Filter Strip Performance and Processes for Different Vegetation, Widths, and Contaminants

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ABSTRACT

Filter strips are widely prescribed to reduce contaminants in surface runoff from agricultural fields. This study compared performance of different filter strip designs on several contaminants and evaluated the contributing processes. Different vegetation types and widths were investigated using simulated runoff event on large plots (3 m × 7.5 or 15 m) having fine-textured soil and a 6 to 7% slope. Filter strips 7.5 and 15 m wide downslope greatly reduced concentrations of sediment in runoff (76–93%) and contaminants strongly associated with sediment (total P, 55–79%; permethrin, 27–83% [(3-phenoxyphenyl) methyl (±)-*cis, trans*-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate]). They had less effect on concentrations of primarily dissolved contaminants [atrazine, −5–43% (2-chloro-4-ethylamino-6-isopropylamino-s-triazine); alachlor, 10–61% [2-chloro-2′6′-diethyl-N-(methoxymethyl) acetanilide]; nitrate, 24–48%; dissolved P, 19–43%; bromide, 13–31%]. Dilution of runoff by rainfall accounted for most of the reduction of concentration of dissolved contaminants. Infiltration (36–82% of runoff volume) substantially reduced the mass of contaminants exiting the filter strips. Doubling filter strip width from 7.5 to 15 m doubled infiltration and dilution, but did not improve sediment settling. Young trees and shrubs planted in the lower one-half of otherwise grass strips had no impact on filter performance. Compared with cultivated sorghum [*Sorghum bicolor* (L.) Moench] grass clearly reduced concentrations of sediment and associated contaminants in runoff, but not volume of runoff and concentration of dissolved contaminants. Settling, infiltration, and dilution processes can explain performance differences among pollutant types and filter strip designs.

FILTER STRIPS are narrow strips of permanent vegetation widely prescribed to reduce contaminants in surface runoff from adjacent agricultural fields. Nonpoint source pollution by contaminants in agricultural runoff is a major cause of poor surface water quality in the USA (National Research Council, 1993). Accurate prediction of water quality improvement resulting from widespread installation of filter strips is hindered by limited quantitative information on design factors that determine performance. Chief among these factors are vegetation composition, width, and the types of contaminants filter strips are employed to control.

Grass vegetation is recommended for filter strips (U.S. Natural Resources Conservation Service, 1997). Extensive research and modeling has been conducted on grass strips (e.g., Arora et al., 1996; Barfield et al., 1979; Dillaha et al., 1989; Hayes et al., 1984; Magette et al., 1989; Williams and Nicks, 1988; Young et al., 1980). Few experimental studies, however, have compared grass with other vegetation types. Forest vegetation has been shown to remove substantial amounts of sediment and nutrients from agricultural runoff (e.g., Cooper and Gilliam, 1987; Lowrance et al., 1984; Peterjohn and Correll, 1984; Vought et al., 1991). Indirect comparisons of forest vegetation and grass reveal no clear differences for retaining sediment and nutrients from surface runoff (Daniels and Gilliam, 1996; Doyle et al., 1977). Contour-planted corn (*Zea mays* L.) was reported to be more effective than grass at retaining feedlot runoff and its contents of solids and nutrients (Young et al., 1980). Comparison of filter strips to agricultural vegetation, such as cultivated row crops, is necessary to properly evaluate the water quality impact of land conversion to permanent vegetation.

Wider filter strips generally obtain greater retention of contaminants in surface runoff than narrower strips. Decreasing concentrations of sediment and nutrients in surface runoff have been observed along forested transects (Peterjohn and Correll, 1984). Rigorous experiments on grass filter strips show a clear nonlinear relationship for sediment, where most sediment (53–86% of suspended mass) is retained within 4.6 m of the uphill edge, with much smaller additional amounts (4–17%) retained by doubling this width (Dillaha et al., 1989; Magette et al., 1989; Mickelson and Baker, 1993). Width relationships for nutrients and pesticides have received less study and the results appear more variable than for sediment (Dillaha et al., 1989; Mickelson and Baker, 1993).

The impact of filter strips on runoff water quality depends on the type of contaminant. Several direct comparisons show sediment in runoff is consistently retained by grass to a greater degree than soluble nutrients and herbicides (Arora et al., 1996; Asmussen et al., 1977; Dillaha et al., 1989; Mickelson and Baker, 1993). Differences in impact among contaminants may be attributed to mechanisms in filter strips that affect each type, such as settling, infiltration, and dilution. Few experimental studies have been conducted that separate the effects of these various processes (Arora et al., 1996).

The objectives of this study were to (i) quantify the impact of filter strips on agricultural surface runoff and several contaminants commonly found in it; (ii) quantify the benefit of doubling filter strip width; (iii) compare the effectiveness of different vegetation compositions; (iv) evaluate and compare settling, infiltration, and dilution processes in filter strips; and (v) estimate the water

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Abbreviations: PVC, polyvinyl chloride; LDPE, low density polyethylene; TSS, total suspended solids; TN, total nitrogen; N+N, nitrate + nitrite nitrogen; TP, total phosphorus; BAP, bioavailable phosphorus; TDP, total dissolved phosphorus; BR, bromide; ATR, atrazine; ALA, alachlor; PER, permethrin.

quality benefit of converting a strip of land from cultivated row crop to filter strip.

METHODS

Study Area and Field Plots

The study was conducted at the University of Nebraska's Agricultural Research and Development Center in east-central Nebraska near Mead (41° 29′ N, 96° 30′ W). In this region, fine-textured soils formed on loess hills are intensively farmed primarily for corn, grain sorghum, and soybeans [*Glycine max* (L.) Merr.]. Annual precipitation is about 690 mm falling primarily during thunderstorms in spring and summer.

The study was conducted on 15-mo-old plots constructed immediately downslope from a contour-cultivated field in a rotation of grain sorghum and soybeans. The plot area had previously been vegetated with mixed grasses and hayed for at least 25 yr. The plots were located along 400 m of field margin having a 6 to 7% slope. The soils are classified as well-drained Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudoll) with a surface texture that changes from silty clay loam (~30% clay) to sandy loam (~14% clay) along the length of the field margin.

Forty plots were established in spring of 1995 having four different vegetation compositions, each at two different sizes. Plot sizes of 3 × 7.5 m and 3 × 15 m represent 7.5-m and 15-m wide filter strips. The experimental design was a randomized complete block with a 2 × 4 factorial (width × vegetation composition) with each block of eight plots replicated five times.

Existing vegetation was killed with glyphosate [N-(phophonomethyl) glycine], except on one 7.5 m and one 15 m plot in each block (designated the 25-yr-old grass plots). Then, the plots to be newly-planted were plowed 21 cm deep, rototilled four times, and smoothed to promote sheet flow down the plots. Borders on the sides and bottom of all plots were lined with galvanized sheet metal buried 10 cm deep and projecting 15 cm above the soil surface in order to contain water flow and guide it into a 10 cm diam. PVC pipe that carries it to a collection tank (Fig. 1). A minimum of 3 m of original grass vegetation separated the plots.

The tilled plots were replanted to either mixed grasses (designated 2-yr-old grass), one-half grass and one-half trees and shrubs (designated 2-yr-old grass–shrub–tree), or grain sorghum that was annually tilled and replanted (designated contour sorghum). The mixed grasses plots (2-yr-old grass) were broadcast planted at a seeding rate of 10 kg ha^{-1} with switchgrass (*Panicum virgatum* L. var. Blackwell) in spring and fall of 1995, and with tall fescue (*Festuca arundinacea* Schreb. var. K-31) in early spring 1996. Volunteer grasses and forbs also became established in these plots, including smooth brome (*Bromus inermis* Lyess.), wild buckwheat (*Polygonum convolvulus* L.), common lambquarters (*Chenopodium album* L.), field pennycress (*Thlaspi arvense* L.), and foxtail (*Setaria* sp.). Species distribution was uneven both within and among plots. Switchgrass tended to form pure stands covering from 0 to 90% of a plot's surface area, while the other species tended to be well-mixed in the remaining areas. Overall cover on these plots, however, was reasonably uniform and ranged from 70 to 100% by the time experiments were conducted.

