MANAGEMENT EFFECTS ON RUNOFF AND SEDIMENT TRANSPORT IN RIPARIAN FOREST BUFFERS

J. M. Sheridan, R. Lowrance, D. D. Bosch

ABSTRACT. *The effectiveness of mature riparian forests in reducing the impact of agriculture on the quality of the nation's water resources has been documented, but the impact of forest management practices implemented within riparian forest buffers on their water quality function has not been evaluated. This article examines the effect of forest management within a Coastal Plain riparian forest buffer system (RFBS) on runoff and sediment transport over a four year period. The RFBS, which conformed to USDA-FS and USDA-NRCS best management recommendations, included a narrow strip of undisturbed forest located adjacent to the stream drainage system (Zone 1), a wide managed pine forest downslope from the grass filter (Zone 2), and a narrow grass filter strip immediately downslope from an agricultural field (Zone 3). Forest management treatments evaluated within Zone 2 were mature forest, clear-cut, and selectively-thinned. Significant reductions in runoff and sediment transport were measured under all three forest management treatments. The primary zone of runoff and sediment reduction was within the grass filter portion of the RFBS. These results indicate that riparian forests within a RFBS may be managed for economic return to the land owner without adversely affecting the runoff and sediment reduction function performed by these buffer systems.*

Keywords. *Forest management, Riparian forests, Riparian forest buffer system, Nonpoint source, Pollution, Water quality.*

Nonpoint source (NPS) pollution is considered one of the most serious forms of contamination threatening the nation's water resources, and agriculture accounts for up to two-thirds of this pollution (Long, 1991). Consequently, emphasis has been placed on development of best management practices, or BMPs, that limit movement of pollutants from agricultural areas. While on-site BMPs reduce pollutant transport from agricultural sources in many cases, on-site BMPs are not adequate to meet national water quality goals in all situations (Clausen and Means, 1989). For example, in humid climatic regions, high-intensity rainfall events can result in storm runoff and erosion with significant pollutant transport off-site and subsequent adverse downstream environmental impacts. Vegetative buffers have received considerable attention as a means of reducing transport of NPS pollutants in runoff from agricultural areas. Riparian forests are a type of vegetative buffer that has shown potential for reducing agricultural NPS pollutants reaching stream drainage networks and, depending on local geology, regional groundwater supplies.

Early research on the quality of streamflow from agricultural watersheds in the Gulf-Atlantic Coastal Plain indicated the magnitude of the role of existing, mature riparian forests in reducing transport of agricultural NPS pollutants (Asmussen et al., 1979; Sheridan et al., 1982; Yates and Sheridan, 1983). Subsequent research at several locations in the Coastal Plain provided an understanding of the physical, biological, and chemical processes that remove NPS pollutants from surface runoff and subsurface flows, as well as the potential for management of agricultural NPS pollution by riparian forest buffers (Lowrance et al., 1983, 1984, 1986; Peterjohn and Correll, 1984; and Jacobs and Gilliam, 1985). The capacity of mature riparian forests within the Coastal Plain for reducing NPS pollution of surface and groundwater supplies by sediment and agrichemicals has been well documented (Gilliam, 1994; Lowrance et al.,1995).

Understanding the beneficial environmental effects of riparian forests has led to development of national standards by USDA-Forest Service (FS) for use of Riparian Forest Buffer Systems (RFBS) for reduction of agricultural NPS pollution (Welsch, 1991). These standards are also currently recommended by the USDA-National Resource Conservation Service (NRCS). The standards specify a riparian buffer system consisting of three distinct functional zones, including; a narrow zone of undisturbed forest adjacent to the stream channel (Zone 1), a wider intermediate zone of managed forest (Zone 2), and a narrow grass filter strip adjacent to the agricultural area (Zone 3).

Recommendations for management of RFBS permit removal of mature trees from Zone 2 on appropriate rotations using standard silvicultural practices. Although previous research has demonstrated the effectiveness of mature riparian forests as sediment and agrichemical filters, little is known about the impact of forest

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management within Zone 2 on the water quality control or mitigation function of the buffer system. Research is needed by federal action and regulatory agencies such as USDA-FS, USDA-NRCS, and U.S. Environmental Protection Agency and by various state agencies to determine the impact of forest management within Zone 2 and to establish specific management recommendations with a strong scientific basis. This information would contribute to guidelines for integrating RFBS into agricultural production systems to provide long-term, sustainable water quality enhancement for surface and groundwater supplies.

This study was designed to examine the impact of forest management on runoff and sediment transport across a riparian buffer system under three Zone 2 forest management practices; mature forest, clear-cut, and selectively thinned. The study is part of a cooperative study between USDA and the University of Georgia begun in 1991 to develop an understanding of the processes associated with NPS pollutant transport within riparian areas on agricultural landscapes and the role of RFBS for reducing NPS pollution of surface and groundwater supplies by sediment, nutrients, and herbicides from agriculture production areas.

The specific objectives of this study were to: (1) determine runoff and sediment transport across a forest buffer system on a Coastal Plain riparian landscape under the three Zone 2 forest management practices; (2) determine differences in seasonal and spatial patterns of runoff and sediment transport under the alternative forest management scenarios; and (3) determine the functional efficiency of the RFBS and the time to buffer function recovery (i.e., restoration of effective control of NPS agricultural pollution) after tree harvest operations. Evaluations of impacts of management on subsurface flow regimes and subsurface agrichemical transport, as well as herbicide transport in surface flows within the riparian forest study area, are presented in separate articles (Bosch et al.,1994,1996; Hubbard and Lowrance, 1996; Lowrance et al., 1997).

