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GRASS-SHRUB RIPARIAN BUFFER REMOVAL OF SEDIMENT, PHOSPHORUS, AND NITROGEN FROM SIMULATED RUNOFF[1]

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ABSTRACT: Riparian buffer forests and vegetative filter strips are widely recommended for improving surface water quality, but grass-shrub riparian buffer system (RBSs) are less well studied. The objective of this study was to assess the influence of buffer width and vegetation type on the key processes and overall reductions of total suspended solids (TSS), phosphorus (P), and nitrogen (N) from simulated runoff passed through established (7-year old) RBSs. Nine 1-m RBS plots, with three replicates of three vegetation types (all natural selection grasses, two-segment buffer with native grasses and plum shrub, and two-segment buffer with natural selection grasses and plum shrub) and widths ranging from 8.3 to 16.1 m, received simulated runoff having 4,433 mg/l TSS from on-site soil, 1.6 mg/l total P, and 20 mg/l total N. Flow-weighted samples were collected by using Runoff Sampling System (ROSS) units. The buffers were very efficient in removal of sediments, N, and P, with removal efficiencies strongly linked to infiltration. Mass and concentration reductions averaged 99.7% and 97.9% for TSS, 91.8% and 42.9% for total P, and 92.1% and 44.4% for total N. Infiltration alone could account for >75% of TSS removal, >90% of total P removal, and >90% of total N removal. Vegetation type induced significant differences in removal of TSS, total P, and total N. These results demonstrate that adequately designed and implemented grass-shrub buffers with widths of only 8 m provide for water quality improvement, particularly if adequate infiltration is achieved.

(KEY TERMS: buffer strip; nonpoint-source pollution; nutrients; runoff; simulation; sediment.)

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INTRODUCTION

Riparian buffer systems (RBSs) have multiple benefits in the landscape. They provide wildlife habitat, separation between agricultural activities and streams, and removal of sediment, nutrient, and chemical pollutants from upland surface runoff. Evidence of the role of RBS in nonpoint-source pollution mitigation has been demonstrated by many researchers, including Jordan *et al.* (1993) and Lowrance *et al.* (1984) from the Southeastern United States and Schultz *et al.* (1995) and Lee *et al.* (2003) from Iowa. These studies focused on RBSs that incorporated

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deep-rooted trees and addressed concerns of shallow subsurface flow and pollutant transport. Limited research has addressed the water-quality function of RBSs composed of grasses and shrubs to address surface flow and pollutant-transport concerns (Dosskey, 2001). Grass-shrub buffers are more readily accepted by farmers than tree-based systems (Barden *et al.*, 2003) and have potential for nonpoint-source pollution control in the corn and wheat belts of the mid-Western United States.

Width of vegetative buffers impacts their sediment removal from surface runoff (Hayes *et al.*, 1979). Most pollutant reduction takes place within the first 10 to 15 m of buffers (Lowrance *et al.*, 1984; Peterjohn and Correll, 1984; Jacobs and Gilliam, 1985). Coyne *et al.* (1995) found that 9 m of grass buffer removed 99% of total suspended solids (TSS) from simulated runoff events. Young *et al.* (1980) similarly reported that buffers of 21.3 m width composed of corn, orchard grass, oats, and sorghum/Sudan-grass at 4% slope removed 78% TSS, whereas buffers of 27.4 m width at the same slope and vegetation type removed 93% TSS. However, Desbonnet *et al.* (1994) found sediment removal efficiency was not directly proportional to the buffer width. They determined that increasing buffer width from 17 m by a factor of 3.5, to a maximum of 60 m, improved sediment TSS removals by only 10%.

Infiltration and sedimentation of large particles in buffers leads to decreased concentration and mass of TSS in the outflow runoff (Karr and Schlosser, 1977; Dillaha *et al.*, 1989; Vought *et al.*, 1994). Grassed buffers are intended to spread and maintain runoff in sheet flow, reducing flow velocity. Sheet flow increases infiltration rate and filtration by the soil matrix during percolation, and increases contact time and subsequent filtration and sorption by surface residues during overland flow (Karr and Schlosser, 1977; Dillaha *et al.*, 1989; Vought *et al.*, 1994). Dillaha and Inamdar (1997) observed that stiff-stemmed grasses in the buffer adjacent to the crop field edge slowed runoff, causing large soil particles to settle. Alberts *et al.* (1981) reported that a 2.7 m wide buffer strip removed 100% of particles >0.05 mm, and 85% of the sediments exiting the buffer were <0.035 mm. As a consequence, TSS concentration in outflow surface runoff was reduced by 99%.

