reducing runoff ($p < 0.05$) and sediment ($p < 0.01$) transport. B-Fescue-FS was also more effective than Fescue-FS for reducing losses of organic N, NO$_3$–N, NH$_4$–N, particulate P, and PO$_4$–P ($p < 0.01$). Fescue-FS and B-Native-FS were equally effective for reducing runoff, sediment, and nutrient loss. Effectiveness of FS increased with distance with 18% of runoff, 92% of sediment, and 71% of nutrient leaving the source area being reduced in the first 4 m of the FS. An equation to predict sediment associated with runoff ponding above barriers explained approximately 70% of the variability between measured and predicted values of sediment, organic N, and particulate P transport. Combination of switchgrass barriers with FS is an effective alternative to Fescue-FS alone for reducing sediment and nutrients in runoff.

S EDIMENT, N, and P in runoff are major sources of nonpoint-source (NPS) pollution. Despite current use of soil and water conservation practices, losses of sediment, N, and P from rural lands remain high (USEPA, 1996). Annual sediment loss in the USA exceeds 10^9 t and costs society $44 billion in degraded water resources (USEPA, 1996). Introduction of cost-effective practices to reduce NPS pollution is desirable.

Grass barriers show promise as an economical alternative to existing conservation practices for reducing NPS pollutants. Grass barriers are narrow strips (approximately 1.2 m) of tall, erect, stiff-stemmed, native warm-season perennial grasses planted on the field contour (Kemper et al., 1992). Barriers form natural terraces (Dabney et al., 1999), slow runoff and promote infiltration (Meyer et al., 1995), enhance deposition of soil and organic matter (Melville and Morgan, 2001), promote degradation of sediment-bound chemicals (Groffman et al., 1991), and enhance wildlife habitat (Schultz et al., 1995). This approach for reducing NPS pollution can be a less-costly alternative to terraces where slopes are not too steep.

Grass barriers differ from FS because FS are typically much wider (>5 m). Vegetative filter strips are established between field borders and waterways. Narrow-row stiff-stemmed barriers may be more acceptable to farmers because they occupy much less land than FS. In addition, short statured plants such as fescue provide little benefit to wildlife. Vegetative filter strips of native perennial, usually tall, warm-season grass species when used with barriers may afford adequate control of NPS pollutants and provide habitat for upland wildlife.

Studies on value of FS for reducing sediment, N, and P in runoff have recently been published (Dillaha et al., 1989; Daniels and Gilliam, 1996; Srivastava et al., 1996; Melville and Morgan, 2001). Laboratory (Dabney et al., 1995; Ghadiri et al., 2001) and field (Chaubey et al., 1995; Rankins et al., 2001) studies indicate that FS significantly reduce sediment and nutrient loss in runoff. The most widely used grass for FS in the USA is fescue with extensive use in midwestern states (Sleper and Buckner, 1995; Rankins et al., 2001).

Information on grass barriers is limited (Meyer et al., 1995; Dabney et al., 1999). Most studies have been conducted in the laboratory (Dabney et al., 1995; Meyer et al., 1995; Ghadiri et al., 2001). Field studies are few (McGregor et al., 1999; Eghball et al., 2000; Gilley et al., 2000). Moreover, few studies have evaluated comparative effectiveness of fescue FS vs. barriers when used in combination with fescue or native plant species FS for reducing NPS pollution (Lee et al., 2003).

Modeling NPS pollution transport through FS and grass barriers is needed to understand and predict pollution transport. While equations have been developed to estimate effectiveness of FS for trapping sediments (Tollner et al., 1977; Foster, 1982; Flanagan et al., 1989), validation of equations with field and plot data is scarce. Moreover, prediction of barrier performance for trapping sediment has received little attention.

Objectives of this study were: (i) to determine effectiveness of a fescue-FS vs. B-fescue-FS or B-Native-FS in reducing runoff, sediment, N, and P loss from 8-m long runoff plots on an Aeric Vertic Epiaqualf; and (ii) to evaluate methods to predict transport of sediment, N, and P through switchgrass barriers and fescue filter strips.

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Abbreviations: B-Fescue-FS, switchgrass barrier in combination with the fescue-FS; B-Native-FS, switchgrass barrier in combination with a native grass and forbs species filter strip; CCF, continuous cultivated fallow; FS, vegetative filter strips; NPS, nonpoint source.

MATERIALS AND METHODS

Site Description and Field Plots

The study was conducted at the University of Missouri's Bradford Center located 17 km east of Columbia, MO. The site is an east-facing area of 23 by 85 m with a slope of 4.9 ± 0.6%. Soil was a Mexico silt loam (fine, smectitic, mesic, Aeric Vertic Epiaqualfs) maintained in perennial fescue for more than 10 yr. The site was surveyed for slope and depth to Bt horizon. Depth to Bt was determined on a 7.5-m grid using a 10-mm diam. hand probe. Soil texture and color changes were used to estimate depth to Bt. The site has a depth to Bt of 85 ± 6 mm and is typical of moderately eroded Mexico soil.

Twelve 1.5- by 16-m plots with four treatments replicated three times were arranged in a randomized complete block design (Fig. 1). The length of the plots was oriented up- and downslope. Soil berms 200 mm in height and 250 mm in width were constructed as plot borders. Berms were treated with polyacrylamide at a rate of 9 kg ha^{-1}, and covered with geotextile fabric to reduce berm erosion to nondetectable levels. Plots were planned with a 1.5 by 8 m sediment source-area (or source-area) managed under CCF, above a downslope area under FS or CCF of the same size (Fig. 1). Each pair of parallel plots included a 3-m alley oriented up- and downslope between plots to facilitate positioning a rainfall simulator. Glyphosate herbicide (N-phosphonomethyl-glycine) was applied at 8 L ha^{-1} to kill vegetation in the sediment source-area in June 2001. The source area was tilled with a rototiller to a depth of approximately 80 mm in July 2001. The source area was managed under CCF and rototilled after major rainfall events. The area below the source area in the CCF treatment was managed the same as the source area. Four treatments were (i) a check managed in CCF without switchgrass barrier or filter strip, (ii) Fescue-FS, (iii) B-Fescue-FS, and (iv) B-Native-FS (Fig. 1). The word barrier is used to reference switchgrass barriers throughout this paper.

