THE EFFECTIVENESS OF STREAMSIDE MANAGEMENT ZONES IN CONTROLLING NUTRIENT FLUXES FOLLOWING AN INDUSTRIAL FERTILIZER APPLICATION

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Abstract—Many State best management practice programs recommend streamside management zone (SMZ) widths based on limited or inadequate data with regard to nutrient fluxes from silvicultural activities. Diammonium phosphate and urea were applied to subwatersheds of 2- to 3-year-old loblolly pines (*Pinus taeda*) upslope from 12 SMZ study areas in Buckingham County, VA. Three replications of four SMZ treatments (30.5 m, 15.2 m nonthinned, 15.2 m thinned, and 7.6 m) were studied using ionic exchange membranes. Our hypothesis is that nitrogen and phosphorous levels will decrease in a forested SMZ setting as distance from the harvest boundary to the creek increases. Furthermore, we hypothesize that wider, unthinned SMZs are more likely to prevent nutrients from reaching the creek than narrower and/or thinned SMZs. Preliminary results indicate stream water quality is unaffected by fertilization at all SMZ width treatments. Nutrient movement in the upper soil and litter layer through the various SMZ widths will be discussed.

INTRODUCTION

Public concern over the health of the Nation's waters led to the development of the Federal Water Pollution Control Act of 1972 (P.L. 92.500) and subsequent amendments, which are commonly known as the Clean Water Act (Ice and others 1997). The Clean Water Act "set water quality standards for all contaminants in surface waters" (U.S. Environmental Protection Agency 2008). In order to comply with guidelines established by the Clean Water Act, the State of Virginia established best management practices (BMP) for forestry operations (Virginia Department of Forestry 2002). BMP guidelines are environmentally and economically significant because they influence the potential management on 6.2 million ha (61 percent of the total land base) of potentially commercial forest land in Virginia (Virginia Department of Forestry 2002). Virginia landowners implement BMPs voluntarily except within Chesapeake Bay Preservation Area where BMP usage is required. Furthermore, all silvicultural practices must not produce water toxicity levels higher than national standards or cause increased sedimentation as regulated by the Virginia Silvicultural Water Quality Law (Virginia Department of Forestry 2002).

Streamside management zones (SMZ) are commonly used BMPs for preventing water-quality degradation from forest silviculture operations (Aust and Blinn 2004). Streamside forests help prevent excess sediment and nutrients from reaching the stream, protect streams from thermal pollution, correct negative aquatic effects of pesticides, and help generate food sources that promote aquatic productivity and diversity (Welsch 1996). Additional principle functions of riparian areas are to stabilize streambanks, provide a source of spawning gravel, moderate riparian microclimates, and provide wildlife habitat (O'Laughlin and Belt 1995). Walbridge (1993) noted that forested wetlands provide eight biogeochemical functions—sediment deposition, denitrification, sulfate reduction, phosphorous sorption, nutrient uptake, decomposition of waste organics, sorption of heavy metals, and retention of toxics—that improve water quality and two biogeochemical functions—carbon storage and methane production—that influence global atmospheric changes. During the first year following a harvest in Mississippi, Keim and Schoenholtz (1999) found that streams in logged watersheds without SMZ implementation had approximately three times the sediment concentration as found in nonharvested watersheds and concluded that SMZs are most effective for controlling sedimentation when the forest floor is undisturbed. Adequate buffer width depends on the condition of the buffer, e.g., amount of vegetation and soil disturbance, the relative functional value of the water body, e.g., disturbance regime and plant origin, and the impact potential of adjacent land, e.g., park land vs. residencies or farms (Castelle and others 1994).

Various widths of SMZs have been recommended and implemented based on the level of protection desired for a particular type of water body and the percent slope of adjacent lands (Virginia Department of Forestry 2002). However, recommended widths are arbitrary guidelines most often determined by politics and established with little or no scientific basis with regard to effectiveness of various widths in controlling targeted pollutants (Castelle and others 1994). Additionally, science-based width recommendations were established mostly for perceived adequate sediment control rather than for nutrients. A 15.2-m wide SMZ is the most commonly utilized for a typical upland Piedmont forested stream.

