Change in filter strip performance over ten years

M.G. Dosskey, K.D. Hoagland, and J.R. Brandle

ABSTRACT: Effectiveness of filter strips may change over a period of years because key soil and vegetation conditions change after conversion of cultivated farmland to permanent vegetation. The main objectives of this study were to: 1) determine if effectiveness of a filter strip changes over years since establishment, and 2) determine if temporal change depends on vegetation type. Four vegetation treatments were replicated five times in 3 x 7.5 m (10 x 25 ft) plots. Plots containing all-grass (New Grass) and grass with trees and shrubs (New Forest) were established in spring of 1995 among otherwise similar plots that contained either grass since ca. 1970 (Old Grass) or were re-cultivated and re-planted annually with grain sorghum (Crop). Once each summer, in 1995, 1996, 1997, 2003, and 2004, identically prepared solutions containing sediment, nitrogen (N) and phosphorus (P) fertilizer, and bromide tracer were applied to the upper end of each plot during a simulated rainfall event of 2.5 cm (1 in) in 30 minutes, and the load and concentration of runoff components were measured in outflow from the plots. Retention of solution components and reduction of their concentrations by the New Grass and New Forest plots improved from effectiveness similar or less than the Crop plots to effectiveness similar to the Old Grass plots within three growing seasons. Improvement coincided with the development of denser vegetative ground cover and a slower rate of runoff flow through the plots. Change in infiltration accounted for most of the improvement in overall effectiveness. There was no evidence of divergence in the performance of New Grass and New Forest plots. We conclude that filter strip performance improves over a period of years since establishment. Most of the change occurs within three growing seasons after establishment. Infiltration characteristics account for most of that change. Grass and forest vegetation are equally effective as filter strips for at least 10 growing seasons after establishment.

Keywords: Buffer, nonpoint source pollution, soil quality, vegetation type, water quality

Properly designed filter strips can help mitigate pollutant transport from agricultural crop land to streams and lakes. Filter strips [U.S. Department of Agriculture (USDA) practice code No. 393] are installed by converting a portion of cultivated field near its margin to permanent vegetation (USDA, 1997). Pollution control is provided by natural processes of vegetation and soil that immobilize and transform pollutants in field runoff, including sediment, fertilizers, and pesticides. Other buffer practices, such as riparian forest buffer (code 391) and riparian herbaceous cover (code 390) are also designed to function in this way.

The level of positive impact that filter strip installation will have on agricultural runoff depends on many factors. A comprehensive review of previous research (Dosskey, 2001) identified several important variables related to site condition (e.g., soil type, slope) and filter design (e.g., vegetation type, width). However, even after accounting for these variables, estimates of probable effectiveness still vary widely due, in part, to other potentially important processes and impact-governing variables that are not well-understood.

Michael G. Dosskey is a research ecologist at the U.S. Department of Agriculture Forest Service's National Agroforestry Center in Lincoln, Nebraska. **Kyle D. Hoagland** and **James R. Brandle** are professors in the School of Natural Resource at the University of Nebraska in Lincoln, Nebraska.

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One of those potentially-important variables is time since establishment of the filter strip. For a given site and filter design, effectiveness may change over a period of years due to changes in soil properties and vegetation condition that alter the processes that immobilize and transform pollutants in runoff.

In general, soil and vegetative properties change over time after cessation of tillage and establishment of permanent vegetation (Dick et al., 1991; Lull, 1964; Parr and Bertrand, 1960). Soil structure and macroporosity redevelop after cessation of tillage (Edwards et al., 1988; Huang et al., 2002; Mazurak et al., 1960; Rhoton, 2000; Weinhold and Tanaka, 2000). Such changes are caused primarily by the action of roots and soil macro-invertebrates (Ehlers, 1975; Gaiser, 1952; Hopp and Slater, 1948; Zachmann et al., 1987). Change in infiltration characteristics of soils occurs gradually over many years, but significant change has been measured within four years (Mazurak et al.,1960; Weinhold and Tanaka, 2000).

Vegetation properties also change over time. Biomass of plant roots, shoots, and surface debris increase over time. Rapid nutrient uptake patterns in early years moderate as permanent vegetation establishes complete coverage of a site and nutrient reserves increase (Vanek, 1991). Nutrient saturation and cessation of net nutrient uptake by vegetation after several years of nutrient trapping has been suggested (Groffman et al., 1992; Hanson et al., 1994; Osborne and Kovacic, 1993; Vanek, 1991). Over longer periods, natural succession of plant species leads to changes in vegetative compositions, usually toward domination of sites by trees, and subsequent changes in soil infiltration properties (Auten, 1933; Coile, 1940; Metz and Douglas, 1959; Wood, 1977).

Gradual change in soil and vegetation conditions may alter the function and effectiveness of vegetative filters. Improved soil structure and macroporosity should enhance infiltration of runoff water and dissolved pollutants. Increased infiltration will promote sediment deposition by reducing sediment transport capacity of the remaining runoff (Hayes et al., 1984; Lee et al., 1989) and promote dilution of dissolved pollutants by rainfall on the filter by reducing volume of the remaining runoff (Overcash et al., 1981). Modeling studies suggest that increasing the density of vegetation and debris on the soil surface will reduce runoff velocity, thereby enhancing infiltration and deposition within a filter strip (Barfield et al., 1979; Kao and Barfield, 1978; Williams and Nicks, 1988). Nutrients that were previously sequestered in soil and vegetation may release to subsequent runoff in increasing amounts as sites becomes nutrient rich (Magette et al., 1989; Young et al., 1980).

Previous research on filter strips has not experimentally tested for change in their effectiveness over time. Many published studies do not report the age of the filter strips that were examined (Arora et al., 1996; Barfield et al., 1998; Coyne et al., 1995, 1998; Dillaha et al., 1989; Magette et al., 1989; Robinson et al., 1996). Other studies examined filters at one month to five years after establishment on previously cultivated ground (Clausen et al., 2000; Lee et al., 2000; Lowrance et al., 1997; Patty et al., 1997; Schmitt et al., 1999; Sheridan et al., 1999; Uusi- Kämppä et al., 2000). Direct comparison of these studies does not provide clues to change in function over time because of wide ranging differences among them in other important site and design factors.

Different types of vegetation may promote changes in filter effectiveness to different degrees. Infiltration capacity in soils of filter strips that contained grass and trees was greater than in grass-only strips within five years (Bharati et al., 2002) and six years (Seobi et al., 2005) after establishment. However, no significant differences in pollutant retention between grass and forest types have been reported after three years (Udawatta et al., 2002) and seven years (Uusi-Kämppä et al., 2000). The positive influence that trees have on infiltration properties of filter strip soils may accrue over many years as trees get larger and more-fully occupy the site. On the other hand, larger trees will suppress grasses and forbs that provide the surface roughness to slow runoff flow and promote sediment deposition and runoff infiltration. Faster-growing trees probably exert these influences sooner than slower-growing species.

This study evaluated the importance of filter strip age as a variable that determines the effectiveness of filter strips for mitigating surface runoff from agricultural fields. The specific objectives were to: 1) determine if effectiveness of filter strips changes over years since establishment; and 2) determine if temporal change in effectiveness depends on vegetative composition. Further analysis was undertaken to determine how change in filter effectiveness partitions among the fundamental processes of infiltration, deposition, and dilution.

Materials and Methods

Study area and field plots. A plot study was conducted at the University of Nebraska's Agricultural Research and Development Center in east-central Nebraska near Mead. In this region, fine-textured soils formed from loess are intensively farmed primarily for corn, grain sorghum, and soybeans. Annual precipitation is about 69 cm (27 in) and falls primarily during thunderstorms in spring and summer.