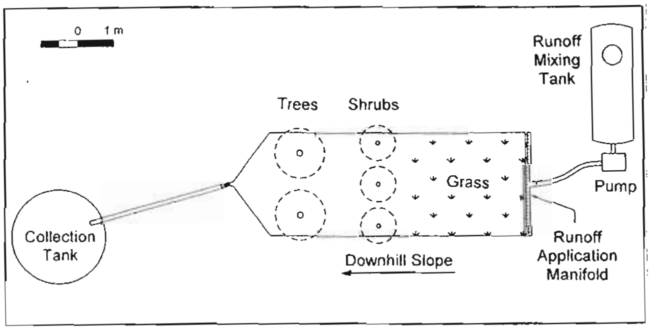

Fig. 1. Schematic diagram of a 3 × 7.5 m grass–shrub–tree plot showing the position of vegetation, runoff application system, and outflow collection system.

The grass–shrub–tree plots (2-yr-old grass–shrub–tree) consisted of an uphill one-half of each plot planted in mixed grasses by the same methods as the 2-yr-old-grass plots, and a downhill one-half planted to rows of shrubs [bush honeysuckle (*Lonicera maackii*) and golden currant (*Ribes aureum*)] and trees [eastern cottonwood (*Populus deltoides* Bartr.) and silver maple (*Acer saccharinum* L.)]. The 3 × 15 m plots had two rows of shrubs (3 per row) planted adjacent to the grass and two rows of trees (2 per row) planted on the lower end of the plot, while the 3 × 7.5 m plots were planted with one row of trees and one row of shrubs (Fig. 1). By the time experiments were conducted, the trees and shrubs were 0.5 to 2 m tall and formed about 30% crown cover with volunteer herbaceous cover (mowed to reduce competition with trees and shrubs) ranging from 60 to 95%.

The contour sorghum plots were contour-planted with grain sorghum (var. NC+ Hybrid 6B50) at 10.5 plants m^{-1} of row and a standard 76 cm row-spacing. In early fall, the stalks were mowed and the debris was left on the plots. The following spring, these plots were rototilled and replanted with grain sorghum. No fertilizers or pesticides were applied. Weeds were periodically removed by hoeing between the rows. Evaluations were conducted 6 to 7 wk after planting when plants were 50 to 100 cm tall. All sorghum plots were weeded 3 d prior to evaluations.

Experimental Procedures

In July 1996, we simulated a single rainfall and runoff event onto each plot and evaluated the subsequent outflow. The simulated rainfall event was 25.4 mm of rain in 30 min. This intensity represents a storm having a 1-yr return frequency in the study area (Hershfield, 1961). Simulated rainfall was applied to plots using an overhead sprinkler system consisting of a PVC pipe frame fitted with seven Weathermatic Model 404SF jet irrigator nozzles (Weathermatic, Dallas, TX) and a 1.4 KPa pressure regulator. Each sprinkler unit provided uniform coverage and proper intensity for a 3 × 7.5 m plot (566 L). Two units were used on 3 × 15 m plots (1132 L). Water from local wells was used for simulated rainfall.

Simulated field runoff was created in a polyethylene tank for application to the top of each plot. The required volume of simulated runoff, 1887 L, was derived using the USDA curve number method (U.S. Soil Conservation Service, 1972) for our storm intensity under conditions that describe the up-gradient crop field at our site: contour row crop, hydrologic soil group B, antecedent soil moisture type III (>5.33 cm of rainfall in the prior 5 d), and an above-buffer field length of 81 m. This field length translates to field-to-buffer area ratios of 10.8:1 and 5.4:1 for the 7.5 and 15 m plots, respectively.

Agricultural chemicals and sediment were added to the simulated runoff to represent peak concentrations of contaminants that may be found in runoff from a corn field during a post-plant thunderstorm (Table 1). Concentrations used here were estimated from related data in the literature. Potassium bromide also was added to the runoff mixture as a conservative tracer to distinguish between tank solution and simulated rain-

Table 1. Concentrations of constituent contaminants applied to filter strip plots in simulated runoff. Values represent averages of samples collected from five different tanks.

Constituent	Concentration
Total suspended sediment	10 019 mg L^{-1}
Total N	67.8 mg L^{-1}
N+N	28.0 mg L^{-1}
Total P	4428 μg L^{-1}
Bioavailable P	1765 μg L^{-1}
Total dissolved P	589 μg L^{-1}
Atrazine	436 μg L^{-1}
Alachlor	221 μg L^{-1}
Permethrin	6.0 μg L^{-1}
Bromide	9.4 mg L^{-1}

fall contributions to outflow from each plot. The tank solution was prepared by adding premeasured amounts of fertilizers, pesticides, sediment, and potassium bromide to the tank water (Table 2) and vigorously churning for 1 h using a gasoline-powered pump (2.6 KW) and circulation system. The circulation system was designed to produce 230 to 270 L min^{-1} flow through 16 pairs of spray jets located along the bottom of the tank in order to prevent settling of sediment particles and to carry them along with the solution to the surface in a boiling motion. The solution continued to be churned throughout the subsequent application period in order to maintain a reasonably homogeneous mixture until all of the contents of the tank had been applied to a plot.

Application of simulated runoff to the plots was performed by diverting a portion of the circulating tank mixture evenly across the top of the plot at 75.7 L min^{-1} through a 3 m-long section of 2.5 cm-diam. PVC pipe having 6-mm-diam. holes, spaced every 10 cm along its length. This application rate produced a runoff period of 25 min. Flow meters (Multi-jet, Master Meter, Longview, TX) were used to measure and monitor application rates and volumes of simulated runoff and rainfall.

Each plot was prepared for evaluation by irrigating with 19 mm of simulated rainfall at four different times during 4 d prior to evaluation (total of 76 mm; Table 3). This was done to wet the surface soil to the antecedent conditions that were specified in the runoff volume model. No natural rainfall occurred immediately prior to or during the evaluations.

Evaluations were designed to mimic the progression of natural rainfall and runoff during a typical spring storm (Table 3). First, simulated rainfall was initiated. After 10 min of rainfall, simulated runoff from the mixing tank was initiated at the up-slope end of the plot. Rainfall continued on the plot for approximately 20 min until 25.4 mm had been applied. Simulated runoff continued to be applied for another 5 min until the entire runoff mixture was emptied from the tank. Outflow from plots normally stopped within 5 min after the input of simulated runoff stopped.

Water that flowed from the bottom of each plot was collected in a 2700-L steel tank. The solution was vigorously stirred, using a circulation pump and mixing manifold, as grab samples were being collected for analysis of the various chemical constituents. Volume was measured using a flow meter as the solution was pumped out of the collection tank.

Samples of the simulated runoff mixture and rainfall were collected from one randomly selected plot from each of the five blocks of plots. The simulated runoff was sampled from the tank circulation system, while it was operating, immediately prior to application to a plot. Samples for sediment and nutrient analysis were collected in acid-washed LDPE bottles, and samples for pesticide analyses were collected in acid-washed 1-L amber glass bottles. All samples were immediately stored on ice in the field.

Table 2. Ingredients of each tank containing simulated runoff.

