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NPS Pollution Related to Forest Management Activities in Southern States

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Abstract. Southern forests, which rely on intensive management practices, are some of the most productive forests in the United States. Intensive forest management utilizes forest operations, such as site preparation, fertilization, thinning, and harvesting, to increase site productivity and reduce rotation time. These forest operations are essential to meet the ever-increasing demands for timber products. Forest operations are tools used by forest managers in an attempt to manage the nation's forestlands for multiple uses while maintaining or improving resource quality. Forest operations, a man-induced modification to ecosystems, have the potential for impacts on ecological processes and future conditions. Forest operations can influence nonpoint source pollution (NPS) by upsetting natural processes that maintain water quality. In recent years, NPS has been identified as the nation’s largest source of water quality problems. Forest management activities have been identified as activities influencing NPS pollution in the South. Results of studies in the 13 southern states investigating the effect of forest operations on water quality are highly variable based on this review. However, the results taken collectively indicate that forest operations have little impact on the quality of water draining from forests in the south. Based on this review, BMPs show the potential to protect water quality following forest operations; however accurate assessments of the overall effectiveness of BMPs are not possible because the benefits of BMPs on different scales are relatively unknown.

Introduction

In recent years, nonpoint source pollution (NPS) has been identified as perhaps the greatest threat to the nation's water quality (USEPA 2003). As of 1999, 20,000 of the nation's water bodies, including 300,000 river and shore miles and 5 million lake acres were identified as polluted (USEPA 1999). The reduction of runoff of pollutants through more efficient use of water, fertilizer, and pesticides is an action suggested by the EPA for cleaner waters while TMDL's are developed. Within watersheds on 303(d) lists many nonpoint sources are extremely difficult to pinpoint, measure, and control due to the intertwined land use categories within a given watershed. Possible nonpoint sources of sediments in forested lands include harvesting, roads, and site preparation.

Intensive management practices have been reported to influence water yield and quality. The use of intensive management practices in the South has made the region one of the most productive in the world (Prestemon and Abt 2002). The use of intensive management practices in combination with the abundant water resources in the region increases the potential for water quality impacts. In this context, the South would likely be the optimal region to evaluate the extent and nature of the water quality impacts of forest operations. The objective of this paper is to provide a review of the research on the nature and extent of NPS pollution attributed to forest operations, specifically harvesting, site preparation, fertilization, and road construction and maintenance, in the South. The paper also explores the role of BMPs in NPS issues related to forest operations.

NPS Pollution in the South

Major environmental concerns related to water quality exist in the 13 states (Figure 1) that constitute the southern region of the United States due to the 1.5 million km of rivers and streams flowing through the region. In 1998, approximately 25 percent of the rivers and streams flowing through the region were assessed and reported in the state water quality inventories (USEPA 2000). Based on these inventories, 55 percent of the assessed rivers and streams fully supported their designated uses. The remaining 45 percent of assessed rivers and streams in the southern states were impaired by some form of pollution.

Point sources of pollution (municipal, urban runoff, industrial, and land disposal activities) are the major contributors to impaired state rivers and streams in Georgia and Texas. Nonpoint sources are the leading cause of impairment to rivers and streams, lakes, due to pollution in the other states in the southern region. The NPS pollution activities include agriculture, hydrologic/habit modification, resource extraction, storm sewers/urban runoff, construction, silviculture, and natural activities. Agricultural activities are by far the leading nonpoint source activity accounting for 71,000 km of impaired rivers and streams in the southern region during the period from 1988 to 1998 (USEPA 2000). Agricultural activities accounted for more polluted miles than the combination of all point sources and greater than 60 percent of the total assessed nonpoint source pollution (110,000 impaired km) impairing rivers and streams in the South. Silviculture accounted for 5,900 km of impaired rivers and streams and ranked

9th of the 10 leading sources of pollution of rivers and streams in the South (West 2002). The contribution of silviculture; hereafter referred to as forest operations, to pollution of rivers and streams in the South is relatively small (8 percent of total impaired rivers and streams). However, forestry operations have the potential to impact water quality and fisheries habitat (Fulton and West 2002).