The plots were constructed about 7 m (23 ft) downslope from the margin of a contour-cultivated field in a rotation of grain sorghum [*Sorghum bicolor* (L.) Moench] and soybeans [*Glycine max* (L.) Merr]. The plot area had previously been vegetated with mixed grasses that were harvested annually for hay for at least 25 years. The plots were located along 400 m (1,312 ft) of field margin having a six to seven percent slope. Soil at this site is classified as well-drained, Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudoll). Surface soil texture (top 21 cm or 8 in) was measured in every plot and changed from silty clay loam (30 percent clay) to sandy loam (14 percent clay) along the length of the field margin.

Forty plots were established in the spring of 1995 having four different vegetation compositions, each at two different sizes. Plot sizes of 3 x 7.5 m (10 x 25 ft) and 3 x 15 m (10 x 50 ft) represented 7.5 m (25 ft) and 15 m (50 ft)-wide filter strips. The experimental design was a randomized complete block with a 2 x 4 factorial (width x vegetation composition) with each block of eight plots replicated five times.

Existing vegetation was killed with Roundup® (Monsanto Company, St. Louis, Missouri) in mid-April 1995, except on one 7.5 m (25 ft) and one 15 m (50 ft) plot in each block (designated the "Old Grass" plots). In mid-May, the plots to be newly-planted were plowed to 21 cm (8 in) deep, then rototilled four times to 15 cm (6 in) deep over a two-week period prior to planting, and then raked smooth. All plots were oriented on the slope to promote sheet flow down the plots. Borders along the sides and downhill end of all plots were lined with galvanized sheet metal buried 10 cm (4 in) deep and projecting 15 cm (6 in) above the soil surface in order to contain water flow. A 10 cm (4 in)-diameter PVC pipe carried plot outflow to a collection tank. A minimum of 3 m (10 ft) of mown grass separated the plots.

The tilled plots were planted in mid-June of 1995 to either mixed grasses (designated "New Grass"), half grass and half trees and shrubs (designated "New Forest"), or grain sorghum that was re-tilled and re-planted annually (designated "Crop").

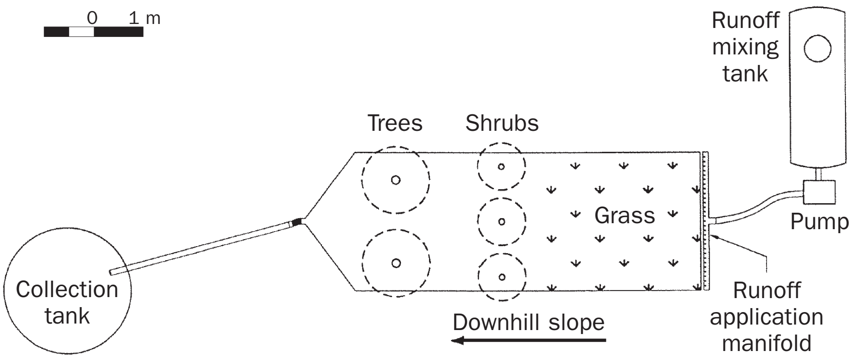
The New Grass plots were broadcast planted with switchgrass (*Panicum virgatum* L. var. Blackwell) and tall fescue (*Festuca arundinacea* Schreb. var. K-31). Volunteer establishment of additional grasses and forbs also occurred, including smooth brome (*Bromus inermis* Lyess.), wild buckwheat (*Polygonum convolvulus* L.), common lambquarters (*Chenopodium album* L.), field pennycress (*Thlaspi arvense* L.), and foxtail (*Setaria* spp.). By the end of the third growing season, the forb component had diminished and grasses had become dominant.

The New Forest plots consisted of an uphill half of each plot planted in mixed grasses by the same methods as the New Grass plots, and a downhill half planted to rows of shrubs [bush honeysuckle *(Lonicera maackii)* and golden currant *(Ribes aureum)*] and fast-growing trees [eastern cottonwood (*Populus deltoides* Bartr.) and silver maple (*Acer saccharinum* L.)]. The 3 x 15 m (10 x 50 ft) plots had two rows of shrubs (three shrubs per row) planted adjacent to the grass and two rows of trees (two per row) planted on the lower end of the plot, while the 3 x 7.5 m (10 x 25 ft) plots were planted with one row of trees and one row of shrubs (Figure 1). The trees and shrubs were 30 to 60 cm (12 to 24 in)-tall bareroot nursery stock obtained from the USDA Forest Service Nursery in Halsey, Nebraska. Volunteer grasses and forbes became established among the trees and shrubs and were mowed periodically during the initial three growing seasons. After that time, the woody vegetation overtopped and retarded the growth of herbaceous vegetation in these portions of the New Forest plots. By the tenth growing season, the shrubs had grown to 1 to 3 m (3 to 10 ft) high with dense crowns and the trees were 3 to 8 m (10 to 26 ft) tall.

The Crop plots were rototilled and contour-planted with grain sorghum [*Sorghum bicolor* (L.) Moench] in each of the first three seasons of this study. No fertilizers or pesticides were applied. Between fall of 1997 and spring 2003, these plots were unmanaged and developed a volunteer cover consisting primarily of smooth brome grass. In spring 2003, these plots were re-treated with Roundup®. They were rototilled several times and planted with grain sorghum. Tillage and replanting was repeated again in 2004. In all years, individual sorghum plants were spaced at about 10 plants m^{-1} (three plants ft^{-1}) in the row with standard 76 cm (30 in) row-spacing. Weeds were removed from between the rows by periodic hoeing. Planting was done in mid-June of 1995 and in mid-May of all other years.

Figure 1

Schematic diagram of a 3 x 7.5 m New Forest plot showing the positions of vegetation and the tank application and outflow collection systems. Grass plots were the same size and slope as forest plots, but were entirely planted in grass.



Field experimental procedures. In August 1995, July 1996, July 1997, July 2003, and July 2004, when the sorghum was six to eight weeks-old and 50 to 100 cm (20 to 40 in) high, a single runoff event was simulated on each plot and the subsequent outflow was measured. The event simulated rainfall and field runoff from one year return frequency storm in the study area amounting to 2.54 cm (1 in) of rain in 30 minutes (Hershfield, 1961). Simulated rainfall was applied to plots using an overhead sprinkler system consisting of a polyvinyl chloride (PVC) pipe frame fitted with 7 Weathermatic® model 404SF "jet irrigator" nozzles (Weathermatic, Dallas, Texas) and a 207 KPa (30 psi) pressure regulator. Each sprinkler unit provided fairly uniform coverage and proper intensity for a 3 x 7.5 m (10 x 25 ft) plot (566 L or 150 gal). Two units are used on 3 x 15 m (10 x 50 ft) plots (1132 L or 300 gal)). Water from local wells was used for simulated rainfall.

Simulated field runoff was created in a polyethylene tank for application to the uphill end of each plot. The required volume of simulated runoff, 1887 L (500 gal), was derived using the USDA Curve Number method (USDA, 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 or 2.1 in of rainfall in the prior five days), and an above-buffer field length of 81 m (266 ft).

Agricultural chemicals and sediment were added to the simulated runoff water to approximate peak concentrations of contaminants that may be found in runoff from a corn field during a post-plant thunderstorm: 18.9 kg (41.6 lbs) dry weight of sediment (same source each year; 12 percent sand, 30 percent clay, 3.0 percent organic matter); 287 g (10.1 oz) of ammonium nitrate fertilizer (33-0-0); 5.7 g (0.20 oz) of superphosphate fertilizer (0-46-0, coarse powder); 28.2 g (1.0 oz) of potassium bromide (67.1 percent Br). Concentrations of sediment and chemical components in the tank mixture were measured in samples collected from several tanks at the time of application to the plots (Table 1).