OBJECTIVES

The primary goal of this study was to determine SMZ width necessary for prevention of nitrogen (N) and phosphorous (P) from reaching a creek following typical diammonium

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phosphate (DAP) and urea (UREA) application on a young loblolly pine (*Pinus taeda*) stand. Previous studies indicate that forested riparian areas act as nutrient sinks (Fox and others 2007, Lowrance and others 1984, O'Laughlin and Belt 1995). Jacobs and Gilliam (1985) found that Coastal Plain buffer strips of <15.2 m significantly reduced nitrate levels in agricultural drainage water before it reached the stream. However, the typical SMZ width needed to prevent increased N and P levels in upper Piedmont streams of a forested setting is unclear. This project is aimed at identifying appropriate SMZ width by examining water movement above the soil surface, within the primary rooting zone, and through deeper subsurface flow. Establishing the transportation patterns of N and P through a SMZ could help forest land managers appropriately designate future harvest boundaries. This study examined three SMZ widths and differences between a nonmanaged and a thinned 15.2-m (50-foot) SMZ, currently the most common SMZ width in Virginia.

METHODS

Twelve study subwatersheds were located in Buckingham County (37°33'00" N, 78°33'30" W) in the upper Piedmont of central Virginia. The subwatersheds are part of a larger watershed research project described by Lakel and others (2006a). The upper Piedmont has rolling terrain and typical elevations ranging from 60 to 460 m above mean sea level (Lakel and others 2006a). Typical land management actions coincide with industrial forest operations and include loblolly pine plantations, clearcutting, ground skidding, fire breaks, chemical application, and controlled fire. Annual precipitation for this region is 107 cm. Average winter (December to February) temperature is 3.3 °C while average growing season (April to September) temperature is approximately 21 °C (Wiseman and Seiler 2004). Soils are generally highly eroded due to previous abusive agricultural activities. Shallow Ultisols with thin surface Ap horizons over subsurface argillic horizons are typical. The Ap horizon is usually low in organic matter and eluvial E horizons are generally slight or absent. Soil textures are frequently gravelly loam to gravelly sandy loam over 1 to 1 clay subsoils (Wiseman and Seiler 2004). Riparian areas on the test sites often have higher levels of organic matter, sand, and coarse fragments than the harvested treatment area.

All sites were on MeadWestvaco properties and were clearcut harvested between summer 2003 and spring 2004 using standard equipment and systems (ground-based harvesting with rubber-tired feller bunchers and skidder) and then site-prep burned by fall of 2004. Within each of the 12 study watersheds (first-order intermittent and perennial streams), a smaller contributing subwatershed (zero order, ephemeral drain) was selected in the clearcut area for the study of fertilizer nutrient movement through various SMZ widths. These subwatersheds ranged from 0.2 to 1.4 ha in size. Treatments were arranged in a completely random design with three replications of the following four treatment widths described by Lakel and others (2006b):

1. 7.6-m (25-foot) wide SMZ (with varying degrees of SMZ harvest but no management)
2. 15.2-m (50-foot) wide SMZ with no SMZ harvest
3. 15.2-m (50-foot) wide SMZ with 50 percent SMZ harvest
4. 30.5-m (100-foot) wide SMZ with no SMZ harvest

DAP and UREA fertilizers were applied to the 12 subwatersheds at common industrial rates of 140.3 and 250.4 kg/ha (125 and 223 pounds per acre), respectively, by ATV and by hand. Application yielded 28.1 kg/ha (25 pounds per acre) elemental P and 140.3 kg/ha (125 pounds per acre) elemental N. DAP and UREA are the primary fertilizer compounds used for forestry fertilization. Slopes, soils, and vegetation were relatively constant among treatments; therefore, it was hypothesized that differences in SMZ width and harvest level would impact the amount of fertilizer nutrient capable of moving from the ephemeral watersheds into the larger study streams.