A 0.7-m wide by 1.5-m long barrier was established at the downslope edge of the source area in each of the plots above the fescue or native species FS. Barriers were established by transplanting 1-yr-old plants in July 2001. Gaps between plants were replanted to establish dense barriers. Existing fescue was used for filter strips. The Fescue-FS area was mowed to approximately 100 mm when needed. Three 1.5 by 8 m plot areas below the source area were treated with glyphosate herbicide and rototilled before the establishment of B-Native-FS treatment. The B-Native-FS was established in July 2001 from seed and transplants consisting of a mixture of eastern gamagrass (*Trypsicum dactyloide*), Indian grass (*Sorghastrum scoparium*), big bluestem (*Andropogon gerardi*), gray-head coneflower [*Ratibida pinnata* (Vent.)Barnhart], and purple coneflower [*Echinacea purpurea* (L.) Moench].

Rainfall Simulation

Simulated rainfall was used to evaluate treatments in August 2002. A rotating-boom rainfall simulator was used to apply rain at an intensity of 66 mm h^{-1} for 1 h (Swanson, 1965). The rainfall simulator was positioned to apply rainfall to a pair of plots concurrently. The simulator uses 10 booms with 30 nozzles, with nozzles positioned at radii of 1.5, 3.0, 4.5, 6.0, and 7.6 m with 2, 4, 6, 8, and 10 nozzles, respectively, on each successive radius. Nozzles were 2.7 m aboveground and rotated in a circle while continuously spraying. Diameter of the rainfall simulator is approximately 16 m, allowing rainfall to cover both the source and filter strip areas. Rain gauges were set at 1-m intervals along the simulator boom radius to monitor rainfall distribution.
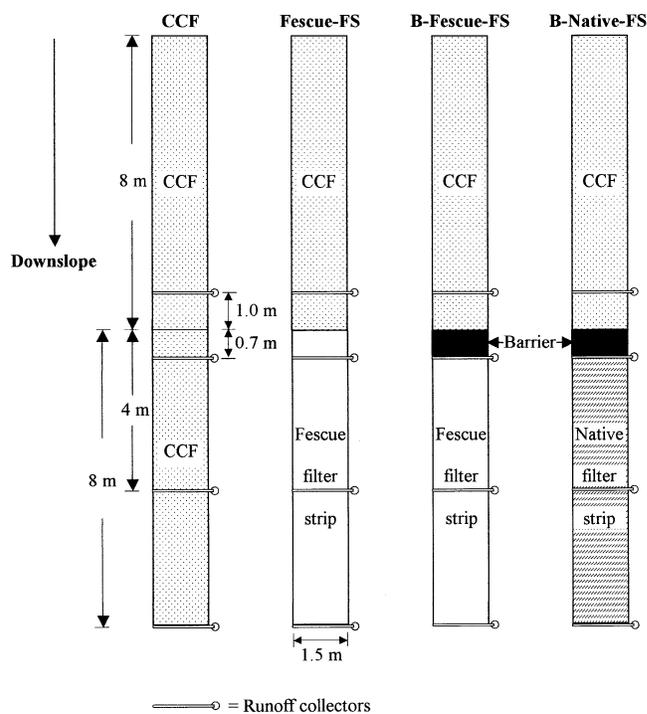

Fig. 1. Experimental treatments showing the 8-m area managed under continuous cultivated fallow (CCF) as the sediment source area above an 8-m test area under CCF or switchgrass barrier and fescue (B-Fescue-FS) or native plant species filter strip (B-Native-FS). Fescue-FS is fescue filter strip.

Mean simulated rainfall application was 66 ± 1.6 mm h^{-1}. Rainfall intensity at the edge was less than near the center of the simulator (61 ± 1.2 vs. 70 ± 0.4 mm h^{-1}). Mean wind velocity for all runs was 15 ± 2 km h^{-1}. However, rainfall intensity near the outside edge of the application area was probably reduced by wind combined with centrifugal effects. The simulator was adjusted during the study to produce a uniform intensity throughout the area of application; however this effort was not perfect. Variable rainfall intensity with distance from the center occurred for all runs. Thus, this variability should not be a factor in assessing relative differences among treatments.

Water supplied to the simulator from a nearby lake had an electrical conductivity of 1 dS m^{-1}. Simulated rainfall protocol began with a dry soil run at 66 mm h^{-1} for 1 h. A subsequent wet-run simulation was done approximately 24 h later at 66 mm h^{-1} for 1 h. Dry and wet runs were designed to simulate large natural rainfall events with a recurrence interval of a 10-yr return period for mid-Missouri. Granular fertilizer (13% N, 44% P, and 83% K) was applied to the source area 24 h before rainfall simulation at 80 kg ha^{-1} of N, 35 kg ha^{-1} of P, and 66 kg ha^{-1} K. Although no crop was grown, fertilizer application facilitated evaluation of the effectiveness of barriers and filter strips to reduce nutrient transport. This fertilizer rate is the amount that would have been applied based on the soil test if a crop had to be grown. Fertilizer was uniformly broadcast and incorporated to a depth of approximately 80 mm with a rototiller.

Runoff Collection and Sampling

Watertight runoff collectors of a V-shape (0.08 m wide, 1.5 m long, and 0.06 m deep) were constructed with angle iron for sampling runoff. Each collector was covered with a hinged metal cover fitted with a rubber gasket. The cover was fit with

clamps to secure it to the trough between sampling periods. Hinges allowed the collector cover to be quickly opened and closed for runoff sampling. Collectors were affixed with four 250-mm long spikes to anchor them into the soil. Collectors were set to a 3% slope to allow runoff into collection pits containers. In the cover-closed position, runoff passed over the cover. Runoff collectors were installed across the plots at 1 m above the downslope edge of the source area and in the FS area at 0.7, 4, and 8 m below the source area. Collection pits were created to position a 4-L container for collecting runoff.

