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# Riparian zones in southern Appalachian headwater catchments: Carbon and nitrogen responses to forest cutting

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ABSTRACT

There is little understanding about the role eastern US forested headwater riparian areas play in protecting aquatic habitats and water quality from impacts of side slope forest harvest. To better understand this important riparian area function, we selected three sites from management units with a 2-age regeneration silvicultural prescription located on the Nantahala National Forest, North Carolina, USA. Each site was harvested and a riparian buffer was left uncut along the stream. Buffer widths were 10 m and 30 m; we included a 0 m buffer to experimentally determine nutrient and riparian zone responses to forest cutting under extreme conditions. A fourth site was selected to serve as an uncut reference. Transects were established perpendicular to a 200 m stream reach, from streamside to 50 m upslope for intensive study. Forest cutting increased extractable $NO_3^-$ at both 0–10 cm and 10–30 cm soil depths compared to pre-treatment concentrations. Soil solution $NO_3^-$ concentrations increased only in harvested areas, on all sites; increases were greater in sites with narrow riparian buffers. Stream water $NO_3^-$ concentration increased significantly following site harvest only on the 0 m buffer site. Dissolved organic C and N did not respond to harvesting in either soil solution or stream samples. Our results suggest that riparian buffers are effective in removing $NO_3^-$ from soil solution prior to its entering the stream.

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## 1. Introduction

The riparian zone is the interface between terrestrial and aquatic ecosystems through which water and materials move. Forested riparian zones are not easily delineated being a mosaic of landforms, above and belowground communities, and environmental conditions (Gregory et al., 1991). Naiman et al. (2000) examined large streams with steep gradients and large inputs of coarse wood in the Pacific Coastal Rainforest of North America. They concluded that boundaries of riparian areas could be delineated by changes in soil conditions, vegetation, and other factors that reflect aquatic and terrestrial interactions. However, regional climatic differences result in varying patterns of debris and sediment movement in the Pacific Northwest region (PNW) compared with those in the eastern US, making direct comparisons of stream characteristics among regions difficult.

First-order streams are the dominate stream type (i.e., 50% of total stream network length) in most forested watersheds (National_Research_Council, 2002; Wifli et al., 2007) yet, most of the scientific knowledge about riparian zone structure and function has been derived from studies of higher order streams, where geomorphic and fluvial controls are much more important (Verry et al., 2004). First-order streams in forested catchments are closely linked to terrestrial systems with a high edge-to-area ratio and increased shading and vary greatly throughout the US. These streams often have little geomorphological differentiation between the side slope and riparian area, however plant species and soil series often differ in near-stream areas (Moore et al., 2005; Moore and Wondzell, 2005; Richardson and Danehy, 2006).

In the steep headwater catchments of the southern Appalachians, morphological, soils, and vegetation inventories are required for riparian area definition prior to management prescriptions (Joan Brown, Nantahala Ranger District Silviculturist; personal communication). Studies have found greater total C and lower C:N ratios in stream side and cove soils (convergence areas). Near-stream soils also have greater total and available N concentrations, as well as higher N mineralization rates compared to upper-slope soils (Garten et al., 1994; Knoepp and Swank, 1998). This, coupled with decreased C:N ratios suggests improved soil organic matter quality and greater C and N turnover rates in riparian zone soils. Riparian areas often have higher plant diversity than upper-slope areas (Richardson and Danehy, 2006), although this may not be the case in small headwater catchments (Clinton et al., personal communication).

It has been shown that soil nutrient cycling responds to silvicultural treatments with increased availability of N (Burger

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and Pritchett, 1984; Donaldson and Henderson, 1990; Knoepp and Swank, 1993). However, soil solution $NO_3^-$ responses to harvest are low in magnitude. For example, $NO_3^-$-N concentrations increased from 0.03 mg N $L^{-1}$ in an undisturbed forest to 3.7 mg N $L^{-1}$ following site harvest in the southern Appalachians (Montagnini et al., 1991); stream concentrations increased from <0.01 to 0.17 mg $NO_3^-$-N $L^{-1}$.

Forestry best management practices (BMPs) are applied during harvest activities to minimize forest floor disturbance and soil exposure, reducing measurable fluxes of nutrients and sediment to streams. Most state forest BMPs require riparian zones to remain unharvested to mitigate potential effects of upslope disturbance on stream water quality. While nutrient and sediment responses to timber management activities may be less than responses to agricultural practices the protection of stream water quality is central to overall resource management objectives. Due to the importance and abundance of headwater stream ecosystems, understanding of the effectiveness of riparian buffers for the protection of aquatic resources is essential to forest land managers.

Our objectives were two-fold, (1) characterize carbon and nitrogen cycling responses in forested headwater catchment riparian zones following harvest, and (2) determine the effectiveness of varying riparian buffer widths for mitigating impacts of upslope site disturbance on streams.

## 2. Materials and methods

### 2.1. Site description

Study sites were located at 35°6′N, 83°6′W, on the Nantahala Ranger District of the Nantahala National Forest in the Blue Ridge Physiographic Province of western North Carolina. The area has abundant rainfall (approximately 1800 mm $yr^{-1}$) which is distributed evenly throughout the year (Swift et al., 1988); greatest rainfall is generally in March and least in October. Less than 5% of total annual precipitation falls as snow or ice. Mean annual air temperature is 12.6 °C ranging from 3.3 °C in January to 21.6 °C in July. Four headwater catchments with similar vegetation, topography, and soils were selected for the study. Three of the sites were selected by the Nantahala National Forest to receive a 2-age regeneration treatment (Miller et al., 1995), leaving 3.4–4.6 $m^2$ $ha^{-1}$ residual basal area of 30–40 cm diameter at breast height overstory vegetation. The fourth site was not harvested and served as a reference. All catchments were east-facing, ranged in size from 6 ha to 10 ha, in elevation from 850 m to 950 m, and had stream gradients ranging from −0.07% to −0.23%.

Sites have similar soils that are generally loamy to coarse loamy and derived from material weathered from high grade metamorphosed rock or from colluvium. Side slope soils range from 15% to 50% slope and are mapped in the Evard–Cowee complex (fine-loamy, mixed, mesic Typic Hapludults) which includes about 20% inclusion of the Trimont series (fine-loamy, mixed, mesic Humic Hapludults). These Ultisols are moderately well-drained to well-drained, deep (solum thickness ∼1 m) and greater than 1.5 m to bedrock. The saprolite layer beneath the solum may be up to 6 m deep (Thomas, 1996). Cove or stream side soils were formed in colluvium, 15–50% slope, and are mapped in the Cullasaja series. These soils are loamy-skeletal, mixed, mesic Typic Haplumbrepts, very deep, well-drained soils; solum thickness is <1.5 m; >1.8 m to bedrock (Thomas, 1996).

Forests in the southern Appalachians are generally considered N limited (Swank and Vose, 1997; Knoepp and Swank, 1998). Nitrogen deposition averages 9.5–12.6 kg N $ha^{-1}$ $yr^{-1}$, increasing with elevation and is composed of 40% $NO_3^-$-N, 40% $NH_4^+$-N, and 20% organic N (Knoepp et al., 2008).