Ingredient	Amount
Water (from local wells)	1887 L
Sediment (from local drainage ditch; clay 30%; sand 12%; OM 3.0%; CEC 17.4 cmole kg^{-1}; pH 5.3; Bray and Kurtz-1 P 98 mg kg^{-1})	18.9 kg dw
Ammonium nitrate fertilizer (33–0–0)	287 g
Superphosphate fertilizer (0–46–0; prills ground to coarse powder)	5.7 g
Atrazine 40.8%	1.96 mL
Alachlor 45.1%	0.99 mL
Permethrin 25.6%	0.16 mL
Potassium bromide (Br 67.1%)	28.2 g

Laboratory Procedures

Field samples were analyzed for soluble and sediment-bound forms of atrazine, alachlor, and permethrin, and for total suspended solids (TSS), total nitrogen (TN), nitrate plus nitrite nitrogen (N+N), total phosphorus (TP), bioavailable phosphorus (BAP), total dissolved phosphorus (TDP), and bromide (BR). At the end of each day, samples to be analyzed for the dissolved constituents N+N, TDP, and BR, were centrifuged at 3500 × *g* for 7 min, filtered through 0.45 µm Gelman GN membrane filters (Gelman Sciences, Ann Arbor, MI), and the filtrates stored frozen at −10°C. Samples for analysis of pesticides and TSS were transferred directly to a cooler at 4°C. Samples for analysis of BAP, TP, and TN were transferred directly to a freezer at −10°C.

Bromide analysis was performed by the University of Nebraska Soil and Plant Analytical Laboratory using ion chromatography with a Dionex DX 100 chromatograph (Dionex Corp., Sunnyvale, CA; U.S. Geological Survey, 1985). Pesticide samples were analyzed for both sediment and soluble forms by Olson Biochemistry Laboratories at South Dakota State University. Pesticide samples were filtered through 0.45-µm nylon filters. Pesticides were extracted from the filtrate with methylene chloride (U.S. Environmental Protection Agency, 1980) and from the sediment with ethyl acetate (Sanchez-Brunete et al., 1994; Gorder and Dahm, 1981) by sonicating in warm solvent after standing overnight. Concentrations of pesticides in the extracts were determined by gas chromatography on a Varian 3700 (Varian Analytical Instruments, Sugarland, TX) and Tremetrics/Finnigan 9001 (Finnigan Corp. Austin, TX) using N–P detection for atrazine (ATR) and alachlor (ALA), and electron capture detection for permethrin (PER). Total suspended solids was determined by residue-on-filtration of entire contents of each 125-mL sample bottle using Gelman A/E glass-fiber filters according to APHA method 2540D (American Public Health Association, 1992). Nitrate plus nitrate nitrogen (N+N) was determined by hydrazine reduction (Downes, 1978). Bioavailable phosphorus (BAP) was determined using the Fe-impregnated paper method (Sharpley, 1993). Total phosphorus (TP) and total dissolved phosphorus (TDP) were determined by persulfate

Table 3. Chronologic order of procedures for evaluation of each plot.

Procedure	Time
19 mm irrigation	−4 d
19 mm irrigation	−2 d
19 mm irrigation	−24 h
19 mm irrigation	−18 h
Prepare tank mixture (runoff)	−1 h
Initiate simulated rainfall event	0:00 min
Initiate runoff application	10:00 min
Rainfall stops	~30:00 min
Runoff application stops	~35:00 min
Outflow from plot stops	~40:00 min

digestion (Menzel and Corwin, 1965) and colorimetry (Murphy and Riley, 1962). Total nitrogen (TN) was determined by persulfate digestion (D'Elia et al., 1977) and ultraviolet-spectrophotometry corrected for organic matter (American Public Health Association, 1992). Colorimetric and ultraviolet tests for forms of N and P were performed using a Perkin-Elmer lambda 3B UV-VIS spectrophotometer (Perkin-Elmer Corp., Norwalk, CT).

High sediment concentration created high variability among subsamples and unstable readings during spectrophotometric evaluation of TN and TP. Two steps were added to the conventional methods to minimize these problems. First, subsamples were pipetted from field bottles as they mixed vigorously on a magnetic stirplate. Second, after digestion and colorization steps were performed, a portion of the solution was drawn into an acid-washed syringe, subsequently fitted with a glass-fiber syringe filter (1.0 μm pore diam.), and passed through the filter into the spectrophotometer cuvette for reading.

Data Analysis

Concentrations of contaminants in outflow from each plot were corrected to eliminate contributions from the well water that was used for simulated rainfall. Corrections were made using the bromide tracer results and a two-component mixing model (Sklash, 1990). Mass of each pollutant was calculated as the product of outflow volume and the corrected concentration.

Outflow volumes and concentrations (corrected) and masses of the contaminants were analyzed by ANOVA for a randomized complete block design using SAS (SAS Institute, 1990), with treatments in a 4 × 2 factorial arrangement (vegetative composition × width). Contrasts were not all orthogonal, but were chosen for the specific objectives of this study. To control experiment-wise error rate, significance of a contrast was evaluated only if the corresponding overall *F*-test was significant ($P < 0.05$).

Impacts on runoff water volume and contaminant concentrations and masses by each plot type were calculated as the difference between the runoff application tank average and the outflow average from each plot type relative to the application value. The impact of conversion from cultivated row crops to filter strips was calculated as the difference between outflow from the sorghum plots and outflow from the corresponding width of each perennial vegetation type relative to the sorghum value.

RESULTS

In general, concentrations of contaminants in outflow from plots of all vegetation compositions and widths were lower than input values (Table 4; Fig. 2). Since the volume of outflow from the plots also was substantially reduced from what was applied as simulated runoff, mass of these contaminants was reduced to a greater degree than concentration (Table 4; Fig. 3). Relative to amounts applied to the top of the plots, concentration and mass of TSS was reduced to a greater degree than other contaminants, particularly dissolved forms such as N+N, TDP, and Br (Fig. 2 and 3).

Model *F* tests indicated significant differences in outflow volume, concentration and mass of each contaminant among vegetation compositions and/or plot widths ($P < 0.05$; Table 5). There was no significant interaction between vegetation and width for water volume and each contaminant, except concentration of atrazine ($P = 0.0099$), so main effects of vegetation and width were evaluated (Table 5). For atrazine concentration, simple effects were evaluated (Table 6).

Width

Outflow volume and contaminant concentrations and masses were generally lower from 15-m plots than from 7.5-m plots of the same vegetation composition (Table 4; Fig. 2 and 3). Exceptions were observed only for atrazine and alachlor concentrations from contour sorghum plots (Table 4; Fig. 2). Statistical analysis indicated that width had a significant experiment-wide effect ($P < 0.05$) on volume and concentrations and masses of all contaminants, except atrazine concentration (Table 5). For atrazine, a significant effect of width was detected in 25-yr-old grass and contour sorghum, but not in 2-yr-old grass and 2-yr-old-grass–shrub–tree plots (Table 6).

Among the different contaminants, concentration of TSS was reduced to the greatest degree by both widths, but changed the least between 7.5 and 15 m, averaging 77 and 83%, respectively, for all vegetation compositions (Fig. 2). In contrast, reduction in concentration of dissolved contaminants, such as N+N, TDP, and BR, were lower than for TSS, but changed the most from

Table 4. Average values for outflow from each vegetation type and plot width: sample size (*n*), water volume (VOL), bromide (BR), total suspended solids (TSS), total nitrogen (TN), nitrate plus nitrite nitrogen (N+N), total phosphorus (TP), bioavailable phosphorus (BAP), total dissolved phosphorus (TDP), atrazine (ATR), and permethrin (PER). All values have been corrected to remove contributions from simulated rainfall. For comparison, volume and concentrations of the runoff application are included.