Runoff collection was done only during the wet-runs. Runoff was sampled every 10 min for 5 s at all collectors during runoff. Samples at a given time were collected first from the collector at the downslope end of the plot and then successively from each collectors upslope. This allowed sampling without affecting runoff downstream. Six samples were collected from each location for a total of 24 samples from each plot-event, totaling 432 samples from the 18 plots. Volume and weight of runoff of each sample were recorded. Runoff volume was regressed vs. time of collection, and the resulting regression equations were integrated over 0 to 60 min to compute the runoff volume on a 1-h basis. Runoff depth was computed by dividing runoff volume by the corresponding contributing area above each sampling position in accord with Sheridan et al. (1999) and Lee et al. (2003). Runoff ponding above grass treatments was measured vertically by inserting a meter stick into the pond.

Sediment, Nitrogen, and Phosphorus Analysis

Runoff samples were stirred to suspend sediments, and two aliquots were taken for analysis. A 0.5-L aliquot was used for determination of sediment concentration. Sediment concentration was measured using the evaporation method that consisted of decanting water after 48 h and drying at 105°C (Brakensiek et al., 1979). A 0.25-L aliquot of a composite of samples for each sampling position was used to determine N and P concentration. These samples were stored in an insulated cooler and transported to the laboratory within approximately 4 h after a run. Samples were filtered through Whatman #1 filter paper for determination of nitrate (NO_3–N), ammonium (NH_4–N), and orthophosphate (PO_4–P) and then stored at 4°C until analyzed. Total N and P concentrations were determined from unfiltered aliquots. Analysis of N and P was done using a Lachat flow injection analyzer (Lachat Quik-Chem 800 Zellweger Analytics, Milwaukee, WI). Sediment mass and nutrients were computed as the product of runoff and concentration. Organic N was calculated as the difference of NO_3–N and NH_4–N from total N. Particulate P was calculated as the difference of total P minus PO_4–P. Sediment loss per unit area was computed by dividing sediment by the corresponding contributing area above each sampling position.

Sediment Transport Prediction with Barriers and Fescue Filter Strips

Equations compiled by Haan et al. (1994) based on work of Tollner et al. (1977) and Flanagan et al. (1989) were used to predict sediment trapping efficiency (T_s) of Fescue-FS and B-Fescue-FS assuming: (i) steady runoff and sediment flow, and (ii) sediment deposition beginning at the upper portion of the grass strips. Inputs included incoming sediment discharge, runoff rate, density and height of vegetation, calibrated Manning's roughness, width of Fescue-FS and B-Fescue-FS (m), and soil slope. Prediction of sediment trapping considered two zones. Zone 1 was the upper portion of the strip where most sediment deposition occurs. Zone 2 was the remaining lower strip where fine sediment settles. Prediction was conducted

using data collected every 10 min during the 1-h run. Eighteen data values for each grass treatment were used for the prediction, corresponding to samples collected at 1 m above, 0.7 and 4 m below the source area.

Flow depth and hydraulic radius for each zone of Fescue-FS and B-Fescue-FS (0.7, 4, and 8 m) were estimated using a calibrated Manning's equation (Tollner et al., 1977) as follows:

$$d_f = \frac{1.5 \, q_w x n}{R^{\frac{2}{3}} S^{\frac{1}{2}}} \quad [1]$$

$$R = \frac{S_s d_f}{2 d_f + S_s} \quad [2]$$

where d_f is flow depth (m), q_w is runoff rate (m^3 s^{-1}), xn is Manning's roughness based on vegetation roughness and stiffness, R is hydraulic radius (m), S is soil slope, and S_s is vegetation spacing (m).

Sediment transport rate of silt and clay (q_{si}) in Zone 1 was calculated as

$$q_{si} = q_{si\text{-total}} f_{ri}^1 \quad [3]$$

where $q_{si\text{-total}}$ is sediment discharge and (f_{ri}^1) is fraction of soil particles <0.05 mm.

The fraction of soil trapped by settling (T_s) in Zone 2 based on Reynold's Number (R_e), and the fall number of soil particles (N_f in m s^{-1}) was computed as:

$$R_e = \frac{V_m R}{v} \quad [4]$$

$$N_f = \frac{V_s L}{V_m d_f} \quad [5]$$

$$T_s = \exp(-1.05 \, 10^{-3} \, R_e^{0.82} \, N_f^{-0.91}) \quad [6]$$

where v_m is the Manning's flow velocity (m s^{-1}), v is dynamic viscosity of water (m^2 s^{-1}), v_s is settling velocity of the sediment particles (m s^{-1}), and L is total width of grass barrier or fescue filter strip (m).

An adjusted trapping efficiency (f_d) for sand, silt, and clay was estimated accounting for sediment trapped by infiltration using an effective saturated hydraulic conductivity (K_{eff}; 0.34 mm h^{-1}) for the Mexico claypan soil (Blanco-Canqui et al., 2002).

$$f_d = \frac{T_s + 2K_{eff} (1 - T_s)}{1 + K_{eff} (1 - T_s)} \quad [7]$$

The total trapping efficiency (f_{to}) was computed as:

$$f_{to} = [f + f_{d\text{-sand}} (1 - f)](1 - f_{ri}^1) \quad [8]$$
$$+ f_{d\text{-silt}}(f_{ri}^1 - f_{ri}^0) + f_{d\text{-clay}} f_{ri}^0$$

where f is fraction trapped as bedload sediment in Zone 1, and $f_{d\text{-sand}}$, $f_{d\text{-silt}}$, $f_{d\text{-clay}}$ are soil fractions trapped in Zone 2. The f_{ri}^0 is the fraction of inflow sediment <0.002 mm. Details of computations followed Haan et al. (1994).

Data Analysis

Statistics were calculated for runoff, sediment, and nutrient data. The General Linear Models (GLM) procedure of SAS (SAS Institute Inc., 1999) was used to test hypotheses that runoff, sediment, and nutrient reduction differences between adjacent sampling positions are the same among treatments. Orthogonal contrasts at the same sampling positions were used to compare main effects for Fescue-FS vs. B-Fescue-FS, Fescue-FS vs. B-Native-FS, and CCF vs. the mean of all grass treatments. Regression was used to study relationships of run-

Table 1. Mean surface runoff and sediment loss ($n = 3$) for the four treatments by sampling position.