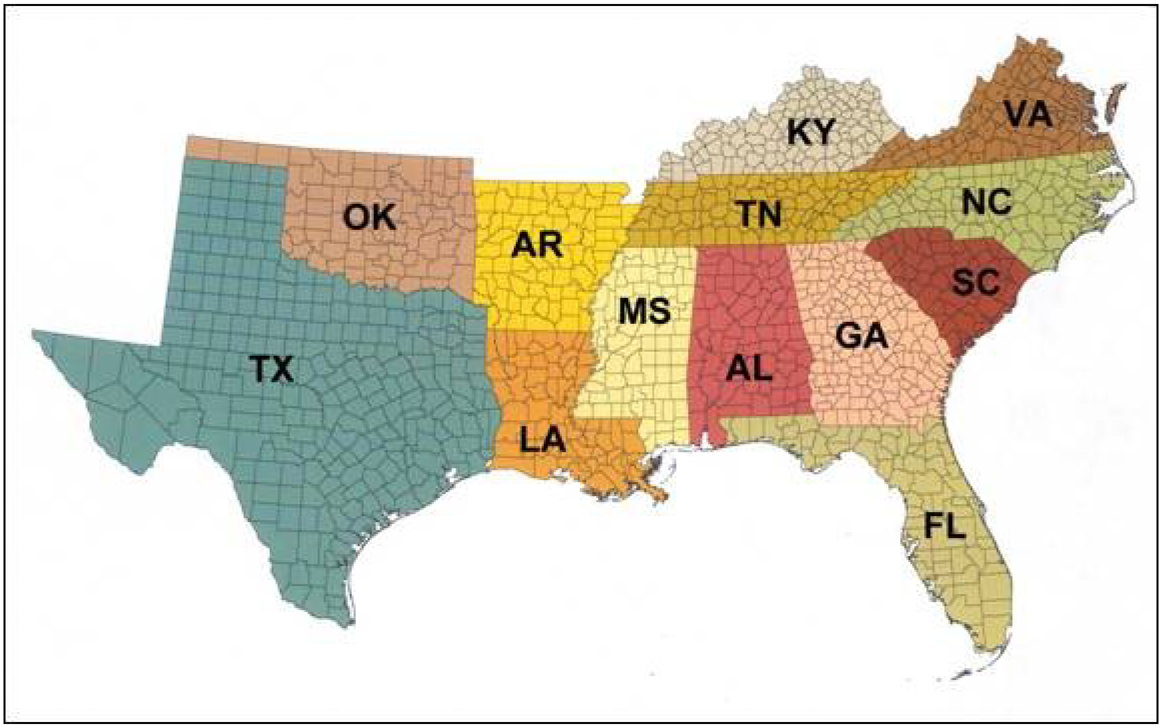

Figure 1. The thirteen state region (Southern Region) considered in the review of NPS related to forest management activities.

Harvesting

The primary influence of harvesting and thinning on hydrology is increased water yield due to decreased evapotranspiration. Water yield increases as a result of forest canopy removal have been well documented over the past 40 years (Beasley and Granillo 1982; Blackburn and others 1986; Douglass and Swank 1972; Douglass and others 1982; Grace and Carter 2001; Grace and others 2003; Hewlett and others 1984; Hibbert 1966; McBroom and others 2002; Riekerk 1983; Swindel and others 1983a, 1983b; Van Lear and others 1985; Williams and others 1999). The magnitude of these water yield increases vary considerably from watershed to watershed depending on factors such as soils, topography, climate, and forest type. Hibbert (1966), based on a world-wide review of watershed studies (thirty-nine studies) of the effect of canopy removal on water yield, presented an upper limit increase of 4.5 mm/yr for each percent reduction in forest canopy. However, the majority of treatments in the review produced less than 2.25 mm/yr and results of treatments were largely unpredictable. Similarly, Neary and others (1982) found water yield increases of 2.5 mm per percent of forest canopy removed in humid regions. Equations incorporating additional factors describing the effect of canopy removal on water yields have been developed for a more detailed description of hydrologic influences (Swank et al. 1988).

