Sediment and Chemical Load Reduction by Grass and Riparian Filters

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ABSTRACT

Vegetated filter strips help reduce non-point source pollution from agricultural areas. Even though they are an accepted and highly promoted practice, little quantitative data exist on their effectiveness under field conditions. The objective of this research was to determine the amount of nutrients and sediment removed by natural and planted filters. This was achieved by collecting and analyzing runoff at field edges and at various locations in vegetated buffers. Total weight of sediment and nutrients in runoff from North Carolina agricultural fields showed that the grass and riparian filter strips studied reduced runoff load by 50 to 80%. Total sediment decrease through the filters was about 80% for both grass and riparian vegetation. The reduction in the chemical load depended on the nutrient and its form. Filters reduced total P load by 50%, but 80% of the soluble PO_4-P arriving at the field edge frequently passed through the filters. The filters retained 20 to 50% of the NH_4 and approximately 50% of the total Kjeldahl N and NO_3. High-volume flows commonly overwhelmed both grass and riparian filters next to cultivated fields. Forested ephemeral channels had little vegetation and were effective sediment sinks during the dry season but were ineffective during large storm events because there was little resistance to flow. When possible, drainageways should be designed to hold sediment and to disperse the discharge into a riparian area.

CONCERNS ABOUT AGRICULTURAL SOURCES of pollution have stimulated much research on Best Management Practices (BMPs) to control runoff from agricultural land. Vegetative filter strips are a proven practice for reducing sediment loads in surface runoff, and they are promoted by state and federal programs. The USDA Natural Resource Conservation Service has guidelines for VFS installation, but it has little quantitative information on their effectiveness for sediment and nutrient removal.

Available data show that VFS are ineffective where runoff is concentrated before entering the filter (Dillaha et al., 1987, 1988, 1989). Consequently, VFS are sometimes installed in areas where the soil and geomorphic conditions make their value very low.

In addition to constructed VFS, naturally vegetated or riparian areas occur next to many streams. Research in the early 1980s showed large removals of N from shallow groundwater by riparian vegetation. Jacobs and Gilliam (1985) found that NO_3–N in North Carolina Coastal Plain subsurface water decreased from >10 to <1 mg L^{-1} while passing through a 50-m-wide riparian zone. They estimated that 35 kg N ha^{-1} yr^{-1} entered the riparian zone and that <5 kg N ha^{-1} yr^{-1} left the watershed in stream flow. Lowrance et al. (1984) found that 52 kg N ha^{-1} yr^{-1} entered a riparian ecosystem in the Georgia Coastal Plain and only 13 kg N ha^{-1} yr^{-1} left in stream flow. Peterjohn and Correll (1984) estimated that the riparian zone they studied in Maryland removed 45 kg NO_3–N ha^{-1} yr^{-1} from subsurface flow. Cooke and Cooper (1988) reported similar observations for pasture land in New Zealand.

Riparian areas in a watershed remove much of the sediment leaving agricultural fields in surface runoff. Cooper et al. (1987) estimated that 90% of the sediment leaving agricultural fields in a North Carolina Coastal Plain watershed remained in the wooded riparian zone. Most of the sediment remained within 100 m of the field edge, indicating that relatively narrow buffers next to streams can effectively remove sediment. Lowrance et al. (1986) concluded that riparian ecosystems are important sediment sinks.

Riparian zones are less effective in removing P than either N or sediment. Cooper and Gilliam (1987) estimated that riparian areas in a North Carolina Coastal Plain watershed removed only about 50% of the P from runoff. Lowrance et al. (1984) found that riparian areas retain less P than Ca, Mg, or N. Phosphorus removal in the riparian areas of the New Zealand watersheds (Cooke, 1988) was also less than N removal. Riparian areas may be less effective in removing P than other potential contaminants, but P trapping is still very important. Phosphorus is generally the nutrient limiting algae production in freshwater bodies.