Total-P retention seems to be a function of physical trapping of fine sediments, coupled with the use of vegetation to increase P uptake into plant tissue (Karr and Schlosser, 1977; Peterjohn and Correll, 1984; Osborne and Kovacic, 1993; Lowrance *et al.*, 1997). Schultz *et al.* (1995) concluded that the high biomass produced by native grasses (NG) was useful in trapping sediment and nutrients from surface runoff. Doyle *et al.* (1977) found that 3.7-4.6 m buffer widths of both fescue and forest buffers were effective in removing suspended and soluble pollutants from runoff.

Studies have shown that RBSs remove N from influent runoff (Dillaha *et al.*, 1988, 1989; Magette *et al.*, 1989). Vought *et al.* (1994) showed a width of 10-20 m of RBS was sufficient to remove most forms of N from surface runoff. Daniels and Gilliam (1996) found grass and forested buffers removed 20-50% of both total nitrogen (TN) and nitrate-N. A study of forested buffers in Illinois found that RBSs reduced nitrate in surface runoff by 95% (Osborne and Kovacic, 1993).

The RBS design characteristics that would simultaneously have minimum width, simple implementation, and ready acceptability by farmers are not well understood (Dosskey, 2001). In Kansas, current NRCS guidelines require a minimum width of 23 m and a maximum average buffer width of 46 m for a single field (NRCS, KS, 2002; Barden *et al.*, 2003). For the general USDA-NRCS design guidelines, Welsch (1991) suggested 6.1 m of mature forest extending from the edge of the stream, followed by 3.1 m of shrubs and 6.1 m of grass between the shrubs and the edge of the crop field. Barden *et al.* (2003) reported that Kansas farmers are skeptical of this design because it requires 1.5 ha of productive land per stream kilometer or double that if installed on both sides of the stream. In addition, this guideline perpetuates the concept of a "fixed-width" buffer, rather than one designed following a line of constant elevation along the crop field edge to force uniform inflow into the RBS.

The objective of this study was to measure the impact of buffer width and vegetation type on surface water, sediment, phosphorus and nitrogen reductions by using simulated runoff events passed through established grass-shrub RBSs. Data from this study also were used to assess the accuracy of a new surface Runoff Sampling System (ROSS; Ngandu and Mankin, 2004).

MATERIALS AND METHODS

Site Description and Plot Design

The study site was located in Northeastern Kansas, Geary County, along a tributary of the West Branch Mill Creek in the Flint Hills physiographic province (Barden *et al.*, 2003). The riparian buffer soil was a Hobbs silt loam (fine silty, mixed, nonacid, and mesic Mollic Ustifluvents), a soil common to the bottom-lands associated with secondary streams in the region (Bidwell, 1960), with a gravelly layer starting at about 60-cm depth and bedrock at about 1.2 m. The riparian buffer was 7 years old at the time of the study (established in 1995). Three of 30 established RBS segments were selected according to the predominant vegetation (Barden *et al.*, 2003) as follows: (1) NS: natural succession grasses, which developed from a strip left fallow since buffer establishment; (2) NG/P: an upslope strip of 5 m planted with NG followed by three rows of American plum (*Prunus americana*) spaced 1 m within rows by 2 m between rows (where rows roughly followed the stream); and (3) NS/P: an upslope 5-m strip of natural succession grasses followed by three rows of American plum spaced 1 by 2 m. About 60% of NS vegetation consisted of cool-season grasses, with about 50% downy brome (*Bromus japonicus*). The NG area was dominated by warm-season perennial grasses (>80%), such as Indian grass (*Sorghastrum nutans*) and switch grass (*Panicum virgatum*), which had been planted. The planted American plums had reached crown closure and averaged 2.5 m in crown height and canopy width, with numerous suckers between the rows. Both the NS and NG areas were in good condition with greater than 98% ground cover.

