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**EFFECTS OF RIPARIAN BUFFERS ON REMOVAL OF NUTRIENTS AND  
SEDIMENT IN URBAN STREAMS**

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## ABSTRACT

We studied the effectiveness of urban grassy and forested riparian buffers by conducting an experimental addition of nutrient enriched ( $\text{NH}_4$ ,  $\text{NO}_3$ ,  $\text{PO}_4$ ) water and by sampling natural rainfall events along 50m riparian zone transects perpendicular to North Buffalo Creek, an urban stream in Greensboro, NC. Due to drought conditions, sampling of rainfall events was not informative. However, the experimental application of nutrient enriched water allowed us to examine the effect of season, sampling time (pre-addition, and days 1 and 2 post addition), location along the 50 m down slope transect, soil depth, and vegetation type. All nutrients showed a decrease in concentration along a down slope gradient across the riparian zone. Concentrations of all nutrients decreased significantly with soil depth. Treatment responses indicated that all nutrients showed greater changes in concentrations in the forested compared to the grassy sites.  $\text{NO}_3$  and  $\text{PO}_4$  exhibited progressively greater changes with progression of seasons from winter to spring, but  $\text{NH}_4$  did not change significantly with season. Patterns in nutrient retention during summer were more difficult to interpret because we experienced a severe drought.

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## SUMMARY AND CONCLUSIONS

Urban riparian zones are underutilized for removing anthropogenic nutrients derived from storm water. These areas have the potential to function similarly to riparian buffers in forested or agricultural areas, where they are recognized for their importance in protecting water quality in receiving systems. We studied the effectiveness of urban grassy and forested riparian buffers by conducting an experimental addition of nutrient enriched ( $\text{NH}_4$ ,  $\text{NO}_3$ ,  $\text{PO}_4$ ) water and by sampling natural rainfall events along 50m riparian zone transects perpendicular to North Buffalo Creek, an urban stream in Greensboro, NC, that drains a headwater watershed of the Cape Fear River basin. Due to drought conditions, sampling of rainfall events was not informative; there was no surface runoff and no downslope movement of nutrients through soil water. However, the experimental application of nutrient enriched water allowed us to examine the effect of season, sampling time (pre-addition, and days 1 and 2 post addition), location along the 50 m downslope transect, soil depth, and vegetation type. All nutrients showed a decrease in concentration along a down slope gradient across the riparian zone. Concentrations of all nutrients decreased significantly with soil depth. Treatment responses indicated that all nutrients showed greater changes in concentrations in the forested compared to the grassy sites.  $\text{NO}_3$  and  $\text{PO}_4$  exhibited progressively greater changes with progression of seasons from winter to spring, but  $\text{NH}_4$  did not change significantly with season. Patterns in nutrient retention during summer were more difficult to interpret because we experienced a severe drought. These results show that urban riparian zones are underutilized in removing nutrients from storm water, as well as for moderating storm water hydrology. Although forested riparian zones are more effective, grassy riparian zones also have considerable potential for retaining water and nutrients from storm water.

## **RECOMMENDATIONS**

Nutrient removal capacity of urban riparian zones could be increased by routing stormwater across vegetated buffers rather than piping it directly into streams, which would serve to reduce nutrient inputs to receiving water and reduce peak stormwater discharge. The benefit gained would increase with buffer width. In addition, use of forested rather than grassy buffers would also enhance retention of nutrients and stormwater, although grassy buffers provide considerable benefit.

## INTRODUCTION

High order coastal plain rivers in the United States and most other countries are severely impacted by excess nutrients, especially nitrogen, which causes fish kills and human health problems, damages coastal shellfish fisheries, and results in deterioration of recreational uses of our waters (Glasgow and Burkholder 2000, Mallin et al. 2000). Recent research has shown that efforts to improve water quality in receiving waters need to focus on low order streams where the majority of the water comes from. Nutrient processing and retention capacity is highest in these small streams (Peterson et al. 2001). All anthropogenic land uses can strongly influence the supply of nutrients and fine sediment to streams, which impact stream morphological features, algal productivity and fish and invertebrate populations (Lenat 1984, Everest et al. 1987, Lloyd et al. 1987, Swanson et al. 1987, Munn et al. 1989, Osborne and Kovacic 1993, Lenat and Crawford 1994, Richards et al. 1996).

Terrestrial and aquatic ecosystems interact at riparian zones where important buffering mechanisms intercept nutrients entering streams (Hynes 1970, Osborne and Wiley 1988, Gregory et al. 1991, Stanford 1998, Tabacchi et al. 1998, Osborn and Kovacic 1993, Hubbard and Lowrance 1997, Hunt et al. 1999). In agricultural areas, runoff water is particularly enriched by fertilizers and sediments, which severely impact receiving streams. Federal and state agencies have recognized the potential of riparian buffers to reduce nutrient delivery to streams, and have begun the process of reclaiming these riparian buffers as a means of improving stream water quality (the USDA Conservation Resource Enhancement Program, <http://www.fsa.usda.gov/pas/newsroom/>, <http://www.nc.nrcs.usda.gov/Tools/Programs/CREP/crep.htm>). This focus on buffer zones in agricultural streams is important because such streams drain a large spatial area and are severely impacted by agricultural runoff. However, urban streams are also seriously impacted by human activities (Meyer 1997), and improved management of these streams is imperative for meeting federally mandated water quality standards.

Despite the recognition that buffer zones control nutrient delivery to streams, relatively little scientific data are available to provide explicit parameters for riparian buffer management. In addition, little work has been done to incorporate site-specific features into management plans (Shirmohammadi and Shoemaker 1989, Shirmohammadi et al. 1996, Lowrance et al. 2000, McQuaid and Norfleet 1999). Furthermore, implementation of site-specific characteristics on a basin-wide or broader scale will be difficult unless there is a better quantitative understanding of riparian buffering capacity. Therefore, additional research focusing on quantifying buffer effectiveness for water quality in different types of riparian zones as well as the effectiveness of the major buffer mechanisms needs to be incorporated in any plan.

Stream restoration, including buffer re-establishment, is becoming a national agenda (Charbonneau and Resh 1992, NRC 1996, Kondolf 1995, 1996, Roni et al. 2002), with participation by management agencies (i.e., the USDA CREF program) as well as citizens' groups. Despite the interest in restoration, little attention has been paid to effectiveness of these projects at restoring ecological function. The EPA (Brady 1996) and others (Roni et al. 2002, Kondolf 1995, 1996) have emphasized the need to focus on restoration of ecological processes in order for restoration efforts to be meaningful. However, management agencies rarely have funds to conduct such studies; doing so is not usually in their mandate. Successful restoration of riparian buffers should lead to enhancement of nutrient retention in small streams and consequent enhanced water quality in downstream large rivers, reservoirs, and estuaries.

One limitation to successful restoration of ecological function is that riparian processes are incompletely understood. Soil nitrogen processes have been clearly elucidated through many studies (Williams et al. 1992, Binkley & Hart 1989, Silver et al. 2001, Vitousek et al. 2002), and there have been several nutrient and biotic impairment studies in agricultural streams. However, relatively little quantitative information is available about nitrogen processing in urban streams, or the degree to which forested and grassy buffers ameliorate nutrient delivery.

Major processes that retain inputs of and transform inorganic nitrogen ( $\text{NH}_4$  or  $\text{NO}_3$ ) in the soil environment include soil adsorption, plant uptake, ammonia volatilization, soil microbial assimilation, nitrification, dissimulatory nitrate reduction to ammonia (DNRA), and denitrification (Binkley and Hart 1989, Williams et al. 1992, Osborne and Kovocic 1993, Hill 1996, Schlesinger 1999, Brady and Weil 1999, Silver et al. 2001, Vitousek et al. 2002). Ammonia volatilization occurs in soils at high pH, including agriculture soils in rapid wet-dry situations (Brady and Weil 1999) and may not be important in Piedmont urban riparian buffers. Previous studies have shown that nitrate levels were reduced from 7-40 ppm at an agricultural forest interface to 1 ppm near the stream banks (Peterjohn and Correll 1984, Wahl et al. 1997). However, Peterjohn and Correll (1984) discovered that plant uptake only explained approximately 30% of the reduction, leaving 70% of nitrate reduction unexplained. They speculated that denitrification was a primary sinking process in consuming  $\text{NO}_3$ . Williams et al. (1992) demonstrated that both nitrification and denitrification are important in N biogeochemical cycles. The latter prevades in anaerobic conditions that are common in water logged soils, and water-filled soil micro-pores when soils are not saturated. Duff and Triska (1990) showed that denitrification is significant in buffer zones, but increases with distance from the stream. Denitrification was limited by available oxygen near the stream channel, and by  $\text{NO}_3$  at inland sites (Duff and Triska 1990). Recently, Silver et al. (2001) have shown that the DNRA pathway can be quantitatively significant relative to denitrification for reducing nitrate under certain soil conditions. Immobilization by soil organisms, mainly soil microbes, was also found to significantly reduce soil available N in grassy vegetation (Hubbard and Lowrance 1997).