Many questions remain about the effectiveness of vegetated filters, but they are a water-quality BMP. Data have indicated that some planted filters are very ineffective and some do a very good job in removing pollutants from runoff. There is essentially no information on effect of type of vegetation (grass, forest, or weeds) on filter effectiveness. Much of the recent data on riparian vegetative filters is from Atlantic Coastal Plain soils.

Planted and natural vegetated filters should be effective in the North Carolina Piedmont because sheet and rill flow represent a major part of the runoff from Piedmont fields. However, the Piedmont area may have higher sediment loads because the slopes are steeper and infiltration is less than in the Coastal Plain. The purpose of this study was to determine the effectiveness of VFS in removing sediments and nutrients in the North Carolina Piedmont.

MATERIALS AND METHODS

The study was conducted at two locations representing different major soil-geomorphic systems in the North Carolina Piedmont. One location contains soils with sandy loam to clay loam surface horizons developed from felsic rocks. The predominant soil present is Cecil (clayey, kaolinitic, thermic Typic Kanhapludult). The other location contains mostly Georgeville soils (clayey, kaolinitic, thermic Typic Hapludults) developed from silty rocks of the Carolina Slate Belt. The

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Abbreviations: BMP, best management practice; VFS, vegetated filter strips; TKN, total Kjeldahl nitrogen.

Table 1. Properties of grass and riparian filters and their contributing watershed in the Cecil soil area.

Plot	Filter Vegetation	Flow length line no. 2	3	4	Filter slope Avg.	Max.	Watershed Length	Slope Avg.	Max.	Run-off events
		— m —			— % —		m	— % —		no.
1	Fescue	3	6		4.9	10	84	1.2	2	26
2	Fescue	3	6		2.1	8.8	86	1.1	2.2	35
3	Fescue & field lane groundcover†	5	13		3.3	7.7	48	9.7	14	50
4	Fescue & field lane trees	7	18	27	4.1	6.8	53	7.7	9.6	35

† Groundcover of weeds and vines.

Georgeville soils have silt loam to silty clay surface horizons. Both study areas have broad, gently convex uplands. The valley slopes are 4 to 15% and grade to first and second-order ephemeral and intermittent stream channels.[1]

Runoff was monitored from cultivated fields at four sites in the Cecil soil area at the field edge and through the filter. Runoff from all fields entered fescue (*Festuca arundinacea* Schreb.) (Table 1). The runoff from two fields flowed through a narrow strip of fescue, across a field lane, and then into either a groundcover (Plot 3) or a cover of mixed hardwood and pine trees (Plot 4). The runoff from the other two fields entered a grass waterway after flowing through the fescue filter. The fescue cover was 80 to 100%. The riparian area was a mixture of weeds and small shrubs where the runoff water entered and larger trees within a few meters of the edge. The riparian area had a continuous layer of tree litter.

Figure 1 shows the arrangement of the field and grass filter, and locations of sample collection devices for one site in the Cecil soil area. Runoff from the field rows was by sheet and rill flow. The collectors were 3 m apart at the field edge and placed to collect runoff from between two field rows. Within the grass filter areas, the collectors were spaced 3 and 6 m downslope from the field edge. The collectors downslope were placed in two lines perpendicular to the filter slope (not necessarily perpendicular to the field edge). The distances between lines of collectors varied in the riparian areas to conform with the local topography, but all plots had three lines of three samplers if the topography was suitable.