Three runoff plots were constructed with minimal disturbance in each RBS segment, for a total of nine plots (Table 1). The plots were designed to evaluate the "ideal" condition in which RBS inflow was well distributed across the inlet width and confined to uniform downhill flow. Each plot was 1 m across, defined by two steel-plate borders (15 cm above and 7.5 cm below ground surface) oriented up-and-down the slope. Similar to many RBSs in this physiographic region, the RBS in this study was originally designed as a fixed-width band of vegetation along the streambank. Because neither the uphill edge (field border) nor the downhill edge (streambank) of the RBS was along a contour of constant elevation, the slope and buffer width varied with position in the buffer and, thus, among plots (Table 1).

TABLE 1. Mill Creek RBS Plot Characteristics and Treatment Effects.

RBS Type	Plot No.	Width (m)	Slope (%)	Mean Mass Reductions (n = 3) TSS (%)	TP (%)	TN (%)
NS	1	13.9	3.7	99.8	89.5	89.7
NS	2	16.1	4.3	99.9	96.3	97.0
NS	3	16.0	4.1	99.9	98.6	98.3
Average		*15.3*	*4.0*	*99.9*	*94.8*	*95.0*
NG/P	4	13.4	3.8	99.9	97.4	98.2
NG/P	5	12.9	3.7	99.9	97.4	97.3
NG/P	6	10.6	3.9	99.7	93.4	92.6
Average		*12.3*	*3.8*	*99.8*	*96.0*	*96.0*
NS/P	7	10.7	3.7	99.5	84.9	86.6
NS/P	8	10.2	3.8	99.2	76.8	78.5
NS/P	9	8.3	4.2	99.5	92.1	90.9
Average		*9.7*	*3.9*	*99.4*	*84.6*	*85.3*

Notes: TSS = total suspended solids, TP = total phosphorus, TN = total nitrogen, NS = natural selection of grasses, NG/P = native grasses and American plum shrub, NS/P = natural selection of grasses and American plum shrub, RBS = riparian buffer system.

The ROSS (Figure 1; Ngandu and Mankin, 2004) were installed for collecting flow-weighted samples of runoff entering and exiting the RBS plots. Each ROSS delivered the runoff collected in a sump to a V-shaped splitter that separates successive fractions of the total flow using six dividers. Flow exiting from each divider was either delivered to a collection tank or returned to the ground via tubing.

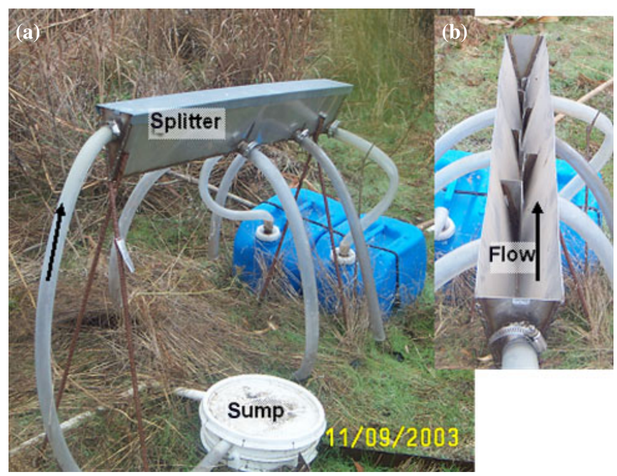

FIGURE 1. (a) ROSS Unit and (b) Splitter Assembly Installed on Riparian Buffer Site.

Runoff Simulation

Before each runoff event, about 4.0-6.5 cm depth of water (depending on initial soil wetness) was hand sprinkled, using a low-pressure shower nozzle, gently and uniformly across the experimental plots until runoff from the outlet was observed for 15 min. This outflow [with no TSS, TN, and total phosphorus (TP) amendments in the water] was sampled to represent background RBS runoff.