BACKGROUND

The Gulf-Atlantic Coastal Plain physiographic region extends from Virginia into Texas. The region, which includes about 70% of the land area of the southeastern U.S., contains major groundwater aquifers with extensive recharge areas near the inner margin of the region. Agriculture is an important economic activity of the Gulf-Atlantic. The combination of high annual rainfall and intense storm events, permeable surface soils, high agricultural land use with multicropping and extensive agrichemical use, and shallow groundwater resources makes the region susceptible to contamination of surface and groundwater supplies by agricultural NPS pollutants despite use of recommended on-site BMPs. Previous research has established that mature riparian forests, a characteristic feature of the Gulf-Atlantic landscape, can be effective in reducing or controlling nutrient and sediment transport in runoff from agricultural lands. Riparian forests are frequently the only remaining forest on the Coastal Plain agricultural landscape. Typically, agriculture occupies well-drained upland soils, while poorly drained, low-lying areas are occupied by naturally occurring riparian forests. Riparian buffers are particularly effective when pollutant movement is by diffuse, non-concentrated overland flow or by shallow subsurface flow (Schnabel et al., 1994). These conditions are present in much of the Gulf-Atlantic Coastal Plain of the southeastern U.S.

Riparian forest buffer standards, developed by the USDA-FS in consultation with the USDA-Agricultural Research Service and other research organizations (Lowrance, 1991; Welsch, 1991), recommend a three zone buffer system that can be briefly described as follows:

- *Zone 1* is a narrow zone of permanent, native riparian tree and shrub vegetation located adjacent to, or including, the stream channel. Zone 1 provides stream bank stabilization, moderation of stream temperatures by shading, as well as woody debris inputs to the stream ecosystem. Zone 1 is limited to sheet flow (diffuse surface runoff) or subsurface flow only; concentrated surface flow must be converted to sheet flow prior to entering Zone 1.
- *Zone 2*, the primary zone of pollutant removal, is a managed forest zone immediately upslope from Zone 1. Zone 2 provides opportunity for infiltration of surface flows and deposition of sediment and sediment-borne pollutants, as well as reduction of nutrients and other agrichemicals by vegetation uptake, denitrification, and other microbial processes. Periodic harvesting of timber is required to remove nutrients and pollutants sequestered in riparian forest growth. Zone 2 is limited to shallow, sheet flow or subsurface flow only.
- *Zone 3* is an herbaceous filter strip located upslope from Zone 2, adjacent to the agricultural field. The primary purpose of Zone 3 is spreading concentrated storm flow, thereby providing greater infiltration as well as increased settling and deposition of sediments prior to flows entering Zone 2. While flow spreading is recognized as a primary Zone 3 function, use of appropriate in-field BMPs are also critical to reducing concentrated flow entering the buffer system. Vegetative growth in Zone 3 requires periodic harvest or removal of biomass.

The potential effectiveness of the riparian buffer system is indicated by previous research on mature riparian forests and grass filter strips. Zones 1 and 2 of the buffer system may be considered analogous to existing mature riparian forest, and Zone 3 to a vegetated grass filter strip. Previous research on sediment transport in streamflow from Coastal Plain watersheds with mature riparian forests reported 84 to 95% reductions when sediment loads in streamflow were compared to sediment loads at the field edge (Sheridan et al., 1982; Lowrance et al., 1986; Cooper et al., 1987), with significant deposition occurring near the field-forest interface. Near-stream riparian vegetation also provides beneficial effects on streambank stability, biological diversity and stream temperatures (Karr and Schlosser, 1978).

The potential of Zone 3 for infiltration of storm runoff and for deposition of sediment is indicated by available research on grass filter strips. For shallow, non-concentrated flows, relatively short herbaceous filters have been shown to slow runoff and remove sediment and sediment-bound pollutants. Reported trapping efficiencies ranged from 70 to 94% (Asmussen et al., 1977; Neibling and Alberts, 1979; Dillaha et al., 1989; Magette et al., 1989). Primary concerns regarding grass filter strip performance relate to long-term effectiveness for sediment control (Dillaha et al., 1989; Magette et al., 1989).

METHODS AND MATERIALS

STUDY AREA DESCRIPTION

Location. This research was conducted at the Gibbs Farm located near the University of Georgia Coastal Plain Experiment Station at Tifton, Georgia. The Gibbs Farm Site (GFS) is located in the Tifton-Vidalia Upland (TVU) of the Gulf-Atlantic Coastal Plain. The GFS riparian forest is considered representative of mature riparian forests found throughout the TVU of Georgia and South Carolina.

Climate. The climate is humid subtropical (Strahler, 1975) with long, warm summers and short, mild winters. Precipitation occurs almost exclusively as rainfall, with an annual mean of 1208 ± 214 mm (1922-1988) at Tifton, Georgia (Sheridan and Knisel, 1989). Rainfall distribution within the year is highly variable, although the fall months are typically dry. Rainfall is generally greatest in the spring and summer months when convective thunderstorms occur associated with cyclonic storms. Heavy rainfall may occur in the late summer and fall months as a result of tropical storms. Low-intensity frontal events with moderate rainfall amounts are typical of winter and spring months. The annual mean temperature is 19.1°C, with a monthly mean minimum of 4.2°C in January and a monthly mean maximum of 32.7°C in August (Crosby et al., 1970).

Soils. The soil in the riparian forest is an Alapaha loamy sand (fine-loamy, siliceous, acid, thermic *Typic Fluvaquents*) on a 3.5% slope. The soil of the adjacent cropped upland area is a Tifton loamy sand (fine-loamy, siliceous, thermic, *Plinthic Kandiudult*) on a 2.5% slope (Calhoun, 1983). The cropped upland field at the GFS contains a restrictive subsurface argillic horizon at 0.5 to 1.8 m which directs subsurface flow into the study area (Bosch et al., 1994).