### 2.2. Sample collection and experimental treatment

The three harvest sites were assigned one of the following buffer widths; 30 m, 10 m, and 0 m. We selected a 200 m stream reach at the lower end of each harvest unit for intensive study. Site layout and sampling were identical on the reference site. A transect-based sampling approach was used to quantify changes in soil and soil solution nitrogen. Eight 50 m transects, spaced 25 m apart, were established perpendicular to the stream reach on alternating sides of the stream (four on each side) (Fig. 1). Four

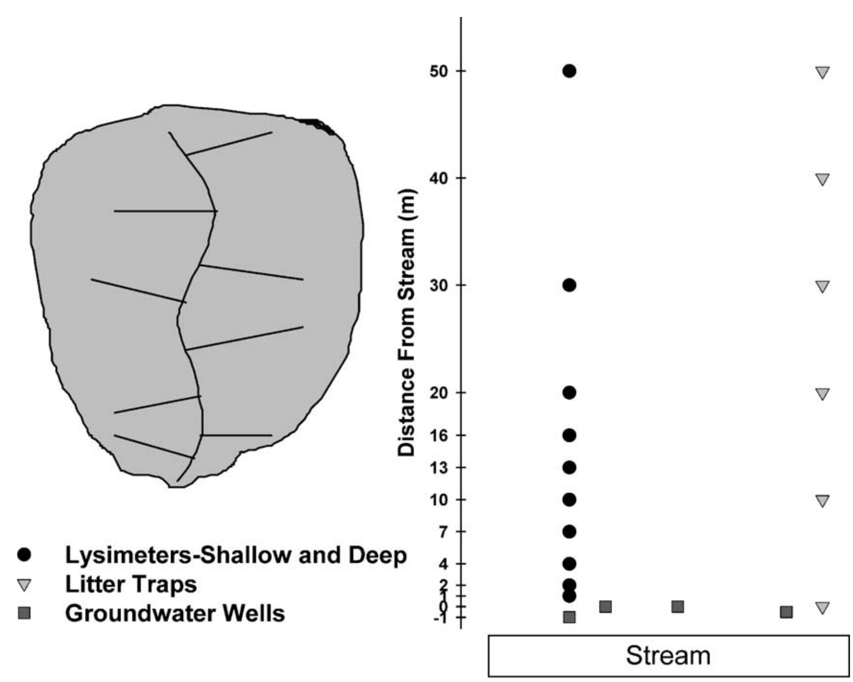


**Fig. 1.** Graphic depiction of site transect layout along the 200 m stream reach. Nutrient cycling transects are centered on litter fall traps, with tension lysimeters off-set from transect center-line by 7.5 m. Groundwater wells are located between the end of the transect and the center of the stream. Soil sample collections take place at randomly selected location along the sample line.

**Table 1**
Site harvest dates and sample collection dates. All pre-treatment data presented are spring, summer, and fall 2005.

| Site | Harvest begin | Harvest end | Post-treatment soil and soil solution collections |
|---|---|---|---|
| Reference | n/a | n/a | Spring, summer, fall 2006 |
| 30 m | July 2006 | February 2007 | Spring, summer, fall 2007 |
| 10 m | October 2005 | December 2005 | Spring, summer, fall 2006 |
| 0 m | January 2006 | July 2006 | Summer, fall 2006; spring 2007 |

transects were randomly selected for nitrogen cycling measurements. Transects ran from near-stream to upper-slope, the portion in the harvested area ranged from 50 m (0 m buffer site) to 20 m (30 m buffer site). The number of transects sampled varied depending on the parameter. Sampling intensity was greater within 20 m of the stream to increase the likelihood of detecting responses within the riparian zone.

Harvesting began in October, 2005 on the 10 m site and concluded in February 2007 on the 30 m site. Treatment was a 2-age harvest prescription (previously described) using primarily cable-yarding techniques to facilitate access to areas difficult or impossible to harvest with a conventional rubber-tired skidder. An added benefit of cable-yarding is the reduction in forest floor disturbance because logs are suspended above the forest floor during removal (Miller and Sirois, 1986). Site harvest and sample collection dates are presented in Table 1. The percent of the total watershed length harvested was 30 m—28%, 10 m—40%, and 0 m—54% (Joan Brown, Nantahala Ranger District Silviculturist; personal communication).

*2.2.1. Stream sample collection and analysis*

Stream sample collection began in January 2004. Weekly grab samples were collected below each harvest unit, and on the reference site. Weekly samples were analyzed for $NO_3^-$ and $NH_4^+$ concentrations, by ion chromatography and colorimetrically by the alkaline phenol method (USEPA, 1983a,b), respectively. Most (95%) stream samples were collected during baseflow conditions. Intensive hydrologic studies within Coweeta Hydrologic Laboratory showed that in low elevation first-order watersheds approximately 50% of rainfall occurs as runoff with 5% occurring as storm runoff (Swift et al., 1988). Estimates of stream discharge were not made due to the short length of the study reach (200 m).

*2.2.2. Soil sample collection and analysis*

Pre-treatment soil sampling was conducted to characterize the near-stream to upper-slope gradient. Soil profiles along each of the four nutrient cycling transects were described and sampled during the summers of 2004 and 2005; two transects each year. Sample locations were 1 m, 2 m, 4 m, 7 m, 10 m, 13 m, 16 m, 20 m, 30 m, and 50 m from the stream. At each sample location we used a 2.5 cm soil probe to describe the mineral soil profile and collect soil samples by horizon. Soil samples were collected by horizon down to saprolite. Minimum horizon depth was 5 cm, horizons greater than 20 cm deep were divided (uniformly) for sample collection; 80–100 samples were collected per transect. Maximum profile depth was 110 cm. Soil profiles were described using basic Soil Taxonomic characterization (USDA, 1996), based on changes in color and texture. Samples were placed in re-sealing plastic bags and mixed thoroughly. Approximately 10 g of fresh soil was added to 50 mL, 2 mol KCl $L^{-1}$ in pre-weighed 125 mL plastic bottles for $NO_3^-$ and $NH_4^+$ extraction within 1 h of collection. Bottles plus soil were weighed upon returning to the laboratory to determine actual soil weight and allowed to settle overnight. KCl supernatant was subsampled for analysis. Concentrations of $NH_4^+$ and $NO_3^-$ were determined on an autoanalyzer using alkaline phenol (USEPA, 1983a,b) and cadmium reduction (USEPA, 1983a,b) techniques, respectively. Pre-treatment soil $NO_3^-$ and $NH_4^+$ concentrations are reported on a fresh weight basis. Total C and N concentrations were determined by combustion using a Thermo Electron/Carlo Erba Flash EA 1112[1] on air-dried, sieved (<2 mm), and powdered subsamples from each horizon. Soil profile nutrient content was determined using average bulk density values (total g $cm^{-3}$) from other soil experiments in the southern Appalachians (Knoepp, unpublished data) along with measured $NO_3^-$, $NH_4^+$, total C, and total N concentrations. We calculated pre-treatment nutrient content for depths 0–10 cm and 10–30 cm using depth weighted means of N concentrations from appropriate soil horizons to allow pre- and post-treatment comparisons.

Post-treatment soil sampling was conducted at each distance from the stream along each transect at a randomly selected distance along the contour from the transect center (Fig. 1) in spring, summer, and fall. At each location 3–4 individual soil samples, collected from a 0.25 $m^2$ area, were composited from 2 depths, 0–10 cm, and 10–30 cm. KCl extractable $NO_3^-$ and $NH_4^+$ were determined in the field on soils sieved <6 mm as described above. A 10–20 g subsample of each soil sample was weighed, dried overnight at 105 °C, and reweighed to determine percent moisture of the original soil sample. One year (spring, summer, and fall) post-treatment soil collections were used to determine treatment effects and make site comparisons. Post-treatment $NO_3^-$ and $NH_4^+$ concentrations are presented on an oven-dried weight basis.

Total C and N concentrations were determined on the first post-treatment soils collection. Air-dried soils were sieved to <2 mm, powdered, and analyzed for total C and N as described above.

*2.2.3. N transformation indices*

We used $NO_3^-$ and $NH_4^+$ adsorption by anion and cation exchange resin membrane sheets as an index of soil nitrogen transformation, nitrification and mineralization, respectively (W. Jarrell, personal communication, 1996). Cation and anion resin sheets were charged prior to use by repeated washing (3 times for 10 min each) in 0.5 mol $NaHCO_3$ $L^{-1}$ solution to charge all exchange sites. One pair of resin sheets were placed at each distance along each of four transects on all sites (40 cation and 40 anion sheets per site), 5 cm below the mineral soil surface, and left in place for 14 days. Sheets were removed from the soil, excess soil and organic matter removed and placed in one zipper type plastic bag per sample location. Before extraction, resin sheets were rinsed thoroughly with deionized water to remove any remaining soil and organic matter particles. Resin sheets (anion and cation) from each sample location were placed in a 10 cm petri dish with 25 mL of 0.5 mol HCl $L^{-1}$ and shaken gently for 20 h. Solutions were analyzed for $NO_3^-$ and $NH_4^+$, colorimetrically as described above. Nitrogen absorption values are presented as $\mu g\ cm^{-2}$ of resin sheet surface area.