The potassium bromide was added to the mixture as a conservative tracer (Bowman, 1984) to distinguish between tank solution and simulated rainfall contributions to outflow from each plot. The tank solution was prepared by adding pre-measured amounts of fertilizers, sediment, and potassium bromide to the tank water and vigorously mixing for one hour using a gasoline-powered pump (2.6 KW or 3.5 hp) and circulation system. The circulation system was designed to produce 230-270 L min^{-1} (61 to 72 gal min^{-1}) flow through 16 pairs of spray jets located in the bottom of the tank in order to prevent

Table 1. Volume and component concentrations of the tank solution that was applied to the plots as simulated field runoff.

Component	Volume or concentration
Water	1887 L
Sediment (TSS)	10,000 mg L^{-1}
Total nitrogen (TN)	68 mg L^{-1}
Nitrate plus nitrite nitrogen (NN)	36 mg L^{-1}
Total phosphorus (TP)	4723 ug L^{-1}
Total dissolved phosphorus (TDP)	523 ug L^{-1}
Bromide (BR)	9.7 mg L^{-1}

Table 2. Pairwise-contrasts of the four vegetative compositions and the codes used in Figures 2, 3, and 4 to indicate statistical significance.

	Significance code	
Contrast	$P < 0.05$	$P < 0.01$
Crop vs Old Grass	1	1
Crop vs New Grass	2	2
Crop vs New Forest	3	3
Old Grass vs New Grass	4	4
Old Grass vs New Forest	5	5
New Grass vs New Forest	6	6

Table 3. Total rainfall at the study site for the two-month period prior to the field similations in each year of the study, and mean bromide (BR) mass retention during field simulations by Old Grass and Crop plots in those years.

	Year of field experiment				
	1995	1996	1997	2003	2004
Rainfall (cm)	5.9	32.5	9.3	23.4	20.0
Bromide mass retained (%)	99+	64	94	89	74
Old Grass plots					
Crop plots	75	53	82	80	45

Table 4. *P*-values of the F-test for each tank component across all vegetative compositions and times (main effects) and their interaction. Significance is indicated where $P < 0.05$.

	Main effect *P*		
Component	Vegetation composition	Time	Veg. x Time Interaction *P*
Mass			
Bromide (BR)	0.05	<0.01	<0.01
Total suspended solids (TSS)	<0.01	<0.01	<0.01
Total phosphorus (TP)	0.02	<0.01	<0.01
Total nitrogen (TN)	0.02	<0.01	<0.01
Total dissolved phosphorus (TDP)	0.03	<0.01	<0.01
Nitrate plus nitrite nitrogen (NN)	0.03	<0.01	<0.01
Concentration			
Bromide (BR)	0.64	<0.01	0.66
Total suspended solids (TSS)	<0.01	<0.01	<0.01
Total phosphorus (TP)	<0.01	<0.01	<0.01
Total N (TN)	0.14	<0.01	0.10
Total dissolved phosphorus (TDP)	0.77	<0.01	<0.01
Nitrate plus nitrite nitrogen (NN)	0.65	<0.01	0.81
Through-flow time	<0.01	<0.01	<0.01

settling of sediment particles and to carry them along with the solution to the surface in a boiling motion. The solution continued to be mixed throughout the subsequent application period in order to maintain a reasonably homogeneous mixture until all of the contents of a tank were 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 upper end of the plot at 75.7 L min^{-1} (20 gal min^{-1}). The mixture was applied through a 3 m (10 ft)-long section of 2.5 cm (1 in)-diameter PVC pipe having 6 mm (0.25 in)-dia. holes spaced every 10 cm (4 in) along its length (Figure 1). The application rate produced a runoff period of about 25 min. Flow meters (Multi-jet®, Master Meter, Inc., Longview, Texas) were used to measure and monitor application rates and volumes of simulated runoff and rainfall.

Each plot was prepared for evaluation by irrigating with 1.9 cm (0.75 in) of simulated rainfall at four different times over four days prior to evaluation (total of 7.6 cm or 3 in). This was done to wet the surface soil to the antecedent conditions that were specified in the runoff volume model. Any natural rainfall that occurred within this 4-d window was considered part of the 7.6 cm (3 in) requirement.

The simulated event was designed to mimic the progression of natural rainfall and runoff during a typical spring storm. First, simulated rainfall was initiated. After 10 minutes of rainfall, application of tank solution was initiated to the upper end of the plot. Rainfall continued on the plot for another 20 minutes (approximately) until 2.54 cm (1.0 in) had been applied. Tank solution continued to be applied for another five minutes (approximately) until the entire mixture was emptied from the tank. Outflow from plots normally stopped within five minutes after cessation of application from the tank.

Water that flowed from the lower end of each plot was collected in a 2700 L (715 gal) steel tank. The outflow solution was stirred vigorously using a circulation pump and mixing manifold as grab samples were collected for analysis of sediment and the various chemical constituents. The total volume of outflow from each plot was measured using a flow meter as the solution was pumped out of the collection tank.

Each year, samples of the simulated runoff (tank solution) and the simulated rainfall (well water) were collected at one randomly-selected plot from each of the five blocks of plots. Field blanks were prepared and periodic duplicate samples were collected for quality control evaluation.

All samples were collected in acid-washed polyethylene (LDPE) bottles and stored immediately on ice in the field.

Laboratory procedures. All samples were analyzed for total suspended solids (TSS), total nitrogen (TN), nitrate plus nitrite nitrogen (NN), total phosphorus (TP), total dissolved phosphorus (TDP), and bromide (BR).

At the end of each day, samples to be analyzed for the dissolved constituents nitrate plus nitrite nitrogen, total dissolved P, and bromide, were filtered through 0.45 µm (2.1 x 10^{-4} in) Gelman GN membrane filters (Gelman Sciences, Inc., Ann Arbor, MI), and the filtrates stored frozen at -10°C (14°F) until analysis. Samples for analysis of total suspended solids were transferred directly to a cooler at 4°C (39°F). Samples for analysis of total P and total nitrogen were transferred directly to a freezer at -10°C (14°F).