Position	CCF	Fescue-FS	B-Fescue-FS	B-Native-FS	SD†
			Treatments		
m					
			Surface runoff, mm		
−1	58.6	57.3	55.3	55.4	1.7
0.7	57.6	50.0	45.9	46.3	0.9
4	50.9	45.4	40.5	40.1	1.3
8	44.4	38.6	36.3	32.0	1.6
			Sediment, Mg ha^{-1}		
−1	10.1	10.2	10.8	10.3	0.9
0.7	9.0	2.0	0.8	0.9	0.3
4	8.1	0.7	0.4	0.7	0.3
8	7.2	0.3	0.2	0.2	0.2

†Pooled standard deviation of the mean of the four treatments.

off, sediment, and nutrient reduction with distance. Analysis of confidence intervals of means was conducted to test differences among treatments with distance (Snedecor and Cochran, 1989).

A small decline in runoff depth with distance occurred in the downslope area of all the treatments as discussed earlier (Table 1). This difference is not expected to significantly influence treatment effects because relative amounts of runoff, sediment, and nutrients between the CCF and the three other treatments (Fescue-FS, B-Fescue-FS, and B-Native-FS) at all sampling positions were large. The CCF produced the most runoff, sediment, and nutrient loss (Tables 1 and 2). Because of the decline in runoff with distance, relative amounts of runoff, sediment, and nutrients vs. distance of Fescue-FS, B-Fescue-FS, and B-Native-FS were illustrated by using data normalized with the CCF data, allowing for comparison of reductions due only to grass treatments effects. Relative runoff, sediment, and nutrients were computed by dividing the amount leaving each sampling position (0.7, 4, and 8 m) by the amount collected at 1 m above the downslope end of the 8-m source area. Graphs were prepared using these relative values scaled vs. the CCF treatment that had no barrier or filter strip. Relative values of runoff, sediment, and nutrients were discussed as percentages.

RESULTS AND DISCUSSION
Runoff Reduction

Mean runoff values are presented in Tables 1 and 2. Figure 1 shows that runoff was reduced by 11% in Fes-

cue-FS and by 15% in B-Fescue-FS when compared with CCF treatment ($p < 0.01$; Tables 1 and 2). Fescue-FS reduced runoff less than B-Fescue-FS at the 0.7-m position ($p < 0.05$; Table 2). Results suggest that switchgrass barriers in the B-Fescue-FS treatment improved runoff detention time. In addition, we speculate that the deep-rooting system and dense surface debris in switchgrass barriers improved infiltration. Field observations showed that ground under the barriers had a proliferation of root and earthworm channels, and a visibly loose soil compared with Fescue-FS although no data were collected. A recent study reported that switchgrass barriers significantly reduced runoff from tilled soils (Gilley et al., 2000).

Runoff did not differ between the Fescue-FS vs. B-Native-FS and Fescue-FS vs. B-Fescue-FS (Table 1 and 2; Fig. 2a) at 4 and 8 m. This shows that B-Native-FS was as effective as Fescue-FS in reducing runoff. A related study by Tufekcioglu et al. (1999) reported that native species form a network of roots to a depth of 1.5 m, increasing potential for infiltration. Early stages of infiltration may be improved; however, long-term infiltration will be dominated by the very slowly permeable Bt horizon (Blanco-Canqui et al., 2002). Results suggest that switchgrass barriers in combination with Fescue-FS are a potential alternative to Fescue-FS alone for improving infiltration in claypan soils, thereby reducing surface runoff. Runoff reduction due to infiltration can have practical implications for removing fine sediments and soluble nutrients from runoff.

Sediment Reduction

Mean sediment rates are presented in Tables 1 and 2. B-Fescue-FS reduced sediment loss significantly more than Fescue-FS at 0.7 m ($p < 0.01$; Table 2). Seventy eight percent of the sediment leaving the 8-m sediment source area was trapped in the Fescue-FS treatment while 91% of sediment was trapped in front of the B-Fescue-FS treatment vs. the CCF treatment (Fig. 2b). Greater effectiveness of B-Fescue-FS vs. the Fescue-FS is in accord with results of Lee et al. (1999) who reported that 3-m switchgrass barriers reduced sediment loss by 69% and an equal width of Fescue-FS reduced sediment

Table 2. Statistical significance of differences in runoff, sediment, and nutrients for the treatments.

Source	df	Runoff	Sediment	Organic N	NO$_3$–N	NH$_4$–N	PO$_4$–P	Particulate P
					$p < F$			
Block contrast‡§	2							
Fescue-FS vs. B-Fescue-FS	1	0.04*	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**
CCF vs. all	1	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**
Block contrasts¶	2							
Fescue-FS vs. B-Fescue-FS	1	ns†	ns	ns	<0.01**	<0.01**	<0.01**	ns
Fescue-FS vs. B-Native-FS	1	ns	ns	ns	ns	<0.01**	<0.01**	<0.01**
CCF vs. all	1	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**
Block constrasts#	2							
Fescue-FS vs. B-Fescue-FS	1	ns	ns	ns	ns	ns	ns	ns
Fescue-FS vs. B-Native-FS	1	ns	ns	ns	ns	ns	ns	ns
CCF vs. all	1	<0.01**	<0.01**	<0.01**	<0.01**	<0.03*	<0.01**	<0.01**