Each runoff event used a simulated-runoff solution created to match concentrations of pre-experiment field-runoff samples (4,433 mg/l TSS, 1.6 mg/l TP, and 20 mg/l TN) by mixing 4 kg top soil (collected on-site and passed through a 2-mm sieve), 6.9 g sodium phosphate, and 45 g ammonium nitrate with 794 l tap water. The volume of simulated runoff was the same for each experimental plot. The equivalent runoff depths for this runoff volume would vary with drainage area. For this study site, the cropland drainage areas ranged from two to ten times larger than the RBS area (Ngandu, 2004). In this context, the equivalent simulated runoff depth would range from 0.8 to 2.7 cm and would be associated with rainfall events ranging from approximately 1.2 cm (for drainage area 10 times larger than RBS area) to 5.7 cm (for drainage area two times larger than RBS area, where 5.7 cm corresponds to a 5-year return period, 1 h duration rainfall event), based on runoff estimates using a cropland runoff curve number of 86 (USDA-SCS, 1972). The simulated-runoff solution was delivered to the inlet ROSS pump sump (Figure 1) continuously at a rate adjusted to match the pumping rate of the ROSS unit, to ensure that the sump did not overflow. An average of 50 min was needed to empty the 794-l tank into the buffers. Approximately 10 min travel time was needed for runoff to pass through the buffers to the outlet ROSS sampler. This procedure was repeated three times (August 26, 2002; September 5, 2002; and November 7, 2002) for each of nine RBS plots. A total of 129 mm of natural rainfall fell on 12 different days during August through November 2002: 8/9 (3 mm), 8/10 (<1 mm), 8/12 (<1 mm), 8/13 (48 mm), 8/17 (27 mm), 8/19 (5 mm), 8/21 (27 mm), 8/26 (4 mm), 8/28 (<1 mm), 9/13 (2 mm), 9/14 (3 mm), and 9/19 (7 mm).

The ROSS units were installed at the inlet and outlet of each buffer plot. Runoff water was spread uniformly across the inlet edge of the buffer plot from the discharges of dividers #1, #2, #4, and #5 and the residual following divider #6. Dividers #3 and #6 were connected to 19-l carboys. The total water samples collected from dividers #3 and #6 during each event were weighed (±1 g) and used to provide two estimates of total flow volumes according to calibration factors and procedures developed by Ngandu and Mankin (2004). The difference in volumes between buffer-plot inlet and outlet was used as a measure of infiltration volume.

Laboratory Analyses

After each event, the carboys were agitated vigorously and 250 ml of homogenous subsamples were collected and transported on ice to the laboratory for analysis. Unfiltered samples were analyzed for TN and TP by using a potassium persulfate digestion (Hosomi and Sudo, 1986) followed by Griess-Ilosvay cadmium-reduction method for nitrate (Keeney and Nelson, 1982) and molybdate-blue method with ascorbic acid reduction for phosphate (Murphy and Riley, 1962). Total suspended solids (TSS) was determined gravimetrically from 50 to 100 ml of vacuum-filtered (0.451 μm) samples (Csuros, 1987). Filtrate from the TSS procedure was analyzed colorimetrically using an Alpkem RFA autoanalyzer (Alpkem Corporation, Wilsonville, OR, USA) for NH_4 by using the salicylate-hypochlorite method (Crooke and Simpson, 1971), for NO_3 by using cadmium reduction (Keeney and Nelson, 1982), and for ortho-P by using the molybdate-blue method with ascorbic acid reduction (Murphy and Riley, 1962).

Statistical Analyses

For the nine ROSS units located at the RBS inlets, estimated volumes measured by dividers #3 and #6 were compared with the actual 794 l applied during each test. Measurement repeatability for ROSS units was assessed by using the empirical rule procedure (Ott and Longnecker, 2001; Ngandu and Mankin, 2004). This common quality-assurance procedure identifies measurements that are outside an acceptable confidence band. For n measurements having standard deviation σ and mean μ, 95% of the measurements should lie in the interval $\mu \pm 2\sigma$ (Ott and Longnecker, 2001). In this study, a coefficient of variation (CV) of 10% was used to calculate the allowable standard deviation for each divider that would ensure that 95% of samples would be within the interval given by $2(\sigma)$ or $2(\mathrm{CV}\ \mu_{\mathrm{standard}})$, where μ_{standard} was set by the average of a single set of field calibration tests (Ngandu and Mankin, 2004).

An experimental design with three RBS treatments (NS, NG/P, and NS/P) and three replicate plots (runoff plots) was used. Runoff plots had differences in vegetation and width and had minor differences in slope (Table 1) but were consistent in other respects, including soils, antecedent soil moisture, event volume, and sediment and nutrient constituent concentrations. Data were collected from three observations (simulated events) for each runoff plot.