Ionic Exchange Membranes

Gaskin and others (1989) state that lateral near-surface flow is an important path of nutrient movement in surface horizons. Fluxes of SO_4, Cl, NO_3-N, K, Ca, Mg, and H are greatest in the B/A horizon and decrease with depth. The greatest lateral flow is higher in the soil profile under dryer conditions (Gaskin and others 1989). Denitrification potential is highest in the top 2 cm of surface soil and occurs at higher rates when the soil has higher levels of organic matter (Ambus and Lowrance 1991). Historically, cation and anion exchange resin bags have been used to quantify nutrient movement in upper soil horizons. However, ion-exchange membranes (Ionics, Inc., Watertown, MA), also known as IEMs, are becoming more popular due to their many advantages over resin bags (Elliot 2006). In contrast to the resin bag form, the membrane form offers advantages because their flat structure ensures a constant surface area and better contact with the soil (Huang and Schoenau 1996). Diffusion problems are reduced because the two-dimensional structure ensures more surface area will be in contact with the soil which undergoes minimal disturbance during installation. Furthermore, the IEM is physically and chemically durable and has a high correlation with soil solution P at low-solution concentrations (Cooperband and Logan 1994). IEMs were installed horizontally in the A/B soil horizon (1 to 10 cm deep) as well as the litter layer/A horizon fringe. The litter layer/A horizon interface was studied because a major source and sink of plant nutrients is the litter layer. In regards to N, the largest proportion of water soluble N and supply rates of organic N can be found in the lowest, most decomposed horizon of the litter layer.

IEMs (6.35 cm by 6.35 cm) were installed symmetrically across the width of each SMZ. A set of four membranes included a cation and anion membrane which were inserted in a slit under the O horizon in addition to a cation and anion membrane which were inserted in the A or top of the B horizon (1 to 10 cm below the soil surface) with a gardening trowel. Membranes were placed as flat as possible to minimize the chance for preferential flow. Before the membranes were placed in the field they were rinsed with deionized water to remove excess NaCl solution. Initially membranes were removed/reinstalled approximately every 2 weeks, but the timeline was altered based on the membranes saturation potential and movement of fertilizer nutrients across the membrane's surface. The number of membranes installed in each treatment was as follows:

Treatment 1 (7.6 m) – 12 membranes per replication
Treatment 2 (15.2 m) – 12 membranes per replication
Treatment 3 (15.2 m) – 20 membranes per replication
Treatment 4 (30.5 m) – 24 membranes per replication

Data were analyzed as a completely randomized design with three replications of four treatments. When treatment differences (alpha = 0.1) were found treatment differences were separated using Tukey's mean separation test at a 0.1 alpha level.

RESULTS AND DISCUSSION

Cation and anion membranes were utilized at various time intervals in the field for over a year to serve as an index for ammonium and nitrate movement at the litter layer-soil layer interface and at the A/B soil horizon. Our results are for four periods that compare normal and "worst-case" conditions: prefertilization, immediately following fertilization, following a heavy rainfall, and 10 months after fertilization. During these four periods, spatial differences among membranes positioned in the clearcut, at the dripline of the SMZ, and at the creek were examined among treatments. One would expect nitrate and ammonium levels to be greatest in the clearcut and at the SMZ dripline following fertilization with decreasing nutrient levels existing at the creek as SMZ width increases. Furthermore, elevated nutrient levels following fertilization are expected to eventually return to prefertilization levels.

Prior to Fertilization

Membranes analyzed prior to fertilization indicate that ammonium and nitrate levels were <2.5 mg/m^2/day for any given treatment (fig. 1). There is no significant difference among cation or anion membrane locations prior to fertilization. Nitrate and ammonium values in the clearcut were naturally higher than at the SMZ dripline and stream positions most likely due to increased decomposition and microbial fixation—an example of the assart effect.

Immediately Following Fertilization

Results from membranes analyzed immediately following fertilization indicate that ammonium levels ranged from 24 to 230 mg/m^2/day in the clearcut but <5 mg/m^2/day at the SMZ dripline and <2.5 mg/m^2/day at the creek for any given treatment. There are significant differences among cation membrane locations immediately following fertilization. The clearcut positions on all four treatments, in addition to the SMZ dripline position on the 30.5-m treatment, are significantly related (fig. 2).

The clearcut position on the 7.6-m, 15.2-m, and 15.2-m thin treatment are also statistically similar (fig. 2). Nitrate levels were much lower than ammonium levels immediately after fertilization and ranged from only 3 to 9 mg/m^2/day in the clearcut but <0.5 mg/m^2/day at the SMZ dripline and <0.4 mg/m^2/day at the creek for any given treatment. There are significant differences among anion membrane locations immediately following fertilization. These statistical differences were only apparent in the clearcut areas across the four treatments (fig. 2).