Water yield increases for harvest treatments ranged from 69 to 210 mm/yr for the studies in this review (Table 1). These increases alone do not present a significant environmental concern, however when combined with sediment and nutrient concentrations following harvesting they may result in increased pollutant export. Sediments are perhaps the greatest risk to water quality following harvesting operations. Sediments can transport attached nutrients directly to stream systems. In addition, suspended sediments have the potential to degrade water quality by altering light penetration into water bodies altering photosynthetic fixation of energy by aquatic plants (Kirk 1994). Increased turbidity also has the potential to reduce visual clarity which affects the behavior of visual predators in aquatic ecosystems and influences aesthetic quality (Davies-Colley and Smith 2001).

In the studies in this review, the influence of harvesting on suspended sediments was highly variable. Sediment concentrations were elevated in treatment watersheds for some watersheds and decreased in others (Table 1). Perhaps of greater importance than elevated sediment concentration is the quantity of sediment exported following harvesting due to increases in water yield. The greatest quantity of sediment export observed was less than 1.5 t/ha/yr following a clear-cut harvest and site preparation (Beasley and Granillo 1982). However, a clear-cut harvest without BMPs, which represents a worst case scenario, exported less than 1.0 t/ha of sediment during the first seventeen months (Authur et al. 1998). Yet, despite the disregard to BMP practices, sediment export observed in the investigation was much less than typically observed from agricultural practices.

Harvesting can also elevate nutrient concentrations of water flowing from treated watersheds in comparison to undisturbed controls, however responses are highly variable (Table 1). The primary nutrient concentrations of concern related to forest practices are phosphate and nitrate. Phosphate is of concern because elevated concentrations can result in eutrophication of estuaries and freshwater lakes. A phosphate concentration standard of 0.1 µg/L was established to protect estuaries and a threshold of 0.5 mg/L is considered acceptable to protect freshwater lakes (MacDonald et al. 1991). Elevated nitrate concentrations greater than the drinking water standard (>10 mg/L) are of concern due to drinking water risks for infants.

Of the ten watershed studies considered here, only two found significant increases in nitrate concentrations following harvesting. Elevated nitrate concentrations were reported from three paired watersheds located on the Robinson Forest within the Cumberland Plateau in southeastern Kentucky (Authur et al. 1998). Nitrate concentrations during a 17-month post-treatment period increased from 1.0 mg/L on the unharvested control to an average of 4.5 mg/L from clear-cut watersheds. These increases in nitrate concentrations in the Kentucky watersheds returned to control levels within a short period (2 years). Fox et al. (1983) also reported elevated nitrate concentrations (0.70 mg/L greater than the control) following clear-cut harvesting in the Virginia Piedmont. However, nitrate concentrations were well below the drinking water standard of 10 mg/L (USEPA 1986) in each of the watersheds following harvesting.

Based on the results of studies in this review (Table 1) taken collectively, harvesting does not appear to adversely impact water quality of waters flowing in southern states.

Site Preparation

Site preparation is commonly used by forest managers to increase site productivity and reduce rotation time (Gent et al. 1983). Site preparation typically prepares the soil to facilitate planting and control vegetative competition. However, site preparation has the potential to increase sediment and nutrient concentrations by exposing soil for detachment and transport (Beasley 1979; Beasley 1982; Blackburn and others 1986; Edwards and Larson 1969; Harr and Fredriksen 1988; Schoch and Binkley 1986; Ursic 1979; Van Lear and Danielovich 1988; Yoho 1980). The extent of soil erosion and potential NPS pollution is largely dependent upon site preparation treatments (Beasley 1979; Blackburn et al. 1986; Grace and Carter 2001; Switzer and others 1978). Mechanical methods (i.e. shearing, plowing, ripping, raking, chopping, bedding, and windrowing) scarify the surface and expose mineral soil to the energy of raindrop impact. In addition, mechanical methods remove much of the litter layer and debris which can reduce the erosion energy in surface runoff. Site preparation burning also increases potential for sediment and nutrient losses by removing forest floor cover and exposing bare soil for erosion. Mechanical, burning, and chemical site preparation methods result in the removal of forest vegetation which typically results in increased water yields, soil moisture, and solar radiation on the soil surface. These changes can initiate accelerated decomposition, mineralization, and weathering processes, thereby increasing mobile nitrate (Clinton and others 2003; Knoepp and Swank 1993; Vose and Swank 1993) and phosphate carrier anions (Johnson et al. 1986). An increased pool of nutrients in combination with increased water yield resulting from vegetation removal can translate to increased export from treated watersheds. However, research on the effect of site preparation on sediment and nutrient loss are highly variable (Table 2).