General Hydrology. Permeable surface soils in the TVU permit rapid infiltration of rainfall, thereby limiting production of runoff, particularly from well-drained upland soils. Deep seepage and recharge to regional groundwater aquifers is limited, however, by relatively impermeable shallow subsurface horizons consisting of plinthic materials and a confining geologic unit (the Hawthorn Formation). Therefore, excess precipitation in the TVU moves to drainage networks as surface runoff during storm events or as lateral shallow saturated or unsaturated subsurface flow. Hydrologic response characteristics for Coastal Plain watersheds demonstrate distinct seasonal patterns with relatively high runoff production for the first four months of the year (Sheridan, 1997).

Riparian Buffer System. A three-zone riparian buffer system that conforms to USDA-FS specifications was established at the GFS starting in late 1992 (fig. 1). Zone 3, an 8-m grass filter strip, was established during summer 1991, and winter 1991-1992. Zone 3 was seeded in common Bermudagrass (*Cynodon dactylon* L. Pers.) and Bahiagrass (*Paspalum notatum* Flugge). The grass strip was also interplanted with perennial ryegrass (*Lolium perrene* L.) to provide biomass production and nutrient uptake during the first winter. Biomass was harvested from Zone 3 twice annually, however standing biomass was retained during all times of the year. Vehicular traffic was not allowed on the grass filter. Zone 2 is a 45- to 55-m-wide band of managed forest which, prior to timber harvest, consisted primarily of slash pine (*Pinus elliottii* Engelm.) and long leaf pine (*Pinus palustris* Mill.) about 45 years old. Zone 1 is a 10 m wide band of predominantly hardwood trees including yellow poplar (*Liriodendron tulipifera* L.) and swamp black gum (*Nyssa sylvatica* var *biflora* Marsh.). The entire buffer system averages about 70 m in width along an intermittent second-order stream channel.

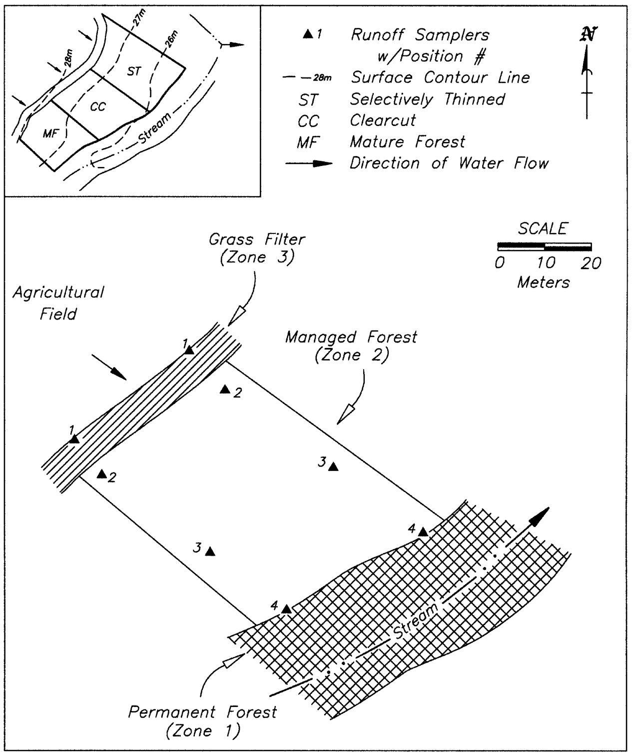

Figure 1–Diagram showing forest management treatment plots and runoff sampling sites at the Gibbs Farm riparian study area.

Contributing Upland Area. The field above the riparian buffer system (0.93 ha contributing area) on the west side of the stream was planted in continuous corn (*Zea mays* L.) in the summer of 1993 and 1994, with a summer crop of pearl millet (*Pennisetum americanum* L. Leeke) in 1995 and peanuts (*Arachis hypgea* L.) in summer 1996. Crops were grown using conventional agronomic production practices for the region, except for peanuts. Peanuts were planted in small plots with bare alleyways. Crop residues were incorporated after harvest.

MANAGEMENT TREATMENTS

To evaluate the effects of forest management within RFBS, three management treatments were imposed within Zone 2 of a riparian buffer system. Forest management treatments were clear-cutting, selective-thinning, and the mature forest as a reference. Management treatment plots were about 40 m wide and 55 m deep. In November 1992, approximately one-third of Zone 2 (fig. 1) was clear cut with all merchantable timber removed. Another one-third of Zone 2 was selectively thinned according to Georgia Forestry Commission (GFC) recommendations, with the standing biomass removed from all size classes to a target basal area of about 25 m^2 ha^{-1} (Georgia Forestry Commission, 1993). Timber was cut using a commercial feller buncher and transported from the plot using a rubber-tired grapple skidder. Some surface soil was exposed during harvest, particularly within the clear-cut plot. The clear-cut plot was reforested in winter 1993 by planting improved slash pine at a rate of 1,560 trees ha^{-1} based on GFC recommendations. All woody debris greater than 60-mm diameter was removed during timber harvest operations, and remaining debris was distributed uniformly within the respective plots by hand. There was little or no exposed soil remaining in either the clearcut or thinned treatment plots after harvest debris was redistributed. The remaining one-third of Zone 2 mature riparian forest was left uncut as a reference area. Trees and shrubs in Zone 1 were not disturbed during harvest operations within Zone 2.