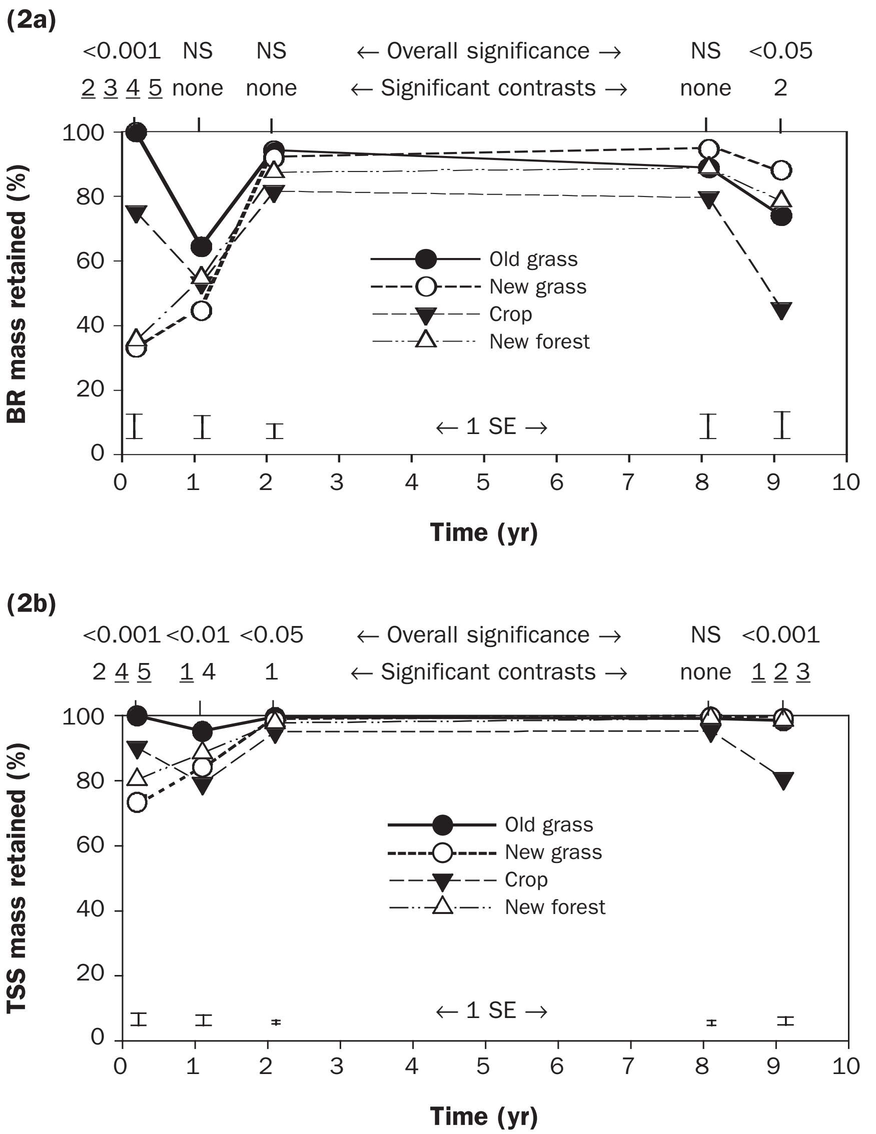
Bromide analysis was performed using ion chromatography (USGS, 1985). Total suspended solids was determined by residue-on-filtration of entire contents of each 125 ml (7.6 in^3) sample bottle using Gelman A/E glass-fiber filters according to APHA method 2540D (APHA, 1992). Nitrate plus nitrite nitrogen was determined by hydrazine reduction (Downes, 1978). Total phosphorus and total dissolved P were determined by persulfate digestion (Menzel and Corwin, 1965) and colorimetry (Murphy and Riley, 1962). Total nitrogen was determined by persulfate digestion (D'Elia et al., 1977) and UV-spectrophotometry corrected for organic matter (APHA, 1992). Colorimetric and UV tests for total nitrogen, nitrate plus nitrite nitrogen, total P, and total dissolved P were performed using a UV-VIS spectrophotometer.

Data analysis procedures. The effectiveness of each plot was quantified by calculating the amount of each runoff component from the tank mixture that was retained (mass) and modified (concentration) by the plot during the field experiment. Effectiveness was calculated as the difference between the tank-applied amount and the measured outflow amount expressed as a percentage of the tank-applied amount.

The concentrations of chemical components in outflow from each plot were adjusted to negate contributions from the well water that was used for simulated rainfall. The adjustments were made using the bromide tracer results and a two-component mixing model (Sklash, 1990). The mass of each component in outflow from a plot was calculated as the product of outflow volume and the adjusted concentration.

Figure 2 - a, b

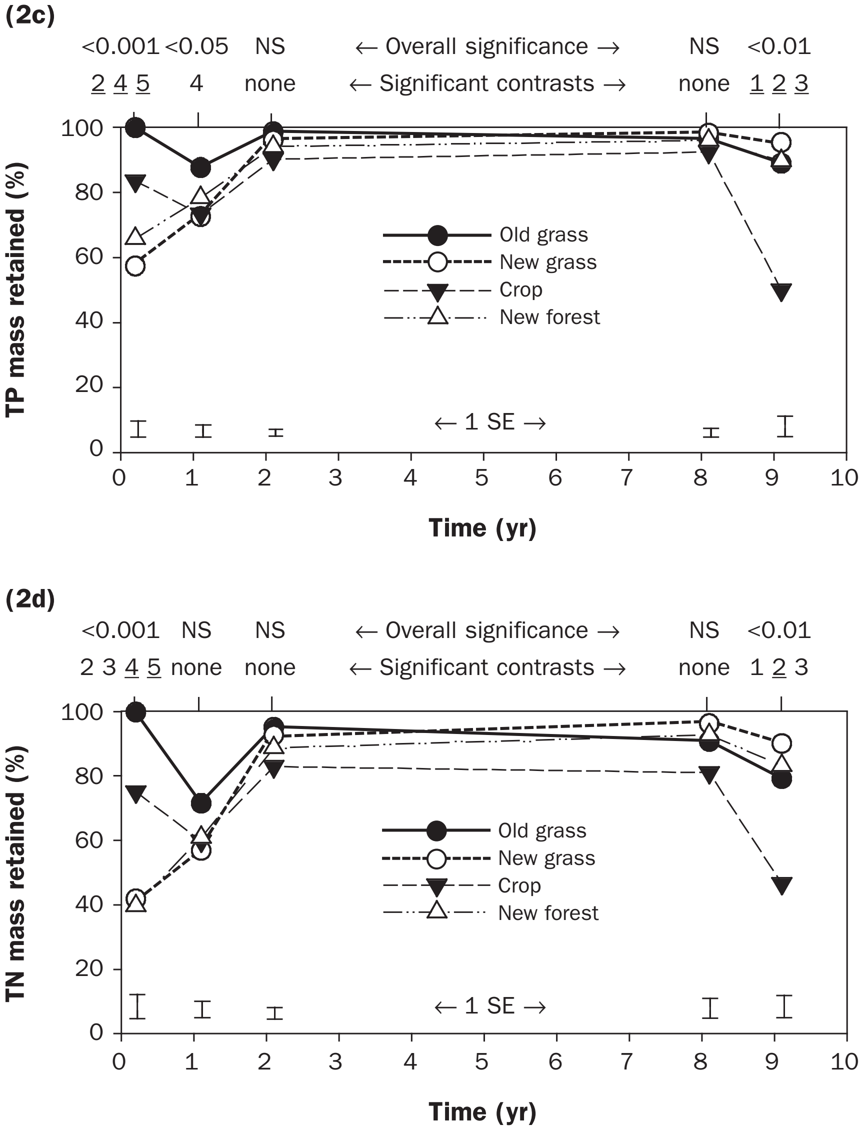
Average percentage of component mass from the tank source that was retained by the 7.5 m-length plots as a function of time since plot establishment: (a) Bromide or BR, (b) Total suspended solids or TSS. Also shown for each time point are: *P*-value of the overall F-test, significance level indicators for the individual treatment contrasts, and the pooled standard error (SE) for multiple comparisons. The numeric codes for indicating significance of individual contrasts are displayed in Table 2.



Two hypotheses were tested: 1) Effectiveness of new filter strips changes over years since establishment, and 2) Temporal change in effectiveness of a new filter strip depends on vegetation composition of the filter strip. Contributions of major filter strip processes to overall effects of time and vegetation treatment were evaluated by the following relationships: Net Deposition = total suspended solids mass retained; Dilution = bromide concentration reduction; Infiltration = bromide mass retained.