Water yield increases similar to those reported for harvesting above were observed following site preparation prescriptions. A water yield increase of 480 mm was reported by Beasley (1979) during the first year for brush chopping, shearing and windrowing, and bedding on contour in the Mississippi coastal plain. Water yields during the second year continued to be elevated for each of the treatments ranging from 210 to 320 mm. Beasley (1979) also reported significant increases in sediment concentrations in water draining site preparation treatment areas. The increased water yield, in combination with elevated sediment concentration, resulted in significant increases in sediment export from treatments in comparison to the control in Beasley’s experiment. Similarly, water yield increases have been reported by during the first two years following site preparation treatments in Texas (Blackburn et al. 1986) and in the Piedmont of Georgia (Neary et al. 1986) (Table 2). However, sediment concentrations and exports were not significantly increased in the two above mentioned studies. Sediment losses were within the range typically observed from undisturbed forest lands in the region (< 0.30 t/ha/yr).

Nutrient concentrations of water draining from the site prepared watersheds in this review are also highly variable. In central Arkansas, Lawson and Hileman (1982) reported no significant impact on nitrate concentrations and a significant increase in ammonia concentrations (0.20 mg/L) following burning and planting. However, Neary and others (1986) reported significant increases in nitrate concentrations (870 mg/L) following herbicide application in the upper Piedmont of Georgia. The significant increase in nitrate concentrations in the above study translated to less than 0.01 t/ha of nitrate nitrogen export.

Based on the studies in this review, water yield increases are likely following mechanical, chemical, and burning site preparation treatment, although water yield increases don't necessarily translate to degraded water quality. Sediment and nutrient concentrations increased for some studies while remaining constant or decreasing for other studies. Sediment concentrations did reach levels greater than 500 mg/L in the majority of the studies reviewed, but this increase was typically a short lived response following treatment. Nitrate concentrations remained below the drinking water standard for the studies in this review.

Fertilization

Similar to results of harvesting and site preparation studies, the results of studies of the effects of fertilization on forest water quality vary considerably. The majority of these studies have been conducted outside of the southern United States. In studies of 6 watersheds in Oregon and Washington, Fredriksen et al. (1975) found peak nitrate-nitrogen concentration increases averaging 0.37 mg/L following fertilization with 225 kg-N/ha as urea. However, the conclusion from these investigations was stream water concentrations were not raised to degrading levels by fertilization.

Investigations conducted at the Fernow Experimental Forest, which borders the region considered by this review, in West Virginia are in contrast to the Pacific Northwest studies. Peak nitrate-N concentrations were 16 mg/L, exceeding the drinking water standard (10 mg/L), following fertilization with 225 kg-N/ha as urea. Similarly, in the Fernow Forest peak nitrate-N concentrations exceeded the drinking water standard for three weeks following fertilization with 340 kg-N/ha as ammonium nitrate and 100 kg-P/ha as triple super phosphate (Edwards and others 1991; Helvey and others 1989;). Concentrations (NO_3-N, Ca^{++}, and Mg^{++}) from treated watersheds in both these investigations were detected as greater than control watersheds up to three years following fertilizer application.

In one of the few studies in the southern U.S., Liechty et al. (1999) investigated fertilization with 440 kg-N/ha as urea and 140 kg-P/ha as diammonium-phosphate on a 150 ha watershed in the Ouachita Mountains of Arkansas. Total organic N (TON) concentrations showed a dramatic increase (to its maximum level) five hours following urea fertilization from 0.3 mg/L to 44 mg/L. Similarly, NH_4-N concentrations peaked within 24 hours after urea application at 4.9 mg/L. Nitrate-N concentration response was not as immediate as TON and NH_4-N. Nitrate-N concentrations began to increase following urea application and peaked at 3.6 mg/L nearly 50 days after application. Nitrate-N concentration elevations were also observed downstream (in the 2270 ha watershed) of the fertilized watershed during the 1-month period immediately following urea fertilization.