*2.2.4. Soil solution collection*

We installed porous cup tension lysimeters (5 cm diameter PVC) vertically into the soil along two transects perpendicular to the stream at each distance from the stream (Fig. 1). We used the

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

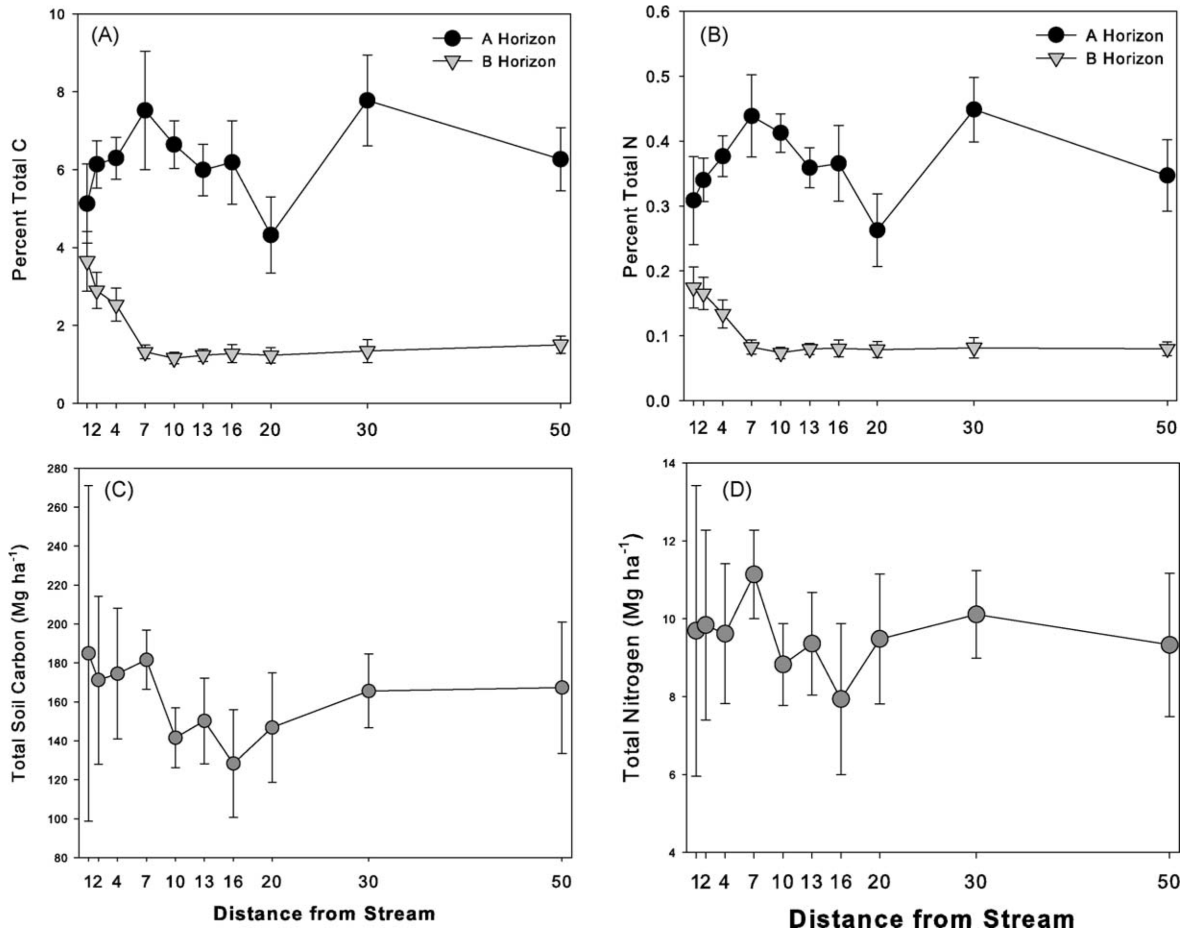


**Fig. 2.** Total C and N through the soil profile along the transect for near-stream to upper-slope position. Data represent the mean value of pre-harvest soil collection from all four sites ($n = 4$) at each distance from the stream. Error bars represent one standard error of the mean. (A) Carbon concentration (%) in the A and the B horizon soils. (B) Nitrogen concentration (%) in the A and B horizon soils. (C) Total C in the soil profile Mg ha$^{-1}$ from soil surface to surface of the saprolite. (D) Total C in the soil profile Mg ha$^{-1}$ from soil surface to surface of the saprolite.

falling tension method; each week after sample collection 0.03 MPa of tension was applied to the lysimeter, to begin collecting the sample for the following week. Lysimeters equilibrated in the soil for six weeks before water samples were collected for chemical analyses. During the equilibration period, lysimeters were pumped out weekly to flush through the system. After four weeks test samples were analyzed for $NO_3^-$-N to insure a consistent pre-treatment concentration before sample collection began. At each location we installed two lysimeters, one 15 cm deep, one at the bottom of the B horizon above saprolite (depths: 36–100 cm). Soil solution chemistry collected from shallow lysimeters indicates mobile soil nutrients and nutrient availability. The deep soil solution sample is below the major rooting zone and above the saprolite measuring nutrients potentially moving out of or leaching from the soil. Shallow lysimeters were 30 cm in length, the center of the porous cup was 15 cm deep. The deep lysimeters were 60 cm in length, polypropylene tubing attached to the vacuum, and sample ports allowed access from the soil surface. Soil solution samples from both shallow and deep lysimeters were collected weekly. A monthly composited sample was generated by freezing a 10 mL subsample following collection of each weekly sample. We determined $NO_3^-$ and $NH_4^+$-N as previously described.

### 2.2.5. DOC and DON concentrations

We measured dissolved organic carbon (DOC) and total dissolved nitrogen (TN) concentrations in soil solution, groundwater and streams on all four sites. Groundwater wells were installed at the stream end of each transect to collect solution within the hyporheic zone; between 3 and 5 wells were located within 1 m of and in the middle of the stream (Fig. 1). We collected well solution samples once monthly. Wells were pumped out one week prior to sample collection. This monthly sample collection coincided with lysimeter and stream sampling. Lysimeter samples were not composited prior to DOC and TN analysis. Well and stream samples were filtered on collection day, through a 0.45 μm glass-fiber filter. DOC and TN were determined in each sample on a Shimadzu TOC-$V_{CPH}$ with a TN analyzer attachment. $NO_3^-$ and $NH_4^+$ were determined in each sample as described above. Dissolved organic nitrogen (DON) was calculated as TN-($NO_3^- + NH_4^+$).

### 2.2.6. Statistical analysis

We analyzed the overall effect of harvest treatment as a split plot design using site and distance from stream as fixed variables; transects served as replicates within a site, a random variable. Comparing slope sections within a site is also a split plot design. We also examined differences in the buffer widths among the 4 sites; a split–split plot experimental design. We used analysis of covariance for post-treatment comparisons within and among sites using pre-treatment data as the covariate. For soil solution data we used the seasonal means for each transect and buffer width for analysis, the same season of the pre-treatment year was used as the covariate. Percent total soil N and C, and KCl extractable $NO_3^-$ and $NH_4^+$ concentrations used pre-treatment soil profile data. Pre-treatment DOC and DON data were limited; therefore only post-treatment comparisons were conducted. We used the mixed procedure in SAS (SAS, 2000) for all analyses; significant differences reported are at $\alpha \leq 0.05$ unless otherwise noted.

Treatment effects on stream water chemistry were determined by comparing treated and reference streams using pre- and post-treatment data to identify significant treatment impacts. Test statistics were generated using regression analysis on the differences in $NO_3^-$ concentration between the reference watershed and each treated watershed, by comparing before treatment differences to post-treatment differences in concentrations using the GLM procedure of SAS (SAS, 2000). Significant differences were evaluated at the $\alpha \leq 0.05$ level.

## 3. Results and discussion

### 3.1. Total N and C

Depth of soil to saprolite varied significantly with distance from the stream (Clinton et al., personal communication). Total depth was just over 40 cm near the stream, increased until 13 m from the stream, then remained constant across the slope. A horizon depth averaged between 15 cm and 20 cm across the entire slope transect. Percent total soil C and N varied across the slope transect. A horizon total C and N increased from 1 m to 7 m from the stream (Fig. 2) and then became variable. B horizon C and N, on the other hand, decreased between 1 m and 7 m from the stream and then remained constant to 50 m. This pattern, increased concentration at shallow soil depth near the stream and decreasing concentrations with increasing depth away from the stream, led to a fairly constant total C and N content within the soil profile along the near-stream to upper-slope transect (Fig. 2).