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Not significant.
‡ Difference of runoff, sediment, or nutrients between the sampling position 1-m above and 0.7-m below the downslope edge of the source area.
§ Differences of runoff, sediments, or nutrients among blocks were not significant ($P > 0.10$).
¶ Difference of runoff, sediment, or nutrients between the 0.7- and 4-m sampling positions.
# Difference of runoff, sediment, or nutrients between the 4- and 8-m sampling positions.
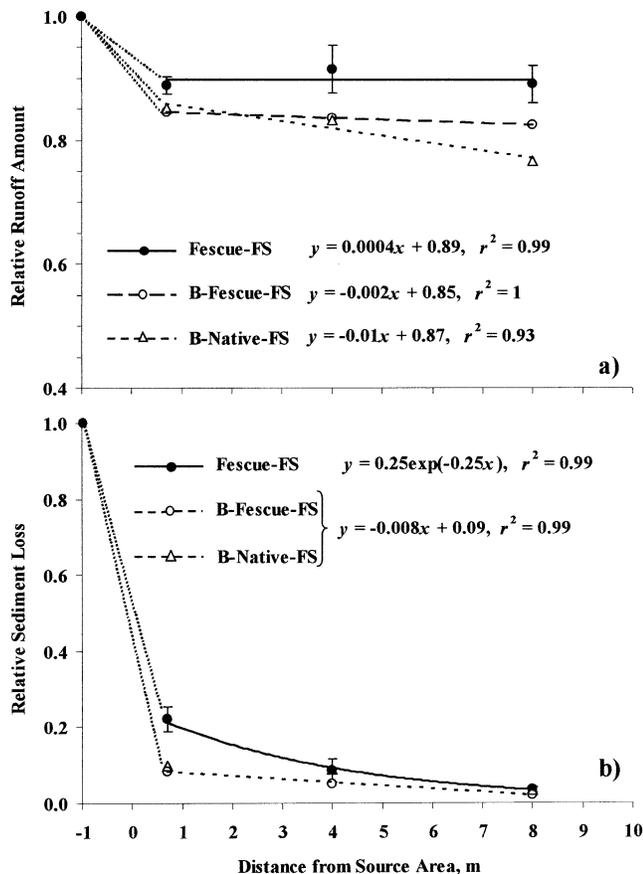
Fig. 2. Relative amount of mean (a) runoff and (b) sediment rate of fescue filter strip (Fescue-FS), switchgrass barrier above Fescue-FS (B-Fescue-FS), and switchgrass barrier above a native species filter strip (B-Native-FS). Error bars in Fescue-FS are the pooled standard deviation for the three treatments ($n = 9$).

loss by 62%. The B-Fescue-FS effectiveness was greater than that reported by Gilley et al. (2000) who found that 0.8-m switchgrass barriers trapped 63% of the sediment on a Monona silt loam with slopes of 8 to 16%. We believe that the lesser effectiveness reported by Gilley et al. (2000) was due to steeper slopes. Increased slope-steepness increases runoff velocity, resulting in decreased sediment deposition by barriers (Haan et al., 1994).

Reduction of transported sediment in the B-Fescue-FS treatment was mostly due to ponding upslope of barriers that reduced runoff velocity and promoted sediment deposition. The maximum ponding depth was 0.03 ± 0.01 m and extended 0.7 ± 0.05 m above the barriers. Runoff through B-Fescue-FS was delayed by increased detention storage created by barriers. These observations agree with Ghadiri et al. (2001) who reported that runoff ponding caused sediment deposition upslope of barriers, thereby reducing sediment loss. Runoff ponding above Fescue-FS was negligible. Fescue residues and submerged plant parts within the Fescue-FS treatment enhanced the performance of fescue for reducing sediment in runoff (Jin et al., 2002).

Sediment loss was not different between the Fescue-FS vs. B-Fescue-FS treatments at either the 4- and 8-m positions (Table 2). The 4-m strip reduced sediment loss

by approximately 93% in both treatments. The 8-m strip reduced sediment loss by 97% agreeing with Coyne et al. (1995) who found that a 9-m Fescue-FS reduced 99% of sediment loss on a Maury silt loam. Performance of 4-m Fescue-FS in our study is slightly higher than that reported by Dillaha et al. (1989) who found that a 4.6-m filter strip retained only 83% of sediment. This small difference may be attributed to a much greater simulated rainfall application rate. Large rainfall events would be expected to diminish the benefit of Fescue-FS.

Sediment reduction by the 0.7-m B-Fescue-FS was equivalent to reduction by 4 m of Fescue-FS. This indicates that only 15% of the land required for Fescue-FS is needed for B-Fescue-FS for the same effectiveness, reducing the amount of land taken out of production. We conclude that narrow switchgrass barriers in combination with FS improve the performance of Fescue-FS.

Sediment loss did not differ between the Fescue-FS vs. B-Native-FS (Table 2). Both Fescue-FS and B-Native-FS reduced sediment loss by 91% within 4 m (Table 1). The width increase from 4 to 8 m reduced the sediment loss by an additional 5%. This indicates that native species filter strips, when used in conjunction with barriers, can be as effective as Fescue-FS for trapping sediment in runoff. Our results support Rankins et al. (2001) who found that effectiveness of native species and Fescue-FS for sediment reduction was the same.

Foster (1982) stated that sediment transport through grass strips diminishes exponentially with increasing grass width. The relative sediment loss shown in Fig. 2b did not follow this model. The reason for this is because of the settling of sediment in front of the first 0.7 m of Fescue-FS and B-Fescue-FS. This sediment settling was too high to fit data collected below this point. Exclusion of the data from the ponding area and top edge of the grass improved the exponential regressions significantly ($p < 0.01$). However, regressions are far below the incoming sediment load at -1 m, confirming the dominant role of the upslope edge of the grass with associated ponding on sediment retention of grass barriers and even fescue filter strips. Sediment in runoff decreased exponentially with increasing width of Fescue-FS ($r^2 = 0.99$; Fig. 2b), but decreased linearly in B-Fescue-FS and B-Native-FS ($r^2 = 0.98$). The linear response in B-Fescue-FS is likely due to the reduction of sediment in the ponding area above the barriers.