Treatment effects were analyzed using two methods. First, an analysis using the GLM procedure in SAS (2002) included the following factors: vegetation types, plots nested within vegetation types, and events nested within plots, which was the residual. The mean-squared error for testing vegetation type was that of plots within vegetation types, and the mean-squared error for testing plots was that of events within plots or residual. No adjustment was made for width. The second analysis used the MIXED procedure in SAS with the response adjusted for width. The analysis included the following factors: vegetation type as a fixed effect, plots nested within vegetation type as a random effect, width as a fixed effect covariate, and events nested within plots as a random effect, which was the residual. Significance for all tests was set at α = 0.05.

RESULTS AND DISCUSSION

Surface Runoff

In 26 out of 27 cases (96%) for divider #3 and 21 out of 27 cases (78%) for divider #6, measured volumes fell within a 95% confidence interval of the actual volume applied (794 l; Figure 2). Divider #3 volume was comparable with laboratory and field calibration tests that gave 96% agreement, whereas divider #6 performed even better than the 56% agreement achieved during the same laboratory and field calibration tests (Ngandu and Mankin, 2004). This confirms the established repeatability of the ROSS units.

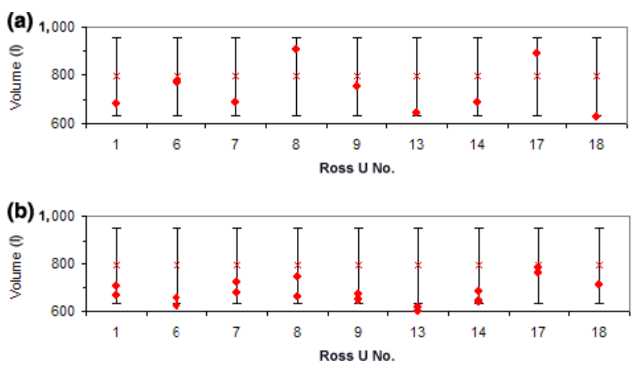

FIGURE 2. Volumes (●) Estimated by (a) Divider #3 and (b) Divider #6 for Three Events on Each of Nine Inlet ROSS Units. Error bars correspond to 95% confidence interval about 794 l actual inlet volumes (×).

There was substantial runoff reduction in all the buffers, with the shortest-width buffers (NS/P) having the lowest percentage runoff reduction and the greatest average infiltration depth (Table 2). The shortest-width buffer treatment (NS/P) had almost 200% more outflow volume than the treatment with the least outflow (NG/P). But because of the smaller buffer area, the NS/P treatment had 34% greater infiltration depth than the treatment with widest plots (NS). The high-volume reductions indicate that infiltration was an important buffer process.

Sediment Removal

Even with clean-water influent, buffer-plot effluents averaged 17-23 mg/l TSS (Table 3), which were considered to represent background concentrations. Effluent TSS concentrations during periods with simulated runoff influent were 2-7× greater than background concentrations. The observation increase in TSS concentrations from background concentrations suggests that the TSS source was primarily the influent runoff, and the buffer itself contributed only a small fraction of sediments contained in buffer-plot effluents in this study.

Mass reductions of TSS from the three runoff events averaged 99.2% (NS/P) to 99.9% (NS; Table 1). Slightly smaller reductions (92% TSS mass removal) were reported by Lee *et al.* (2000) in a study with simulated runoff on grass/woody buffer plots. Concentration reductions and mass removals of TSS were ranked NS > NG/P > NS/P. Based on the analysis of

TABLE 2. Inflow and Outflow Volume Mean ± Standard Deviations (n = 9) for Each Riparian Buffer System.

	NS	NG/P	NS/P
Inflow (l)	686 ± 15	646 ± 10	684 ± 12
Outflow (l)	62 ± 7	53 ± 7	155 ± 12
Infiltration depth (mm)[1]	41	48	55
Volume reduction (%)	91.0	91.8	77.4

Notes: NS = natural selection of grasses, NG/P = native grasses and American plum shrub, NS/P = natural selection of grasses and American plum shrub.
[1]Average infiltration depth estimated by (inflow-outflow)/plot area.

TABLE 3. Total Suspended Solids Mean ± Standard Deviations (n = 9) of Inflow Concentrations, Outflow Concentrations, and Reductions for Each Riparian Buffer System.