We compared the pre- and post-treatment total N and C concentration in the unharvested buffer zones and harvested areas by distance from the stream; referred to as near-stream (0–10 m), mid-slope (10–30 m), and upper-slope (50 m), respectively. Pre-treatment, we found that only the 0 m site had significant differences in surface soil (0–10 m) total C along the slope. The near-stream section had significantly greater C than upper-slope section (Fig. 3). Total C in subsurface soil (10–30 cm) of the 0 m

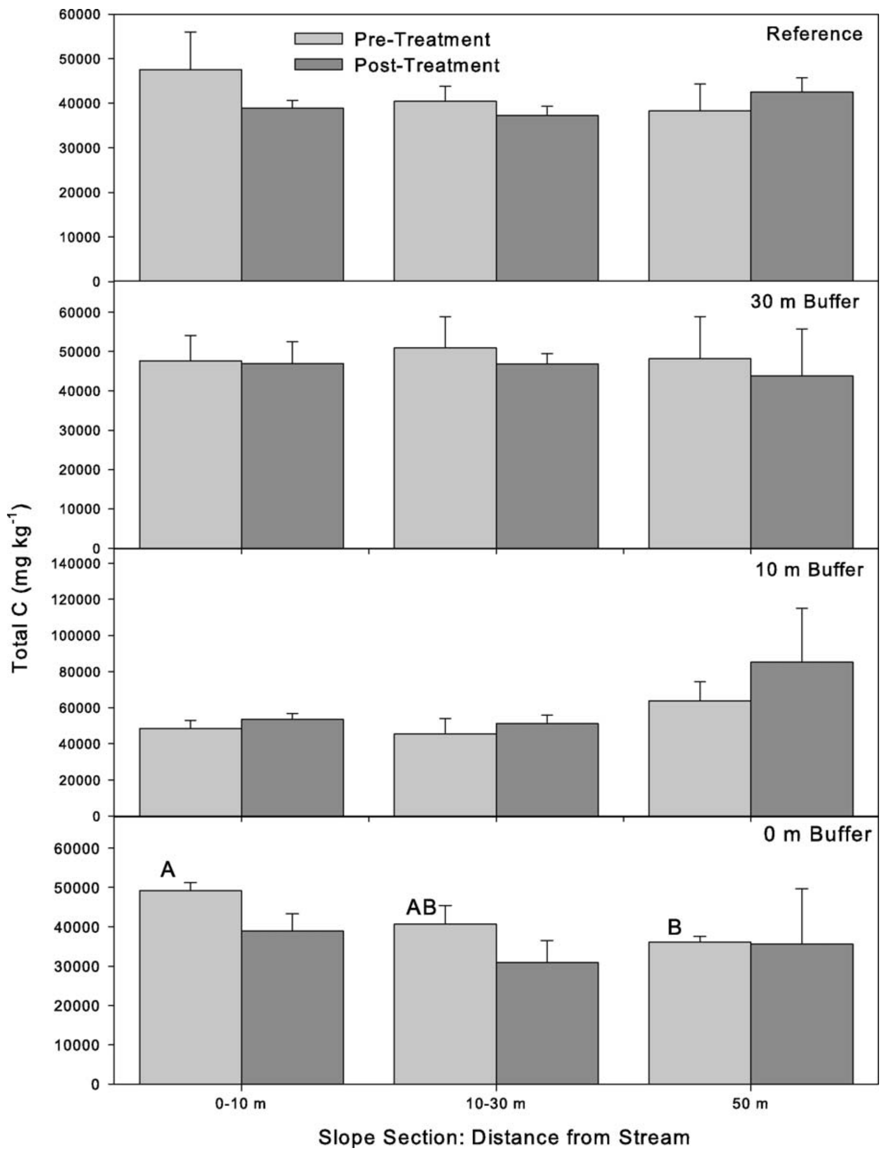


**Fig. 3.** Total soil C concentration in surface soils (0–10 cm), pre- and post-treatment in the reference, 30 m buffer, 10 m buffer, and 0 m buffer sites along the slope including near-stream, mid-slope, and upper-slope positions. Post-treatment data are the mean values of the first soil sample collection; of each sample transect ($n = 4$) for each slope section. Error bars represent one standard error of the mean. Bars within a site with different letters (A, B, C) designate significant differences among slope sections within a site. Bars within a slope section with different letters (x, y, z) designate significant differences for a slope section between sites.

near-stream section also tended to be greater than other slope sections ($P < 0.07$) (data not shown). There were similar differences for total N. Both the near-stream and mid-slope sections had greater total N than the upper-slope surface soils; however, subsurface soil total N was greater only in near-stream soils. The reference site also had greater subsurface total N in the near-stream position. This pattern of greater soil total C and N in near-stream soils is common among soils in the southeastern US (Garten et al., 1994; Knoepp and Swank, 1998; Knoepp et al., 2000). This results in a lower C:N ratio in near-stream soils, suggesting greater soil organic matter quality and increased C and N turnover rates in riparian zone soils (Knoepp et al., 2000). Changes in soil C is a soil property used to define riparian areas and riparian soils. This transition between riparian and side slope soils was evident in the county soil survey as noted in the site description. Rosenblatt et al. (2001) were successful in using the Soil Survey Geographic data base to identify potentially effective riparian zones across Rhode Island.

There was no measurable impact of site harvest on total soil C (Fig. 3) or N (data not shown) in any of the sites, in either harvested or unharvested buffer sections at either soil depth. Total C and N responses to forest harvest have been shown to vary considerably among studies. Johnson et al. (2002) examined the long-term impacts of whole-tree, complete tree, and sawlog harvest on total soil C content in sites across the southeastern US. They found initial soil C responses to harvest only on sites with intensive sampling schemes following harvest; other sites showed no response. All sites showed long-term changes in total C although they were not attributed to harvest treatment. Knoepp and Swank (1997) measured a rapid increase in total soil C and N content of surface soils following clear-cut harvest in the southern Appalachians. This response was attributed to root mortality and rapid decomposition of logging residue, such as leaves and small branches. On the other hand, when examining three different harvest methods in similar forests (2-age regeneration, shelterwood, and group selection), Elliott and Knoepp (2005) found no total soil C or N response following harvest.

### 3.2. Extractable $NO_3^-$ and $NH_4^+$ and N transformation indices

Pre-treatment extractable soil $NO_3^-$ concentrations did not differ between near-stream, mid-slope, or upper-slope sections for any site in either the surface or subsurface soils (Fig. 4). $NH_4^+$ concentrations