				Concentration										Mass	
Vegetation	Width	*n*†	VOL	TSS	TN	N+N	TP	BAP	TDP	ATR	ALA	PER	BR	TSS	BR
	m		L	mg L⁻¹			μg L⁻¹						mg L⁻¹	g	
Contour sorghum	7.5	5	1023	3 748	50	23	2315	1085	408	335	166	5.9	8.1	3 987	8.3
	15.0	2	353	3 512	44	20	2170	950	298	433	180	3.1	7.4	1 300	2.6
25-yr-old grass	7.5	5	797	1 127	44	21	1305	825	419	359	143	1.7	7.7	932	6.3
	15.0	2	337	670	33	15	918	612	335	248	87	1.0	6.5	240	2.2
2-yr-old grass	7.5	5	1206	2 378	48	21	1983	1073	479	459	199	4.4	8.2	3 009	9.9
	15.0	4	657	1 269	39	18	1319	813	411	393	173	2.0	6.6	838	4.2
2-yr-old	7.5	5	1025	2 128	49	21	1907	1029	476	388	182	3.5	7.9	2 162	8.1
grass–shrub–tree	15.0	5	925	1 208	40	16	1264	776	385	346	135	2.0	6.5	1 159	6.1
Runoff application		5	1887	10 019	68	28	4428	1765	589	436	221	6.0	9.4	18 904	17.8

† Number of replicates with outflow volume > 0 L yielding samples for concentration measurement.

7.5 to 15 m, averaging 23 and 38%, respectively, for N+N, 24 and 39% for TDP, and 15 and 28% for BR (Fig. 2). Most other contaminants were intermediate in behavior between TSS and these dissolved contaminants. For atrazine concentrations, however, simple effects analysis detected significantly less reduction by 15-m plots than the shorter 7.5-m plots on contour sorghum plots ($P = 0.0137$; Table 6; Fig. 2). This anomalous observation may reflect low sample size for 15-m sorghum plots (outflow from only two such plots; Table 4) combined with normal variability in field plot behavior and measurement methods.

The volume of outflow from the plots was significantly lower ($P = 0.0012$) from 15-m plots (70% average reduction for all vegetative compositions) than from 7.5-m plots (46% reduction; Table 5; Fig. 3). The reduction of volume greatly contributed to the reduction of contaminant masses. Thus, masses of all contaminants also were reduced significantly, and more so by the 15-m plots (ranging from 75% reduction for atrazine to 95% for TSS) than by the 7.5-m plots (ranging from 52% for atrazine to 87% for TSS; Table 5; Fig. 3).

Vegetation Composition

Vegetation composition did not significantly affect outflow volume ($P = 0.0786$), N+N concentration ($P = 0.1599$), N+N mass ($P = 0.1575$), and BR mass ($P = 0.0858$); consequently significance of differences in the runoff volume and N+N between individual vegetative compositions could not be determined (Table 5). Vegetative composition, however, did significantly affect both outflow concentration and mass of the remaining contaminants ($P < 0.05$; Table 5).

Compared to contour sorghum, the perennial vegetation plots (2-yr-old grass, 2-yr-old grass–shrub–tree, and 25-yr-old grass) exhibited generally lower concentrations of contaminants in outflow (Fig. 4). Concentration of TSS was reduced to a greater degree than other contaminants, 37 to 70% lower than sorghum for

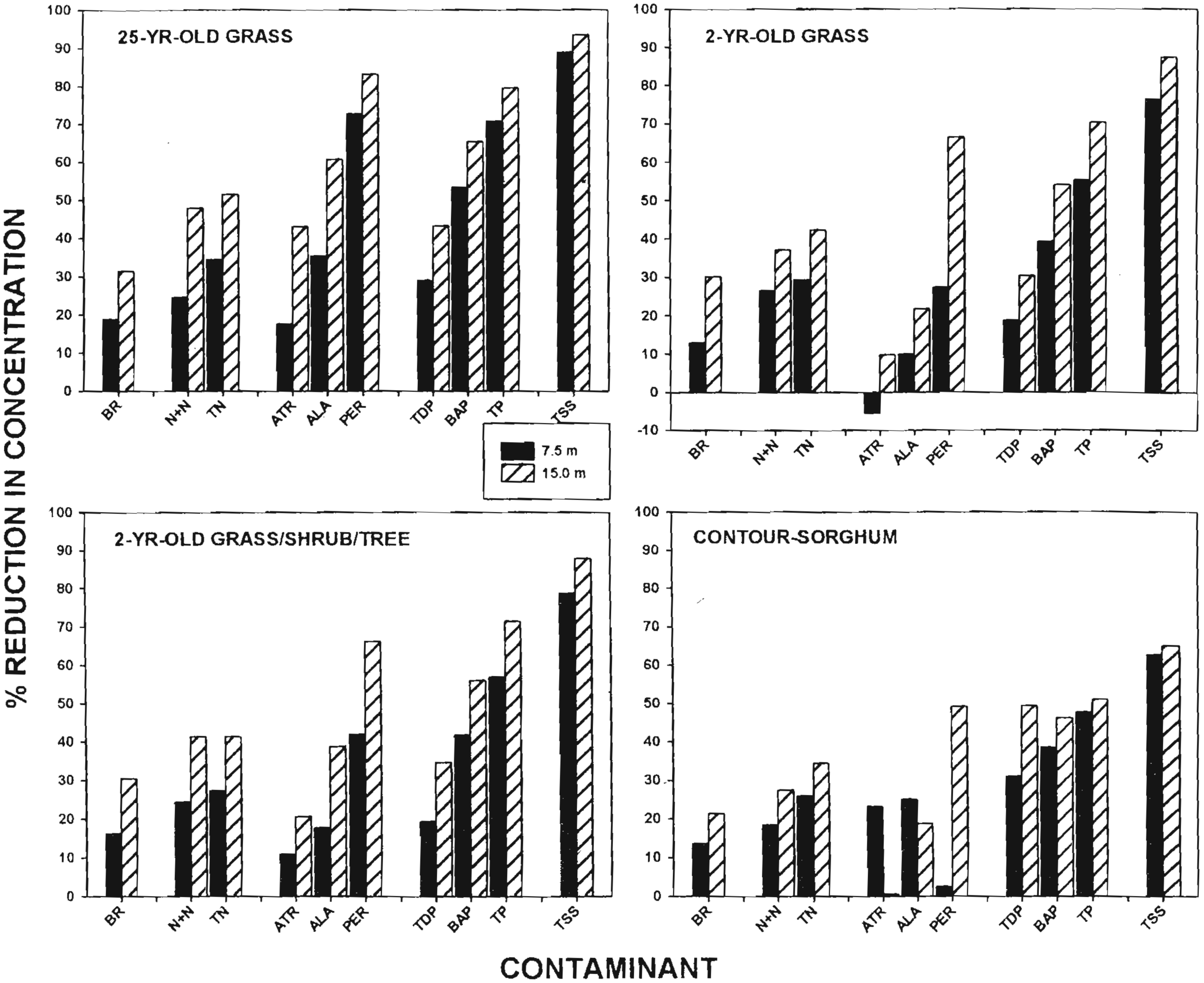

Fig. 2. Percentage of reduction of contaminant concentration by 7.5 m (solid bars) and 15 m plots (cross-hatched bars) of each vegetative composition, relative to the applied tank mixture. N+N, nitrate plus nitrite; TN, total nitrogen; ATR, atrazine; ALA, alachlor; PER, permethrin; TP, total phosphorus; BAP, bioavailable phosphorus; TDP, total dissolved phosphorus; TSS, total suspended solids; BR, bromide.