Following Heavy Rainfall

Membranes analyzed following a heavy rainfall indicate that ammonium levels ranged from 30 to 112 mg/m^2/day in the clearcut but <5 mg/m^2/day at the SMZ dripline and <1 mg/m^2/day at the creek for any given treatment. There are significant differences among cation membrane locations following heavy rainfall. Significant differences were between the clearcut position and the dripline and stream positions (fig. 3).

Nitrate levels were slightly higher than ammonium following a heavy rainfall and ranged from 54 to 165 mg/m^2/day in the clearcut but <28 mg/m^2/day at the SMZ dripline and <6 mg/m^2/day at the creek for any given treatment.

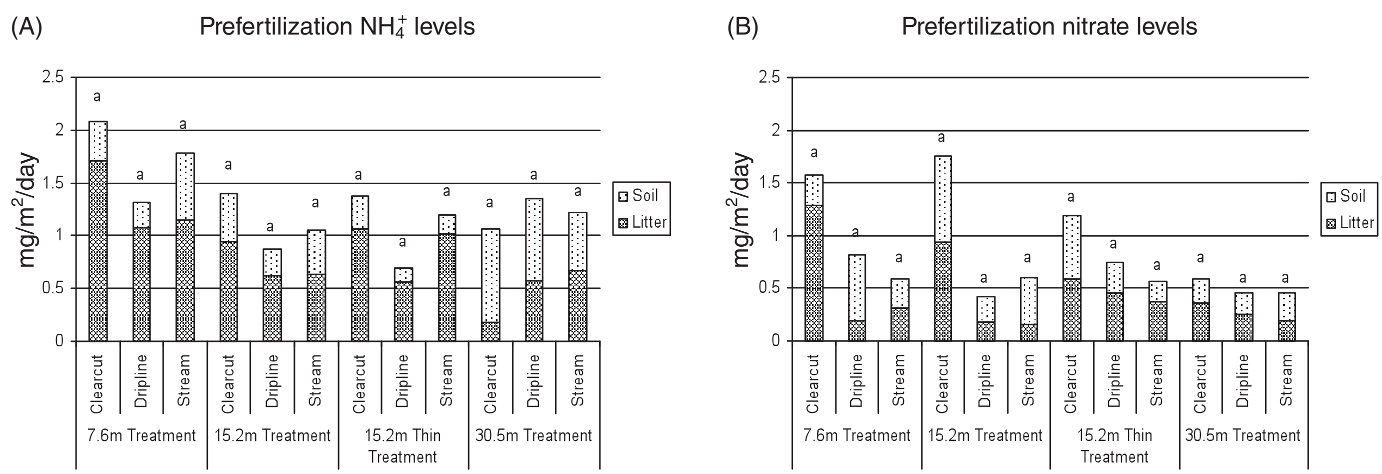

Figure 1—(A) Average ammonium and (B) nitrate levels for all treatments prior to fertilization.