Role of BMPs

Reviews of BMP guidelines for have reported differences related to forestry activities (Blinn and Kilgore 2001; Grace 2002; Stringer and Thompson 2000). Perhaps the greatest difference in BMP programs pertains to legislation for BMPs. Grace (2002) reviewed BMP guidelines for the 13 state region and reported differences in regulatory legislation and evaluation standards. For example, with the exception of Kentucky, Georgia, and North Carolina, states in the region have voluntary (non-regulatory) forestry BMP guidelines. Kentucky is the only state in the region with comprehensive laws regarding forestry BMPs enacted in 2000. North Carolina and Georgia BMP's are quasi-regulatory, that is, having components that are both regulatory and non-regulatory in nature.

Reported compliance with both regulatory and non-regulatory programs across the region is high (>80 percent in Arkansas, Florida, South Carolina) and expected to continue to increase as BMP awareness increases (Adams 1998; Eagle and Hameister 2002; Vowell and Lima 2002). This trend in BMP compliance is the key to further reducing the impacts of forest operations on water quality. Vowell (2001) concluded that proper application of BMPs can provide adequate protection of water quality based on stream bioassessment effectiveness studies. State effectiveness monitoring programs seem to support this conclusion and indicate that BMPs are effective in protecting water quality when properly applied. For example, in perhaps the most complete BMP effectiveness study, Vowell and Lima (2002) reported a 97 percent compliance for all forest operations in 2001 in Florida. Compliance in Florida has increased from around 85 percent in the early 1980's to 97 percent in 2001.

Forest operations account for only a small fraction of NPS pollution problems in the southern U.S. However, BMPs for forestry activities may be essential to avoid potential and mitigate existing, NPS pollution problems. The effect of BMP practices on protecting water quality from clearcutting in the Cumberland Plateau of southeastern Kentucky was studied by Authur et al. (1998) (Table 1). The investigation revealed no significant differences in sediment export from a watershed protected with BMPs and a watershed without BMPs during a 17-month post treatment period. Both watersheds had significantly elevated sediment exports during this 17-month period in comparison to the untreated control. However, results reported in relation to nitrate nitrogen exports indicated that buffer strips on the BMP protected watershed may have played a role in reducing nitrate nitrogen impacts.

In contrast, BMPs resulted in a ten-fold reduction in suspended sediments following harvesting and no significant changes in nitrate concentrations in the South Carolina Piedmont (Williams et al. 1999). Conclusions from the Williams et al. (1999) study suggested that with the exception of sediment concentrations, watersheds with and without BMPs resulted in high water quality.

Summary and Conclusions

The results of watershed water quality studies on the impact of selected forest operations on water quality are as varied as the physiographic regions contained in the 13 southern states considered in this review. Clearly, the relative contribution of forest activities to NPS pollution in the region is small in comparison to agriculture and generally all other NPS activities in the South. This is evident by forest operations ranking 9th out of the 10 leading NPS activities in the South (West 2002).

Based on this review of watershed research related to the impacts of forest operations on water quality, forest operations can impact the quality of water draining from southern forests. Increased water yields as a result of harvesting are the primary influence of harvesting on waters that drain southern forest. Only two of the ten studies reviewed found significant impacts to forest water quality. Elevated nitrate concentrations were reported in the Cumberland Plateau of southeastern Kentucky (Authur et al. 1998) and in the Virginia Piedmont (Fox et al. 1983) following harvesting operations. Based on the results of studies in this review (Table 2) taken collectively, harvesting does not appear to adversely impact water quality of waters flowing in southern states.

Water yield increases can be expected following mechanical, chemical, and burning site preparation treatment, although water yield increases don't necessarily translate to degraded water quality. Sediment and nutrient concentrations increased for some studies while remaining constant or decreasing for other studies. Similar conclusions to those drawn for harvesting can be drawn for site preparation and fertilization in regards to water quality impacts in the South.