INSTRUMENTATION

Rainfall at the GFS was measured with a tipping bucket raingage located adjacent to the riparian study area. A network of surface flow samplers was installed on the riparian study site in 1992. Storm flow was sampled using low-impact, surface flow samplers developed for use on low-gradient riparian study areas. Sampling devices consist of flow splitters and buried sample collectors that retain flow proportional samples of storm runoff occurring on the ground surface of the buffer system (Sheridan et al., 1996). The sample volume retained, which represents either 1% or 10% of total surface flow, permits estimation of surface flow volume on a 30.48-cm-wide flow transect at the respective landscape sampling position. Samplers have proven effective in providing surface flow samples at multiple locations within riparian study areas while providing little disturbance to the ground surface, vegetation or flows within experimental areas (Lowrance et al., 1997). Comparison of flow volumes across buffer zones has been demonstrated to permit zonal allocation of the surface flow component and, hence, estimation of the net change in runoff across the buffer landscape (Sheridan et al., 1996; Lowrance et al., 1997).

A total of 24 samplers were installed at the GFS, with two sampling devices (one 1% and one 10% sampler) located at each zonal interface and at the Zone 2 midpoints for each of the management treatment plots (fig. 1). Use of 1% and 10% samplers at each landscape sampling position provides adequate sample volumes for both large and small storm events. Samplers at the field-grass filter interface (Position 1) were located 1 m within the grass filter strip to avoid interference with field tillage operations as well as damage to samplers. Samplers at the grass filter-managed forest interface (Position 2) were located 1 m within the riparian forest to avoid interference with mowing of grass filter strip, as well as damage to samplers by mowers. Position 3 samplers were located at the midpoints of the Zone 2 managed forest plots. Position 4 samplers were located at the respective managed forest-permanent forest interfaces.

FIELD SAMPLING

Samples were collected on the day of the storm event or on workdays following storm events. Multiple events occurring on any day were collected as a single sample. Flow samples were pumped from sample collectors in accordance with procedures detailed in Agricultural Handbook 224 (Brakensiek et al., 1979). Pumping was begun after one minute of recirculating the sample with the inlet line of the peristaltic pump to suspend sediment within the collector. Total volume of runoff retained in each sample collector was determined in the field and a surface flow sample adequate for laboratory analyses was retained. Samples were then transported to USDA-ARS Southeast Watershed Research Laboratory where chemical and sediment analyses were performed.

Sediment concentrations were determined using the standard method for suspended solids (APHA, 1989). A well-mixed 200-mL sample was filtered through a dried and weighed glass fiber filter (Gelman AE, 0.45-μm effective pore size). The filter was then dried at 105°C for three days and reweighed. Sediment mass in the sample was the net of filter plus sediment minus filter. Sediment concentration was the sediment mass per volume of sample.

DATA ANALYSIS

Runoff volume data were used to calculate loads of sediment transported at zonal interfaces and at the midpoint of Zone 2. Runoff volumes and sediment concentrations determined at sampling locations were assumed to be representative of surface flows occurring across the respective interfaces. Sediment loads at sampling locations were determined by multiplying sediment concentration by the respective sampler runoff volume for that event. Runoff volumes and sediment loads were accumulated by hydrologic seasons for statistical analyses: Season 1—December, January, and February; Season 2—March, April, and May; Season 3—June, July, and August; and Season 4—September, October, November. This seasonal alignment has been useful in previous hydrologic and environmental studies in the Coastal Plain. The four-year record used in these analyses extends from December 1992 (immediately following forest harvest operations for the clear-cut and selectively thinned plots) through November 1996.

Statistical Analysis. Preliminary analyses of runoff and sediment concentration and load data indicated that these data were not normally distributed. Therefore, runoff and sediment data were analyzed using the NPAR1WAY Procedure with the Kruskal-Wallis test [Statistical Analysis System (SAS) Institute, 1989]. NPAR1WAY is a nonparametric procedure that tests whether the distribution of the variable has the same location parameter across different groups. The Kruskal-Wallis procedure tests the null hypothesis that the groups are not different from each other by testing whether rank sums are significantly different based on a chi-square distribution (Sokal and Rohlf, 1981). Significant differences reported are based on the 0.01 level for the Kruskal-Wallis procedure.

RESULTS AND DISCUSSION

Since infiltration of surface flow and deposition of transported sediments are two primary processes for reducing NPS transport of pollutants, relative reductions in runoff and sediment transport across riparian buffer systems are two primary indicators for evaluating the effectiveness of buffer systems.

RUNOFF

Rainfall for the record period averaged 1127 mm, which is less than the long-term mean of 1208 mm at Tifton, Georgia. Rainfall for hydrologic year 1994, however, totaled 1526 mm, or 27% greater than the long-term mean. A notable event totaling 199 mm in 24-h, which exceeded the 100-year, 24-h rainfall for the area, was recorded in October 1994. For the four year record (Dec. 1992, through Nov. 1996), 103 storm events resulted in runoff capture at one or more sampling locations. This is an average of about 26 storm runoff events per year; however, 1994 alone produced 37 of those runoff events. The number of runoff events was relatively well-distributed seasonally, with Season 3 (June-August) producing the greatest number of events (31) and Season 4 (September-November) the fewest (17).

Treatment by Position. Event mean runoff in millimeters (mm) over the upslope contributing area is shown for the three forest management treatment plots in table 1 for the respective landscape sampling positions. Statistical comparisons of runoff were made between the four sampling locations (the vertical block) and between the three forest management treatments (the horizontal block). Runoff generally decreased as flows moved across the RFBS for all forest management treatment plots, particularly within the upper portions of the buffer system. Changes in runoff volume across the RFBS are the net result of losses by infiltration and gains from throughfall, seepage (reemergent shallow subsurface flow), and increased saturation excess runoff that may occur on lower sampling positions due to proximity to ephemeral stream channel. Reductions in runoff across the RFBS were significant for all three treatment plots at the 0.01 level based on the Kruskal-Wallis tests. There was no significant difference in runoff rank sums between treatment plots at Positions 1 and 2, which is reasonable since these locations are at the field edge-grass filter interface and the grass filter-managed forest interface, respectively. At Positions 3 (the mid-point of the managed forest) and 4 (the interface of the managed forest and the permanent forest), however, there were significant differences between treatment plots. At Position 3, less runoff was measured on the clear-cut and selectively thinned plots than from the mature forest plot. This observation is consistent with previous observations that rapid regrowth of herbaceous vegetation occurred within the harvested zones (Lowrance et al., 1997).