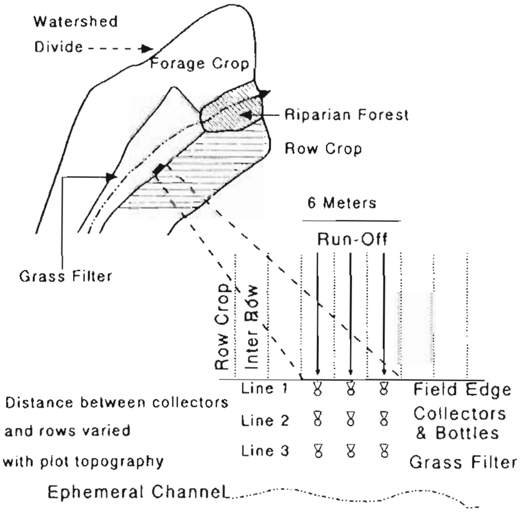

Fig. 1. Typical relationship of field rows, collectors and filter area to ephemeral channels in the Cecil soil area. Sheet and rill flow from the field passed directly into the filter. Runoff from two plots flowed through grass to the channel. Two plots had initial flow through grass and final flow through riparian vegetation.

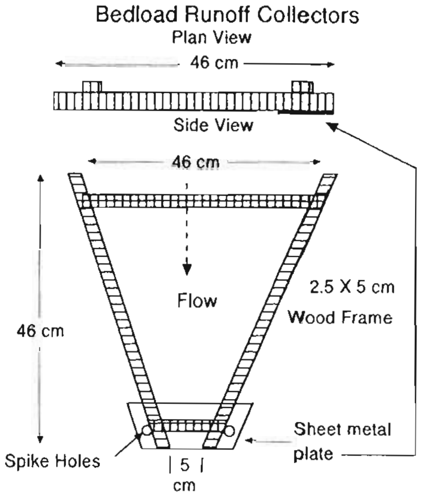

Fig. 2. Plan and side view of wooden triangle used to funnel water to a sample bottle.

The three fields monitored in the Georgeville soil area had collectors in the channel at the field edge and in the adjacent floodplain. The collectors were placed at the field edge and downstream to the junction with a higher order channel. Distances between collectors varied considerably among the three channels. An ephemeral channel and narrow flood plain with hardwood trees and sparse understory accepted the runoff from two fields. A third channel had a similar hardwood vegetation and sparse understory, but the downstream area did have some base flow during the winter months.

At all locations in the Georgeville soil area, the field runoff spread onto a narrow floodplain during major runoff events. Water quality samplers were located in the narrow flood plain at the field edge and downstream. The flood plain had a sparse, discontinuous groundcover. The overstory was largely hardwoods native to the site.

The samples for water quality analysis were taken using a V-shaped passive collector, which directed flow to a funnel and into a buried 1-L bottle with a floating plastic ball (Fig. 2 and 3). The plastic ball closed the mouth of the bottle when

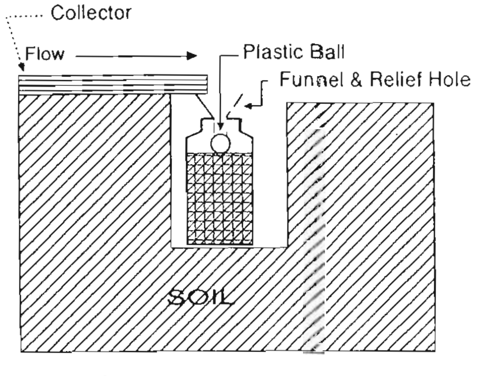

Fig. 3. Side view of sampling triangle, bottle, and funnel.

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[1] A first-order channel has no entering channels; it is not branched. A second-order channel starts where two first-order channels join. Stream order varies with the scale of observation. An ephemeral channel is one that flows only during or shortly after storms. It has no base flow from groundwater seepage. An intermittent channel has base flow during the wet part of the year.

it filled and prevented additional entry of sediment or water. A hole above the stem of the funnel allowed excess runoff to drain, although during large storms sediment filled the funnel. A 6-mm screen placed over the top of the funnel reduced the amount of plant material and gravel entering the bottle.

Runoff samples collected in the field were transported to the laboratory within 18 h of each runoff event and stored at 4°C until analysis. Unpublished data from our laboratory shows insignificant changes in NO_3-N and NH_4-N in runoff samples placed in a refrigerator within 24 h of runoff events.