In this project, we began a study of buffer effectiveness in urban streams. Our specific objectives were: (a) to determine the effect of vegetation type within riparian buffer zones on surface runoff water quality; (b) to determine the effect of riparian vegetation type on sub-surface water quality; (c) to experimentally evaluate loss of nutrient tracers moving across riparian zones of different composition; and (d) to incorporate field experimental and comparative data into a GIS database for future development of a predictive model of the effects of riparian buffer development on quality of water discharging into the Upper Cape Fear River Basin.

## METHODS

We designated the Buffalo Creek riparian zones within the City of Greensboro, NC (Guilford County), as the general study area. Specific study sites were selected with two vegetation types, forest and grass. These were identified from recent aerial photos and site visits. We selected several possible sites based on slope and width of the riparian buffer zones using GIS generated fine-scale 2-ft contour maps overlaid on the aerial photos. We examined these sites in the field and selected 6 experimental sites (3 forested, 3 grassy). We initially also planned to include sites with shrubby vegetation. However, all such sites were comprised of very narrow strips of shrubby vegetation (about 10 m), thus the vegetated width was unsuitable for our study.

At each site, 5 sampling locations were determined at 50-m, 30-m, 20-m, 10-m and 1-m distance from the stream. The sampling locations follow the general flow path of water runoff, which was determined in preliminary trials. To collect subsurface water, two lysimeters, 20-cm deep and 50-cm deep, were installed at each sampling location. Soil type, slope, and aspects were measured for each site (Table 1).

Each season, we collected lysimeter samples after one medium-heavy precipitation event (> 25 mm). Rain events did not result in detectable runoff in our riparian zones. The lysimeters were pumped 12-hr after the rain event, water samples were collected, lysimeters re-pumped, then re-sampled. All samples were immediately placed on ice, returned to the laboratory, frozen, and later analyzed for  $\text{NO}_3$ ,  $\text{NH}_4$ , and  $\text{HPO}_4$  concentrations using an autoanalyzer (Bran-Luebbe TRAACS-2000).

We also conducted a controlled experiment to examine loss of a known concentration of nutrients across the study sites during winter, spring, summer, and fall seasons (sample analysis is incomplete for the fall sampling). We applied one treatment for each site each season. For each site, we applied 6,500 gallons (~25 tons) of nutrient solution ( $\text{NO}_3$ -14ppm,  $\text{NH}_4$ -8ppm,  $\text{P}_2\text{O}_5$ -6.5ppm) from a 3-meter long spreader with an application rate of 55-65 gallons (210-250 liters)/minute. The N content of the solution was 3X the concentration of the highest storm water N concentration measured in the city. The duration of the nutrient application treatment and the travel distance of surface runoff were recorded. Soil samples were also collected for examining soil water content before each treatment.

One-day prior to the treatment, the lysimeters were pumped and water samples were collected immediately before treatment application. During the treatment, surface runoff samples were collected at each sampling location or as far as the runoff traveled. The lysimeters were pumped again 12-hours after the application, and again 24-hours after application. The one set of pre-treatment samples and the two sets of post-treatment samples were compared to evaluate vegetated riparian buffer effectiveness. Samples were handled as with the natural rain event sampling. Soil water contents were examined following standard methods (Rowell 1995).

ANOVA with regression was used to evaluate the response of lysimeter and surface runoff concentration of the three nutrients to treatment (forested vs grassy), season, longitudinal location, soil depth, and collection time.

Table 1. Description of study sites. F indicates forested sites; G indicates grassy sites.

SITE	Soil Series/ Distance from stream bank	Slope	Aspect	Soil Depth	Soil Texture
F-1	Chewacla 0- 10 m	15%	Northeast (35°)	0-42 cm	Sandy Loam
	42-130			Sandy clay loam	
F-1	Cecil > 10 m			>130	Silt loam, clay loam
				0-15 cm	Sandy Loam
				15-132 cm	Clay
				>132	Bedrock
F-2	Chewacla 0- 10 m	8%	Southeast (138°)	0-42 cm	Sandy Loam
	42-130			Sandy clay loam	
F-2	Cecil > 10 m			>130	Silt loam, clay loam
				0-15 cm	Sandy Loam
				15-132 cm	Clay
				>132	Bedrock
F-3	Chewacla 0- 10 m	5%	Southeast (142°)	0-42 cm	Sandy Loam
	42-130			Sandy clay loam	
F-3	Cecil > 10 m			>130	Silt loam, clay loam
				0-15 cm	Sandy Loam
				15-132 cm	Clay
				>132	Bedrock
G-1	Chewacla 0- 10 m	17%	Northwest (314°)	0-42 cm	Sandy Loam
	42-130			Sandy clay loam	
G-1	Cecil > 10 m			>130	Silt loam, clay loam
				0-15 cm	Sandy Loam
				15-132 cm	Clay
				>132	Bedrock
G-2	Chewacla 0- 10 m	0 -5%	Northeast (50°)	0-42 cm	Sandy Loam
	42-130			Sandy clay loam	
G-2	Cecil > 10 m			>130	Silt loam, clay loam
				0-15 cm	Sandy Loam
				15-132 cm	Clay
				>132	Bedrock
G-4	Chewacla 0- 10 m	10%	Southeast (160°)	0-42 cm	Sandy Loam
	42-130			Sandy clay loam	
G-4	Cecil > 10 m			>130	Silt loam, clay loam
				0-15 cm	Sandy Loam
				15-132 cm	Clay
				>132	Bedrock

## RESULTS

### EXPERIMENTAL ADDITION OF NUTRIENT ENRICHED WATER

The regression analysis with ANOVA showed that nearly all dependent variables were significant (Table 2, Table 3). The exceptions were the effect of season on  $\text{NH}_4$  concentration and the effect of sampling time on  $\text{PO}_4$  concentration (Table 2). All nutrients showed a decrease in concentration along a down slope gradient across the riparian zone (significant positive coefficients for location, Table 2). Concentrations of all nutrients decreased significantly with soil depth (significant negative coefficients for depth, Table 2). Treatment responses indicated that all nutrients showed greater changes in concentrations in the forested compared to the grassy sites (positive coefficients for treatment as we assigned dummy variable values 1 and 2 to forest and grass, respectively).  $\text{NO}_3$  and  $\text{PO}_4$  exhibited progressively greater changes with progression of seasons (winter, spring, summer with dummy variable values 1, 2, and 3, respectively), but  $\text{NH}_4$  did not change significantly with season (Table 2).

Variables	Nutrient Species					
	$\text{NH}_4$		$\text{NO}_3$		$\text{PO}_4$	
	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
Intercept	2.514	<0.0001	5.251	<0.0001	4.044	0.0001
Time	-0.237	0.0005	-0.299	0.0409	0.093	0.0646
Depth	-1.874	<0.0001	-3.749	<0.0001	-3.542	<0.0001
Location	0.014	0.0017	0.03	0.0019	0.042	0.0014
Seasons	0.046	0.6613	0.448	0.0512	0.818	0.0092
Treatment	0.357	0.0159	0.685	0.0323	2.160	<0.0001
Adj. $R^2$	0.4841		0.4389		0.315	

Variables	Nutrient species								
	$\text{NH}_4$			$\text{NO}_3$			$\text{PO}_4$		
	Regression	Residual	Total	Regression	Residual	Total	Regression	Residual	Total
Df	5	412	417	5	412	417	5	412	417
SS	893.5	929.4	1823	3507.4	4363.4	7870	3853.1	8066.2	11919
MS	178.8	2.26		701.5	10.59		770.6	19.7	
F	79.2			66.2			39.2		
p-value	0.0005			0.0006			<0.0001		

Nutrient responses to each seasonal application are presented in Figures 1-9. Winter application of  $\text{NH}_4$  in grassy riparian sites (Fig. 1) showed a gradual decline in surface water  $\text{NH}_4$  concentration along a down slope transect from the application point (50 m) to the stream-bank (0 m). In forested sites,  $\text{NH}_4$  concentration decreased dramatically down slope up to 20 m from the stream bank, then leveled off (Fig. 1). Progressively on days 1 and 2,  $\text{NH}_4$  concentration in shallow lysimeters was lower than in pretreatment samples. All lysimeters had lower  $\text{NH}_4$

concentration than surface water samples. There was no strong longitudinal pattern along the down slope transect in the shallow or deep lysimeters in either forested or grassy sites (Fig. 1).