Table 1. Event mean runoff (mm) by forest management treatment and landscape sampling position (mean followed by standard error of mean)[a]

Landscape Position	Mean Runoff		
	Mature Forest	Clear-cut	Selectively Thinned
	----------(mm)----------		
1	6.8 (0.79)*	7.4 (1.0)*	8.2 (0.90)*
2	3.0 (0.42)*	2.9 (0.53)*	2.3 (0.22)*
3	3.8 (1.1)*†	2.8 (0.65)*†	1.6 (0.34)*†
4	2.0 (0.39)*†	5.2 (0.88)*†	4.9 (0.43)*†

[a] Statistical comparisons were made for each management treatment between landscape positions and for each landscape position between management treatments.

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within forest management treatment.

† Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among forest treatments within landscape position.

More runoff was measured at the lowest sampling position (Position 4) on the clear-cut and selectively thinned plots than for the mature forest. Greater surface flow at the lower sampling positions on the clear-cut and selectively thinned plots could result from combined effects of seepage, which occurs due to decreasing soil profile thickness above a restrictive subsurface horizon in the riparian forest at the GFS (Bosch et al., 1994), lower sampler elevations and proximity to the second-order ephemeral stream confluence (fig. 1). Companion studies at this site indicate that the ephemeral stream impacts shallow groundwater on the lower riparian landscape (Bosch et al., 1994; Hubbard and Lowrance, 1996). Field observations also indicate that the Position 4 sampling sites tended to be in a wet condition longer and more frequently than the upper sampling positions, particularly for the selectively thinned plot. With the apparent impact of the ephemeral stream channel on the lowest sampling position, it is likely more useful to focus on runoff occurring at the three upper sampling positions, where runoff volume is not highly influenced by proximity to the ephemeral stream.

Figure 2 shows the relative reduction in runoff occurring across the buffer system landscape for the three forest management treatment plots. Significant reductions in runoff occurred on the upper portions of the respective management treatment plots between Positions 1 and 2. Reductions in runoff between Positions 1 and 2 ranged from 56 to 72% of flow at the field edge. Measured reductions are consistent with previous findings for this site which, based on shallow groundwater gradients, indicated that infiltration was occurring primarily on the upper portions of the buffer system (Bosch et al., 1994).

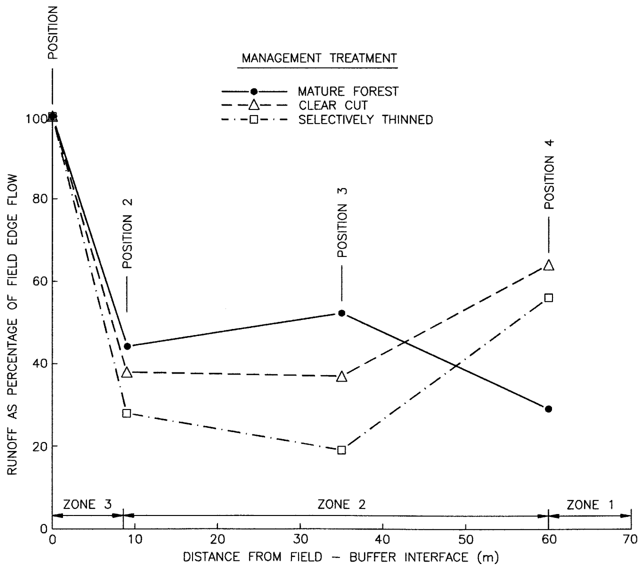

Figure 2–Total runoff at landscape sampling positions as a percentage of field edge flow.

Table 2. Event mean runoff (mm) by forest management treatment and year (mean followed by standard error of mean)[a]

Year	Mean Runoff		
	Mature Forest	Clear-cut	Selectively Thinned
	(mm)		
1993	2.2 (0.57)*	1.8 (0.42)*	3.0 (0.73)*
1994	5.9 (0.75)*	5.4 (0.85)*	5.2 (1.0)*
1995	4.7 (1.1)*	4.8 (0.96)*	4.5 (0.90)*
1996	4.8 (0.75)*	6.3 (0.90)*	4.6 (0.82)*

[a] Differences were not significant among forest management treatments within year.

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among years within forest management treatment.

Table 4. Event mean runoff (mm) by season and landscape sampling position (mean followed by standard error of mean)

Landscape Position[a]	Mean Runoff			
	Season 1 (Dec - Feb)	Season 2 (Mar - May)	Season 3 (June - Aug)	Season 4 (Sept - Nov)
	(mm)			
1	6.0 (1.1)	8.6 (0.82)*	8.5 (0.64)*	6.7 (1.3)
2	1.8 (0.31)	3.0 (0.36)*	3.2 (0.57)*	3.0 (0.56)
3	2.7 (0.84)	5.0 (1.4)*	2.6 (0.75)*	3.9 (0.89)
4	3.5 (0.71)	4.6 (0.80)*	4.1 (0.84)*	3.4 (0.94)

[a] Differences were not significant among seasons within landscape position.

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within season.

Treatment by Year. Event mean runoff by management treatment and year are shown in table 2. Runoff was significantly different among years for all three forest management practices. However, runoff was not significantly different between management treatments for any of the four years.