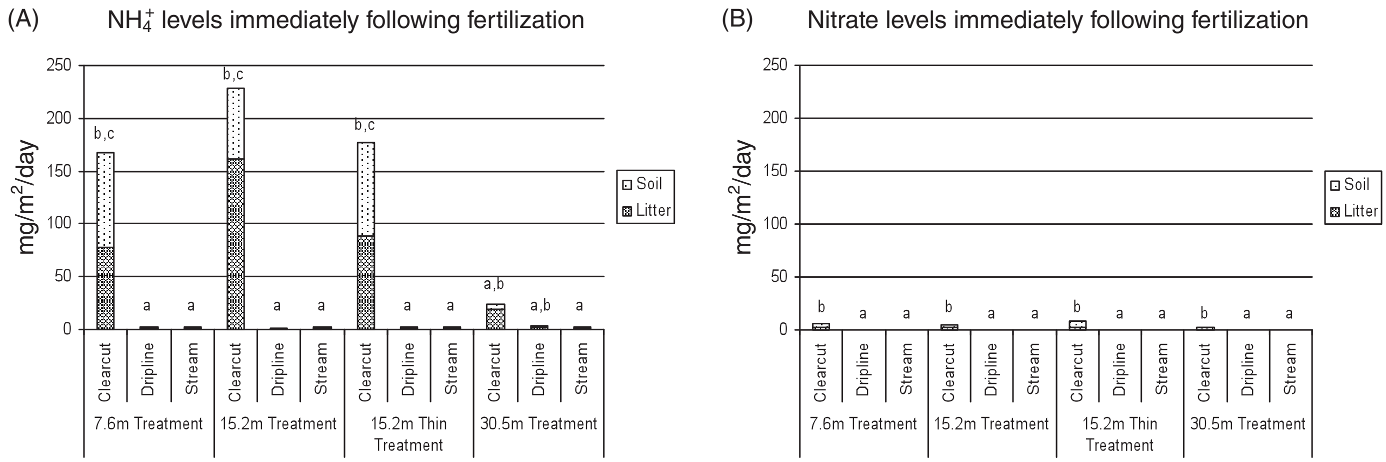

Figure 2—(A) Average ammonium and (B) nitrate levels for all treatments immediately following fertilization.

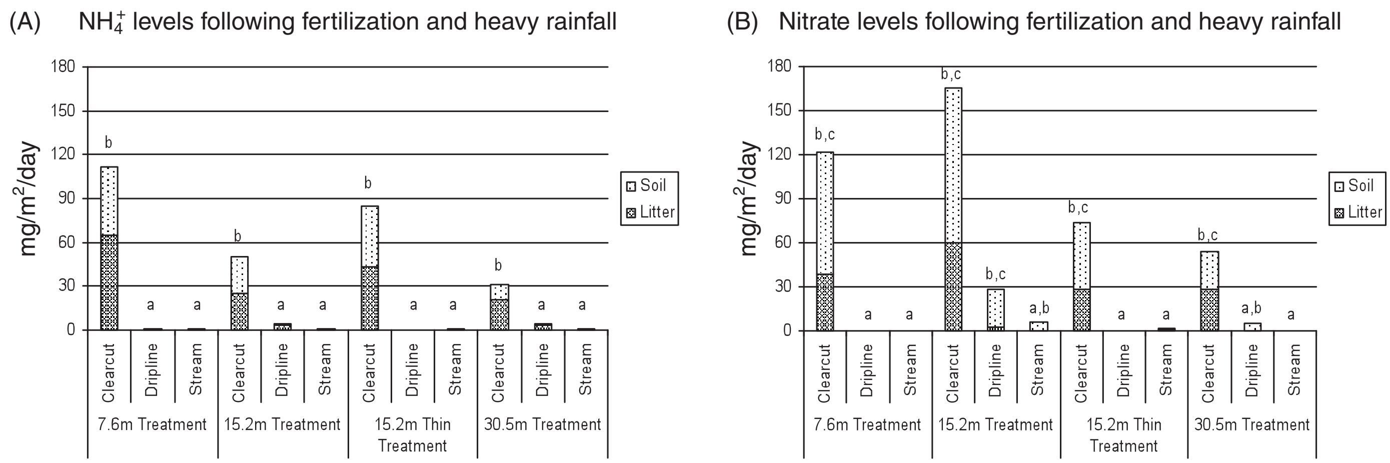

Figure 3—(A) Average ammonium and (B) nitrate levels for all treatments following a heavy rainfall.

There are significant differences among anion membrane locations following heavy rainfall (fig. 3). There is a statistical difference between the clearcut positions and the SMZ dripline position on the 15.2-m treatment and all the other SMZ dripline and stream positions. Furthermore, the stream position on the 15.2-m treatment as well as the SMZ dripline position on the 30.5-m treatment are statistically similar to the clearcut positions and 15.2-m treatment SMZ dripline. These relationships suggest that the largest movement of nitrogen in the upper soil layer and litter layer occurs as nitrate after a heavy rainfall.

Ten Months Following Fertilization

Membranes analyzed 10 months following fertilization indicate that ammonium levels ranged from only 1 to 9 mg/m^2/day in the clearcut but <4.5 mg/m^2/day at the SMZ dripline and <4 mg/m^2/day at the stream for any given treatment. There are no significant differences among cation membrane locations 10 months after fertilization (fig. 4).