	NS	NG/P	NS/P	Average
Background concentration (mg/l)	22 ± 9	23 ± 9	17 ± 7	21
Inflow concentration (mg/l)[1]	4,433 ± 97	4,433 ± 97	4,433 ± 97	4,433
Outflow concentration (mg/l)	51 ± 44	109 ± 70	122 ± 53	94
Mass reduction (g)	3,100 ± 3	3,098 ± 4	3,084 ± 11	3,094
Mass reduction (%)	99.9 ± 0.1 a	99.8 ± 0.1 a	99.4 ± 0.3 b	99.7
Concentration reduction (%)	98.9 ± 1.0 **a**	97.5 ± 1.6 a	97.2 ± 1.2 a	97.9

Notes: Values with the same letter within a row were not significantly different based on analysis of variance with pooled variance (SAS GLM Procedure, α = 0.05). NS = natural selection of grasses, NG/P = native grasses and American plum shrub, NS/P = natural selection of grasses and American plum shrub.
[1]Error range based on precision of measured sediment additions (±1 g) to measured water volumes (±8 l).

variance, a significant effect of vegetation-type treatments was observed in mass reductions but not concentration reductions (Table 3). Mass reductions of TSS were significantly different for the NS/P to NS and NS/P to NG/P comparisons.

Analysis of covariance (with response adjusted for width among plots) found no significant differences in either TSS concentration-reduction or mass-reduction responses to either fixed effect (vegetation type or plot width). Nonetheless, all RBS plots exceeded average ($n = 3$ events) TSS mass-reductions of 99% (Table 1) and TSS concentration-reductions of 96% (not shown). The combination of high-level TSS removal in all buffers with a lack of significance for the width effect reinforces previous findings (Hayes *et al.*, 1979; Alberts *et al.*, 1981; Dillaha *et al.*, 1988) that sediment is removed within the first several meters of effective vegetated buffers and that the additional plot width did not always increase TSS removal.

The TSS reductions in vegetative field buffers results from a combination of infiltration, sedimentation, and filtration. Assuming that suspended sediments moved into the soil profile with (and proportional to) infiltration, 90% of the observed TSS mass removal by NS, 94% by NG/P, and 78% by NS/P in this study could be accounted through this process alone. These results indicate the dominant role of infiltration in the mass removal of sediment from surface flows in this study.

Phosphorus Removal

Background RBS outflow TP concentration (surface outflow from RBS during clean-water pretreatment) for the three RBS treatments averaged 1.1 mg/l, with 64% from dissolved phosphorus (DP; Table 4). Background concentrations of TP and DP differed little among the three events. The average RBS outflow TP concentration was 1.3 mg/l during the simulated runoff events (Table 4), which was slightly higher than the average background concentration (1.1 mg/l) but was lower than inflow TP concentration (2.4 mg/l). This observation of relatively high-RBS outflow concentrations during background conditions, which approximate conditions during the early stages of a runoff event, suggests that RBS outflow in the early stages of a natural runoff event can contribute pollutants to surface waters.

Mass reductions of TP ($n = 3$ events) averaged 76.8% (NS/P) to 98.6% (NS; Table 1). During simulated runoff events, however, the fraction of DP increased from 58% of TP in inflow to 85% of TP in outflow. Detachment and dissolution of P from sediment to surface runoff is likely to have resulted in the average DP concentration reduction by the three treatments being small (16%), whereas TP concentration reduction was greater (43%) due to its association with settled sediments (Table 4). The NS/P vegetation-type plot had the least reductions of DP concentration, TP concentration, and TP mass (Table 4). Based on the analysis of variance with pooled variance, a significant effect of vegetation-type treatments was observed in mass reductions but not concentration reductions (Table 4). Mass reductions of TP were significantly different for the NS/P to NS and NS/P to NG/P comparisons.

Analysis of covariance found a significant effect of vegetation type, but not plot width, on TP mass reduction. Comparison of the least-squared means of the main effect (vegetation type) found significance only in the NS/P to NG/P comparison.

Assuming that TP mass removal was proportional to infiltration, 95% of the 94.8% TP mass removal by NS could be accounted by the infiltration process alone. Results for NG/P and NS/P were similar; NG/P had 97% removal that could be associated with

TABLE 4. TP and DP Mean ± Standard Deviations ($n = 9$) of Background Outflows (with tap water inflows), Inflow Concentrations, Outflow Concentrations, and Reductions for Each Riparian Buffer System.