Statistical analysis was performed on the data from only the 7.5 m (25 ft)-long plots. Too few of the 15 m (50 ft)-long plots pro-

Figure 2 - c, d
Average percentage of component mass from the tank source that was retained by the 7.5 m-length plots as a function of time since plot establishment: (c) Total phosphorus or TP, (d) Total nitrogen or TN. Also shown for each time point are: *P*-value of the overall F-test, significance level indicators for the individual treatment contrasts, and the pooled standard error (SE) for multiple comparisons. The numeric codes for indicating significance of individual contrasts are displayed in Table 2.



duced outflow to provide adequate sample sizes for a robust statistical evaluation. For example, outflow was obtained from only six out of 25 tests on the 15 m (50 ft)-length Old Grass plots, our reference treatment. Clearly, the amount of simulated runoff water and rainfall used in this study was not much greater than the infiltration capacity of the 15 m (50 ft)-long plots. In contrast, measurable outflow was obtained from 19 out of 25 tests on the 7.5 m (25 ft)-long Old Grass plots and 103 out of 125 total tests among all vegetation treatments. The 7.5 m (25 ft)-long plots retained a fairly high fraction of the simulated runoff, but not unlike high values reported in other studies (Arora et al., 1996; Barfield et al., 1998; Coyne et al., 1998; Lee et al., 2000; Patty et al., 1997; Sheridan et al., 1999).

Effectiveness of the different vegetation compositions and their relationships to years since establishment were evaluated by repeated-measures ANOVA over the top of a randomized complete block design using the Proc MIXED procedure of SAS® Release 8.1 (SAS Institute, 2000). The procedure was designed to account for unbalanced sample sizes in the concentration data caused by the occasional absence of plot outflow to sample. First, a test was performed across all vegetation compositions and times for main effects of vegetation, time, and their interaction. Then, an overall F-test among vegetation compositions was performed at each time point, followed by individual pair-wise contrasts of the vegetation compositions (six contrasts at each time point; Table 2). In the first test, a significant vegetation x time interaction ($P < 0.05$) indicated that the relationship among the vegetation compositions changed over time and that individual vegetation compositions must be compared at each time point. Experiment-wise error rate at each time point was controlled by interpreting significance of a specific contrast only if the overall F-test for that time point was significant at $P < 0.01$ (equivalent to a Bonferroni-adjustment to $P < 0.05$ over five measurement times). Significance of a contrast was indicated by a Tukey-Kramer test-adjusted $P < 0.01$.

Effectiveness results for each vegetation composition were plotted as a function of time. Mass and concentration results for each component were graphed separately (Figures. 2 and 3). Significance of the overall F-test and individual contrasts at each time point are indicated in each graph. Significance of individual contrasts is denoted according to the coding system shown in Table 2.

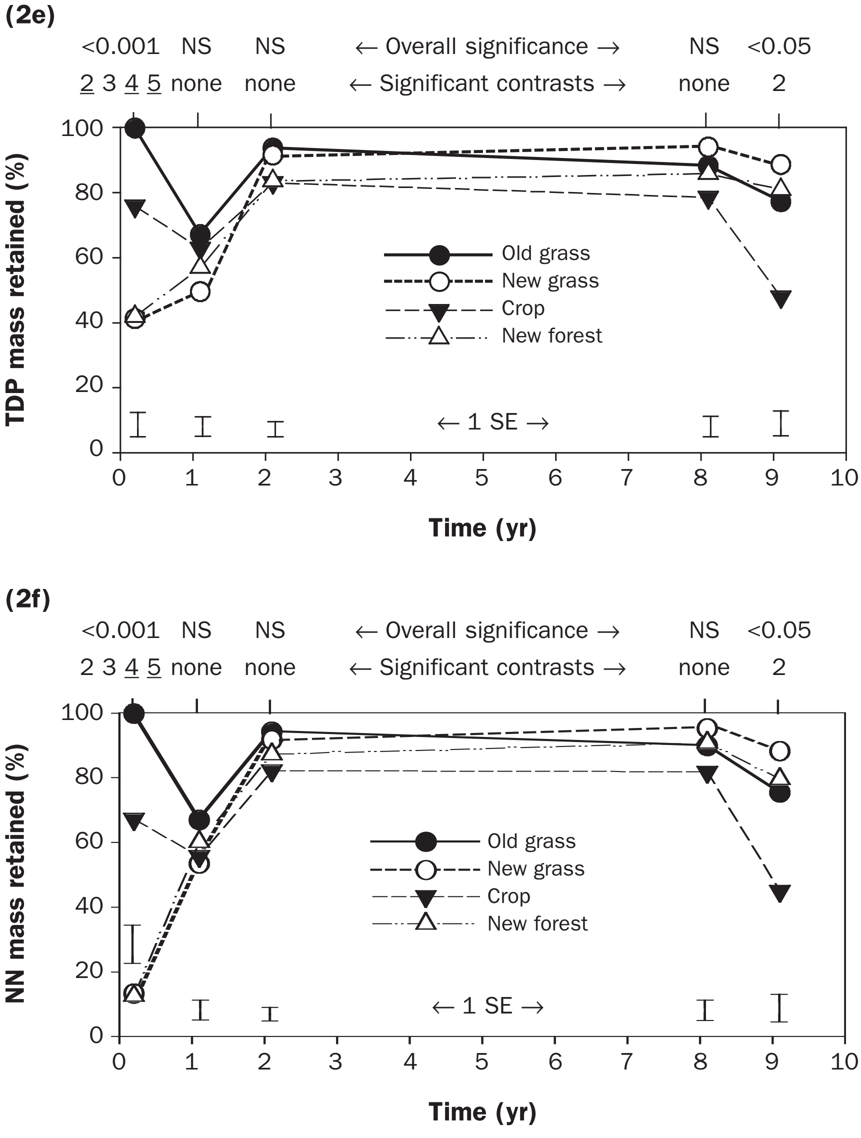
Interpretations of change in effectiveness over years focused on within-year contrasts between the newly-established filter plots (New Grass and New Forest) and the two reference treatments (Crop and Old Grass). The New Grass and New Forest plots were expected to show a trajectory of change from similarity to the initial cultivated condition (Crop) toward similarity to an ultimate condition (Old Grass). New Grass and New Forest plots were contrasted to determine if vegetation composition is an important variable in temporal relationships.

Results and Discussion

Variation in effectiveness of filters over years. Filter effectiveness of the reference plots, Old Grass and Crop, was not constant over the test period. Old Grass and Crop were assumed to

Figure 2 - e, f

Average percentage of component mass from the tank source that was retained by the 7.5 m-length plots as a function of time since plot establishment: (e) Total dissolved phosphorus or TDP, and (f) Nitrate plus nitrite nitrogen or NN. Also shown for each time point are: *P*-value of the overall F-test, significance level indicators for the individual treatment contrasts, and the pooled standard error (SE) for multiple comparisons. The numeric codes for indicating significance of individual contrasts are displayed in Table 2.



have fairly consistent soil and vegetative conditions. But their effectiveness in retaining runoff and its various components varied substantially among the five years that we sampled. For example, the effectiveness of the Old Grass treatment ranged from 64 to 99+ percent for bromide mass; 95 to 99+ percent for total suspended solids mass; and 15 to 25 percent for bromide concentration among the five measurement times 0.2, 1.1, 2.1, 8.1, and 9.1 years after plot establishment (Figures. 2a, 2b, and 3a, respectively). The effectiveness of the Crop treatment ranged from 45 to 82 percent for bromide mass; 79 to 95 percent for total suspended solids mass; and 13 to 21 percent for bromide concentration. Retention of bromide mass, a measure of infiltration of tank water and dissolved components, was the most variable of all components. Most of this variation appears to have a cause that is expressed on an inter-annual basis. Intra-annual variability, such as that caused by consecutive runoff events through its effect on antecedent soil moisture and remobilization of pollutants from within a filter strip (Coyne et al., 1998; Magette et al., 1989), was minimized in this study. The plots were irrigated in the same manner prior to each simulation event and the procedures were conducted only once per year to minimize remobilization of bromide tracer and other components by subsequent simulations.