As with the cation membranes there are no significant differences among anion membrane locations 10 months following fertilization (fig. 4). Nitrate levels 10 months following fertilization ranged from only 12 to 45 mg/m^2/day in the clearcut but <4 mg/m^2/day at the SMZ dripline and <2 mg/m^2/day at the creek for any given treatment.

CONCLUSIONS

Some preliminary conclusions can be drawn from this data. First, high levels of ammonium and nitrate found in the clearcut after fertilization are not evident at the SMZ dripline or the stream positions. Values at SMZ dripline locations reached 28 mg/m^2/day for nitrate on the 15.2-m treatment following a heavy rainfall but never got above 5 mg/m^2/day for any treatment at any time throughout the year-long study period. Furthermore, stream location values never got above 6 mg/m^2/day for either ammonium or nitrate at any treatment.

Second, there appears to be lag time for nitrate to become present after fertilization most likely due to the need for

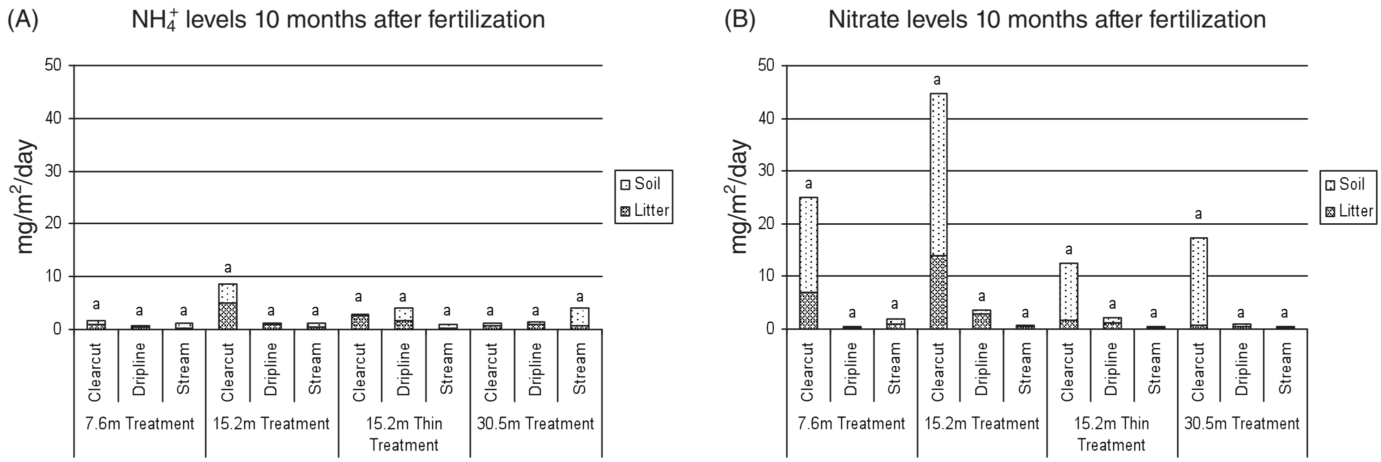

Figure 4—(A) Average ammonium and (B) nitrate levels for all treatments 10 months after fertilization.

mineralization of organic N. Average nitrate levels in the clearcuts 2 weeks after fertilization were <9 mg/m^2/day. Meanwhile average ammonium ranged between 24 and 230 mg/m^2/day in the clearcuts 2 weeks after fertilization. By 10 months, ammonium and nitrate levels in the clearcut are returning to prefertilization levels. After 10 months, values are still higher than prior to fertilization but appear to approach prefertilization levels.

It may seem reasonable to suggest that a 7.6-m wide SMZ with forested vegetation is sufficient for removing N in these Piedmont sites due to lack of ammonium and nitrate found near the creeks. However, it appears that water movement below the litter layer and at shallow soil layers is not an important pathway for N movement because position value differences did not seem to exist among treatments. Furthermore, after fertilization, ammonium and nitrate levels were seldom higher at the stream or even the SMZ dripline than they were prior to fertilization. It seems more reasonable to suggest that if the nitrate and ammonium are moving out of the clearcut, then it is probably in ground water deeper in the soil profile. Therefore, further analysis on subsurface N movement is certainly necessary before an SMZ width can be recommended based on the impact from industrial fertilizer application.

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