Year by Position. Analysis of runoff by year with respect to landscape sampling position showed significant differences in runoff for each year except 1993 (table 3). In hydrologic year 1993, the driest year of record, the buffer system received the lowest runoff from the cropped area. Still, the buffer system showed a reduction in runoff of about 50% for 1993, which was similar to flow reductions for wetter years. While there were significant differences in runoff for the upper sampling positions (Positions 1 and 2) between years, runoff at the lower sampling positions (Positions 3 and 4) did not vary significantly between years. Reductions in runoff from the agricultural contributing area occurred primarily between sampling Positions 1 and 2 in wet as well as dry years.

Season by Position. Runoff decreased during all seasons as flows moved across the buffer system (table 4). While decreases in runoff across the RFBS were noted for all seasons, rank sums were significantly different only in Seasons 2 and 3, the seasons when the RFBS received the greatest runoff. The net reductions in runoff across the upper sampling positions are attributed primarily to infiltration losses. Reductions across the upper sampling positions were evident during both wet and dry seasons, which is significant from the standpoint of assessing the potential effectiveness of RFBS for filtering agrichemicals on a year-round basis. There were no significant differences between seasons within landscape position.

It is noteworthy that there was no evidence of concentrated flow or scour occurring in the grass filter portion of the RFBS for this record, which included a 100-year, 24-h rainfall event. The extreme event did occur in the fall when available storage within Coastal Plain riparian areas is greatest (Shirmohammadi et al., 1986) and conversion of rainfall to runoff is lowest (Sheridan, 1997). No maintenance other than mowing was required for the grass filter.

SEDIMENT

Sediment Concentrations. *Treatment by position*. Mean sediment concentrations (mg L^{-1}) are shown for the three forest management treatments by landscape position in table 5. Kruskal-Wallis tests by landscape position for differences in sediment concentration between management treatment plots showed no significant differences. Therefore, sediment concentration data for the three forest management treatments were combined for further statistical analyses. Mean sediment concentrations by landscape sampling positions are shown in figure 3. For the four year record, mean sediment concentrations in surface flow moving across the RFBS were reduced by an average of 73%, with a 63% reduction occurring between sampling Positions 1 and 2.

Year by position. Sediment concentrations showed significant differences between years for the two upper landscape sampling positions (table 6). By Positions 3 and 4, however, there was no significant difference in sediment

Table 3. Event mean runoff (mm) by year and landscape sampling position (mean followed by standard error of mean)

Landscape Position	Mean Runoff			
	1993	1994	1995	1996
	(mm)			
1	3.6 (0.89)†	10.2 (0.38)*†	7.8 (0.85)*†	8.3 (0.82)*†
2	1.7 (0.22)†	3.1 (0.36)*†	2.2 (0.47)*†	4.0 (0.65)*†
3	1.8 (0.74)	4.1 (0.87)*	4.8 (1.1)*	3.5 (0.83)*
4	2.0 (0.51)	4.6 (0.61)*	3.9 (0.81)*	5.1 (0.93)*

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within year.

† Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among years within landscape position.

Table 5. Event mean sediment concentration (mg L^{-1}) for forest management treatment and landscape sampling position (mean followed by standard error of mean)

Landscape Position[a]	Mean Sediment Concentration		
	Mature Forest	Clear-cut	Selectively Thinned
	(mg L^{-1})		
1	247 (90)*	227 (98)*	162 (55)*
2	94 (30)*	71 (17)*	73 (17)*
3	47 (9.9)*	57 (18)*	45 (9.6)*
4	40 (8.1)*	77 (18)*	62 (15)*

[a] Differences were not significant among forest management treatments within landscape position.

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within forest management treatment.

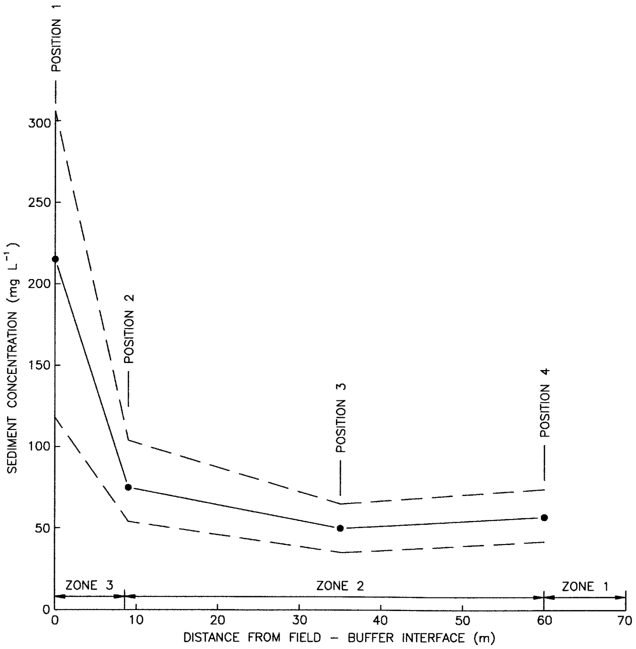

Figure 3–Mean sediment concentration and 95% confidence limits at landscape sampling positions.

Table 6. Event mean sediment concentration (mg L–1) for year and landscape sampling position (mean followed by standard error of mean)

Landscape Position	Mean Sediment Concentration 1993	1994	1995	1996
	--------------------------------(mg L^{-1})--------------------------------			
1	60 (9.1)†	118 (30)*†	75 (13)*†	570 (130)*†
2	83 (17)†	51 (13)*†	31 (9.6)*†	151 (37) *†
3	51 (11)	53 (12)*	16 (3.2)*	69 (21)*
4	55 (11)	64 (19)*	50 (2.3)*	61 (10)*

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within year.

† Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among years within landscape position.

concentration between years. When the cropped field was planted in peanuts (1996), sediment concentrations entering and leaving the grass filter strip were significantly greater than for other years. Peanuts were grown in small plots with bare alleyways to accommodate peanut variety trials. Despite higher field edge sediment loadings in 1996, Position 3 and 4 sediment concentrations were not significantly different than for other years.

Season by position. Mean sediment concentrations at the field edge showed expected seasonal trends: Season 3 (July-August), which is characterized by high rainfall and intense storms events, produced the greatest sediment concentrations and Season 4 (September-November), which typically has less rainfall with lower intensity events, produced the lowest sediment concentrations. While reductions in sediment concentration were noted across the riparian buffer landscape for all seasons, sediment concentrations by sampling position (not shown) were not significantly different between seasons.

Sediment concentrations measured at the GFS were low even at the field edge, which is reasonable for these short slope lengths and for the permeable, low-erodibility soils which were cropped using recommended conservation management practices including residue management. An additional factor possibly contributing to low observed sediment concentrations in this study is placement of samplers. Sampling devices at Position 1 were placed about 1 m within the field-grass filter interface to prevent damage by agricultural tillage and cultural operations, and at Position 2, about 1 m within the managed forest to prevent interference with mowing and maintenance of the grass filter. However, as has been reported for riparian forests (Lowrance et al., 1986; Cooper et al., 1987) as well as vegetative filter strips (Magette et al., 1989; Neibling and Alberts, 1979), sediment deposition can occur immediately upslope and just within vegetative buffers as flow velocities are initially reduced. Sediment concentrations measured at the GFS may be conservative estimates of the rate of sediment movement across RFBS, but comparisons of reductions in sediment loads across the RFBS treatment plots should be reasonable indicators of the relative effect of forest management on the sediment reduction function of RFBS.

Low observed sediment concentrations in runoff from the RFBS are consistent with suspended sediment levels (mean: 15 mg L^{-1}) reported for seven Coastal Plain streams (Sheridan and Hubbard, 1987) and for 33 sites (mean: 13 mg L^{-1}) on seven Coastal Plain river basins (Perlman, 1985). Samples collected beyond the field edge within the riparian forest could frequently be characterized as clear runoff. The observed lack of significant differences in sediment concentrations between the three forest management treatments is not surprising in view of the considerable woody forest residues remaining on the harvested plots, as well as the rapid regrowth of vegetative cover within the riparian forest following harvest operations.

Sediment Load. *Treatment by position*. Reductions in sediment loads across the RFBS were greater than reductions in either runoff or sediment concentration, since sediment loads are a function of both runoff volume and sediment concentration. Event mean sediment loads (kilograms per meter of buffer interface) are shown for the respective landscape sampling positions by forest management treatment in table 7. Kruskall-Wallis tests for significant differences in sediment loads showed no

Table 7. Event mean sediment load (kg m^{-1}) by forest management treatment and landscape sampling position (mean followed by standard error of mean)

Landscape Position	Mean Sediment Load Mature Forest	Clear-cut	Selectively Thinned
	-------------------------------(kg m^{-1})-------------------------------		
1	0.040 (0.016)*	0.058 (0.026)*	0.028 (0.009)*
2	0.009 (0.004)*	0.012 (0.005)*	0.005 (0.001)*
3	0.007 (0.002)*	0.006 (0.003)*	0.002 (0.0004)*
4	0.002 (0.0005)*†	0.015 (0.007)*†	0.009 (0.002)*†

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within forest management treatment.

† Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among forest management treatments within landscape position.

significant differences between forest management treatment plots for the first three sampling positions on the riparian landscape. Differences in sediment loads at Position 4 appear reasonable in that sediment loads for clear-cut and selectively thinned plots were greater than for the mature forest plot. However, increased sediment loads at Position 4 for the harvest treatments were likely due to greater runoff volumes (table 1) occurring at the clear-cut and selectively thinned plot Position 4 sampling sites, since sediment concentrations at Position 4 were not significantly different among the forest management plots.

Differences in sediment loads across the RFBS were significant for all three forest management treatment plots. Total reductions in sediment loads across the RFBS ranged from 74 and 68% for the clear-cut and selectively thinned plots, respectively, to 95% for the mature forest plot (fig. 4). However, at Position 3 (the midpoint of the managed forest), before flow reached the lowest sampling positions and possible impacts due to proximity to the ephemeral stream system, sediment reductions were similar for the three different forest management treatments, ranging from 82 to 93% of loads computed at the field edge-grass filter interface. Reductions in sediment load of 78 to 83% were computed from Position 1 to Position 2.

Year by position. Sediment loads showed significant differences between years for the two upper sampling positions (table 8). Hydrologic years 1994 (the highest rainfall year) and 1996 (the year that peanuts were grown) produced the greatest sediment loads at each sampling position on the buffer system landscape. It is notable, however, that by the third and fourth sampling positions, sediment loads were not significantly different between years. Reductions in sediment loads across the RFBS were significant for all years except 1993. Sediment trapping efficiencies ranged from 67% in the driest year (1993) to 90% in 1996, the year with the greatest sediment inputs to the RFBS.

Table 8. Event mean sediment load (kg m^{-1}) by year and landscape sampling position (mean followed by standard error of mean)

Landscape Position	Mean Sediment Load 1993	1994	1995	1996
	---------------(kg m^{-1})---------------			
1	0.006 (0.002)†	0.036 (0.012)*†	0.015 (0.003)*†	103 (0.031)*†
2	0.005 (0.001)†	0.006 (0.002)*†	0.002 (0.001)*†	0.021 (0.008)*†
3	0.004 (0.002)	0.001 (0.004)*	0.003 (0.001)*	0.005 (0.002)*
4	0.002 (0.001)	0.014 (0.007)*	0.006 (0.002)*	0.010 (0.003)*

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within year.

† Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among years within landscape position.