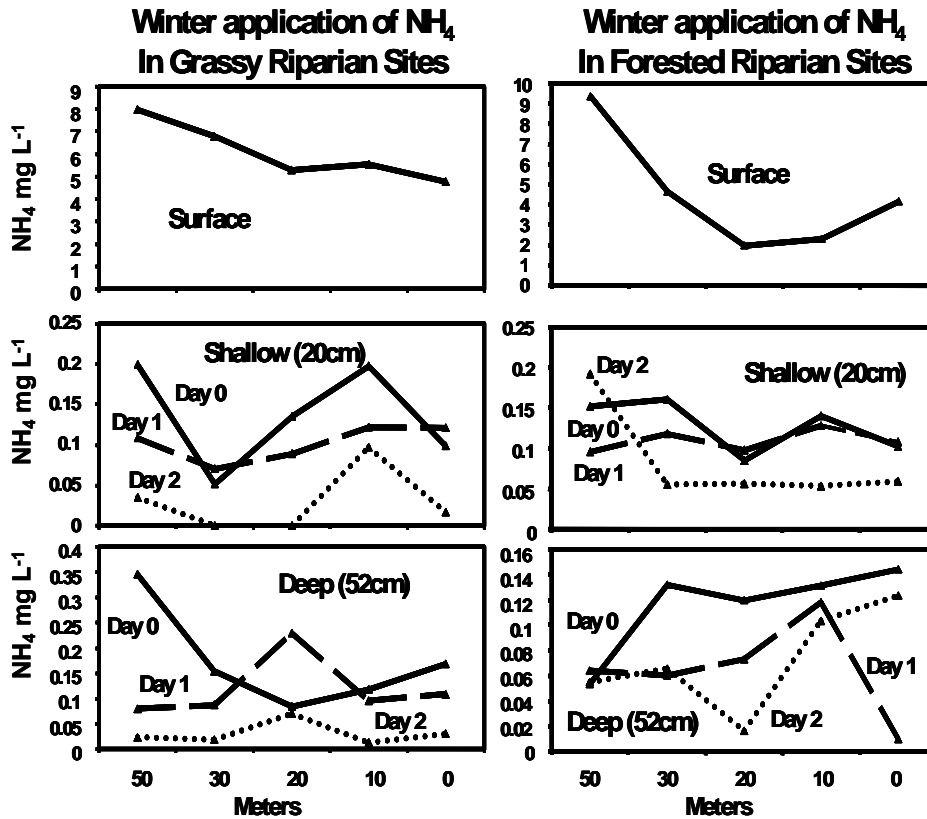


Figure 1. NH<sub>4</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

Surface water NO<sub>3</sub> concentration did not change along a down slope transect following winter treatment in the grassy riparian sites, but declined down slope slightly in the forested sites (Fig. 2). Shallow lysimeters in grassy riparian zones had similar NO<sub>3</sub> concentrations in the pretreatment samples as on day 1 and day 2, and they did not show a down slope change in NO<sub>3</sub> concentration. Deep lysimeters showed a similar NO<sub>3</sub> pattern as shallow lysimeters in the grassy sites. Shallow lysimeters in the forested sites showed a gradual decrease in NO<sub>3</sub> concentration down slope, but this pattern was not evident in deep lysimeters (Fig. 2).

Down slope concentration of PO<sub>4</sub> did not change in surface water, shallow lysimeters, or deep lysimeters following winter application in grassy sites but all declined down slope in forested sites (Figure 3). The overall effect of sampling time was not significant for PO<sub>4</sub> (p=0.0646). PO<sub>4</sub> concentration declined with soil depth, particularly between surface and shallow lysimeter samples (Figure 3).