The sample was poured through a nest of sieves to separate the sand from silt and clay after gentle hand shaking for 15 s for dispersion. An aliquot of the sieved mixture was dried and weighed to determine the amount of silt + clay. The dried sand fraction included varying amounts of non-water-dispersable silt + clay. Total sample weight less total sediment determined the volume of water.

An aliquot of stirred whole sample was taken for digestion in a solution of H_2SO_4, K_2SO_4, and $CuSO_4$ at 350°C for 6 h after the solution cleared (total digestion time $\approx$ 10 h). Digest was brought to a volume of 100 mL and an aliquot was taken for determination of total P using the procedure described by Murphy and Riley (1962). Ammonium was distilled from another aliquot, collected in H_3BO_3, and titrated to obtain TKN of runoff samples (Smith, 1980).

Runoff samples were filtered through Whatman no. 42 filter paper, which gave a clear filtrate on which NO_3-N, NH_4-N, and PO_4-P were determined. The procedure of Lowe and Hamilton (1967) was used for NO_3, NH_4 was determined using the procedure of Smith (1980), and orthophosphate by the Murphy and Riley (1962) method.

Results of 2 yr of monitoring runoff are reported. Within a location it was not unusual for runoff to occur at some plots and not at others because of differences in management or vegetation. This variability in runoff among plots resulted in a range of 26 to 50 events at the four Cecil soil area plots and 6 to 18 at the Georgeville soil area plots.

RESULTS

The weight of sediment, P, and N measured in runoff varied considerably from storm to storm, but usually decreased with distance from the field edge in the Cecil soil area filters, where sheet flow dominated. During the 2 yr of monitoring, 60% of the rainfall events were <25 mm and 90% were <50 mm. Two storms delivered between 50 and 100 mm of rainfall.

Rainfall events <15 mm produced little runoff and few samples. Most rains of 25 to 30 mm filled collectors at the field edge but left many of the second and third row of collectors empty. Only large storms filled all collectors.

Runoff Water Quality from Sheet Flow in the Cecil Soil Area

Data are presented as changes in runoff sediment and chemical quantities in the runoff water as it entered and moved through the filters. All changes of properties relate to the runoff composition at the field edge. To give some idea of the variability within a row, Fig. 4 shows the TKN by collector during the 2-yr study for one plot. The same general variability and changes with increasing distance from the field edge hold for sediment and chemical properties of runoff in all four planted filter sites.

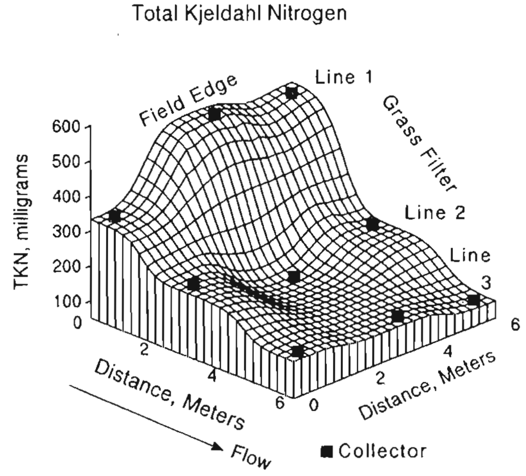

Fig. 4. Total Kjeldahl N delivered to each collector in Plot 2 during the 2-yr study.

A 60-mm rainfall event on 31 Oct. 1988 had considerable influence on the total sediment and, to a lesser extent, P reduction by the filters. This 17-h storm came after cultivation or planting of the fields to wheat (*Triticum aestivum* L.) or a winter cover crop. The storm occurred 4 d after a 15-mm rain. The intensity was not exceptionally high, but it increased throughout the event. This storm produced 60 to 70% of the total sediment and 60 to >90% of the total silt + clay collected during the study period (data not shown). The variability was large between plots, but this storm produced from 2 to 20% of the total P and from 4 to 40% of the soluble PO_4-P collected during the study. The watersheds were extremely vulnerable to erosion at the time that the largest storm occurred, so data are reported as the total sediment and silt + clay collected at each distance from the field