Table 9. Event mean sediment load (kg m^{-1}) by season and landscape sampling position (mean followed by standard error of mean)

	Mean Sediment Load			
Landscape Position[a]	Season 1 (Dec - Feb)	Season 2 (Mar - May)	Season 3 (June - Aug)	Season 4 (Sept - Nov)
	---------------(kg m^{-1})---------------			
1	0.022 (0.006)*	0.041 (0.012)*	0.073 (0.034)*	0.027 (0.013)*
2	0.004 (0.001)*	0.007 (0.002)*	0.013 (0.007)*	0.010 (0.005)*
3	0.003 (0.001)*	0.012 (0.004)*	0.004 (0.002)*	0.002 (0.001)*
4	0.007 (0.002)*	0.013 (0.008)*	0.006 (0.002)*	0.008 (0.003)*

[a] Differences were not significant among seasons within landscape position.

* Indicates that Kruskall-Wallis test rank sums of the groupings were significantly different at the 0.01 level among landscape positions within season.

Season by position. While sediment loads varied in an expected pattern between seasons (Seasons 2 and 3—highest loadings; Seasons 1 and 4—lowest loadings), differences between seasons were not statistically significant (table 9). However, significant reductions in sediment loads, ranging from 68-92%, were noted across the riparian buffer landscape for all seasons. Season 3, the hydrologic season in which the RFBS typically receives the greatest sediment inputs, showed the greatest relative reduction in sediment load, averaging 92% for the record period.

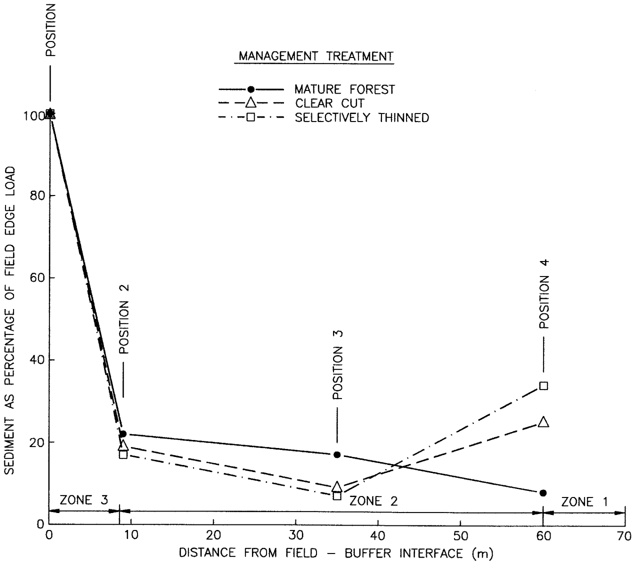

Figure 4–Total sediment load at landscape sampling positions as a percentage of field edge load.

SUMMARY AND CONCLUSIONS

Reductions in runoff and sediment transport across a three-zone riparian forest buffer system (RFBS) were compared for three forest management practices (mature forest, clear cut, and selectively thinned). The three zone buffer system consisted of a grass filter strip and two riparian forest zones (managed and undisturbed). The buffer was established on a typical Coastal Plain riparian forest based on current recommendations of USDA-FS and USDA-NRCS. Runoff and sediment transport were monitored at selected locations within the riparian buffer study area for four years.

Significant reductions in runoff occurred across the RFBS under all forest management treatments, with the greatest reductions measured across the grass filter portion of the buffer system. Reductions in runoff across the grass filter averaged 56 to 72% of runoff measured at the field edge. Reductions in runoff occurred in wet as well as dry seasons and in both wet and dry years.

Sediment concentrations in runoff from the agricultural field were significantly reduced as surface flows moved across the RFBS. Sediment concentrations within the RFBS were not significantly different between the three forest management treatments. Reductions in sediment concentrations across the buffer system averaged 73% for the record period, with the most significant reduction (63%) occurring within the grass filter portion of the buffer.

Significant reductions in sediment loads occurred under all three forest management treatments, with trapping efficiencies for the RFBS ranging from 67 to 90%. Reductions were observed during wet as well as dry seasons, and for wetter and dryer years. Reductions in sediment transport across the grass filter portion of the buffer system ranged from 78 to 83%. The greatest reductions in sediment load were observed in seasons and years with the greatest inputs to the buffer system.

In this Coastal Plain application, the primary zone for infiltration and sediment deposition was within the grass filter portion of the buffer system, prior to entry of surface flows into the riparian forest. Therefore, the RFBS under either forest management treatment appears to provide the opportunity for infiltration and sediment deposition to occur on the upper portions of the buffer as required for subsequent agrichemical uptake, assimilation and transformation processes to occur within the riparian forest—which is consistent with the functional design concept of the RFBS.

There was no evidence of concentrated flow or scour occurring within the grass filter portion of the RFBS over the four year record, even for the highest rainfall year which included a 100-year, 24-h storm event. The RFBS functioned as designed with only routine mowing; no other maintenance was required. For this application, there was no indication of limitations in effective lifespan noted for the grass filter or of reduced effectiveness in capacity for reduction of runoff and sediment transport after harvest. The runoff and sediment reduction aspect of the RFBS water quality enhancement function was maintained following harvest of Zone 2 forests; no period of recovery for this buffer system function was evident.

This portion of the overall Gibbs Farm riparian study indicates that implementation of recommended forest harvest practices had little impact on the runoff and sediment load reduction function of the RFBS for this Coastal Plain application. This means that the landowner can manage Zone 2 forests within RFBS for economic return using accepted timber harvest practices without adversely affecting the runoff and sediment reduction function performed by these buffer systems in the Coastal Plain. Results of field tests evaluating the impacts of the forest management treatments on nutrient and pesticide assimilative capacities of the RFBS are presented separately.

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