Nitrogen and Phosphorus Reduction

Nutrient load passing the sampling positions in the Fescue-FS or B-Fescue-FS are shown in Tables 2 and 3. Reduction of organic N, NO_3–N, NH_4–N, particulate P, and PO_4–P was significantly different between the Fescue-FS vs. B-Fescue-FS treatments at 0.7 m ($p < 0.01$; Table 2). Fescue-FS was less effective than B-Fescue-FS in reducing nutrients in runoff. Values in Fig. 3a indicate that the 0.7-m Fescue-FS reduced 55% of organic N, 36% of particulate P, 27% of NO_3–N, 19% of NH_4–N, and 37% of PO_4–P when compared with the CCF treatment. In contrast, B-Fescue-FS for equal width reduced 67% of organic N, 53% of particulate P,

Table 3. Mean loss of nutrients (*n* = 3) for the four treatments by sampling position.

Position	CCF	Fescue-FS	B-Fescue-FS	B-Native-FS	SD†
m					
			Organic N		
−1	4.73	4.73	4.50	4.08	0.27
0.7	4.06	1.81	1.29	0.96	0.32
4	3.44	0.89	0.94	0.73	0.19
8	2.55	0.58	0.38	0.43	0.19
			NO_3–N		
−1	0.63	0.66	0.61	0.62	0.06
0.7	0.56	0.43	0.16	0.40	0.01
4	0.41	0.20	0.12	0.29	0.01
8	0.34	0.11	0.07	0.11	0.01
			NH_4–N		
−1	1.94	1.90	1.97	1.77	0.19
0.7	1.90	1.49	0.97	0.84	0.20
4	1.37	0.56	0.39	0.30	0.05
8	0.98	0.26	0.18	0.09	0.09
			PO_4–P		
−1	0.85	0.86	0.94	0.81	0.02
0.7	0.74	0.49	0.37	0.30	0.05
4	0.55	0.20	0.19	0.15	0.06
8	0.41	0.12	0.09	0.08	0.03
			Particulate P		
−1	2.19	2.10	2.00	2.15	0.19
0.7	1.60	0.97	0.69	0.62	0.06
4	1.24	0.40	0.32	0.20	0.08
8	0.98	0.10	0.04	0.04	0.05

† Pooled standard deviation of the mean for the four treatments.

68% of NO_3–N, 50% of NH_4–N, and 54% of PO_4–P. Mass of nutrients leaving the 0.7-m Fescue-FS was significantly higher than that leaving the B-Fescue-FS (Fig. 3a). The increased effectiveness of B-Fescue-FS supports a study reporting that 0.8-m wide switchgrass barriers reduced 57% of organic N, 81% of NH_4–N, 33% of NO_3–N, and 68% of particulate P losses (Eghball et al., 2000). Fescue-FS reduced significantly more NH_4–N, NO_3–N, and PO_4–P than B-Fescue-FS at 4 m ($p < 0.01$; Table 2). The 4-m strip reduced approximately 58% of nutrients in Fescue-FS and approximately 71% of nutrients in B-Fescue-FS. These results show that the greatest reduction in Fescue-FS occurred between the 0.7 and 4 m, whereas the greatest nutrient reduction in B-Fescue-FS occurred above 0.7 m.

Reduction of NH_4–N, particulate P, and PO_4–P was significantly different between the Fescue-FS and B-Native-FS treatments at 4 m ($p < 0.01$; Table 2). Compared with CCF treatment, the 4 m of Fescue-FS reduced 58% of NH_4–N, 68% of particulate P, and 62% of PO_4–P, while B-Native-FS of equal width retained 79% of NH_4–N, 84% of particulate P, and 72% of PO_4–P (Fig. 4a, 5). Overall, differences in nutrient reduction at 8-m between Fescue-FS and B-Native-FS were not significant.

The reduction of organic N and particulate P in Fescue-FS is attributed to sediment deposition within the Fescue-FS, while the greater reduction of such nutrients in B-Fescue-FS is explained by sediment deposition above the barriers (>90%).

Reduction of organic N ($r = 0.98$) and particulate P ($r = 0.99$) was positively correlated with trapped sediment. Increased removal of soluble nutrients through
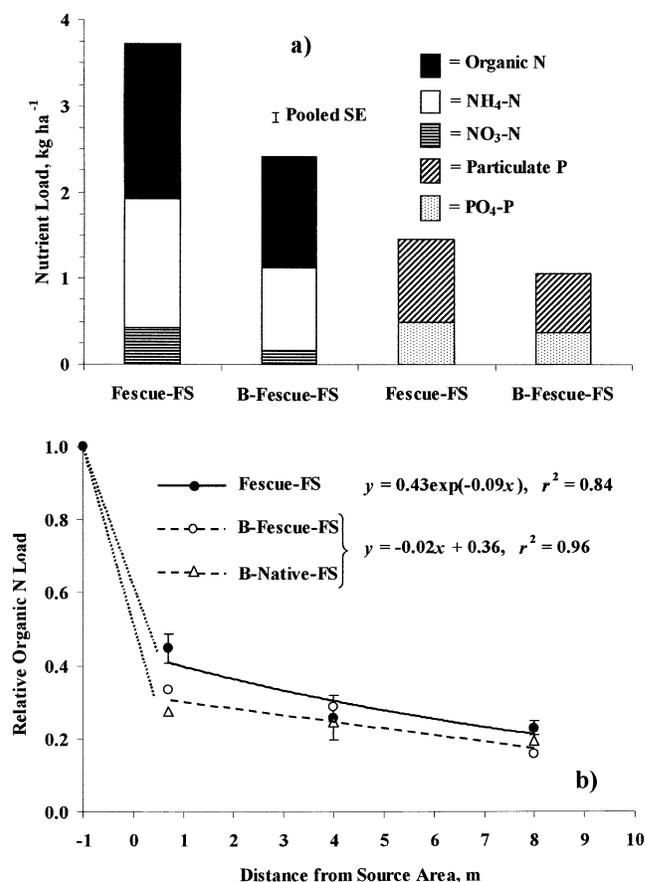

Fig. 3. Mean mass of (a) organic N, NH_4–N, NO_3–N, particulate P, and PO_4–P leaving the 0.7-m fescue filter strip (Fescue-FS) and switchgrass barrier above Fescue-FS (B-Fescue-FS), and (b) organic N load with width of the grass treatments.