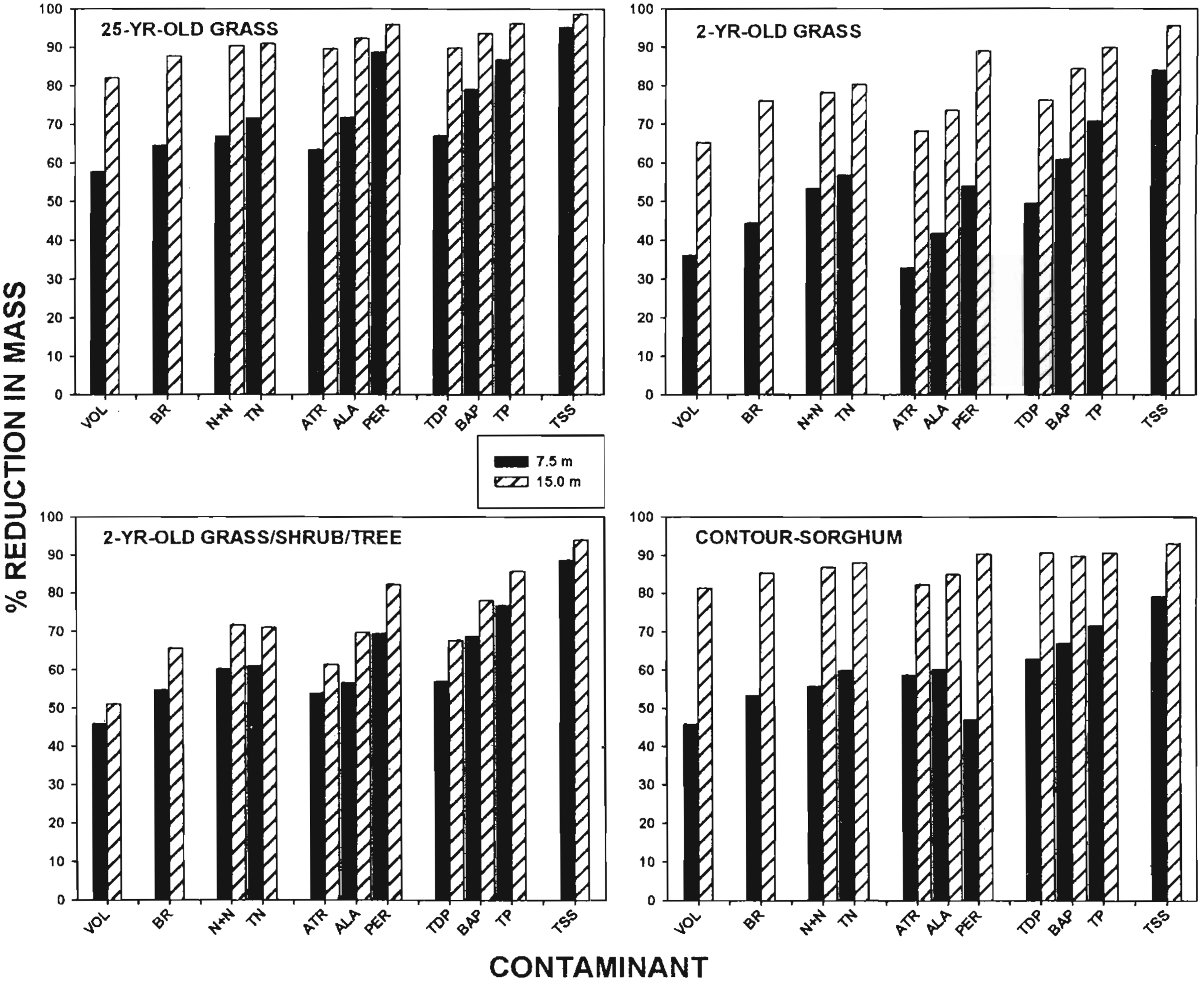

Fig. 3. Percentage of reduction of water volume and contaminant mass by 7.5 m (solid bars) and 15 m plots (cross-hatched bars) of each vegetative composition, relative to the applied tank mixture. VOL, water volume; N+N, nitrate plus nitrite; TN, total nitrogen; ATR, atrazine; ALA, alachlor; PER, permethrin; TP, total phosphorus; BAP, bioavailable phosphorus; TDP, total dissolved phosphorus; TSS, total suspended solids; BR, bromide.

7.5-m plots and 64 to 81% lower than sorghum for 15-m plots (Fig. 4). Only TSS and TP were consistently significantly lower than for corresponding sorghum plots (Fig. 4; Tables 5 and 6). In some cases, atrazine and TDP concentrations were significantly higher in outflow from perennial vegetation than corresponding sorghum (TDP in 2-yr-old grass and grass–shrub–tree plots, and atrazine in the 7.5 m 2-yr-old grass plots; Fig. 4; Tables 5 and 6). Concentrations in outflow from the 25-yr-old grass plots were consistently lower relative to sorghum than for the 2-yr-old grass and grass–shrub–tree plots (Fig. 4).

Effect of vegetation composition on outflow volume and contaminant masses was less consistent than for concentrations. The 25-yr-old grass plots had lower volume and masses of contaminants in outflow than sorghum, but significantly so only for TSS, TP and PER (Fig. 5; Tables 4 and 5). Compared to sorghum, 2-yr-old grass–shrub–tree plots had similar (7.5-m plots) or substantially greater (15-m plots) outflow volume and contaminant masses (Table 4; Fig. 5), but significantly only for higher TDP ($P = 0.0204$) and lower TSS ($P = 0.0433$) than in outflow from the sorghum plots (Table 5). The 2-yr-old grass plots generally appeared to have higher volume and masses of contaminants in outflow compared with sorghum (Fig. 5), but only atrazine, alachlor, and TDP were significantly so (Table 5). Lack of significance for quantitatively large effects on contaminant masses are at least partially attributable to multiplied variability of contributing concentration and volume values.

Two-yr-old grass and 2-yr-old grass–shrub–tree plots behaved similarly in every regard. No significant differences ($P < 0.05$) in main effects for concentration or mass were detected between 2-yr-old grass and 2-yr-old grass–shrub–tree plots for any of the contaminants

Table 5. *P* values for comparisons of contaminant concentration and mass in outflow from plots of different vegetation compositions and widths.