Description	NS	NG/P	NS/P	Average
Background DP outflow (mg/l)	0.7 ± 0.1	0.8 ± 0.2	0.7 ± 0.1	0.7
Background TP outflow (mg/l)	1.0 ± 0.1	1.1 ± 0.1	1.3 ± 0.1	1.1
Inflow DP (mg/l)	1.5 ± 0.5	1.4 ± 0.2	1.3 ± 0.3	1.4
Inflow TP (mg/l)	2.6 ± 0.5	2.4 ± 0.4	2.2 ± 0.3	2.4
Outflow DP (mg/l)	1.1 ± 0.1	1.2 ± 0.1	1.1 ± 0.2	1.1
Outflow TP (mg/l)	1.2 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.3
DP concentration reduction (%)	23 ± 21	14 ± 13	11 ± 14	16
TP concentration reduction (%)	53.1 ± 14.2 a	40.4 ± 12.7 a	35.1 ± 11.5 a	42.9
TP mass reduction (%)	94.8 ± 4.6 **a**	96.0 ± 2.1 a	84.6 ± 7.3 b	91.8

Notes: Values with the same letter within a row were not significantly different based on analysis of variance with pooled variance (SAS GLM Procedure, $\alpha = 0.05$). NS = natural selection of grasses, NG/P = native grasses and American plum shrub, NS/P = natural selection of grasses and American plum shrub, TP = total phosphorus, DP = dissolved phosphorus.

infiltration and NS/P had 91% removal by infiltration. This provided evidence of the dominant role of infiltration in P mass reduction from inflow runoff.

Nitrogen Removal

Background RBS outflow NH_4^+-N plus NO_3^--N concentration averaged 1 mg/l, which was 30% of TN; the remaining 70% of TN was either organic- or sediment-attached N (Table 5). Background TN increased nominally with increasing buffer width (NS > NG/P > NS/P). Resuspension into overland flow from the ground surface was likely responsible for the elevated N concentrations in the early stages of runoff, as measured by the background samples. The average inflow TN concentration in the three runoff events was 27.5 mg/l, which was 33% NH_4^+-N and 36% NO_3^--N (Table 5). Outflow TN averaged 14.6 mg/l with an increased fraction of NO_3^--N (24% NH_4^+-N and 56% NO_3^--N).

Mass reductions of TN ($n = 3$ events) averaged 78.5% (NS/P) to 98.3% (NS; Table 1). The net TN mass removal rates by the three RBS treatments ranged from 85% to 96% and were greater than TN concentration reduction by a factor of about two in each treatment (Table 5). Runoff was also characterized by greater NH_4^+-N than NO_3^--N concentration reductions for all vegetation types (Table 5).

The analysis of variance with pooled variance detected a significant effect of vegetation-type treatment in both mass reductions and concentration reductions (Table 5). Concentration reductions of TN were significantly different for the NS to NS/P comparison only, whereas mass reductions of TN were significantly different for the NS/P to NS and NS/P to NG/P comparisons. Analysis of covariance found a significant effect of vegetation type, but not plot width, on TN mass reduction. Comparison of the least-squared means of the main effect (vegetation type) found significance only in the NS/P to NG/P comparison. Similarly, Schultz *et al.* (1995) found that the amount of vegetative biomass produced in a buffer had a positive impact on sediment and nutrients trapping.

As with TSS and TP, mass reductions of TN could be accounted largely by assuming removal in proportion to infiltration. This assumption would explain 95% of the 95.0% TN mass removal by NS, 97% of the removal by NG/P, and 90% of the removal by NS/P.

Concentration reductions of TN likely were influenced by chemical and biological processes as well. Ammonium volatilization processes could have resulted in the NH_4^+ reduction (48-72%) being significantly greater than the NO_3^- reduction (10-19%). Volatilization, the conversion and loss of NH_4^+ to NH_3 gas, occurs under conditions of higher pH (>8), greater NH_4^+ availability, and moderate to high temperatures (Chen *et al.*, 1999). A study with irrigation water showed that volatilization was temperature dependent, with 48% loss of NH_4^+ per day at 25°C and more than 90% loss per day at 40°C (Norton and Silvertooth, 2001). Because studies reported here lasted only a fraction of a day (about 1 h) under near-neutral pH (≤7.6) and at moderate temperatures (25-30°C), it is likely that NH_4^+ losses by volatilization were <5% of total inflow N.