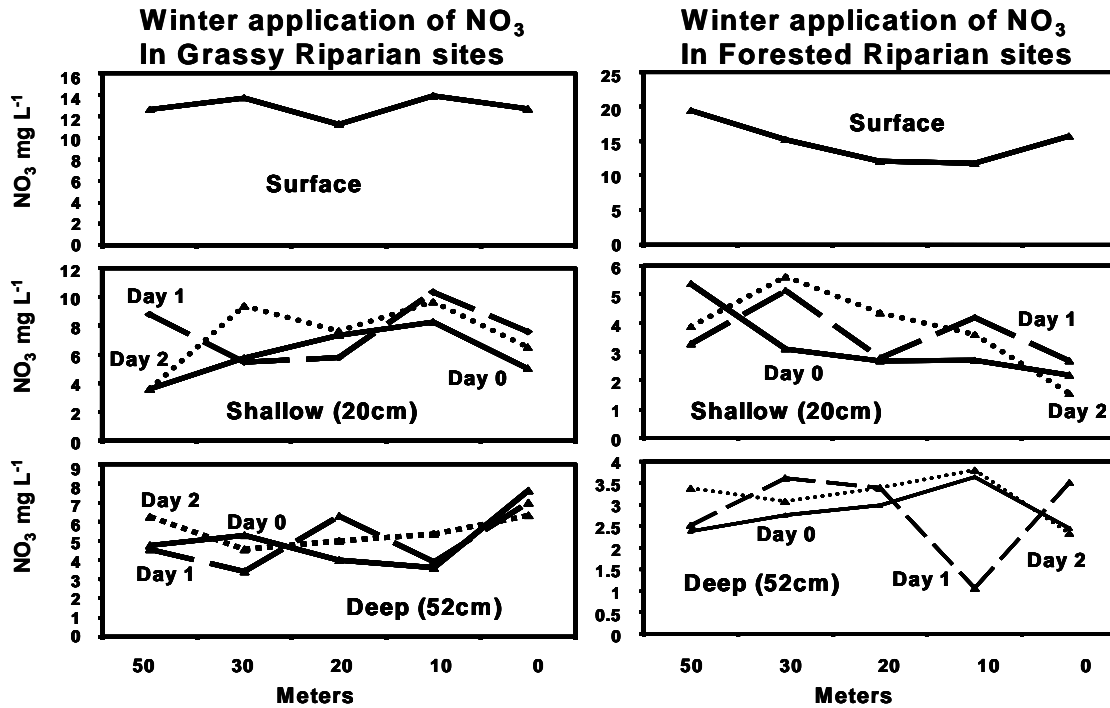


Figure 2. NO<sub>3</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

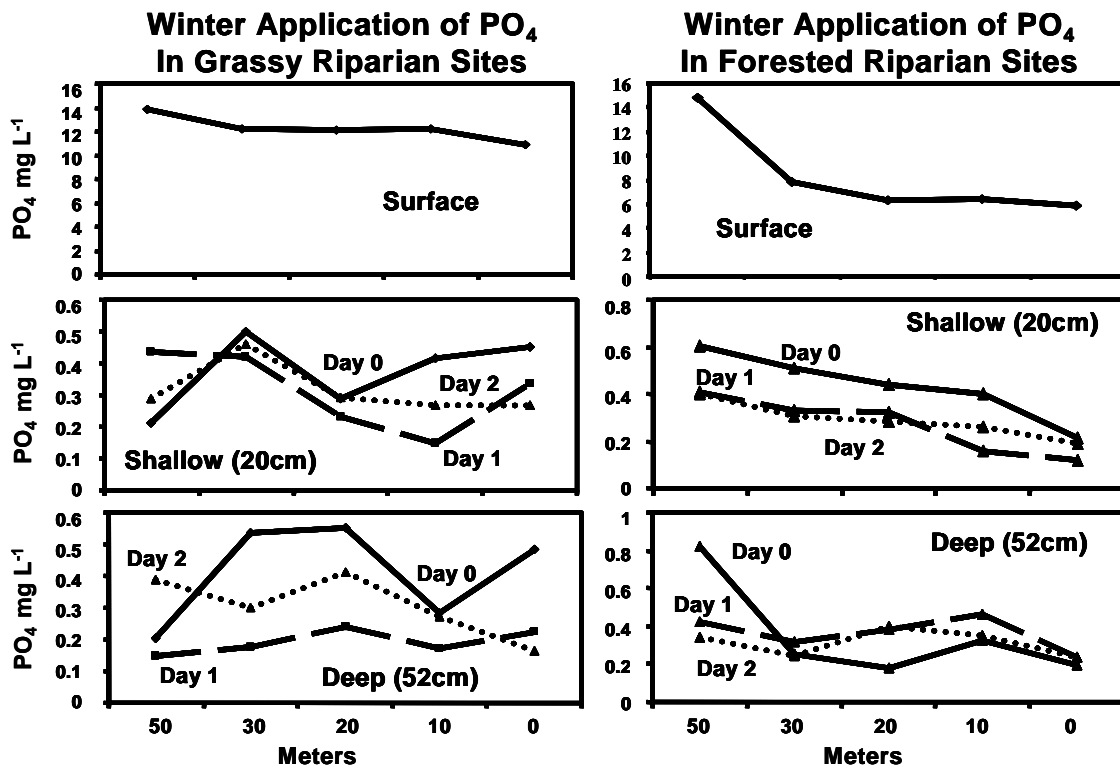


Figure 3. PO<sub>4</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

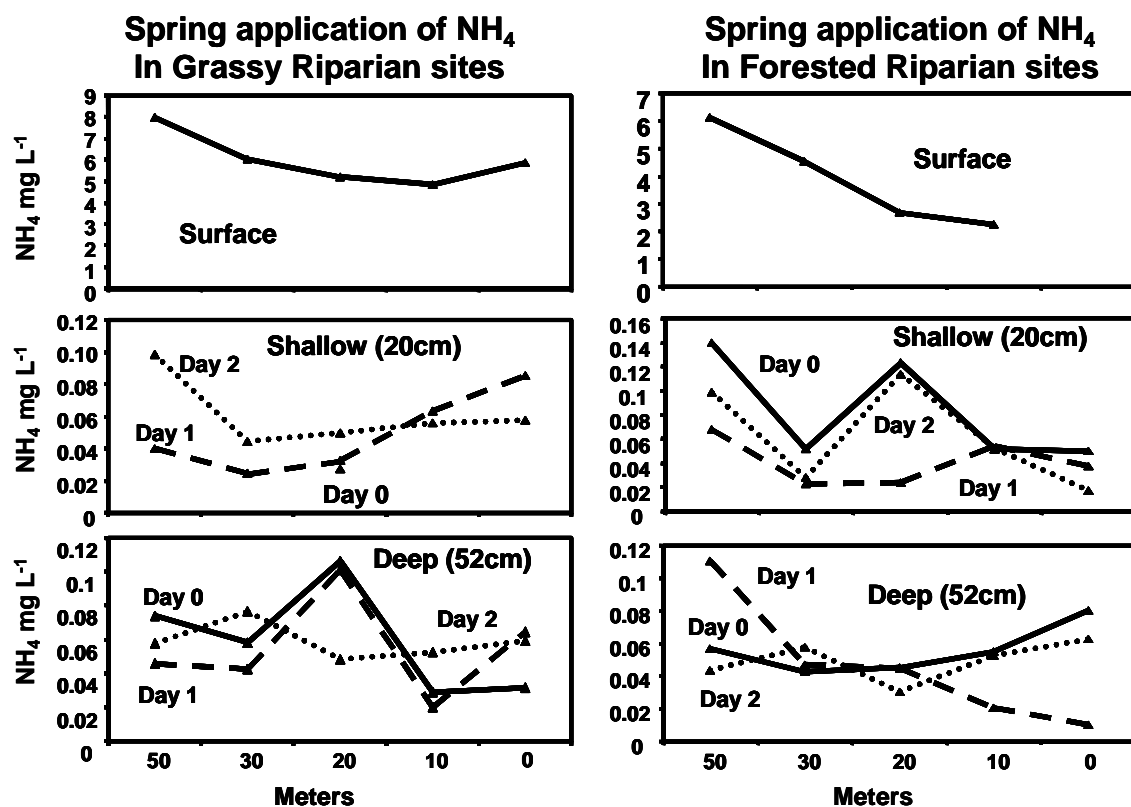


Figure 4.  $\text{NH}_4$  concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

Surface water  $\text{NH}_4$  concentration declined gradually down slope in grassy riparian sites and more abruptly in forested riparian sites following spring application (Fig. 4). Shallow lysimeter samples had about an order of magnitude less  $\text{NH}_4$  than surface water samples in both grassy and forested sites. In grassy sites there was a trend toward increasing  $\text{NH}_4$  down slope on the treatment day (Table 2), but no trend was apparent on day 2. In forested sites shallow lysimeters showed no consistent down slope pattern in pretreatment or post-treatment samples. Deep lysimeter samples in grassy sites showed no longitudinal or temporal pattern related to spring treatment. In forested sites, there were no consistent down slope trends in  $\text{NH}_4$  in deep lysimeters (Fig. 4).

Surface water showed no down slope trend in  $\text{NO}_3$  concentration following spring treatment in either grassy or forested sites (Fig. 5). However, shallow and deep lysimeters showed a down slope decline in  $\text{NO}_3$  on both day 1 and day 2 in both grassy and forested sites (Fig. 5). Pretreatment data are not available for shallow lysimeters from grassy sites due to low soil water content. Shallow lysimeters in forested sites showed no down slope pretreatment trend, and pretreatment samples were generally lower in  $\text{NO}_3$  than day 2 post-treatment samples. Day 1 post-treatment samples were higher in  $\text{NO}_3$  than pre-treatment samples only at the highest upslope site (Fig. 5).

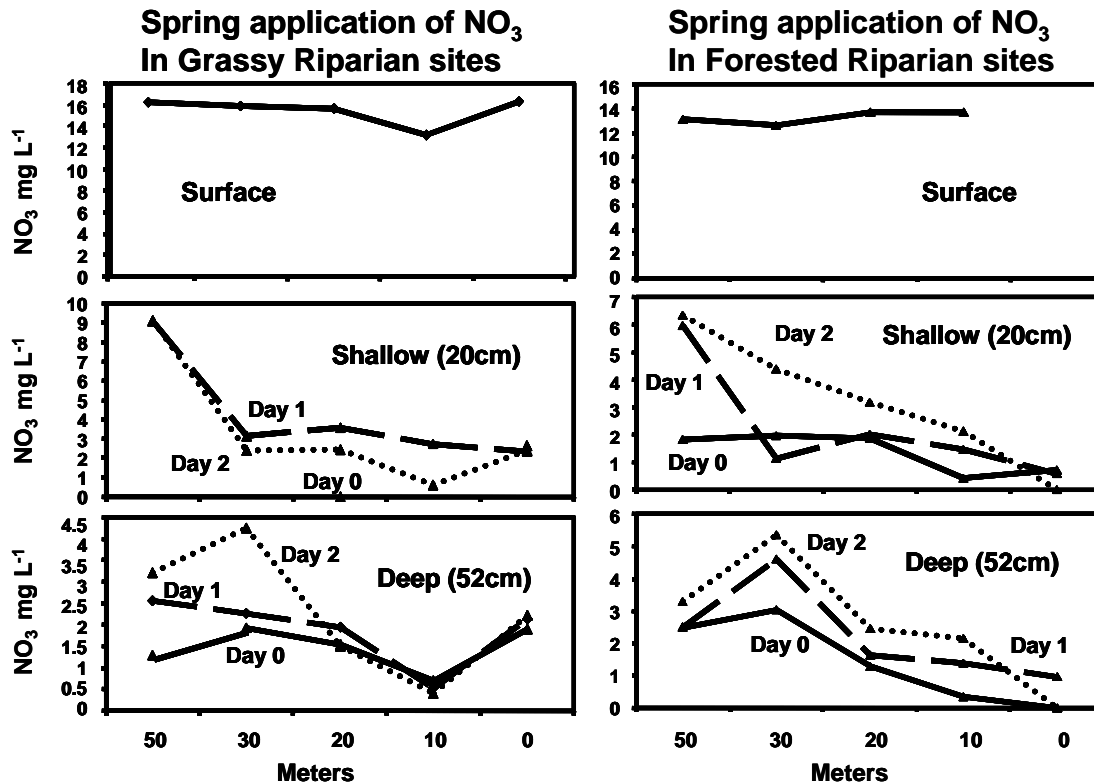


Figure 5. NO<sub>3</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

In grassy sites, there was no down slope pattern in surface water PO<sub>4</sub> concentration following spring treatment, although a steep down slope decline in PO<sub>4</sub> in the forested sites was found (Fig. 6). Both deep and shallow lysimeter samples were about an order of magnitude lower in PO<sub>4</sub> than surface water samples. PO<sub>4</sub> concentration in lysimeters did not show a temporally significant change (Table 2).

The summer treatment was applied in the middle of a severe drought. Many of the lysimeters were dry even after treatment. In the forested sites, surface runoff stopped a few meters before the 20 m sampling station, while in the grassy sites, it stopped between the 20 and 10 m sampling stations. Because of the smaller number of samples, and lack of pretreatment samples, and extreme drought, the summer treatments for all nutrients are difficult to interpret. There was no down slope pattern in surface water NH<sub>4</sub> associated with summer application in either grassy or forested sites (Fig. 7). Similar to winter and spring treatments, lysimeter NH<sub>4</sub> concentrations were more than an order of magnitude lower than surface water (Fig. 7). Following treatment, shallow lysimeters in the grassy sites appeared to increase in NH<sub>4</sub> concentration from the upslope (50 m) site to peak at the 30 m site, then declined down slope toward the stream on both day 1 and day 2. On both day 1 and day 2, there appeared to be a peak in NH<sub>4</sub> at the 30 m site (Fig. 7). Deep lysimeters showed a similar trend in NH<sub>4</sub> as shallow lysimeters for both grassy and forested sites, but few deep lysimeters had water on either sampling day (Fig. 7).