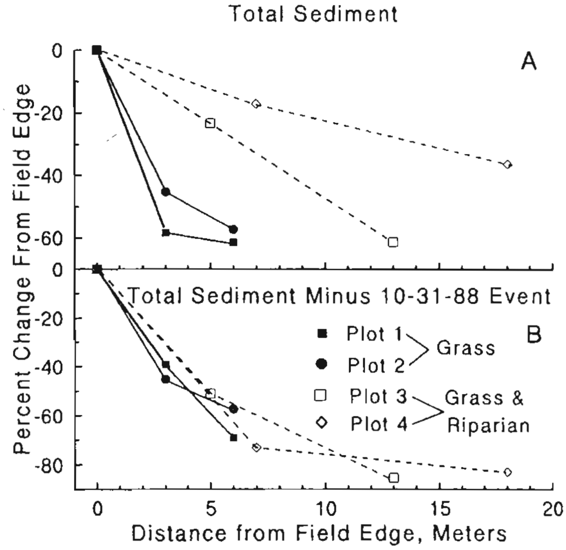

Fig. 5. Filter reduction of total sediment delivered to the field edge in the Cecil soil area during 2 yr: (A) total sediment and (B) total sediment minus 31 Oct. 1988 storm.

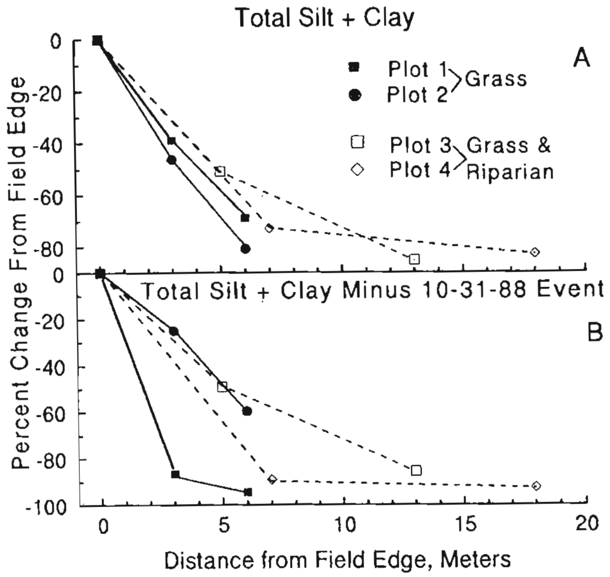

Fig. 6. Filter reduction of silt + clay delivered to the field edge in the Cecil soil area during 2 yr: (A) total silt + clay and (B) total silt + clay minus 31 Oct. 1988 storm.

edge including and excluding this storm (Fig. 5 and 6). Figures were not made for P without this one storm because the effect on P reduction was in the same direction as sediment, but not as dramatic.

The filters reduced total sediment by 30 to 60% (Fig. 5). When eliminating sediment from the 31 October event, the filters reduced total sediment by 55 to 82% (Fig. 5). From 48 to 64% of the total sediment delivered to the field edge was silt + clay (Table 2). The filter strips reduced total silt + clay by 60 to 93% when the 31 Oct. 1988 storm is left out, and by 60 to >80% when including this storm (Fig. 6). The greater the distance the water flowed through the filters, the greater the removal of both total sediment and silt + clay (Fig. 5 and 6), although the removal of sand was greater than the removal of silt + clay as indicated by the progressive increase in proportion of silt + clay with flow distance through all filters (Table 2).

Filters removed about 60% of the total P delivered at the field edge (Fig. 7), but reduced soluble PO_4-P a maximum of approximately 50%. The runoff water at Plot 3 (Fig. 7) had a large increase in soluble P as it passed through the filter. We have no explanation for the increase measured. The filter was downslope from a field road but other sites also had field roads above the filter. The changes in soluble P were variable throughout the sampling period and no one storm was responsible for the increase.