	Contaminant concentration†										
Comparison	VOL	BR	N+N	TN	ATR	ALA	PER	TDP	BAP	TP	TSS
Model (*F*-test)		0.0001*	0.0272*	0.0008*	0.0061*	0.0030*	0.0135*	0.0001*	0.0001*	0.0001*	0.0001*
Vegetation		0.0180*	0.1599	0.0069*		0.0006*	0.0287*	0.0013*	0.0001*	0.0001*	0.0001*
2-yr-old Grass vs. Contour sorghum		0.0757		0.0454*		0.6444	0.1094	0.0015*	0.1053	0.0001*	0.0001*
2-yr-old Grass–shrub–tree vs. Contour sorghum		0.0133*		0.0824		0.1374	0.0389*	0.0071*	0.0160*	0.0001*	0.0001*
25-yr-old Grass vs. Contour sorghum		0.0029*		0.0007*		0.0008*	0.0037*	0.9902	0.0001*	0.0001*	0.0001*
2-yr-old Grass vs. 2-yr-old Grass–shrub–tree		0.3644		0.7257		0.2950	0.5680	0.4126	0.3106	0.4580	0.4738
Width (7.5 m vs 15 m)		0.0001*	0.0009*	0.0001*		0.0429*	0.0187*	0.0001*	0.0001*	0.0001*	0.0004*
Vegetation composition × Width		0.2159	0.4789	0.3492	0.0099*	0.0588	0.7036	0.8524	0.4841	0.0862	0.2556
	Contaminant mass										
Model (*F*-test)	0.0086*	0.0011*	0.0016*	0.0008*	0.0019*	0.0012*	0.0011*	0.0003*	0.0003*	0.0001*	0.0001*
Vegetation composition	0.0786	0.0858	0.1575	0.0498*	0.0113*	0.0092*	0.0255*	0.0122*	0.0229*	0.0114*	0.0012*
2-yr-old Grass vs. Contour sorghum				0.3447	0.0181*	0.0430*	0.7215	0.0259*	0.2327	0.8355	0.1356
2-yr-old Grass–shrub–tree vs. Contour sorghum				0.1613	0.1135	0.1883	0.2621	0.0204*	0.2955	0.9497	0.0433*
25-yr-old Grass vs. Contour sorghum				0.1993	0.4594	0.1902	0.0049*	0.7763	0.0932	0.0069*	0.0001*
2-yr-old Grass vs. 2-yr-old Grass–shrub–tree				0.6367	0.3872	0.4470	0.5756	0.9159	0.8788	0.7866	0.5668
Width (7.5 m vs 15 m)	0.0012*	0.0001*	0.0001*	0.0001*	0.0003*	0.0001*	0.0001*	0.0001*	0.0001*	0.0001*	0.0001*
Vegetation composition × width	0.4098	0.4072	0.4802	0.4250	0.3823	0.6107	0.0779	0.4639	0.3681	0.2923	0.1228

* Significant at the 0.05 probability level.

† Water volume (VOL), bromide (BR), total suspended solids (TSS), total nitrogen (TN), nitrate plus nitrite nitrogen (N+N), total phosphorus (TP), bioavailable phosphorus (BAP), total dissolved phosphorus (TDP), atrazine (ATR), alachlor (ALA), and permethrin (PER).

studied (Table 5). Simple effects for atrazine between these two vegetation compositions also were insignificant at both 7.5- and 15-m widths.

DISCUSSION

The results of this study corroborate previous work that filter strips can retain water and contaminants associated with agricultural runoff. Wider filter strips reduced water and contaminant runoff to a greater degree than narrower ones. Under our study conditions, volume of runoff was substantially reduced, so mass of contaminants was quantitatively reduced to a greater degree than concentration. Statistical significance of mass reductions between treatments, however, was less easily detected due to variability in runoff volume and pollutant concentration, both of which controlled quantification of contaminant mass.

Detailed patterns of performance among vegetation compositions and widths depended strongly on the type of contaminant. Sediment concentration and mass were reduced in outflow to the greatest degree. Contaminants in runoff that are predominantly bound to sediment, including total P, bioavailable P, and permethrin (Table 7), were reduced to a lesser degree than for sediment. The smallest reductions were found for predominantly dissolved contaminants including nitrate, dissolved P, bromide, atrazine, and alachlor.

Processes Controlling Impacts on Runoff Contaminants

Performance differences among contaminants reflect different processes that act on them within a filter strip (Lowrance et al., 1995). Particulate settling removes sediment and sediment-bound contaminants from runoff flow. Infiltration of runoff water carries with it dissolved contaminants, thereby reducing their mass in outflow. Sorption of contaminants to, or remobilization from, surface soil can retain or add, respectively, contaminants to outflow. Dilution of runoff water by rainfall reduces concentrations of all contaminants. Our study produced quantitative evidence for each of these processes that may help explain patterns of performance among different contaminants and their relationships to filter strip width and vegetation composition.

The settling process is approximately described by sediment concentration (TSS). In this study, sediment concentrations were reduced by 87 to 93% in 15-m wide grass and grass–shrub–tree plots (Fig. 2). Most of that reduction (76–89%) occurred within 7.5 m. This nonlin-

Table 6. *P* values for simple effects of vegetation compositions and widths on atrazine concentrations in outflow from plots.†

	Atrazine				
Parameter	7.5 vs. 15 m	G2 vs. CS	GST vs. CS	G25 vs. CS	G2 vs. GST
Vegetation composition					
2-yr-old grass	0.1239				
2-yr-old grass–shrub–tree	0.2416				
25-yr-old grass	0.0340*				
Contour sorghum	0.0137*				
Width					
7.5 m		0.0017*	0.1408	0.4942	0.0525
15 m		0.2100	0.0230*	0.0013*	0.1654

* Significant at the 0.05 probability level.

† Abbreviations: G2 = 2-yr-old grass; GST = 2-yr-old grass–shrub–tree; G25 = 25-yr-old grass; CS = contour sorghum.

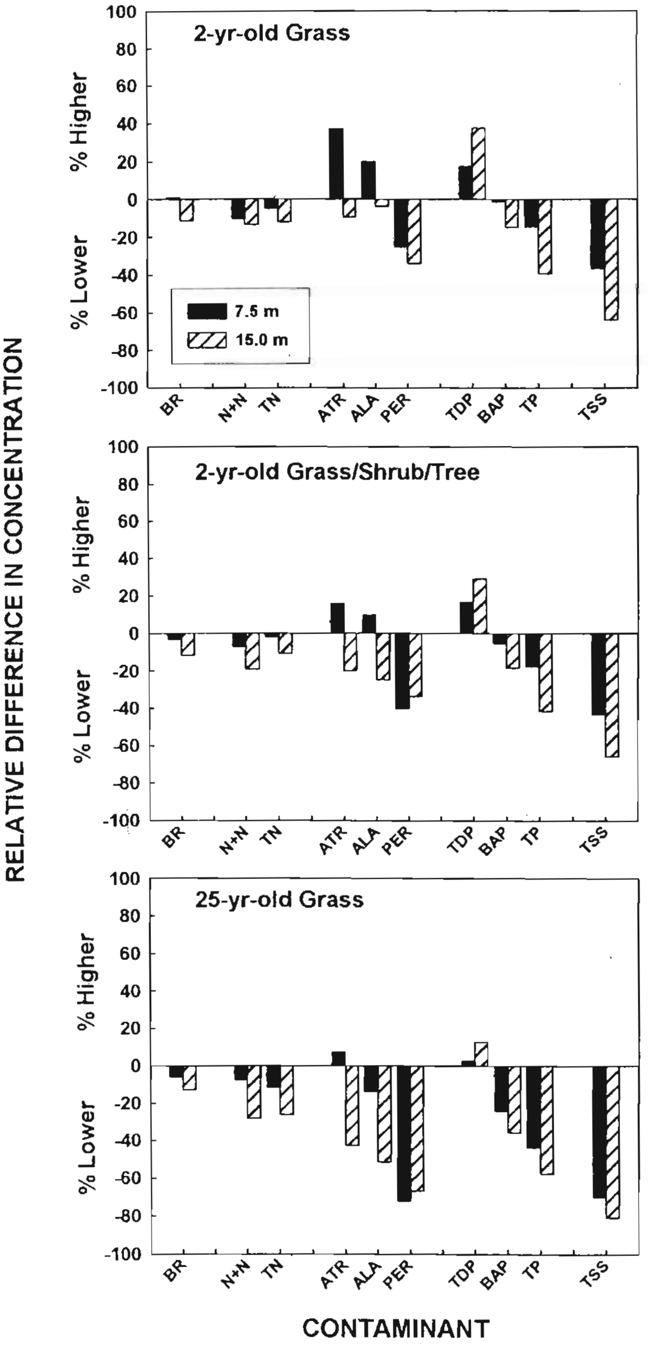

Fig. 4. Difference in the concentrations of contaminants in outflow between each perennial vegetation composition and the annually-replanted contour sorghum plots for 7.5 m (solid bars) and 15 m plots (cross-hatched bars). Differences are expressed as a percentage higher or lower than the contour sorghum plots. N+N, nitrate plus nitrite; TN, total nitrogen; ATR, atrazine; ALA, alachlor; PER, permethrin; TP, total phosphorus; BAP, bioavailable phosphorus; TDP, total dissolved phosphorus; TSS, total suspended solids; BR, bromide.