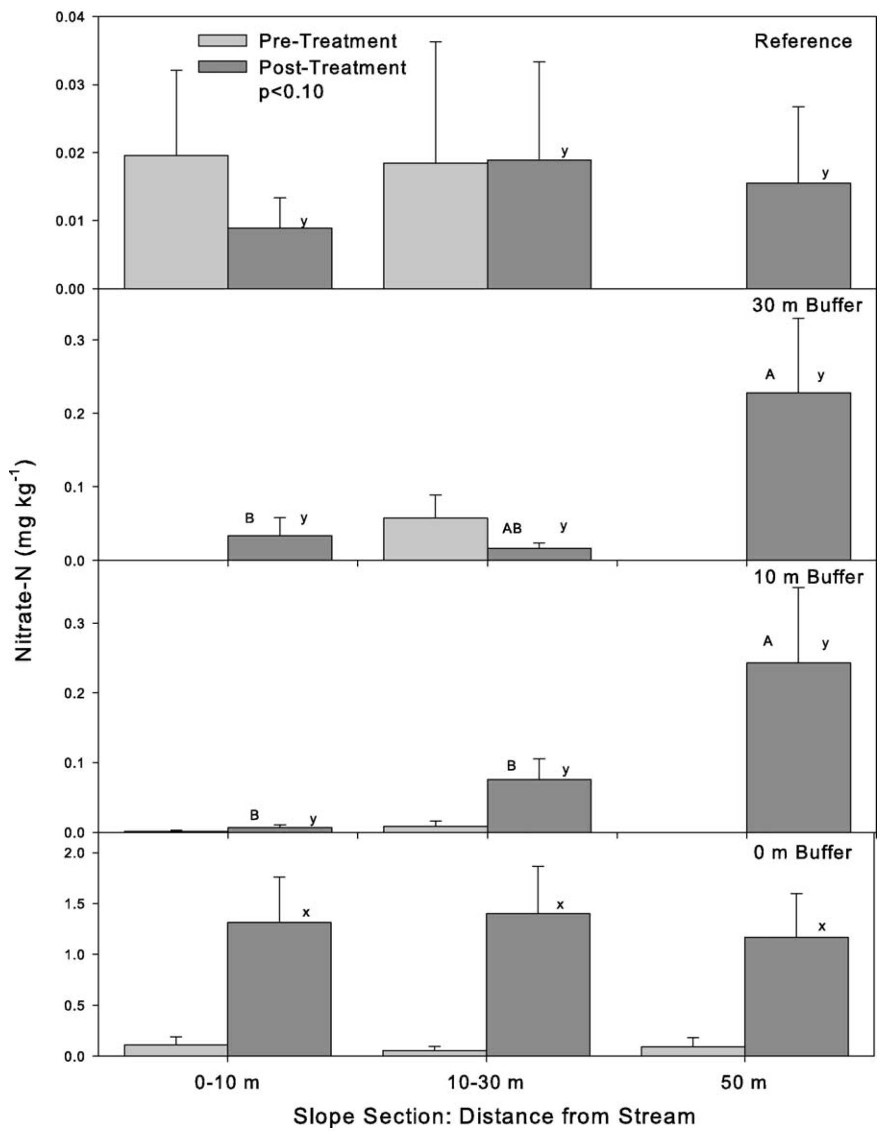


**Fig. 4.** Soil $NO_3^-$-N concentration in surface soils (0–10 cm), pre- and post-treatment in the reference, 30 m buffer, 10 m buffer, and 0 m buffer sites along the slope including near-stream, mid-slope, and upper-slope positions. Post-treatment data shown are the mean values of spring, summer and fall collections, of each sample transect ($n = 4$) for each slope section. Error bars represent one standard error of the mean. Bars within a site with different letters (A, B, C) designate significant differences among slope sections within a site. Bars within a slope section with different letters (x, y, z) designate significant differences for a slope section between sites.

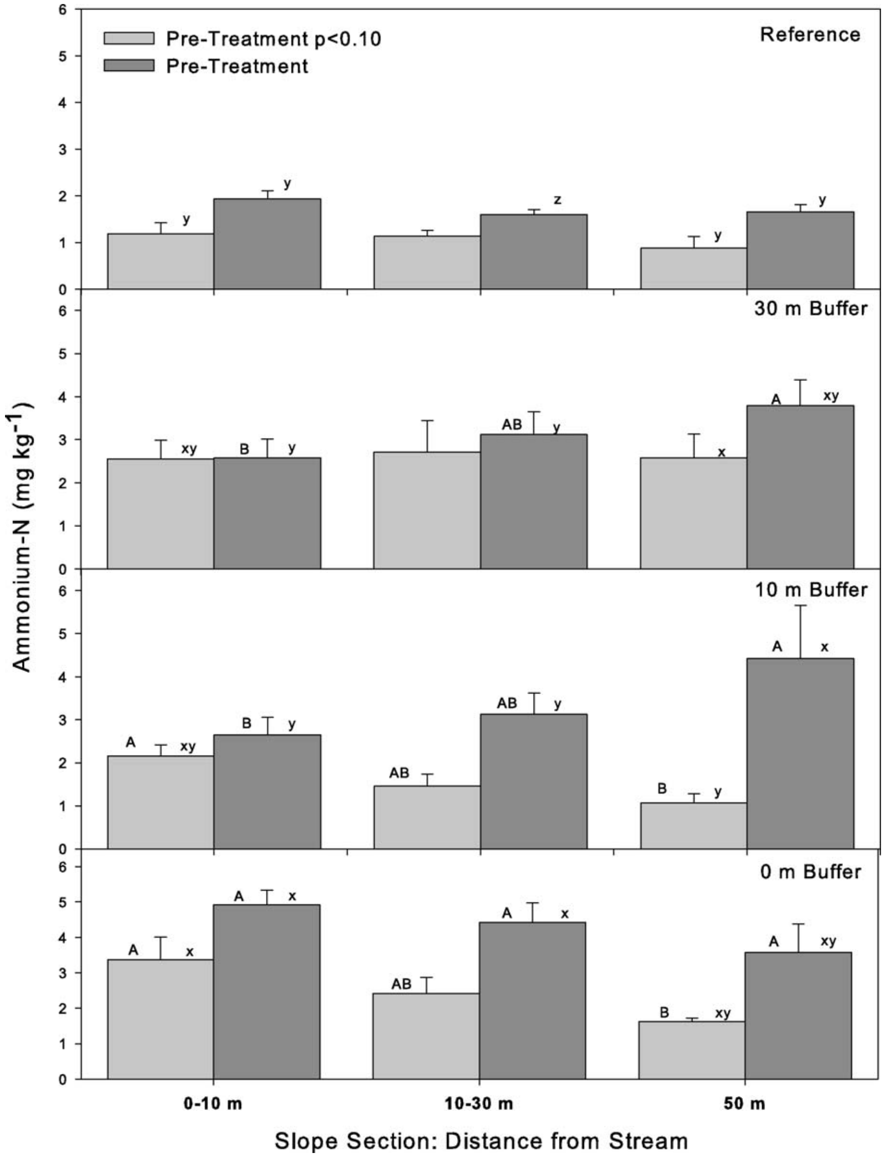


**Fig. 5.** Soil $NH_4^+$-N concentration in surface soils (0–10 cm), pre- and post-treatment in the reference, 30 m buffer, 10 m buffer, and 0 m buffer sites along the slope including near-stream, mid-slope, and upper-slope positions. Post-treatment data shown are the means spring, summer and fall collections, of each sample transect ($n = 4$) for each slope section. Error bars represent one standard error of the mean. Bars within a site with different letters (A, B, C) designate significant differences among slope sections within a site. Bars within a slope section with different letters (x, y, z) designate significant differences for a slope section between sites.

were greater in near-stream surface soils compared to the upper-slope in both the 0 m and 10 m buffer sites (Fig. 5). The pattern of increased extractable N concentrations as well as increased N mineralization rates in the near-stream position is common (Garten et al., 1994; Knoepp and Swank, 1998; Knoepp et al., 2000). This suggests that these soils have increased N cycling rates.

$NO_3^-$ concentrations in surface soils differed among slope positions following harvest. $NO_3^-$ concentrations increased only in the harvested sections of all sites; the upper-slope had the greatest response in the 10 m and 30 m sites; all slope positions had greater $NO_3^-$ compared to pre-treatment in the 0 m site (Fig. 4). $NO_3^-$ in subsurface soils responded to harvest in near-stream and mid-slope sections in the 0 m and 10 m sites (data not shown).

Soil $NH_4^+$ concentrations also increased in slope sections disturbed by harvest (Fig. 5). The 10 m and 30 m site had greatest $NH_4^+$ concentrations in the upper-slope while the 0 m site had increases across all slope positions. Only the 0 m subsurface soils had significant increases in $NH_4^+$. All slope positions responded, the near-stream concentrations were the greatest, followed by mid-slope and upper-slope (data not shown).

Disturbance due to harvest also resulted in increased $NO_3$ and $NH_4$ transformation indices (Fig. 6a and b). There were no pre-harvest differences in N transformations among slope positions on any site (Clinton et al., personal communication). Following harvest, all sites had greater $NO_3$ and $NH_4$ transformations within the harvested slope sections; the response was significant in the upper-slope 10 m and 30 m site, and all slope positions for the 0 m site. In the post-treatment measurements, reference site $NO_3$ transformation was greater at the near-stream position than either the mid- or upper-slope.