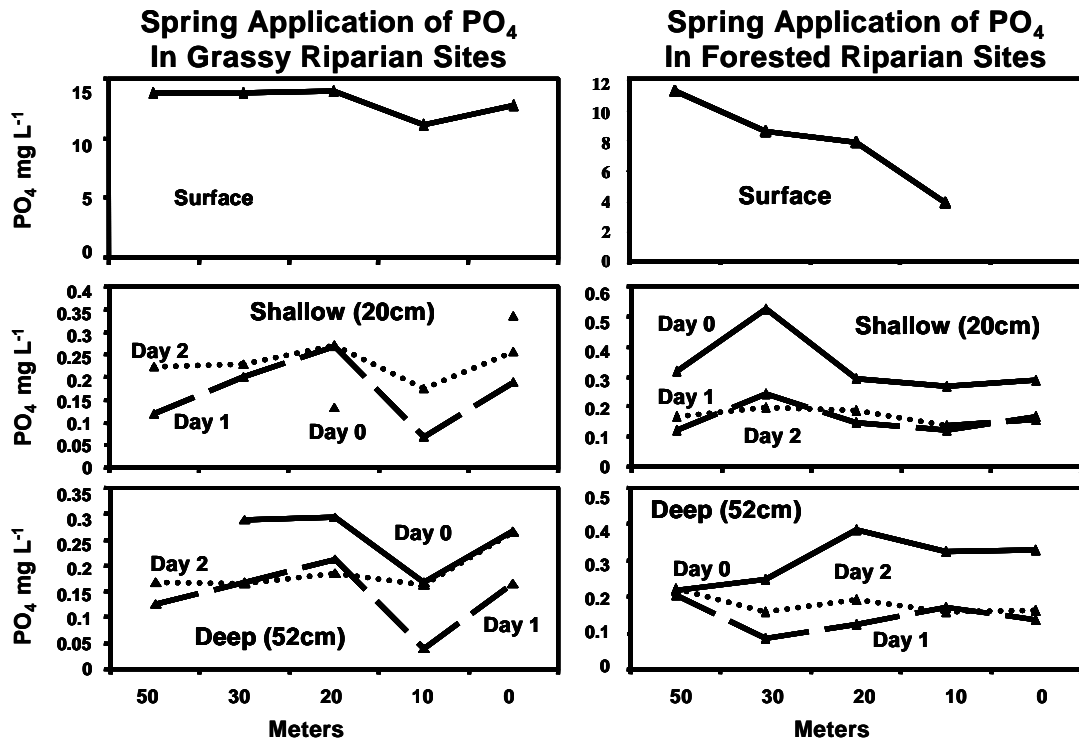


Figure 6. PO<sub>4</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

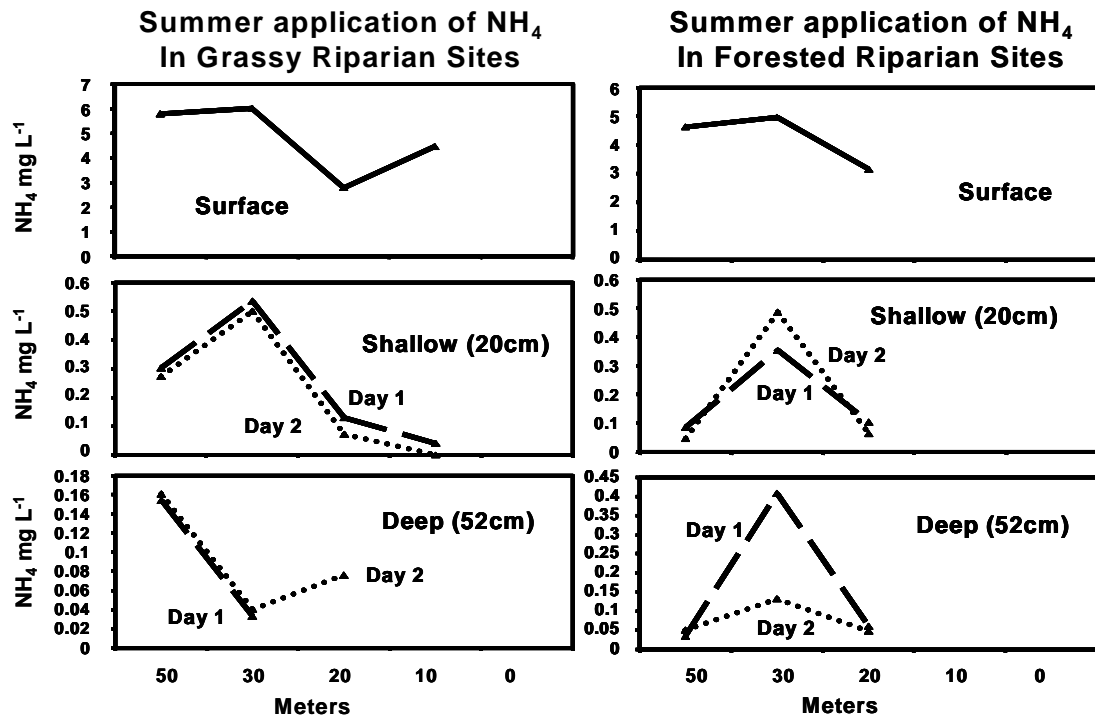


Figure 7. NH<sub>4</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

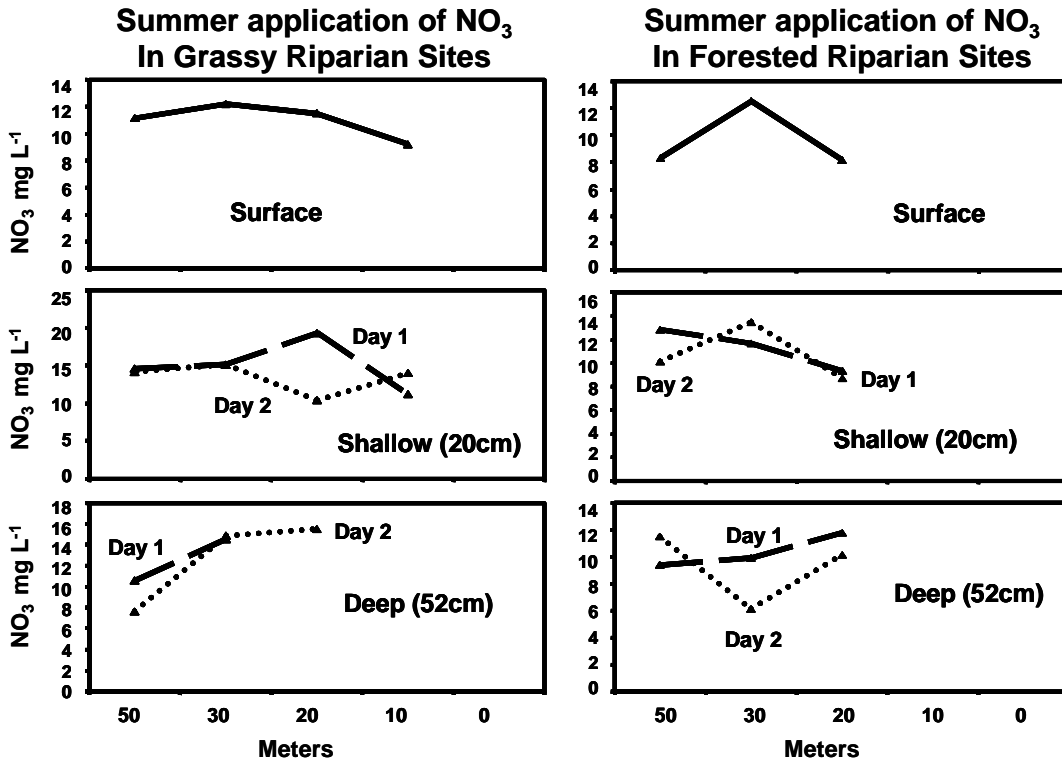


Figure 8. NO<sub>3</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

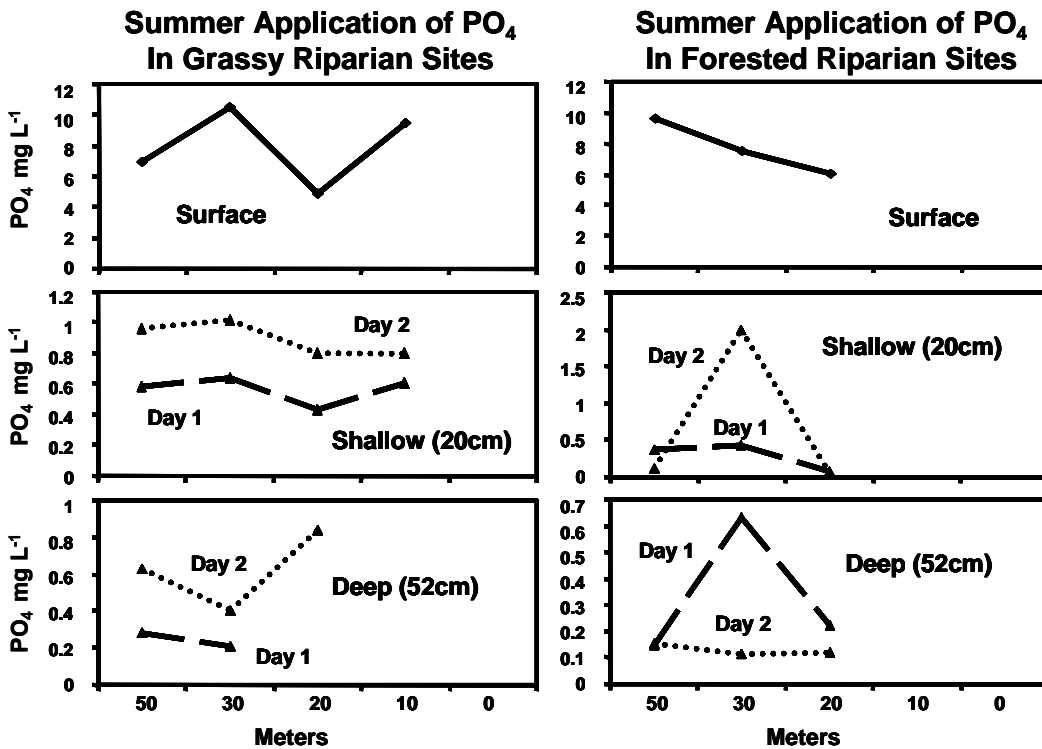


Figure 9. PO<sub>4</sub> concentration at grassy and forested riparian sites immediately before fertilizer application (day 0), on the day of (day 1) and one day following (day 2). Surface water was collected during application.