Table 2. Silt and clay percentage of total sediment related to filter length in the Cecil soil area.

Distance from field edge	Silt + clay			
	Grass filter plots		Grass and riparian filter plots	
	1	2	3	4
m	%			
0	59	48	58	64
3	61	79		
5			70	
6	80	84		
7				78
13			83	
20				79

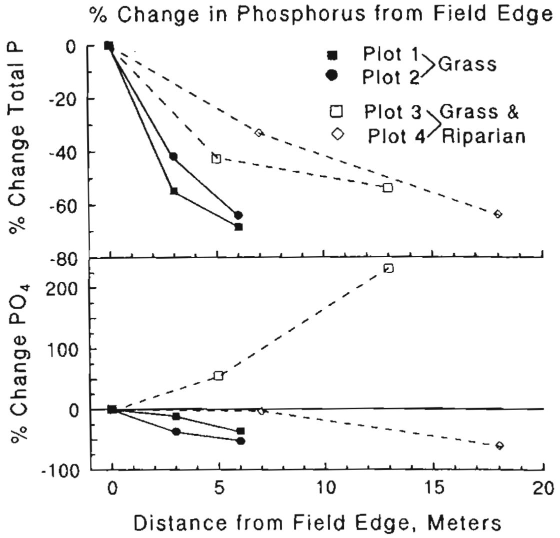

Fig. 7. Filter reduction of total P and soluble PO_4-P delivered to the field edge in the Cecil soil area for all storms.

The filters in the Cecil soil area reduced total Kjeldahl N 35 to 60% or more as the runoff moved through the filters (Fig. 8). Plot 4 had the lowest decrease in Kjeldahl N. At Plot 4, the last row of runoff collectors was in a wooded area with a thick duff layer. Apparently some trash and organic material was incorporated in the runoff through the thick oak and pine duff. Ammonium changes across the filter areas were erratic; three plots showed decreases of 20 to 50% but Plot 3 had an increase. Nitrogen fertilizer was applied to the upslope watershed of Plot 3 just before a storm on 9 July 1987. Without

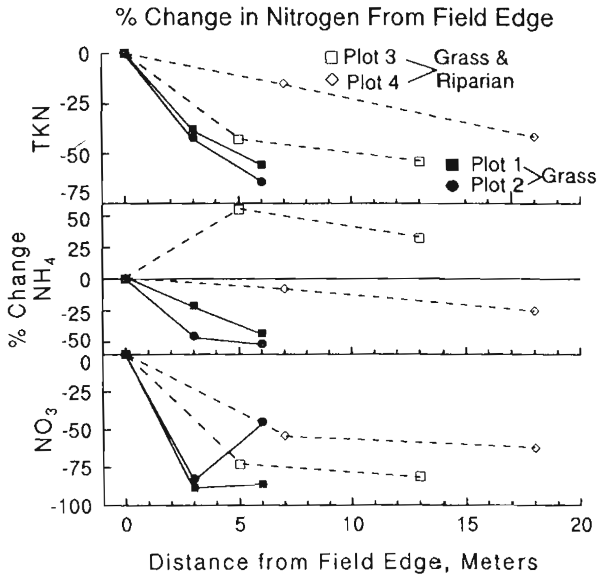

Fig. 8. Filter reduction of total Kjeldahl N, NH_4, and NO_3 in the Cecil soil area compared with the field edge for all storms.

that one storm, the NH_4 changes would have shown a decrease, as did the other three sites.

Nitrate changes ranged from about 50 to 90% across the filters. Nitrate changed very little in runoff where samplers were >7 m from the field edge. The one exception is Plot 2 where NO_3 increased from 3 to 6 m from the field edge.