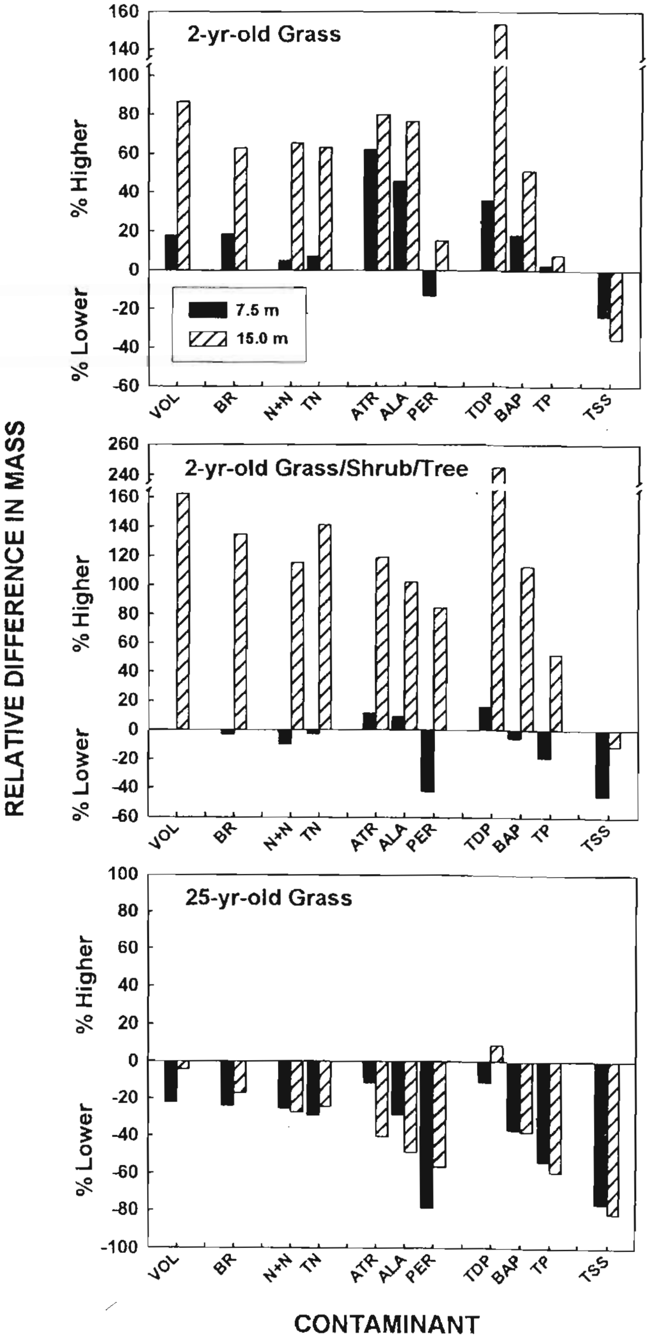

Fig. 5. Difference in the water volume and contaminant masses in outflow between each perennial vegetation composition and the annually-replanted contour sorghum plots for 7.5 m (solid bars) and 15 m plots (cross-hatched bars). Differences are expressed as a percentage higher or lower than the contour sorghum plots. N+N, nitrate plus nitrite; TN, total nitrogen; ATR, atrazine; ALA, alachlor; PER, permethrin; TP, total phosphorus; BAP, bioavailable phosphorus; TDP, total dissolved phosphorus; TSS, total suspended solids; BR, bromide.

ear relationship is illustrated in Fig. 6 by assuming that no settling occurs at 0 m width. It shows averaged results from 2-yr-old grass and grass–shrub–tree plots, both of which performed similarly and had the most replicate outflow samples from 15-m plots. Concentrations of sediment-bound contaminants were reduced to a lesser degree than sediment. For example, concentration of the sediment-bound fraction of P (calculated as the difference between TP and TDP) was not as greatly reduced as sediment (Fig. 6). Departure of sediment-bound P from the TSS relationship probably reflects a predominant association of P with finer particles. Larger sediment particles (e.g., sand) settle more quickly, while

Table 7. Percentage of each contaminant associated with the sediment phase based on analysis of samples collected from the runoff application tank. Negligible values for bromide and nitrate plus nitrite were assumed.

Contaminant	% in sediment phase
Total suspended solids	100
Permethrin	100
Total P	87
Bioavailable P	67
Alachlor	3
Atrazine	2
Total Dissolved P	0
N+N	~0
Bromide	~0

finer particles (e.g., silt and clay) and associated P remain suspended longer and are more likely to reach outflow (Hayes et al., 1984; Peterjohn and Correll, 1984). Similar results were observed for permethrin, which because of its hydrophobicity, we expected to settle in a manner more similar to the clay fraction than to sediment as a whole. As a result, extent of concentration reduction and degree of nonlinearity with width are less pronounced for sediment-associated contaminants than for total sediment. More precise description of the settling process, however, requires factoring out dilution from TSS concentration.

Dilution of runoff by rainfall as it flows through the plots is indicated by bromide (BR) concentration. The amount of dilution integrates several factors, including relative rainfall and runoff volumes, rainfall interception, runoff infiltration, and mixing with soil solution (Overcash et al., 1981). In this study, dilution was linear with plot width, resulting in an overall average 15% reduction in contaminant concentration at 7.5 m, doubling to about 30% by 15 m (Fig. 6). Dissolved contaminants would be expected to behave similarly to bromide, except where there is substantial net sorption or remobilization within the filter strip. In Fig. 6, nitrate (N+N), dissolved P, and alachlor behaved similarly to bromide, but atrazine was relatively enriched in outflow resulting in a lower concentration reduction. Enrichment could have been caused by temporary capture of atrazine in previous runoff from the sorghum field above our plots and its subsequent remobilization by our experimental runoff event. Remobilization of nitrate and phosphate has been reported in other studies (Dillaha et al., 1989; Young et al., 1980).

By factoring dilution out of TSS observations, additional information about the settling process is derived. In Fig. 6, dilution that reduced contaminant concentrations by one-half between 7.5 and 15 m widths would account for the entire change in TSS concentration between those widths. This suggests that all settling occurred within 7.5 m in our 2-yr-old grass and grass–shrub–tree filter strips, and that all sediments able to pass beyond 7.5 m remained in suspension to the outflow at 15 m.

Concentration reduction of contaminants that are partially dissolved and partially sediment-bound, including TP, TN, and BAP, were intermediate to sediment and dissolved contaminants to an extent consistent with the degree each one partitions between solution and sediment phases (Table 7). Total P and BAP concentrations were reduced in a manner similar to sediment P. Total N was mainly soluble ammonium nitrate and behaved much more like bromide. This model, however, does not account for sorption or remobilization processes.