We did not observe clear longitudinal or temporal patterns in either  $\text{NO}_3$  or  $\text{PO}_4$  concentrations following summer treatment (Figs. 8-9). However, we found comparable, or even higher  $\text{NO}_3$  concentrations in soil water than in surface runoff (Fig. 8). Differences in soil nutrient concentrations between day 1 and day 2 were not apparent, except that  $\text{PO}_4$  in grassy sites was higher on day 2 for both shallow and deep lysimeters (Fig. 9).

#### RAINFALL EVENT SAMPLING

We observed few significant changes in nutrient concentration following natural rainfall events. However, drought conditions generally prevailed throughout the study period, and were particularly severe during the summer. There was no surface water runoff during any of the rainfall events. Nutrient concentrations in shallow and deep lysimeters are shown in Appendix 1, Figures A1-A9. Due to small sample sizes, we were able to detect significant differences only when patterns were not variable between sites and trends were very strong.

During the winter rain event sampling, we observed no significant changes in nutrient concentration in any of the lysimeters (Appendix 1, Figs. A1-A3).

During spring, we observed no significant effects on  $\text{NH}_4$  or  $\text{NO}_3$ . However, we did observe a significant location effect in  $\text{PO}_4$  concentration in deep lysimeters on day 1 in both grassy and forested sites (Appendix 1, Fig. A6). In forested sites, this effect reflected a down slope decline in  $\text{PO}_4$  concentration ( $p=0.049$ ). However, in grassy sites, the significant effect reflected a peak in  $\text{PO}_4$  concentration at 30m, and consistently low levels of  $\text{PO}_4$  at all other distances across the riparian zone ( $p=0.001$ ).

Following the summer rainfall event, we again did not observe any significant changes in  $\text{NH}_4$  or  $\text{NO}_3$  concentration (Appendix 1, Figs. A7-A8). Both shallow and deep lysimeter showed a significant effect of location following summer sampling in forested sites. However, these results were very difficult to interpret (Appendix 1, Fig. A9).

## DISCUSSION

Our experimental results suggest that: (1) riparian soils have very strong nutrient buffering capacity; (2) that capacity has a seasonal variation indicating different dominant biogeochemical processes in different seasons; (3) vegetated riparian zones buffer surface runoff, but the distance required is often large for effective buffer function, and may be larger than what is available; (4) hydrologic condition and soil infiltration capacity of riparian buffers are critical to buffer effectiveness; (5) forested soils have a higher infiltration capacity than grassy soils; and (6) longitudinal changes in subsurface water across the buffer zones represent the net effects of input, infiltration, and buffering capacity.

Declining nutrient concentrations were observed in subsurface water relative to surface runoff for all nutrients; these trends were most apparent in forested sites, and were more evident for  $\text{NH}_4$  and  $\text{PO}_4$  than for  $\text{NO}_3$ . (Table 2, Figs. 1-9). Comparing nutrient concentrations between surface runoff and subsurface flow, our results indicated that all nutrients were strongly buffered at the top 20 cm surface soil as the surface runoff infiltrated into the soil (Figs. 1-9). These preliminary results are consistent with other studies of riparian immobilization of N and P (Peterjohn and Correll 1984, Hubbard and Lowrance 1997, Lowrance et al. 2000), but need to be expanded to determine the fate of the added N. A clear comprehension of soil buffering mechanisms is essential for riparian management.

Our observations indicate that forested buffers are more effective than grassy buffers at reducing surface runoff in urban streams. However, even grassy sites provided very considerable buffering of nutrients in surface water. For both riparian types, buffer width is an important consideration. For example, although  $\text{NO}_3$  concentration declined with soil depth,  $\text{NO}_3$  concentration did not change across the riparian buffers in surface runoff (Figs. 2, 5). Thus, effectiveness of the riparian zone for buffering  $\text{NO}_3$  depends on infiltration, which will be a function of soil characteristics, but for pervious surfaces should always increase with distance. A similar pattern was observed for  $\text{PO}_4$  in the grassy sites. These results suggest that a long riparian distance is important to surface retention and subsequent infiltration of runoff water.

Buffering capacity within the soil was very high for  $\text{NH}_4$  during all seasons, which is consistent with other studies in riparian buffer zones (Peterjohn and Correll 1984, Lowrance et al. 1985). This reflects the strong adsorption of the  $\text{NH}_4$  cations to soil particles, especially for soils with high cation exchange capacity (CECs) (Brady and Weil 1999). Thus, with high infiltration and strong soil buffering, most  $\text{NH}_4$  never reached the stream. We noted that in some of the lysimeter samples in both winter and spring,  $\text{NH}_4$  was actually higher in the pretreatment samples than in the post-treatment samples despite the fact that we were introduced a lot of  $\text{NH}_4$  during treatment. We offer the following scenario to explain this phenomenon. Prolonged drought may have resulted in high retention of  $\text{NH}_4$  and inhibited nitrification. Addition of large quantities of water with our treatment may have induced nitrification and denitrification processes in soil (Davidson et al. 1991, Williams et al. 1992). In future studies, we will investigate this hypothesis mechanistically.

This hypothesis is also consistent with the observed higher concentration of  $\text{NO}_3$  on day 2 than day 1 of the spring experiment in shallow and deep lysimeters in forested sites, and in deep lysimeters in grassy sites. We did not observe a similar pattern in winter, but nitrification may have occurred more slowly at the lower temperature. In summer,  $\text{NO}_3$  concentrations were much

higher in lysimeters than in the spring, which is also consistent with high nitrification of  $\text{NH}_4$ . Because our experiment introduced both  $\text{NH}_4$  and  $\text{NO}_3$ , we cannot distinguish between nitrification versus low buffering of  $\text{NO}_3$  as mechanisms to explain the high soil nitrate in the summer. In either case, buffering of soil  $\text{NO}_3$  was clearly stronger in spring than in either winter or summer.

Even with experimental application of 6500 gallons of water, the volume of surface runoff was very low. In part, this reflects the drought conditions that prevailed during the experiment and were extreme during the summer. Rainfall event sampling did not provide much information about riparian buffering capacity, probably due to the drought conditions that prevailed during the study period. However, the results confirmed our experimental finding that infiltration was very high. The high rate of infiltration may also be due to the unique characteristics of many urban riparian zones whereby runoff water from the surrounding watershed is actually plumbed under the riparian zones directly into the stream. Our experimental data show that urban riparian zones have a very high infiltration capacity, which is also linked to their nutrient buffering capacity. Currently, this capacity is not being utilized in urban streams to ameliorate either water quality or water quantity. Incorporation of riparian buffering capacity into water quality and water quantity management programs by re-routing storm water across the buffer could be of great benefit. Quantifying infiltration over a range of soil characteristics and hydrologic regimes would permit optimization of such a management tactic.

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Appendix 1. Figures A1-A9 illustrating the natural rainfall event sampling in Buffalo Creek, NC.