Runoff Water Quality in Filters with Concentrated Flow in the Georgeville Soil Area

Figures 9 and 10 show the changes in runoff water quality and base flow from Channels 1 and 2 in the Georgeville soil area. Data collection of a third channel was abandoned because the watershed was grassed shortly after installation of the study.

The channel in Fig. 9 (no. 1) is a losing system. During runoff periods, the flow volume decreased downstream so that flow reached the main stream only during high-intensity runoff. About 20 to 30% of the area in the wooded riparian area downstream from the field border was bare soil. The vegetation was sparse, as was the cover of hardwood leaves, especially during the late spring and summer. The channel was not incised so runoff spread over a wide area. Our observations at this and other locations suggest that summer vegetation and litter in an ephemeral channel under a continuous hardwood canopy offers little resistance to flow.

Figure 9 shows the changes in sediment and nutrient levels from concentrated flow as it passed from a corn (*Zea mays* L.) and alfalfa (*Medicago sativa* L.) watershed into a forested low-gradient losing channel. This channel never had base flow and the adjacent floodplain soils were well to moderately well drained. Stream order did not change throughout the length shown. There was little change in P or silt + clay throughout the channel. The accumulated weight of TKN and NH_4 was variable downstream from the field edge in the 330 to 450 m of the forested part of the channel. Total sediment, largely sand, increased downstream in the forested area. The increase in sediment probably was from bed scour during heavy flows because the groundcover was discontinuous. It is important to remember that only the largest flows ever reached the main stream through this channel.

Channel 2 (Fig. 10) received runoff from an ephemeral channel in a cultivated field. The filter areas had a sparse vegetative cover of grass and weeds near the entry point, but only leaf litter and scattered plants downstream in the base-flow area. About 20 to 30% of the area was bare soil 10 or more meters from the entry point. The channel downstream from 10 m was incised 15 to 30 cm below the floodplain. This channel had some base flow during wet periods. During periods of base flow, the water volume increased downstream.

The gaining channel (Fig. 10) had little downstream change in total weight of P but an increase in N. Runoff in this channel had an initial increase in total sediment (largely sand) after leaving the field edge (Fig. 10). Channel scour was responsible for the increase within the first 20 m from the field. However, there was a decrease in total sediment weight as the water flowed through the 75-m-long filter area.

DISCUSSION AND CONCLUSIONS

Grass and grass–riparian filter strips in the Piedmont that receive sheet and rill flow reduce the sediment and chemical load of field runoff. The effectiveness varies with the erosiveness of the watershed and storm intensity, but across a wide range of rainfall, filter strips reduce sediment load about 60 to 90% (Fig. 5 and 6). Filter strips reduce runoff nutrient loads less than sediment load, especially for the soluble forms. Reduction of P and N is near 50% for NO_3, TKN, and total P (Fig. 7 and 8). High-energy storms occurring when the water-

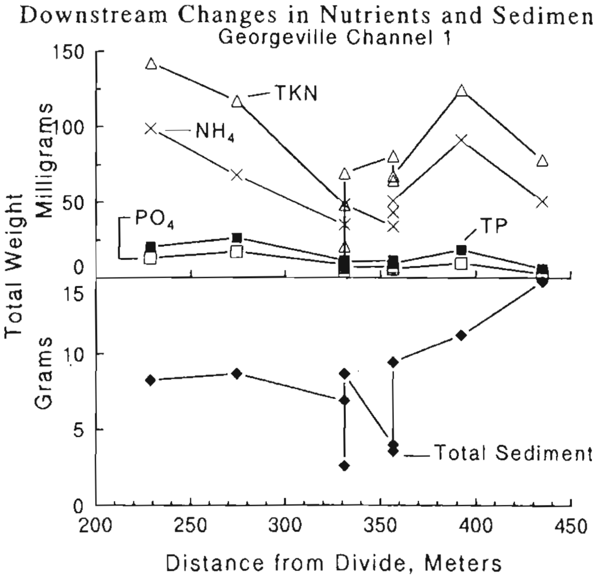

Fig. 9. Downstream changes in nutrients and sediment load in a losing ephemeral channel (Georgeville soil area, Channel 1; the three data points at distances 330 and 360 m are replications).