Increases in extractable soil $NO_3^-$, $NH_4^+$, and N transformation indices following forest harvest are common (Burger and Pritchett, 1984; Donaldson and Henderson, 1990; Knoepp and Swank, 1993). These responses are attributed to both the increased microbial production of $NO_3^-$ and $NH_4^+$ due to increased soil temperature and moisture as well as reduced plant uptake. Soil N responses to forest management practices and disturbance, such as increases in $NO_3$- and $NH_4^+$, vary with disturbance intensity and initial N availability. Responses may be short-lived (Knoepp et al., personal communication) or last for 3–4 years (Waide et al., 1988; Knoepp

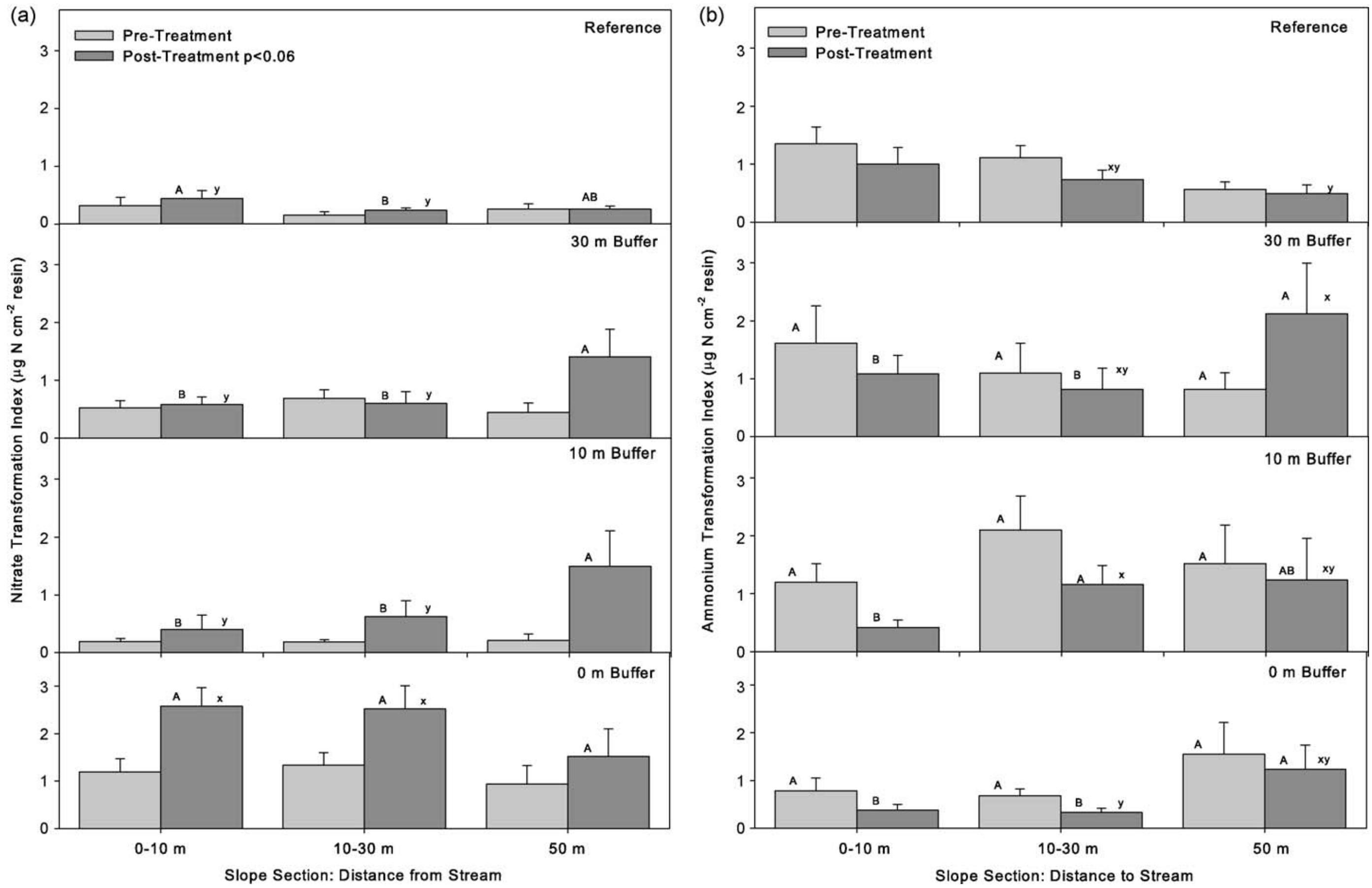


**Fig. 6.** (a) Index of soil nitrification potential as measured using $NO_3^-$-N captured during a 14 day on anion exchange resin sheets, pre- and post-treatment in the reference, 30 m buffer, 10 m buffer, and 0 m buffer sites along the slope including near-stream, mid-slope, and upper-slope positions. Post-treatment data shown are the means spring, summer and fall collections, of each sample transect ($n = 4$) for each slope section. Bars represent one standard error of the mean. Bars within a site with different letters (A, B, C) designate significant differences among slope sections within a site. Bars within a slope section with different letters (x, y, z) designate significant differences for a slope section between sites. (b) Index of soil N mineralization potential as measured using $NH_4^+$-N captured during a 14 day on cation exchange resin sheets, pre- and post-treatment in the reference, 30 m, 10 m, and 0 m buffer sites along the slope including near-stream, mid-slope, and upper-slope positions. Post-treatment data shown are the means spring, summer and fall collections, of each sample transect ($n = 4$) for each slope section. Bars represent one standard error of the mean. Bars within a site with different letters (A, B, C) designate significant differences among slope sections within a site. Bars within a slope section with different letters (x, y, z) designate significant differences for a slope section between sites.

et al., 2004). Even when forest soil responses to disturbance are high, soil N concentrations remain low. In this study, $NO_3^-$ concentrations increased 10 times in the 0 m site following harvest and yet remained below 2 mg $kg^{-1}$.

### 3.3. Soil solution nitrogen

Shallow lysimeter solution N concentrations indicate mobile N within the rooting zone and plant nutrient availability. Pre-treatment $NO_3^-$ concentrations in shallow lysimeters did not differ among slope sections for any site (Fig. 7). While the 0 m site had an overall increase in shallow lysimeter $NO_3^-$ concentrations following harvest, other sites did not show any significant harvesting effect. There was no significant change in solution $NH_4^+$ concentrations between pre- and post-treatment in any site (data not shown).

Soil solution $NO_3^-$ concentration responses to harvest varied. Most harvested slope sections responded to harvest, with increases at all slope positions in the 0 m and in the mid-slope position in the 10 m site. There was no significant response in the 30 m site. There was no evidence of surface solution $NO_3^-$ moving from harvested to undisturbed slope sections. There were no significant differences or patterns along the slope in $NH_4^+$ concentrations in either the pre- or post-treatment sampling periods (data not shown).

Pre-treatment deep lysimeter soil solution $NO_3^-$ differed among slope positions in the 10 m site only, near-stream $NO_3^-$ concentrations were greater than either mid- or upper-slope solutions (Fig. 8). Following harvest, there was a trend toward increased deep soil solution $NO_3^-$ concentrations in both the 0 m and the 10 m ($P = 0.12$) site. However, this trend was also evident in the reference site ($P = 0.10$) in post-treatment sampling. The 30 m site did not exhibit a deep soil solution $NO_3^-$ concentration response to forest cutting. Again, there was no significant $NO_3^-$ increase on slope sections adjacent or below harvested sections, suggesting that $NO_3^-$ movement did not occur. Differences in deep soil solution $NH_4^+$ concentrations between pre- and post-treatment years varied among sites and slope position with no consistent differences or trends (data not shown).

Increased N mobility, as measured by soil solution $NO_3$ concentrations, is common following site disturbance or N additions (Titus et al., 1997; Hentschel et al., 2007; Zotarelli et al., 2007). Regulation of N leaching has been attributed to decreased vegetation uptake, site condition, and soil C:N ratio (Titus et al., 1997; Hentschel et al., 2007).

Increased soil measures of N availability and mobility (extractable $NO_3^-$ and $NH_4^+$, $NO_3^-$ release, and $NO_3^-$ in soil solution) is common following site disturbance. Our data show an increase in extractable N, soil solution N and soil $NO_3^-$ release.