Figure A1

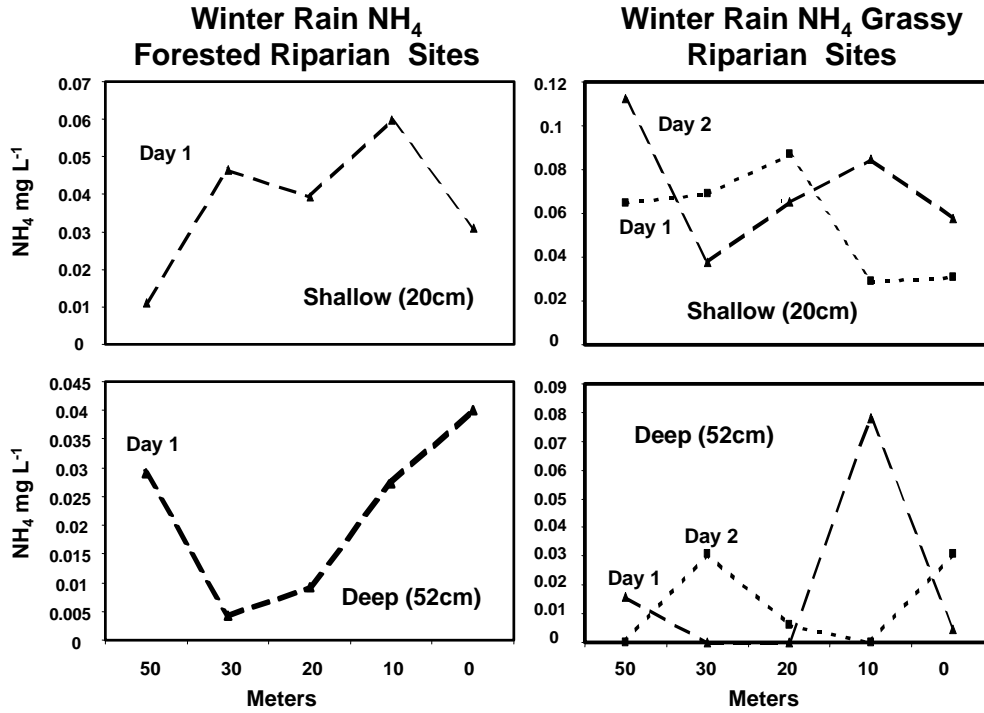


Figure A2

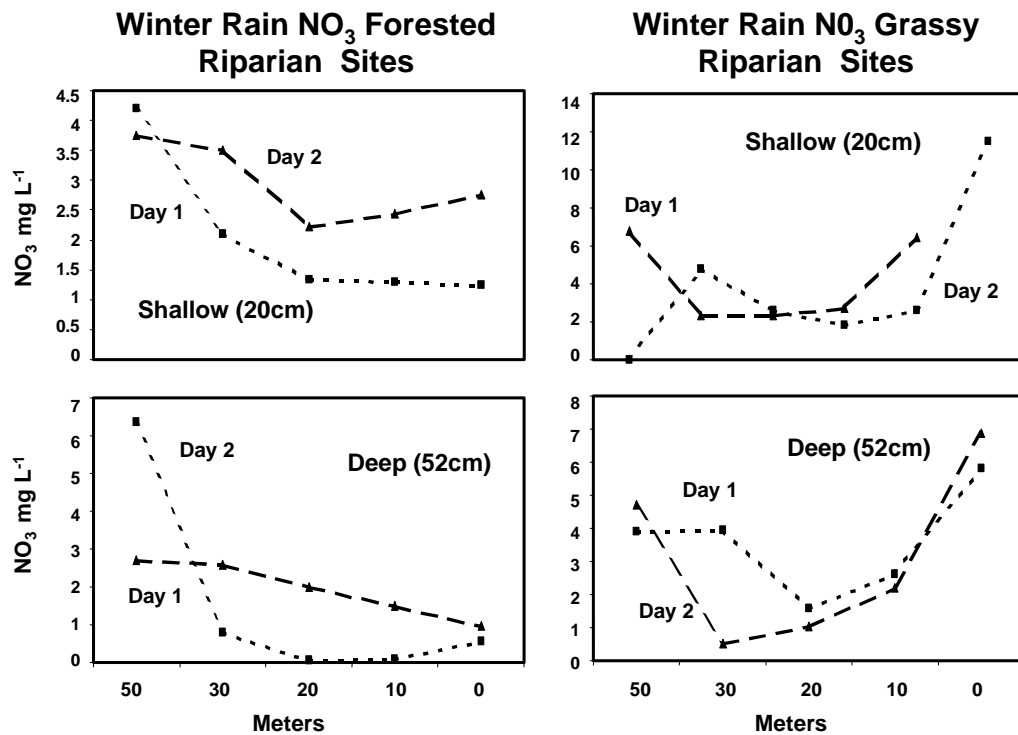


Figure A3

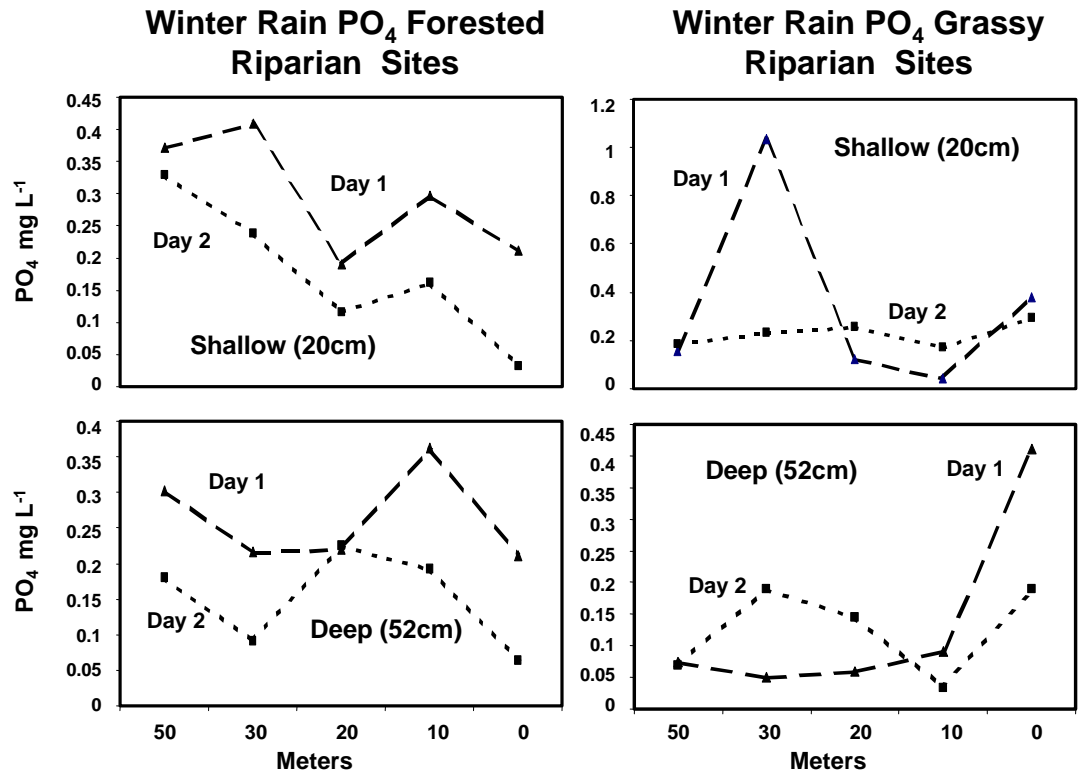


Figure A4

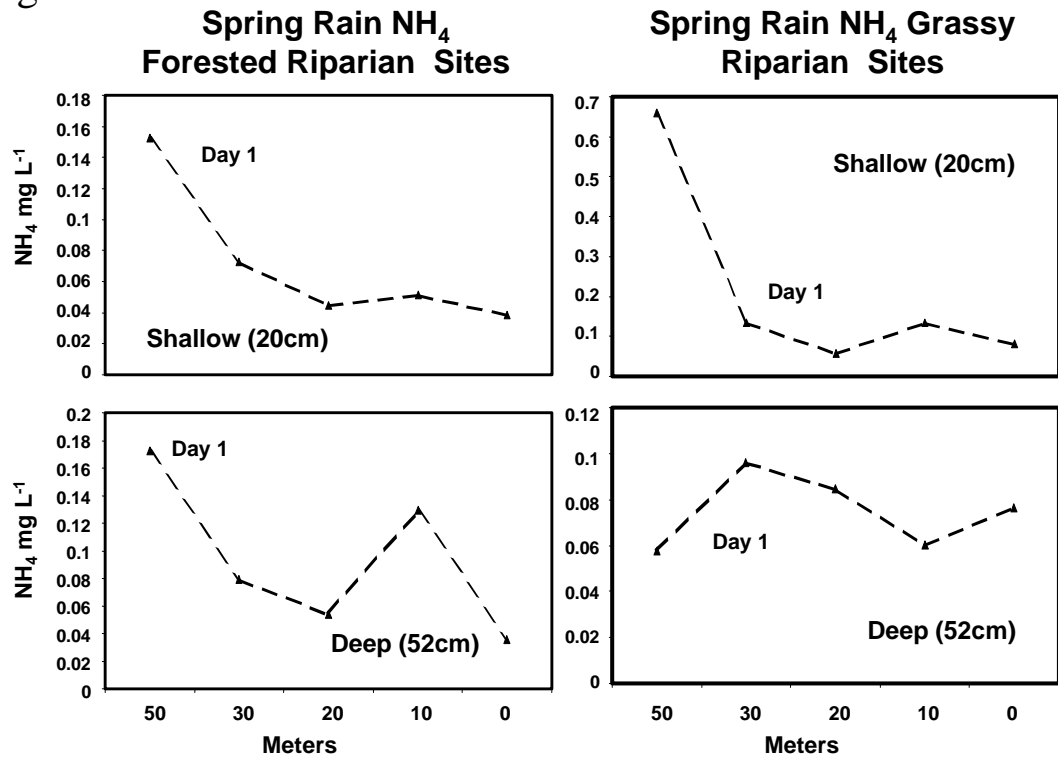