The inter-annual variation observed in both Old Grass and Crop plots followed a pattern that may be related to large annual differences in soil moisture conditions. Antecedent soil moisture is an important determinant of infiltration rate in filter strips (Arora et al., 1996; Muñoz-Carpena et al., 1999). Higher retention of bromide mass was associated with drier weather in 1995 and 1997 (Table 3). Furthermore, in the very dry summer of 1995, soil cracks as large as 2.5 cm (1 in) wide and 70 cm (28 in) deep were noted in non-Crop plots that probably also enhanced infiltration. An annual pattern similar to bromide mass was apparent for the masses of all runoff components (Figure 2), probably due to infiltration of runoff water.

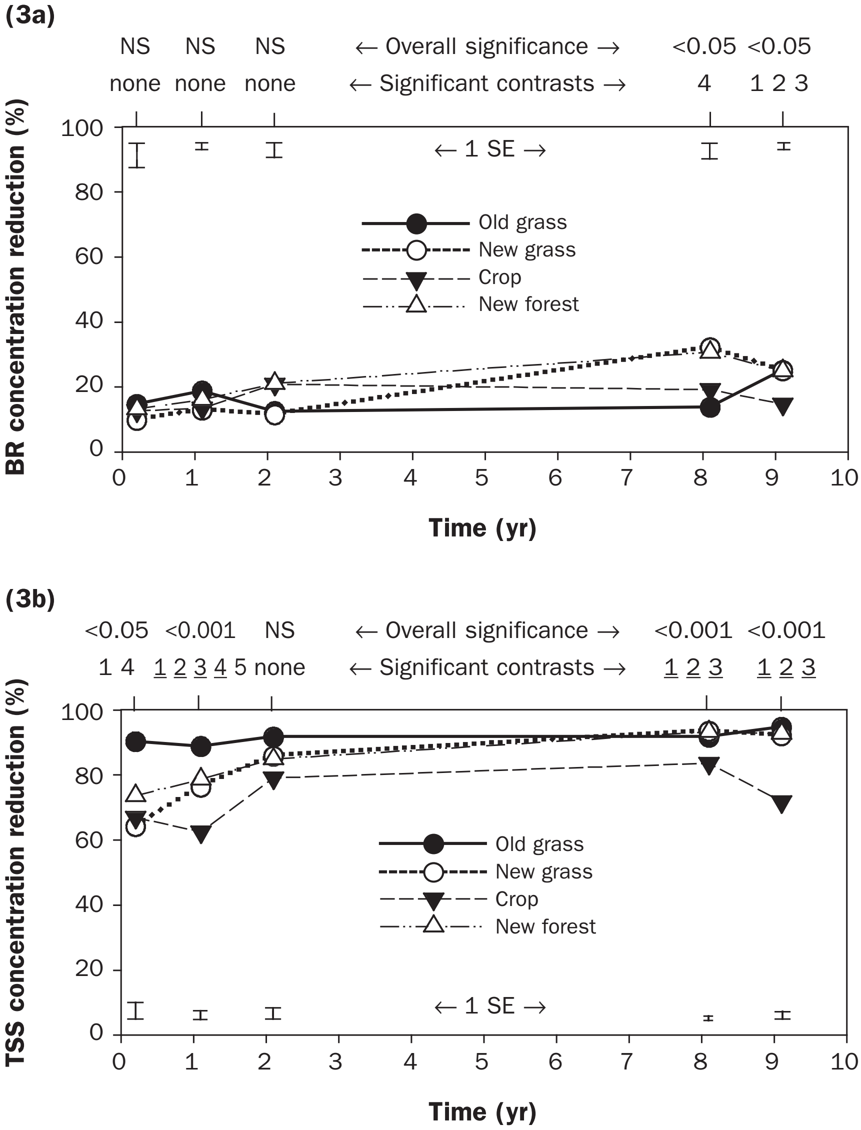
Deposition and dilution processes were not as variable among years as infiltration was. Deposition, as indicated by total suspended solids mass retained, was consistently high in all years (Figure 2b), due in part to the generally high infiltration that occurred. Dilution, as indicated by bromide concentration reduction, was consistently minor in all years (Figure 3a).

Longer-term performance of filter strips can be reduced by sediment accumulations that bury grass vegetation and create non-uniform runoff flow (Dillaha et al., 1989). However, significant sediment accumulations were not observed in our plots. The test loads that were used were small and runoff sediment from the adjacent crop field appeared to be mostly trapped by the 7 m (23 ft) of grass border between the field margin and the top of the plots. This study did not address sediment-accumulation and non-uniform-flow factors on filter strip performance.

The concentration of nitrate plus nitrite nitrogen was relatively enriched in plot outflow leading to negative reduction of nitrate plus nitrite nitrogen concentration in the first season of this experiment (Figure 3f). We do not have a clear explanation for this observation. Others have reported runoff enrich-

Figure 3 - a, b

Average percentage reduction in concentration of components from the tank source after passing through the 7.5 m-length plots as a function of time since plot establishment: (a) Bromide or BR, (b) Total suspended solids or TSS. Also shown for each time point are: *P*-value of the overall F-test, significance level indicators for the individual treatment contrasts, and the pooled standard error (SE) for multiple comparisons. The numeric codes for indicating significance of individual contrasts are displayed in Table 2.



ment by filter strip plots (Dillaha et al., 1989; Uusi-Kämppä et al., 2000) and attributed it to mobilization of contaminants from within plots (Magette et al., 1989). But, this pattern was not apparent for any other components that we tested (Figure 3) nor was it limited to any particular set of plot types. This anomaly occurred similarly for both new filter treatments and reference plots alike, including the Old Grass plots.

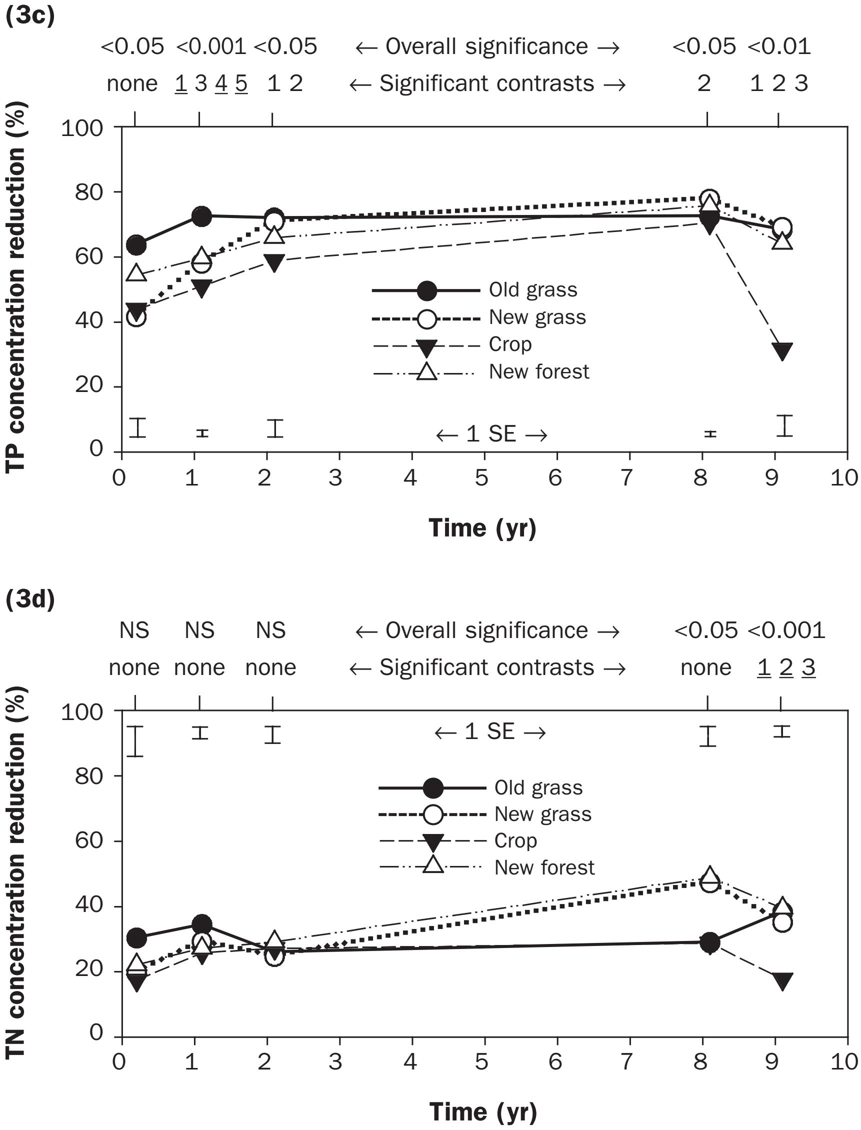
Change in effectiveness of new filter strips over years. Against the backdrop of year-to-year variability, relationships among the different vegetative compositions changed over time. Differences in effectiveness between vegetative compositions depended significantly upon time for most runoff components (Table 4). The exceptions included concentrations of bromide, total nitrogen, and nitrate plus nitrite nitrogen, where some overall change (increase) in effectiveness over time was detected, but a difference between vegetative compositions could not be distinguished.