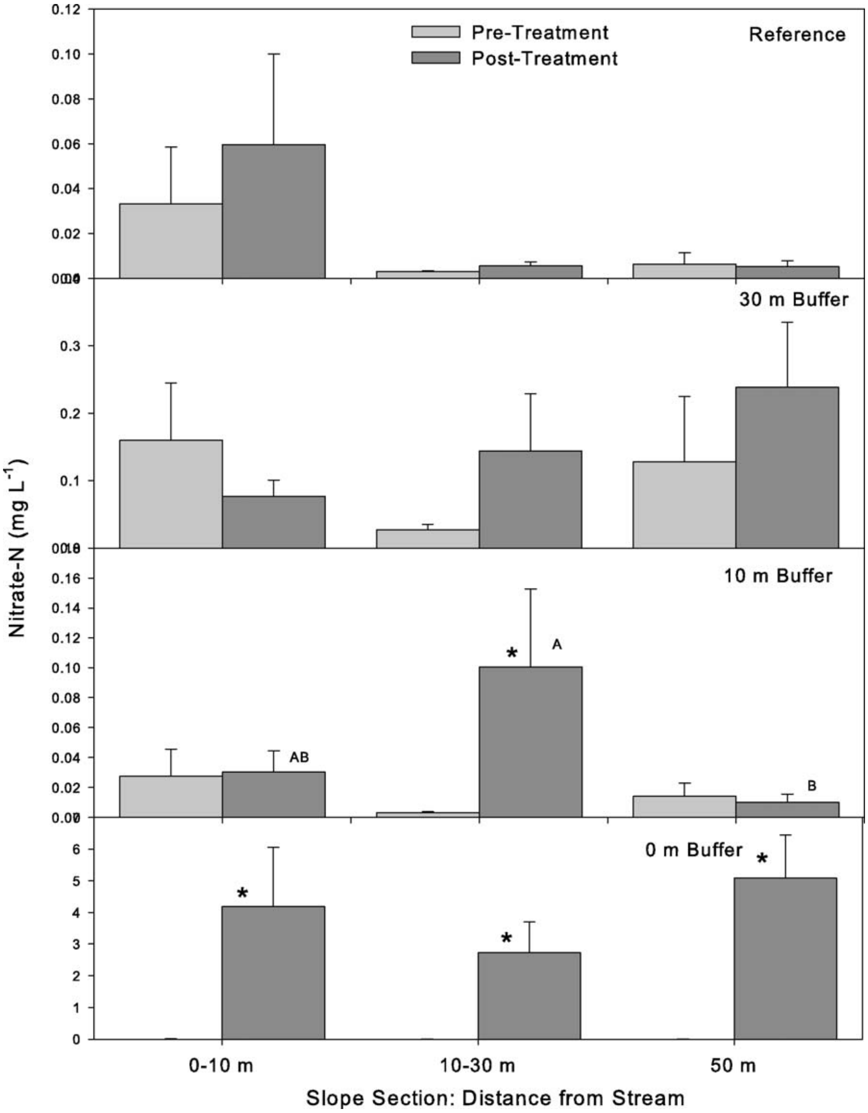


**Fig. 7.** Shallow soil (15 cm) solution $NO_3^-$-N concentrations collected using soil porous cup, tension lysimeters. Site values presented are means of seasonal mean values of monthly composited samples for each transect at each slope position. Bars represent one standard error of the mean. '*' designates significant differences between pre- and post-treatment values for a slope sections within a site. Letters (A, B, C) designate significant differences between slope sections within a site.

While these soil N measures increased there was little evidence of $NO_3^-$ movement between slope sections. Responses within each site were limited to the harvested slope section. N movement beyond the disturbed slope section was only evident in the stream data of the 0 m site, where there was a significant increase in stream $NO_3^-$ concentration after harvest compared to the reference watershed (Fig. 9). There was no stream $NO_3$ response to harvest in the other two harvested sites. In a study of N cycling patterns among vegetation types in the southern Appalachians, Knoepp et al. (2000) found that cove sites (convergence areas) had measurable $NO_3^-$ below the rooting zone less frequently than side slope mixed oak forests, suggesting efficient N retention by this ecosystem type. Yeakley et al. (2003) found increased $NO_3^-$ concentrations in shallow and deep lysimeter solutions as well as stream water for 3 years following understory cutting and overstory windfall on a hillslope. Swank (1988) examined stream responses following the commercial clear-cut of a 59 ha watershed, no riparian buffer was retained. Following this large disturbance there was an immediate stream $NO_3^-$ response; the maximum $NO_3^-$ concentration was measured 3 years following disturbance. The management units cut in our study did not represent the entire watershed drainage area. The percent of the total stream length harvested on each site was, 28% of the 30 m, 40% of the 10 m, and 54% of the 0 m, possibly not enough of the drainage area to alter stream chemistry in the 30 m or the 10 m. Mayer et al. (2007) did a meta-analysis of 45 published studies examining the effectiveness of 89 riparian buffers and found wide variation in N retention following upper-slope disturbance. Retention of surface soil solution $NO_3^-$ was most effective in buffers $>$50 m wide. Their data showed that subsurface $NO_3^-$ retention was more efficient and was not related to buffer width. Effective $NO_3^-$ uptake from soil solution by riparian zone soils requires the movement of the solution through the soil, not seeps and channels. This has been found in glaciated soils of the Northeastern US (Gold et al., 2001), Appalachian soils including the ridge and valley region (Lowrance et al., 1997), and agricultural soils of western Oregon (Wigington et al., 2003). Lowrance et al. (1997) summarized several studies examining the movement of N to the Chesapeake Bay through the various landscape types within the watershed. The coastal plain wetlands, areas closest to the bay, varied in effectiveness in $NO_3^-$ removal from shallow groundwater. Their exploration of the effectiveness of riparian areas for $NO_3^-$ removal within differing landscape types and physiographic regions suggests that Appalachian systems with their deep

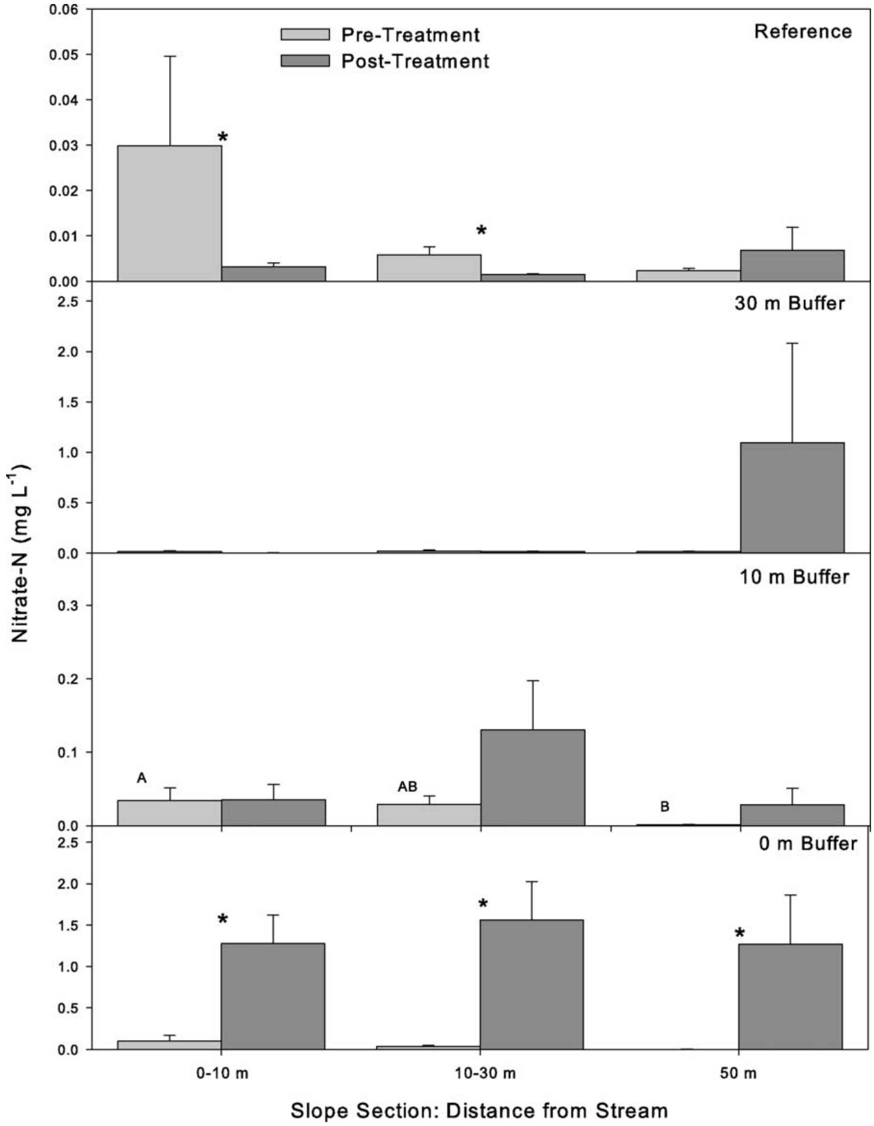


**Fig. 8.** Deep soil (lower B horizon) solution $NO_3^-$-N concentrations collected using soil porous cup, tension lysimeters. Site values presented are means of seasonal mean values of monthly composited samples for each transect at each slope position. Bars represent one standard error of the mean. '*' designates significant differences between pre- and post-treatment values for a slope sections within a site. Letters (A, B, C) designate significant differences between slope sections within a site.