BMPs for harvesting, streamside management zones, site preparation, silvicultural chemicals, and fire management are likely the key to further reducing the impacts of forestry practices discussed previously. Based on effectiveness monitoring programs, BMPs for forest operations are effective in protecting or maintaining forest water quality when properly applied. Based on this review, BMPs appear to have the capacity to mitigate impacts of forest operations on water quality. Two of the three studies in this review reported significant reductions in sediment concentrations from watersheds with BMPs compared to unprotected watersheds.

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Table 1. The effects of harvesting on water yield and quality based on studies in southern states.

Region	Location	Area ha	Primary Forest Cover	Prescribed Treatment	Δ in constituent†	Water Yield Increase mm	Reference
Appalachian Highlands	Coweeta, North Carolina	140	Mixed deciduous hardwoods	Total of 66 percent removal consisting of a 77 ha clear-cut and a 40 ha thinning.	NR	83 mm/yr (5 %) over the first seven years	Hibbert 1966
Coastal Plain Lower	Starke, Florida	64	Slash pine (*Pinus elliottii*, Engelm.), Longleaf pine (*Pinus palustris*, Mill.), and Pond cypress (*Taxodium distichum* (L) Rich.)	Clear-cut harvest, chop, bed, and plant	NO_3-N -0.01 mg/l NH_4-N -0.17* mg/l PO_4-P 0.00 mg/l Sed 2.3 mg/l	69 mm (1st year) -32 mm (2nd year)	Riekerk 1983
Coastal Plain Lower	Starke, Florida	48	Slash pine (*Pinus elliottii*, Engelm.), Longleaf pine (*Pinus palustris*, Mill.), and Pond cypress (*Taxodium distichum* (L) Rich.)	Clear-cut harvest, stump removal, burn, windrow, disk, bed, and plant.	NO_3-N 0.03 mg/l NH_4-N 0.10 mg/l PO_4-P -0.01 mg/l Sed 11.7* mg/l	150 mm (1st year) -33 mm (2nd year)	Riekerk 1983
Cumberland Plateau	Southeastern Kentucky	NR	Deciduous hardwood	Clear-cut harvest with BMPs	NO_3-N 3.5* mg/l NH_4-N mg/l PO_4-P -0.05 mg/l Sed 500* kg/ha	180 mm w/BMPs (1st 17 months)	Authur et al. 1998
				Clear-cut harvest without BMPs	NO_3-N 3.3* mg/l NH_4-N mg/l PO_4-P 0.02 mg/l Sed 1200* kg/ha	210 mm w/o BMPs (1st 17 months)	
Piedmont	Putnam County, Georgia	NR	Loblolly pine (Pinus taeda), shortleaf pine (*Pinus echinata* Mill.), and deciduous hardwood mixed.	Clear-cut harvest	NO_3-N -0.09 mg/l	190 mm/yr (1st 2 years)	Hewlett et al. 1984

Values in parentheses are differences in exports or fluxes for the given nutrients in the associated studies.

* Indicates a statistically significant difference in comparison to control treatment in specified study.

† Change in water quality parameter over that of the experimental control, i.e. treatment value – control value.

‡ Discharge weighted sediment concentrations.

NR – not reported.

Table 1 (cont'd). The effects of harvesting on water yield and quality based on studies in southern states.