Two months after establishment (0.2 years), the New Grass and New Forest filter strips performed significantly worse than Old Grass and Crop. The New filter strip plots retained significantly less runoff water (indicated by bromide mass) and masses of all components than Old Grass plots and of some components than Crop plots (overall $P < 0.01$ and contrast $P < 0.01$; Figure 2). Concentrations of runoff components in outflow from the New filters, however, were not significantly different from the reference plots (Figure 3). Relatively poor effectiveness of the New filters could have resulted from the slow establishment of vegetative cover on these plots. There was only 20 percent cover after 2 months due to drought in 1995. Runoff flowed quickly over the smoothed, relatively-bare ground of the New filter plots (Figure 4). By comparison, the denser ground cover and higher infiltration in the Old Grass plots were very effective at impeding runoff flow.

During the second growing season, at 1.1 years after establishment, the effectiveness of the New filters was not different than Crop (contrast $P > 0.01$), except for greater sediment deposition as indicated by greater reduction of total suspended solids concentration (overall $P < 0.001$ and contrast $P < 0.01$). By this time, the New filters had nearly complete ground cover and the rate of flow through the plots was similar to Crop (Figure 4). The effectiveness of the New filters was less than Old Grass for only total suspended solids and total P concentrations (overall $P < 0.01$ and contrast $P < 0.01$; Figures 3b and 3c). The similarity between results for total suspended solids and total P is probably because most total P was sediment-bound. Analysis of the tank solution shows that only 11 percent of total P was in dissolved (TDP) form (Table 1). Deposition would affect total suspended solids and total P similarly (Schmitt et al. 1999). By contrast, all nitrate plus nitrite nitrogen and bromide are dissolved, and at least half of total nitrogen is dissolved nitrate plus nitrite nitrogen. Most of the remaining total nitrogen is ammonium-N which is expected to be bound to sediments by cation exchange. The New filters were equally effective as Old Grass for dilution and infiltration processes which affect concentration and mass reductions of dissolved components, such as bromide and nitrate plus nitrite nitrogen.

By the third growing season, 2.1 years after

Figure 3 - c, d
Average percentage reduction in concentration of components from the tank source after passing through the 7.5 m-length plots as a function of time since plot establishment: (c) Total phosphorus or TP, (d) Total nitrogen or TN. Also shown for each time point are: *P*-value of the overall F-test, significance level indicators for the individual treatment contrasts, and the pooled standard error (SE) for multiple comparisons. The numeric codes for indicating significance of individual contrasts are displayed in Table 2.



establishment, there were no significant differences detected between the New filter plots and the Old Grass plots for any of the parameters that we measured (contrast $P > 0.05$; Figures 2, 3, 4). In fact, all of the vegetative compositions appeared to perform similarly (overall $P > 0.01$). The quantitative results for Crop total dissolved P concentration were anomalous, since Crop reduced it much more than any of the filter-strip treatments (Figure 3e). This result was relatively consistent among the five replicate Crop plots. There was no corresponding anomalous result for total P concentration, probably because total dissolved P is only a small fraction of total P.

In the ninth growing season, 8.1 years after establishment, there were no significant differences between New filters and Old Grass (overall $P > 0.01$ and/or contrast $P > 0.05$; Figures. 2, 3, 4). The New filter plots reduced total suspended solids concentration somewhat more than Crop plots (overall $P < 0.001$ and contrast $P < 0.01$; Figure 3b), but this difference was not reflected in retention of total suspended solids mass (Figure 2b).

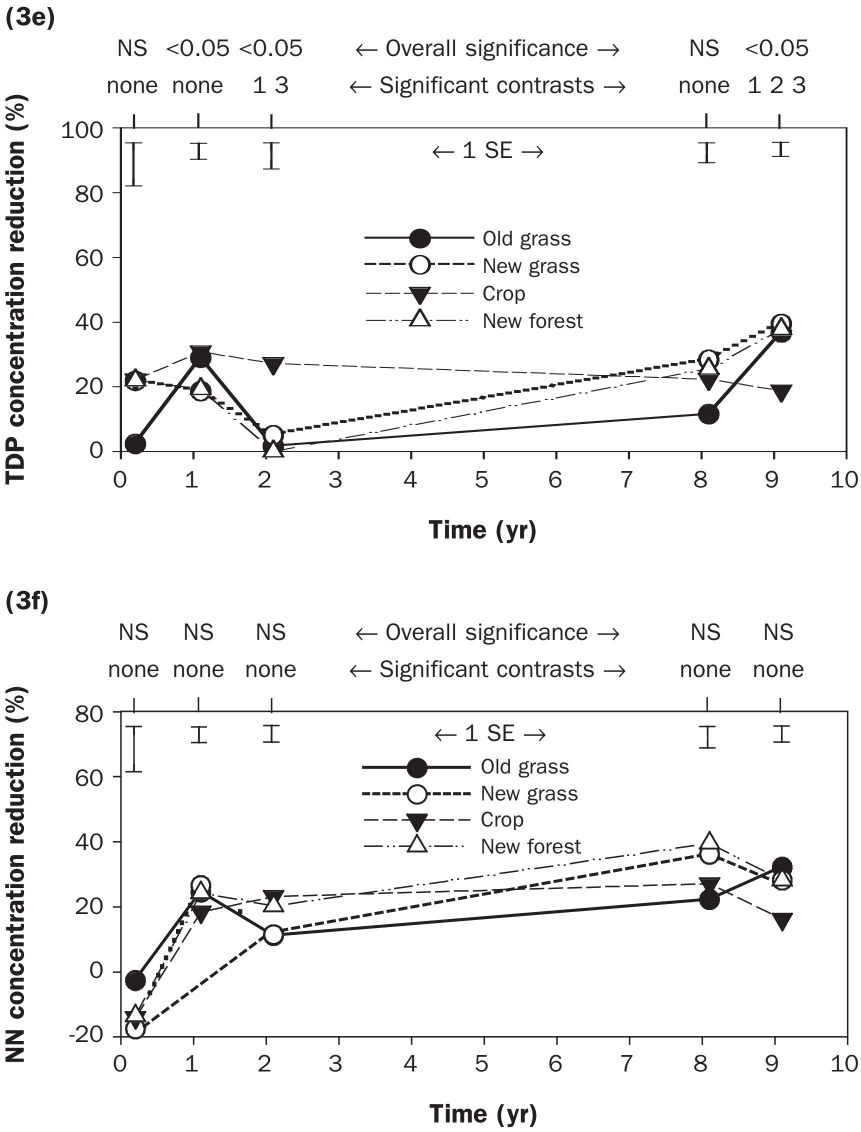
In the tenth growing season, at 9.1 years after establishment, the New filters and Old Grass performed similarly in every respect (contrast $P > 0.05$; Figs. 2, 3, 4). Furthermore, the New filters performed significantly better than the Crop treatment for total suspended solids and total P masses and total suspended solids concentration (overall $P < 0.01$ and contrast $P < 0.01$), and perhaps also for total nitrogen mass, total P concentration, through-flow time (overall $P < 0.01$ and contrast $P < 0.05$), and total nitrogen concentration (overall $P < 0.01$ and contrast $P < 0.01$, but vegetation x time $P = 0.10$; Table 4). Significant differences between Crop and the filter strip treatments seemed to appear abruptly in tenth season of this experiment mainly due to a steep decline in performance of Crop plots. A substantial reduction in furrow and ridge micro-relief from the ninth to the tenth growing season could cause this result, but we did not make this measurement.