B-Fescue-FS at 0.7 m may be due to higher infiltration and adsorption to organic matter, and clay. Infiltration in Mexico silt loam claypan soils is limited under wet conditions because of the slowly permeable Bt horizon; however, infiltration of soluble nutrients near barrier roots penetrating into the Bt horizon likely increase. As discussed, runoff from Fescue-FS was greater than from B-Fescue-FS ($p < 0.05$) at 0.7 m, suggesting that more runoff infiltrates into the barriers. In fact, Schmitt et al. (1999) on a study on a 6% sloping Sharpsburg silty clay loam reported that switchgrass barriers reduced loss of N and P by increasing infiltration within the barriers. Runoff infiltration in the ponded area above barriers is likely reduced by the very slowly permeable Bt horizon (Blanco-Canqui et al., 2002), thus any increased infiltration would be confined to the barrier zone whose deep roots most likely penetrated the Bt horizon. The reduction of NH_4–N, NO_3–N, and PO_4–P in the fescue strips of the treatments may be caused by (i) adsorption by clay particles and plants, and (ii) infiltration of runoff with colloidal particles (Chaubey et al., 1995). Additional pathways for NO_3–N, NH_4–N, and PO_4–P reduction may include immobilization and biological and chemical transformation (Groffman et al., 1991).

As with sediment, nutrient transport decreased abruptly in the 0.7 m particularly in B-Fescue-FS and
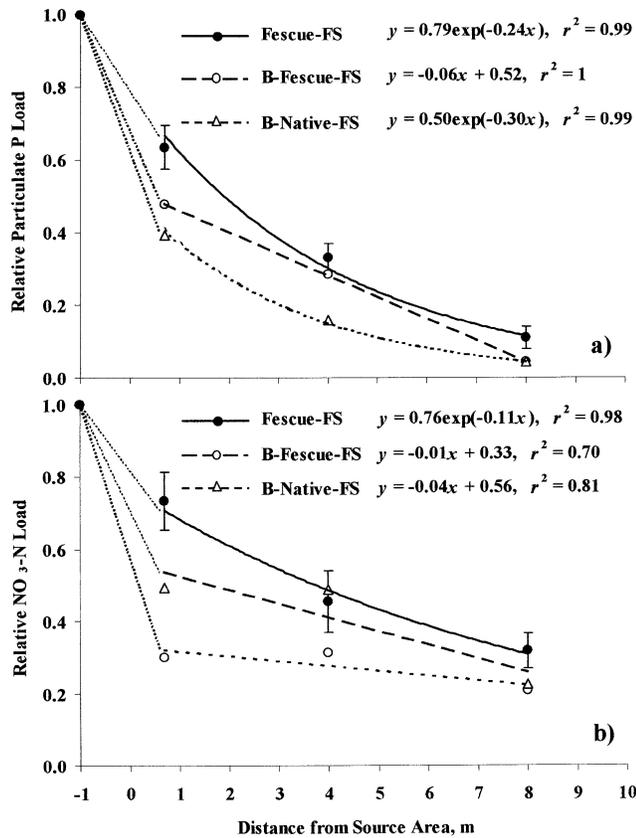
Fig. 4. Relative amount of mean (a) particulate P load and (b) NO$_3$–N load by distance (0.7, 4, and 8 m) of fescue filter strip (Fescue-FS), switchgrass barrier above Fescue-FS (B-Fescue-FS), and switchgrass barrier above native species filter strip (B-Native-FS).

Fig. 5. Relative amount of mean (a) NH$_4$–N load and (b) PO$_4$–P load by distance (0.7, 4, and 8 m) fescue filter strip (Fescue-FS), switchgrass barrier above a Fescue-FS (B-Fescue-FS), and switchgrass barrier above native species filter strip (B-Native-FS).

B-Native-FS producing a poor exponential regression. Exclusion of the data above the 0.7 m improved the regressions (Fig. 3b through Fig. 5b). Nutrients decreased exponentially with width in Fescue-FS ($r^2 >$ 0.96) in accord with Foster (1982). Evaluation of graphs showed that organic N, particulate P, and NO$_3$–N decreased linearly with distance in B-Fescue-FS ($r^2 > 0.96$; Fig. 3b, 4). This is attributed to the large reduction of N and P in sediments above the B-Fescue-FS. The NH$_4$–N and PO$_4$–P decreased gradually with distance of B-Fescue-FS and B-Native-FS following an exponential response ($r^2 = 0.99$; Fig. 5). The exponential decrease of soluble forms of N and P agrees with Srivastava et al. (1996) who showed that N and P were reduced exponentially with Fescue-FS width on a Captina silt loam. In contrast with the sharp decrease of nutrients in the 0.7 m of B-Fescue-FS, Fescue-FS reduced runoff nutrients gradually below the source area.