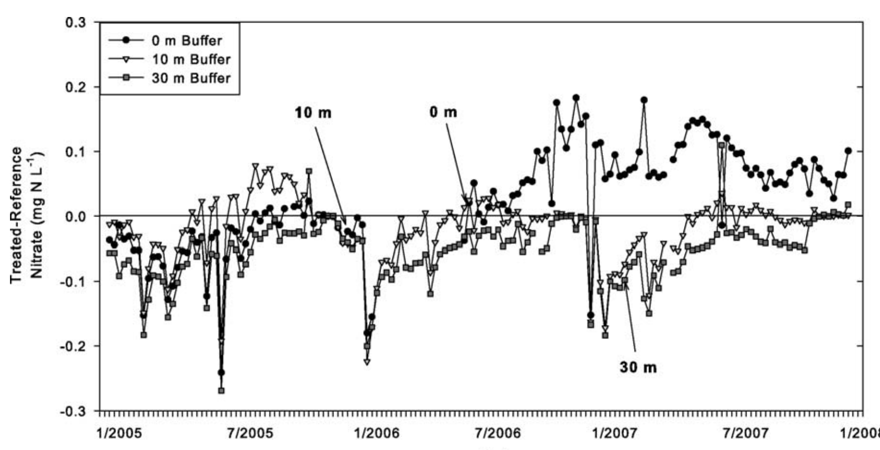


**Fig. 9.** Stream $NO_3^-$-N concentrations response to forest harvest for each of the three riparian zone buffer widths. Stream samples are collected weekly below the harvested area and reference. Values shown are treated minus reference for weekly concentrations, collections began in January 2005. An arrow indicates beginning of post-harvest sample collection for each site.

**Table 2**
DOC and DON concentrations along the hillslope–stream interface for sites with riparian buffer widths of 30 m, 10 m, and 0 m as well as a reference site. Values shown are means of growing season (spring, summer, and fall) stream and groundwater wells, as well as, shallow and deep soil solution samples from near-stream, mid-slope, and upper-slope positions. Data presented are post-harvest. Values followed by different letters within a column section are significantly different ($P \leq 0.05$) as determined by analysis of covariance.

| Sample | Reference | | 30 m | | 10 m | | 0 m | |
|---|---|---|---|---|---|---|---|---|
| | DOC | DON | DOC | DON | DOC | DON | DOC | DON |
| Stream | 0.57 (0.05) | 0.03 (0.01) | 0.46 (0.03) | 0.02 (0.003) | 0.50 (0.07) | 0.03 (0.004) | 0.50 (0.07) | −0.04 (0.06) |
| Groundwater well | 1.10 (0.21) | 0.05 (0.01) | 0.45 (0.03) | 0.02 (0.002) | 0.75 (0.17) | 0.03 (0.005) | 0.54 (0.09) | 0.04 (0.01) |
| Soil solution—shallow (15 cm) | | | | | | | | |
| Near-stream | 8.13a (1.44) | 0.25 (0.03) | 4.28 (0.78) | 0.16b (0.03) | 10.79 (1.78) | 0.36 (0.06) | 11.77a (3.02) | 1.22 (0.50) |
| Mid-slope | 10.37a (1.67) | 0.29 (0.03) | 4.27 (0.75) | 0.15b (0.05) | 7.31 (1.30) | 0.27 (0.06) | 5.57a (0.42) | 0.38 (0.11) |
| Upper-slope | 6.21b (0.97) | 0.18 (0.04) | 5.46 (1.01) | 0.39a (0.17) | 12.95 (6.38) | 0.31 (0.09) | 8.07b (2.23) | 0.32 (0.10) |
| Soil solution—deep (30–100 cm) | | | | | | | | |
| Near-stream | 1.75 (0.29) | 0.05 (0.02) | 0.74b (0.08) | 0.02 (0.003) | 2.33 (0.54) | 0.08 (0.03) | 2.11 (0.58) | 0.31 (0.22) |
| Mid-slope | 1.80 (0.30) | 0.04 (0.01) | 0.97b (0.22) | 0.03 (0.004) | 2.02 (0.32) | 0.06 (0.01) | 2.43 (0.53) | 0.14 (0.02) |
| Upper-slope | 1.22 (0.19) | 0.03 (0.01) | 4.71a (1.29) | 0.21 (0.06) | 3.9 (1.80) | 0.12 (0.06) | 1.35 (0.20) | 0.10 (0.05) |

unsaturated drainage areas would be medium to high, dependent on retention time, and the presence of seeps. Lyons et al. (1998) found that riparian areas had a maximum P retention capacity, and once that maximum was reached, P moved into the stream. Our data suggest that we did not exceed the N retention capacity of the riparian soils in either the 30 m or the 10 m site. The presence of $NO_3^-$ in the deep soil solution (the 10 m site) without its movement into the stream suggests that $NO_3^-$ uptake or transformation (biological or chemical) may take place within the saprolite layer. The loss of $NO_3^-$ through denitrification also decreases N movement to the stream. Davidson and Swank (1987) measured high denitrification potentials in near-stream soils following site harvest, with greatest rates in soil 6–15 cm. Denitrification in deeper soils was limited by C availability (Davidson and Swank, 1987; Addy et al., 1999).

### 3.4. DOC and DON

Shallow soil solution post-treatment values of DOC were significantly lower in the upper-slope position in both the reference and the 0 m site (Table 2). There were no significant differences among slope positions in the 10 m or 30 m sites. In the 30 m site, deep lysimeter solutions in the upper-slope position had the greatest DOC concentrations. DOC concentration in deep soil solutions of the upper-slope position on the 10 m site also tended to be greater ($P = 0.13$). DON concentrations in the upper-slope position on the 30 m site were significantly greater than either the near-stream or mid-slope positions (Table 2). The near-stream position tended to have the greatest DON concentrations in both the 10 m ($P = 0.10$) and the 0 m ($P = 0.14$) sites. There were no significant differences or patterns in DON concentrations evident among slope sections in the sub-soil solution (Table 2).

DOC represents an important energy transfer from terrestrial to aquatic systems (Richardson and Danehy, 2007). Yeakley et al. (2003) examined effects of hillslope understory removal and overstory blowdown on N and DOC movement. Following understory cutting, soil water DOC concentrations increased (small increase), groundwater DOC did not change. However, on the hillslope with overstory blowdown, there were large increases in $NO_3^-$ and DOC concentrations in both soil solution and groundwater. McGlynn and McDonnell (2003) examined patterns of DOC in stream water during storm hydrographs. The hillslope appeared to be disconnected from the stream early in the storm, but as the hillslope water content increased the connection was made and DOC concentrations in the hillslope and in the stream were similar. Bhat et al. found that 73% of the total N output from a forest watershed occurred as overland flow during storm events. Our sample collections represent largely baseflow. This could have precluded our observation of stream DOC or DON responses.

Futter et al. (2007) used models to explore regulatory mechanisms of in stream DOC concentrations of boreal forests with peat. They found that model predictions of stream DOC were most sensitive to climate, litter fall, soil organic carbon content, and soil moisture content. Their predictions support our finding of no DOC response to cutting as related to the fact that we found no total soil C or N responses.

### 3.5. Summary and conclusions

This study examined the effects of timber harvesting activities on near-stream to upper-slope N concentrations and N and C transfer down slope. Our objective was to determine the function of the riparian zone in mitigating upslope disturbance as it relates to soil, soil solution, groundwater, and stream N and C responses. We examined N and C responses for the first growing season following timber harvest. There were significant increases in N availability and movement following harvest, largely within the disturbed areas of the slope. $NO_3^-$ moved below the rooting zone making it available for leaching loss to the stream in all sites. However, there was no evidence of N moving from disturbed slope sections into or through undisturbed riparian buffer areas. Only the stream draining the site with no buffer had increased $NO_3^-$ concentrations following harvest. Data suggest that processes within the saprolite may have retained or transformed the $NO_3^-$ released by site disturbance in the other sites. Additional research is required to understand the long-term effectiveness of riparian buffers and responses to changes in vegetation and organic matter inputs to these stream/riparian ecosystems.

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