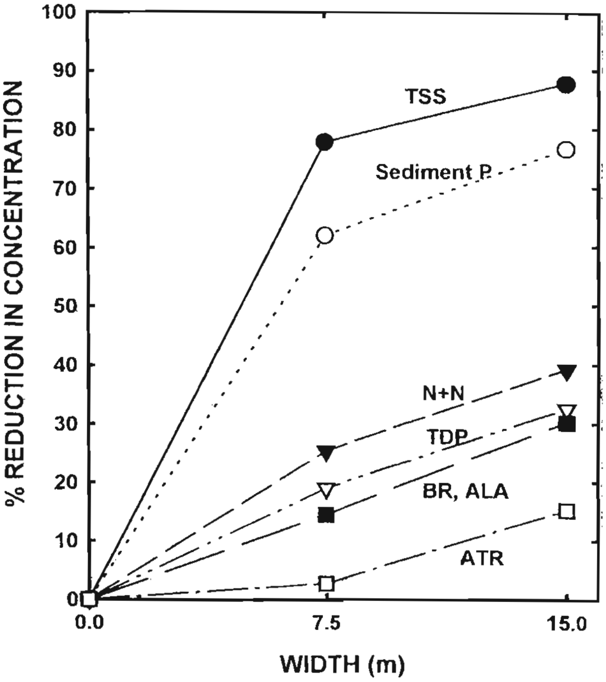

Fig. 6. Percentage of reduction in concentration of contaminants in relation to width of filter strip. Plotted values represent measured averages for 2-yr-old grass and 2-yr-old-grass–shrub–tree plots at 7.5 and 15 m width and assume zero reduction at 0 m width. N+N, nitrate plus nitrite; TN, total nitrogen; ATR, atrazine; ALA, alachlor; PER, permethrin; TP, total phosphorus; BAP, bioavailable phosphorus; TDP, total dissolved phosphorus; TSS, total suspended solids; BR, bromide.

Infiltration of runoff water is indicated by the behavior of bromide mass. Bromide is commonly used as a conservative tracer of water in soils because it is highly soluble, relatively noninteractive with soil particles, and practically absent in most soils. Soil tests prior to experiments confirmed undetectable background levels of bromide in our plots. By this method, infiltration of runoff water was substantial in all plots (36–82%). Infiltration appeared to occur to a somewhat greater degree in the uphill end of our plots. Nonlinear behavior probably reflects a longer contact or opportunity time for infiltration toward the uphill end of the filter strips.

Processes in Different Vegetation Types

Sediment settling was substantially greater in grass and grass–shrub–tree plots than in the annually-cultivated contour sorghum. Numerous stems, thatch, and roots of grasses effectively slow runoff flow, promote settling of suspended sediment, and prevent erosion from within a filter strip. Cultivation reduces stems, surface residue, and roots, and loosens surface soil. There was not much difference in sediment reduction between the perennial vegetation types, although older grass plots (25-yr-old) tended to be more effective than newly-planted plots (2-yr-old). The onset of outflow from older grass plots (7.5 m) took 1.7 × longer than from newly-planted plots, suggesting that further improvement in slowing runoff flow and sediment settling can be expected beyond two growing seasons. Planting the lower one-half of otherwise grass buffers to young trees and shrubs had no impact on performance. The woody plants may have been too small (30% crown cover) to have a detectable impact on sediment settling that might result from shading out herbaceous ground cover. Volunteer grasses and forbs created good ground cover around and under them, and most sediment settling probably occurred in the grass portion of the plots prior to runoff entering the tree and shrub portion.

Infiltration of runoff, as indicated by bromide mass, was not significantly different between any of the vegetation types, including contour sorghum; however, 25-yr-old grass plots tended to have higher infiltration than contour sorghum, while 2-yr-old grass and grass–shrub–tree plots tended to have lower infiltration. These tendencies are consistent with literature indicating that tillage creates short-term macroporosity for infiltration, which subsequently decreases even under cover vegetation (Dabney, 1998). Based on our results, infiltration should improve beyond the second growing season of the filter strips. Some studies report that infiltration is higher under long-term forest vegetation than long-term grass (Lull, 1964), suggesting that our grass–shrub–tree design may ultimately outperform grass alone; however, we are not aware of any direct tests of this hypothesis.

Dilution, as indicated by bromide concentration, was slightly greater with perennial vegetation than with sorghum. Among the component factors, infiltration was not statistically different, surface soil was similarly wetted prior to the evaluations, and all plots had dense stands of vegetation for intercepting rainfall. Interception by tall prairie grasses and fully-grown row crops can amount to 6 mm of a rainfall event (Lull, 1964); however, vegetative cover of sorghum increases from zero to full cover during one growing season, so younger crops may intercept substantially less rainfall, and therefore promote somewhat greater dilution of surface runoff, than we observed in this study.

Conversion from Row Crop to a Filter Strip

Filter strips are commonly installed by planting grass or other perennial vegetation where cultivated crops previously grew. The extent that water quality improves by this conversion is best assessed by evaluating the difference between these alternative land treatments. Figures 4 and 5 illustrate our comparison of filter strips to contour-cultivated sorghum. The results are much less consistent than our assessment of filter strips alone (Fig. 2 and 3). In this study, most of the benefit of conversion to filter strips comes from settling sediment and sediment-associated contaminants from runoff flow. Land conversion to filter strips was generally less effective for reducing concentrations of dissolved contaminants and volume of runoff. In some instances, concentrations and/or masses of dissolved P, atrazine, and alachlor were significantly higher ($P < 0.05$) in outflow from 2-yr-old filter strips than from the unamended contour-sorghum plots.

Our results for filter strips may overestimate performance in typical field conditions. Evidence suggests that performance may degrade after repeated runoff events, particularly where uneven sediment accumulation causes channelized flow through the filter strip (Dillaha et al., 1989; Magette et al., 1989). Sheet flow conditions may be difficult to maintain where high sediment runoff is encountered.

Our results for contour sorghum may be relatively conservative compared with other row crop conditions. Our sorghum plants were almost fully-grown and protected the soil surface from raindrop impact and associated soil sealing that otherwise reduces infiltration and promotes soil erosion. Our contour furrows retained substantial amounts of simulated runoff and rainfall, effectively slowing runoff flow, promoting infiltration, and minimizing erosion. Other studies have indicated that furrow retention is greater in bordered plots than in open fields (Young et al., 1980). Net contaminant retention in our sorghum plots probably benefitted further by our not amending these plots with fertilizers or pesticides, thus minimizing sources of contaminants for remobilization from within the plot area. Evaluations under other conditions, such as earlier in the growing season, where furrows are shallower or noncontoured, where chemicals are applied, and/or in open field situations, would result in less contaminant retention by cultivated crop strips than we observed in our study. Accordingly, estimates of water quality impact resulting from conversion of row crop strips to filter strips under other conditions may vary greatly from ours.

CONCLUSIONS

Our results corroborate previous studies that filter strips can retain water and contaminants associated with agricultural surface runoff. Under the conditions in this present study, we have further determined that:

- Performance of filter strips depends strongly on the type of contaminant. Sediment is reduced in runoff to a much greater degree than dissolved contaminants. Contaminants that are partially dissolved and partially sediment-bound, such as TN, TP, and BAP, are reduced in runoff to an intermediate extent consistent with the degree that they partition between sediment and dissolved phases. Sediment-bound P and PER are reduced to a lesser degree than total sediment, consistent with the hypothesis that they associate with the finer sediment particles.
- Performance depends on width of the filter strip. Doubling filter strip width from 7.5 to 15 m does not improve sediment settling, but does substantially increase infiltration and dilution of runoff.
- Incorporating trees and shrubs into the lower half of filter strips does not affect performance.
- Compared with strips of contour cultivated sor-

ghum, filter strips greatly reduce concentrations of sediment and associated contaminants in runoff, but are less effective at reducing concentrations of dissolved contaminants and volume of runoff.

- Settling of sediment, infiltration, and dilution are important processes controlling the performance of filter strips.

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