Prediction of Sediment and Nutrient Removal

Measured and predicted sediment and nutrient trapping of Fescue-FS and B-Fescue-FS are compared in Fig. 6. The equations by Haan et al. (1994) were used to predict sediment and nutrients. Predicted values for Fescue-FS alone agreed moderately well with measured data (Fig. 6a). Some deviation occurred at higher levels of trapp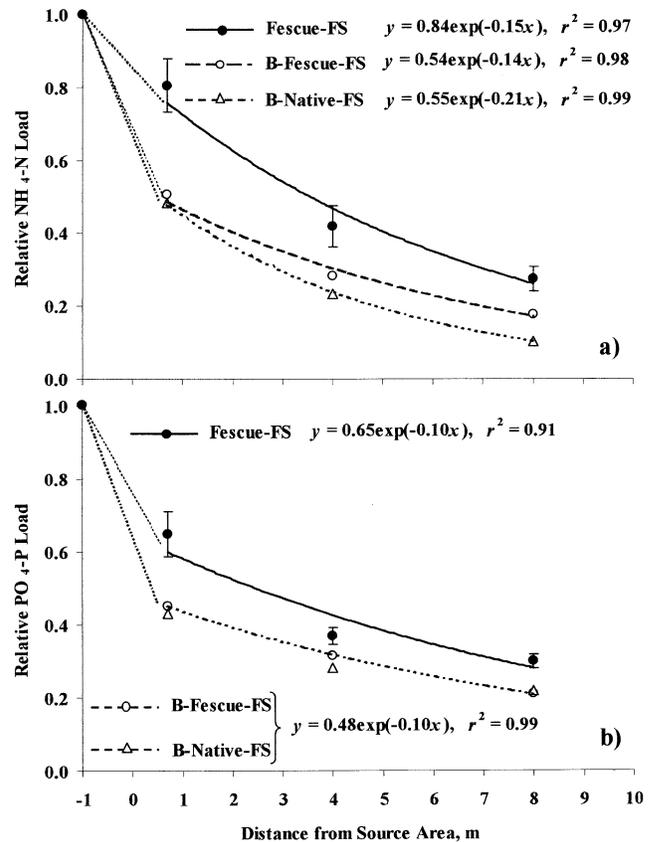ing where the equations slightly underestimated measured values. Linear regression explained 76% of the variance. Agreement between predicted and measured values for the B-Fescue-FS was less adequate than that for Fescue-FS alone ($r^2 = 0.44$). The equations greatly underestimated sediment trapping. Results suggest that applicability of the equations by Haan et al. (1994) is not recommended for use with B-Fescue-FS. Poor performance of the equations is attributed to runoff ponding above the barrier that fails to account for deposition above the barriers. Dabney et al. (1995) and Deletic (2001) stated that current equations only hold for conditions where no runoff-ponding above grass strips occurs. The equations are developed based on the trapping mechanisms of filter-strips rather than barriers. An equation developed by Foster (1982) was used to account for sediment deposition in the ponded area upslope of the barriers:

$$q_{so} = q_{in} \exp(-\alpha L_p) \qquad [9]$$

where q_{so} is sediment leaving the pond (g s^{-1} m^{-1}), q_{in} is sediment entering the pond (g s^{-1} m^{-1}), α is the deposition coefficient estimated from experimental data ($\alpha = -0.6$) based on the pond length (L_p) above the barrier and sediment entering and leaving the pond. Sediment leaving (q_{so}) the ponded area was then used in Eq. [3] instead of $q_{si\text{-}total}$. This adjustment improved the regressions between measured and predicted values ($r^2 = 0.66$; Fig. 6b). These results indicate that adjust-
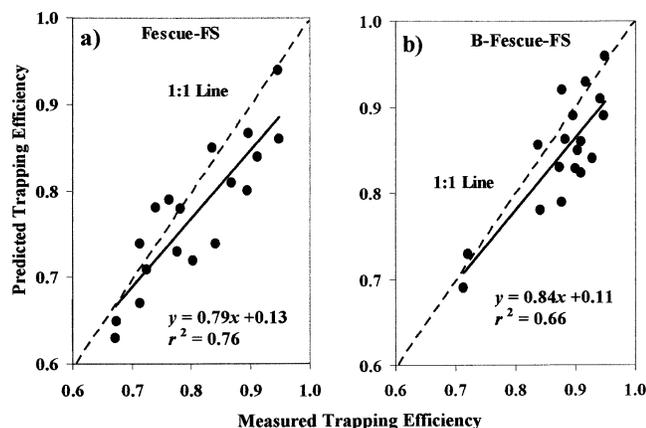
Fig. 6. Measured and predicted sediment trapping efficiency. Prediction used 18 data points corresponding to samples from each sampling position (-1, 0.7, and 4 m) collected every 10 min for the 1-h rainfall simulation.

ment for the runoff ponding is critical for prediction of sediment deposition in barriers. However, predicted values were generally lower than observed values at high values.

Since sediment rate was significantly correlated with organic N ($r = 0.98$) and particulate P ($r = 0.99$), these forms of N and P passing through barriers and Fescue-FS were predicted with equations by Haan et al. (1994) intended for sediment prediction. Predictions were conducted with and without using Eq. [9]. The predicted values of organic N ($r^2 = 0.72$) and particulate P ($r^2 = 0.73$) without using Eq. [9] agreed well with the measured values in Fescue-FS. However, the equations fit poorly for B-Fescue-FS, underestimating organic N ($r^2 = 0.29$) and particulate P ($r^2 = 0.34$) removal. Inclusion of Eq. [9] improved results for B-Fescue-FS. Linear regression explained 63 and 65% of the variability between predicted and measured values of organic N and particulate P, respectively. Despite adjustment for the ponding effect, removal of N and P is slightly underestimated. Regressions were below the 1:1 line of perfect prediction as measured values increased, suggesting that the equations have limitations for higher N and P concentrations. Results indicate that the equations by Haan et al. (1994) adjusted with Eq. [9] can predict sediment and sediment-bound N and P in barriers used with Fescue-FS. Correlations of NO_3–N, NH_4–N, and PO_4–P with sediment were less, indicating that prediction of soluble forms of N and P needs further development.

CONCLUSIONS

The following conclusions were determined from this study:

1. Switchgrass barriers in combination with vegetative filter strips were more effective than an equal width (0.7 m) of fescue filter strips for reducing runoff, sediment, and nutrient loss on a Mexico silt loam soil. Greater effectiveness of the combined practices is attributed to runoff ponding above barriers that reduced transport capacity of runoff and promoted infiltration and sediment deposition.

2. Native grass species filter strips with barriers were as effective as fescue filter strips for controlling runoff, sediment, and nutrient loss. Effectiveness of the grass treatments for reducing sediment and nutrient loss increased with FS width but reductions beyond 4 m were small. Results suggest that barriers in conjunction with Fescue-FS are as effective as 4 m of Fescue-FS for reducing sediment loss.

3. The equation presented by Haan et al. (1994) underestimated sediment and nutrient removal in barriers but performed well for prediction in the Fescue-FS. A modified equation accounting for runoff ponding above barriers explained approximately 70% of the variability between measured and predicted sediment, organic N, and particulate P.

Switchgrass barriers in combination with vegetative filter strips show promise as a conservation tool for reducing sediment and nutrient loss in runoff and complement current conservation practices.

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