The concentration of nitrate plus nitrite nitrogen was the only parameter that did not show *any* evidence of a difference in change over time among any of the vegetation treatments (vegetation x time $P = 0.81$ and $P > 0.05$ for overall and individual contrasts at all time points; Table 4 and Figure 3f). Questionable relationships were detected for total nitrogen concentration (vegetation x time $P = 0.10$; Table 4) and bromide concentration (vegetation x time $P = 0.66$; Table 4) for which some potential divergence was indicated between the New filter strip plots and the Crop plots at 9.1 yr (Figures 3d and 3a, respectively). In general, however, the vegetation compositions that we tested did not distinguish themselves greatly in their effects on concentrations of dissolved components of runoff.

Taken together, the results for all time points show a pattern that effectiveness of New filters improved over 10 years from an effectiveness level worse that Crop and Old Grass to a level better than Crop and similar to Old Grass. Most of the change toward similarity to Old Grass occurred within the first three growing seasons after establishment of the new filters. Infiltration properties changed the most, and had a large impact on the amount of runoff water and the masses of

Figure 3 - e, f

Average percentage reduction in concentration of components from the tank source after passing through the 7.5 m-length plots as a function of time since plot establishment: (e) Total dissolved phosphorus or TDP, and (f) Nitrate plus nitrite nitrogen or NN. Also shown for each time point are: *P*-value of the overall F-test, significance level indicators for the individual treatment contrasts, and the pooled standard error (SE) for multiple comparisons. The numeric codes for indicating significance of individual contrasts are displayed in Table 2.



runoff components. Smaller improvements were observed in component concentrations, mainly related to deposition of sediment. Dilution changed little, if at all, in the New filters over time.

These results confirm that there is improvement in the function of filter strips over a period of years that is associated with change in soil properties and vegetation after conversion from cultivation. While our test storm event was small compared to those that probably contribute most of the pollutant load to streams (Larson et al., 1997), relative differences among the treatments should be similar regardless of storm size (Arora et al., 1996; Lee et al., 2000; Misra et al., 1996). Large storm events, however, may or may not produce substantially smaller retention percentages than measured in this study depending on how much larger the storm event is and what kind of contaminant is being evaluated (Arora et al., 1996; Helmers et al., 2002; Jin and Römkens 2001; Lee et al., 2000; Misra et al., 1996).

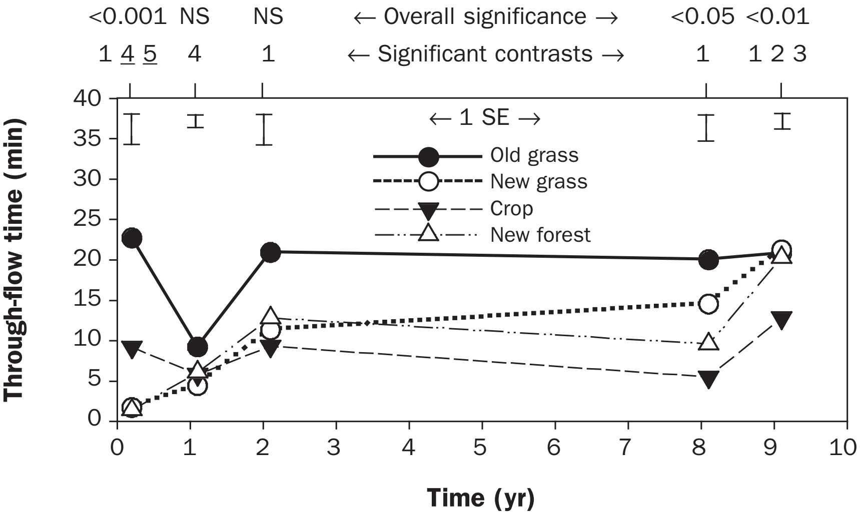
New grass versus new forest. Divergence in the effectiveness of New Grass and New Forest filter strips was not detected among any of the parameters that were measured. Contrasts between New Grass and New Forest plots for retention of water (as indicated by Br mass) and component masses (Figure 2) and reduction of component concentrations (Figure 3) were not substantially different, nor were there any apparent trends to that effect (overall $P > 0.05$ and contrast $P > 0.05$). These results clearly indicate that within the initial 10 years after filter strip establishment, there was no difference between the grass and forest vegetation compositions for filtering agricultural runoff. If some divergence between these vegetation compositions eventually occurs, then it would occur more than 10 growing seasons after establishment of the filter strips.

Lack of divergence between New Grass and New Forest plots may be attributed to important similarities in ground cover condition. Herbaceous ground cover established similarly in both vegetation treatments. By 8.1 years, there was dense grass in the New Grass plots and the upper half of New Forest plots, and only partial suppression of grass underneath the shrubs (1 to 3 m or 3 to 10 ft high) and trees (3 to 8 m or 10 to 26 ft high) in the lower portion of the New Forest plots. Only underneath the bush honeysuckle shrubs was herbaceous growth completely absent, amounting to only a 1 to 2 m (3 to 6 ft) portion of the 7.5 m (25 ft)-length of New Forest plots. So, despite the visually obvious development of fast-growing trees and shrubs on the New Forest plots, conditions at the ground surface were not different enough to create significant differences in effect on surface runoff.

This study did not directly compare trees to grass vegetation. The intent was to compare a grass filter strip (USDA, 1997) to a multi-species forest buffer design (Welsch, 1991; Schultz et al., 1995). In practice, it may be difficult to establish a tree-only filter because of the propensity for voluntary herbaceous undergrowth to become established among the trees, as happened in our plots. Consequently, a comparison between trees (alone) and grass may be academic, and our results are more-broadly applicable to forest and grass filters.

Figure 4

Time elapsed for the leading edge of tank solution to flow from the top of the 7.5 m-length plots to the outflow (Through-flow time) as a function of time since plot establishment. Also shown for each time point are: *P*-value of the overall F-test, significance level indicators for the individual treatment contrasts, and the pooled standard error (SE) for multiple comparisons. The numeric codes for indicating significant individual contrasts are displayed in Table 2.



Summary and Conclusion

From this analysis, we conclude that: Effectiveness filter strips can vary substantially from year to year, due in part to annual differences in antecedent soil moisture and related processes. Effectiveness of newly-established filters improves substantially over several years. In this 10 year study, new filter strips reached nearly full effectiveness within three growing seasons after establishment. If vegetative cover is not established quickly, however, initial performance may be worse than having no filter strip at all. Infiltration-related processes account for most of the improvement. Finally, grass and forest vegetation types are equally effective as filter strips for at least 10 growing seasons after establishment.

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