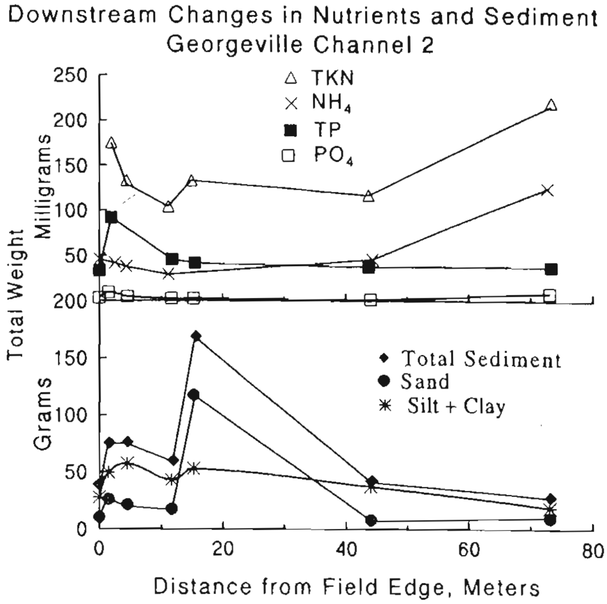

Fig. 10. Downstream changes in total weight of nutrients and sediment from field runoff and base flow for a gaining channel (Georgeville soil area, Channel 2).

sheds have little cover can overwhelm the filter receiving sheet or rill flow.

All sheet flow data collected were from footslopes with gentle to moderate slopes (Table 1). The decreasing slope into the filter would reduce sediment load without any cover if sheet flow dominated. We doubt that extrapolation of the results from footslope filters to valley-side filters of greater slope is valid. Valley-side filters would reduce sediment load, but probably not to the extent shown by our data.

Grass filters with a width of 6 m receiving sheet flow (Plots 1 and 2 of Cecil soil area) were as effective as grass and riparian filters with greater widths that had a field lane between the grass filter and the riparian system (Plots 3 and 4 of Cecil soil area). Traffic on the field lanes during the wet seasons at Plots 3 and 4 exposed bare soil and served as a secondary field edge or sediment source.

Nutrient and sediment load of runoff from cultivated fields concentrated in drainageways changed very little downstream in the hardwood riparian systems studied (Fig. 9 and 10). These small channels have little or no vegetation, drain 10 to 20 ha, and have narrow floodplains. The major impediment to flow during winter and early spring is the concentration of leaves in and next to the channel. These riparian channels and floodplains have only a sparse vegetative cover and during periods of high runoff usually scour their channels. Ephemeral riparian channels need a continuous vegetative cover to be effective filters, an impossibility beneath a full canopy of oak and pine. Our data suggest that most of the filtering action from concentrated flow is in the nearly continuous grass cover of the field channel at the exit point, not in the riparian zone of the channel.

Grass or a combination of grass and riparian vegetation on footslopes receiving sheet flow can reduce the amount of sediment and chemicals reaching the stream channel in runoff (Fig. 5–8). Riparian systems associated with upland ephemeral channels (Fig. 9 and 10) do not effectively reduce sediment or chemical loads from concentrated flow except in losing systems where flow seldom reaches the main stream (Fig. 9). Concentrating runoff in grass drainageways and then discharging it into a small channel in the upland riparian system was not effective in reducing sediment and nutrient load in our study because there is little to impede flow. The concentrated flow needs to be dispersed onto the adjacent floodplain to reduce the energy and flow velocity.

Designing a drainageway to hold sediment, not transport it, is desirable. However, this would require frequent rebuilding of the drainageway. One possible approach to this problem would be to disperse the runoff from the drainageway or ephemeral channel at the footslope so the grass and riparian system could function without being overloaded.

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