Denitrification also may have influenced TN reduction. A study by Ambus (1998) to investigate nitrous oxide production by denitrification and nitrification in riparian grassland showed a denitrification potential of as much as 1,529 ng N/cm^3/h. For a 15 m by 1 m NS buffer in this study, with 10-cm soil depth

TABLE 5. Nitrogen Mean ± Standard Deviations ($n = 9$) of Background Outflows (with tap water inflows), Inflow Concentrations, Outflow Concentrations, and Reductions for Each Riparian Buffer System.

Description	NS	NG/P	NS/P	Average
Background NH_4^+-N (mg/l)	0.4 ± 0.2	0.3 ± 0.2	0.2 ± 0.2	0.3
Background NO_3^--N (mg/l)	0.9 ± 0.2	0.6 ± 0.2	0.6 ± 0.2	0.7
Background TN (mg/l)	3.8 ± 0.4	3.5 ± 0.3	3.2 ± 0.4	3.5
Inflow NH_4^+-N (mg/l)	9.3 ± 2.1	9.3 ± 0.4	8.6 ± 1.1	9.1
Inflow NO_3^--N (mg/l)	10.7 ± 2.3	9.0 ± 2.2	9.9 ± 1.5	9.9
Inflow TN (mg/l)	30.6 ± 16.1	25.3 ± 2.3	26.9 ± 4.5	28
Outflow NH_4^+-N (mg/l)	2.6 ± 0.3	3.3 ± 1.3	4.5 ± 0.9	3.5
Outflow NO_3^-N (mg/l)	8.7 ± 2.1	7.0 ± 0.4	8.9 ± 1.3	8.2
Outflow TN (mg/l)	12.8 ± 3.4	14.0 ± 3.4	17.0 ± 2.0	15
NH_4 concentration reduction (%)	71.7 ± 4.4	64.3 ± 17.3	48.3 ± 9.1	48
NO_3 concentration reduction (%)	18.6 ± 7.7	19.2 ± 17.3	10.1 ± 0.6	16
TN concentration reduction (%)	52.9 ± 16.5 a	44.5 ± 14.0 ab	35.7 ± 9.5 b	44.4
TN Mass Reduction (%)	95.0 ± 4.5 a	96.0 ± 2.7 a	85.3 ± 5.7 b	92.1

Notes: Values with the same letter within a row were not significantly different based on analysis of variance with pooled variance (SAS GLM Procedure, $\alpha = 0.05$). NS = natural selection of grasses, NG/P = native grasses and American plum shrub, NS/P = natural selection of grasses and American plum shrub, TN = total nitrogen.

(approximate depth of infiltrated water), this denitrification rate translates to 0.4 g N loss for 10 min detention time, which represents about 2% of TN losses in this study. No water logging was observed in the RBS, but top soil was saturated before runoff simulation, which could have provided the important anaerobic conditions necessary for the denitrification process. Further, denitrification has been reported to occur in well-oxygenated conditions, suggesting possible sites of local anoxia (Duff and Triska, 1990).

CONCLUSIONS

The grass-shrub buffers studied provided excellent mass reductions of outflow runoff (>77%), sediment (>99%), TP (>85%), and TN (>85%). The least mass reductions in this study were by an individual NS/P plot with 10.2-m width (99.2% for TSS, 76.8% for TP, and 78.5% for TN). These results suggest that properly designed and maintained buffers with widths less than the recommended minimum width of 23 m may be adequate for water-quality improvement.

Vegetation type, rather than width, was the fixed effect that was shown to influence mass removal of TP and TN. The combination of high constituent removal and natural system variability for the on-farm buffer plots used in this study made differentiation among the treatment effects difficult.

Infiltration seemed to be a dominant pollutant removal process in this study, being able to account for >75% of TSS removal, >90% of TP removal, and >90% of TN removal. Emphasis on RBS infiltration enhancement, rather than on increasing the width of buffers, is bound to result in better use of limited land resources and provide increased water-quality benefits.

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