Figure A5

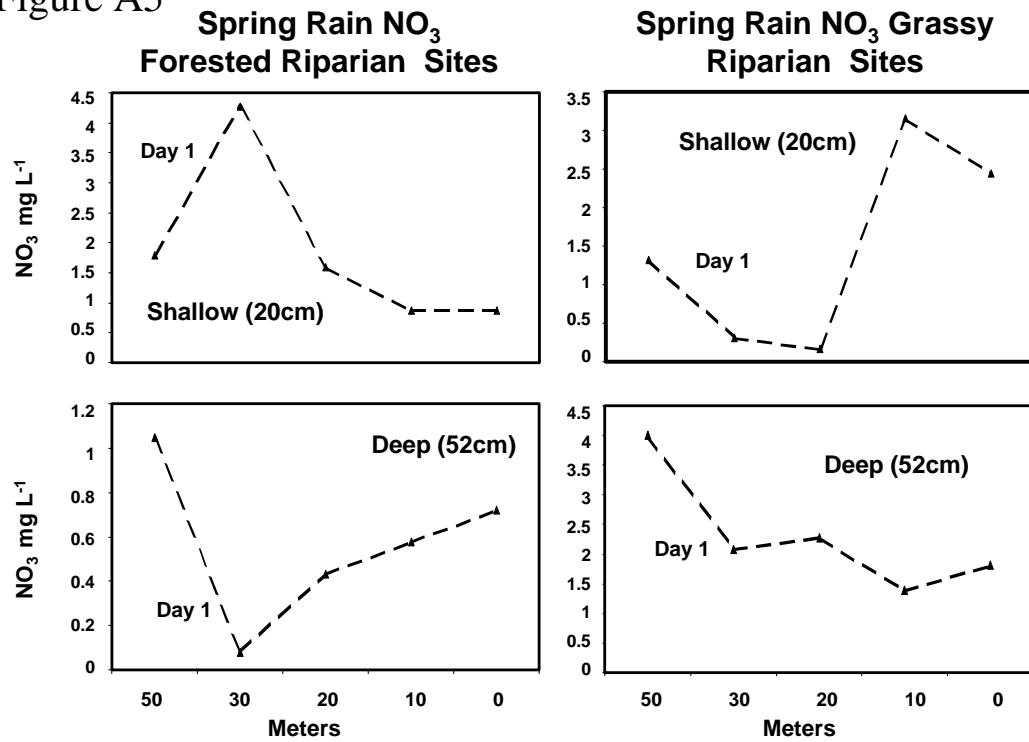


Figure A6

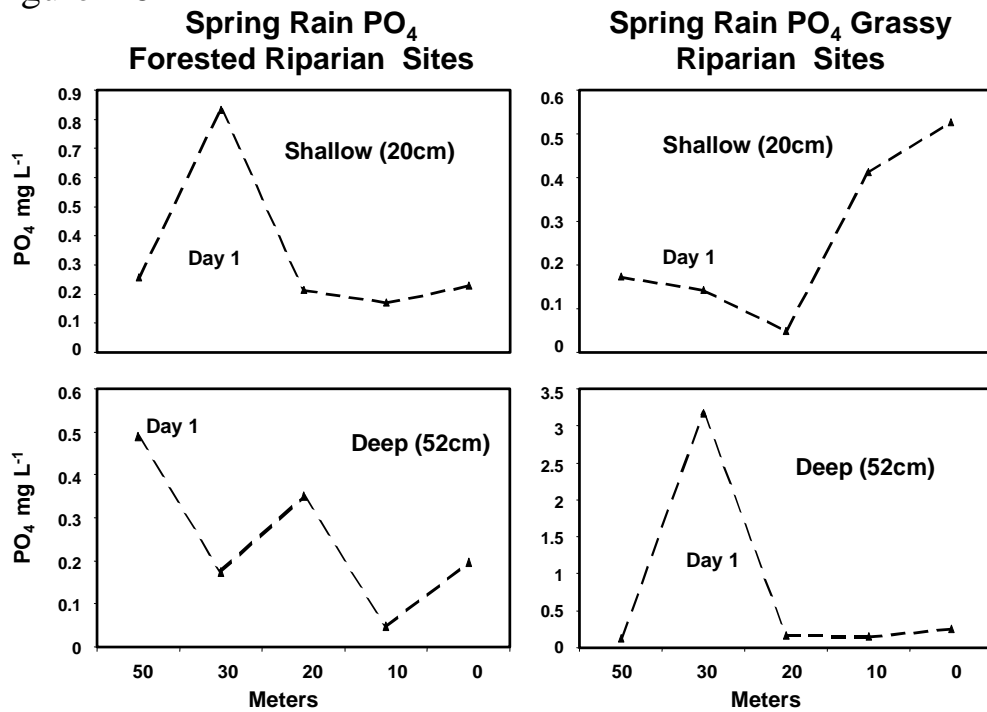


Figure A7

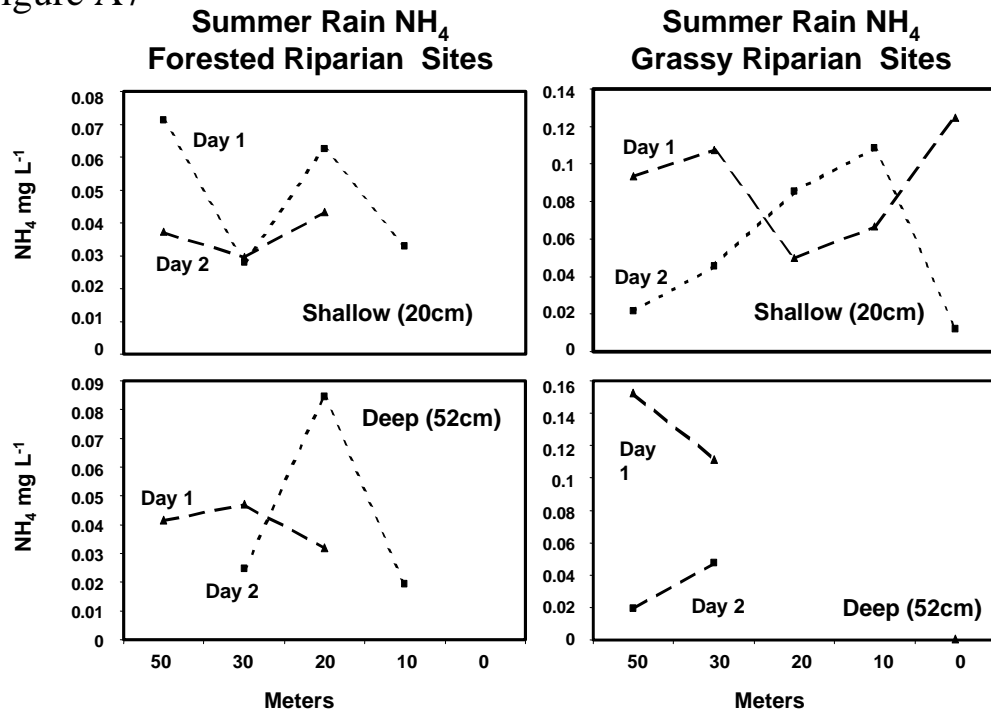


Figure A8

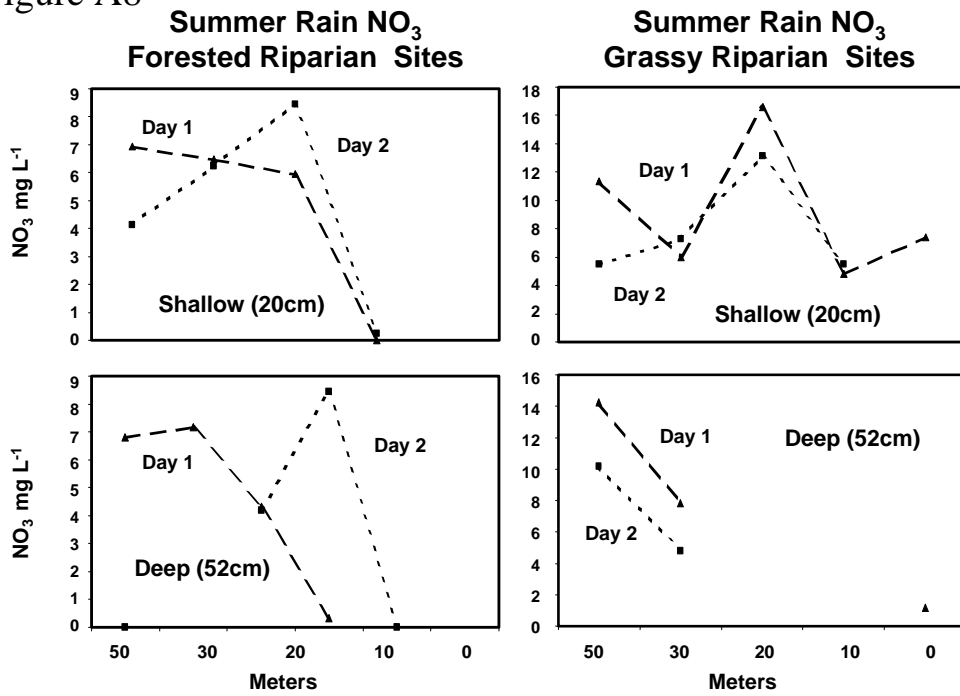


Figure A9