Region	Location	Area ha	Primary Forest Cover	Prescribed Treatment	Δ in constituent †	Water Yield Increase mm	Reference
Coastal Plain Upper	Alto, Texas	3.0	Shortleaf pine (*Pinus echinata* Mill.)and deciduous hardwood mixed.	Clear-cut harvest	NO_3-N -0.02 mg/l	NR	Blackburn et al. 1986
Piedmont	Clemson Forest, South Carolina	0.4-2.2	Loblolly pine (*Pinus taeda* L.)	Prescribe burning followed by clear-cut harvest	(Year 1 Results) NO_3-N 0.01 mg/l NH_4-N 0.00 mg/l PO_4-P 0.00 mg/l Sed 50* mg/l (0.13 t/ha/yr)	> 150 %	Van Lear et al. 1985
Coastal Plain	Monticello, Arkansas	2.3-4	Loblolly pine (*Pinus taeda* L.), Shortleaf pine (*Pinus echinata* Mill.) and deciduous hardwood mixed.	Clear-cut harvested, site prepared, and planted.	Sed 170 mg/l‡ (1.3 t/ha)*	120 mm (1st year)*	Beasley and Granillo 1982
				Selectively harvested to achieve uneven-aged stand	Sed -13 mg/l‡ (0.0 t/ha)*	40 mm (1st year)	
Coastal Plain Upper	Lexington, Tennessee	0.2-0.6	Loblolly pine (*Pinus taeda* L.)	Clear-cut harvested	Sed 100 mg/l *	NR	McClurkin et al. 1985
Piedmont	Patrick County, Virginia	1.6-3.6	Mixed pine hardwood forest	Clear-cut harvested.	NH_4-N 0.71 mg/l* NO_3-N 0.70 mg/l* PO_4-P 0.03 mg/l Sed 328 mg/l*	NR	Fox et al. 1983

Values in parentheses are differences in exports or fluxes for the given nutrients in the associated studies.

* Indicates a statistically significant difference in comparison to control treatment in specified study.

† Change in water quality parameter over that of the experimental control, i.e. treatment value – control value.

‡ Discharge weighted sediment concentrations.

NR – not reported.

Table 2. The effects of site preparation on water yield and quality based on studies in southern states.

Region	Location	Area ha	Primary Forest Cover	Prescribed Treatment	Δ in constituent[†]	Water Yield Increase mm	Reference
Coastal Plain Upper	Mississippi	0.7-1.0	Shortleaf pine (*Pinus echinata* Mill.)and deciduous hardwood mixed.	Three separate site preparation treatments:			Beasley 1979
				(1)Brush chopping	Sed 344 mg/l (10 t/ha)* Sed 277 mg/l (2.0 t/ha)	480 mm (1st year) 320 mm (2nd year)	
				(2) Shearing and windrowing	Sed 710 mg/l (11 t/ha)* Sed 401 mg/l (1.9 t/ha)	420 mm/ (1st year) 250 mm (2nd year)	
				(3) Bedding on the Contour	Sed 462 mg/l (12 t/ha)* Sed 1950 mg/l (4.9 t/ha)	480 mm (1st year) 210 mm (2nd year	
	Alto, Texas	3.0	Shortleaf pine (*Pinus echinata* Mill.)and deciduous hardwood mixed.	Two separate site preparation treatments:			Blackburn et al. 1986
				(1)Shearing, windrowing, and burning	Sed 2030 mg/l (2.9 t/ha) Sed 109 mg/l (0.07 t/ha)	120 mm (1st year)* 40 mm (2nd year)*	
				(2) Roller chopping and burning	Sed -60 mg/l (-0.01 t/ha) Sed -34 mg/l (0.00 t/ha)	57 mm (1st year)* 24 mm (2nd year)*	
	Central Arkansas	0.5-13	Shortleaf pine (*Pinus echinata* Mill.)and deciduous hardwood mixed.	Site Preparation burn and plant	NO_3-N -0.38 mg/l NH_3-N 0.20 mg/l*	NR	Lawson and Hileman 1982
Upper Piedmont	Chattahoochee National Forest, Georgia	0.85-1.09	Shortleaf pine (*Pinus echinata* Mill.)and deciduous hardwood mixed.	Site Preparation herbicide application	NO_3-N 870 mg/l (<.01 t/ha)* NH_4-N -110 mg/l (<0.01 t/ha) $PO^3{}_4$–P -100 mg/l (<0.01 t/ha) Sed 25 mg/l (0.04 t/ha)	660 m^3 or approx. 100 mm (1st 2 years)	Neary et al. 1986
Appalachian Highlands	Nantahala National Forest		Mixed pine hardwood forest	Site preparation burn	NO_3-N 0.07 mg/l	NR	Knoepp and Swank 1993
	Hot Springs, Arkansas	150-325	Loblolly pine (*Pinus taeda* L.) and pine-hardwood forest	Urea (437 kg/ha) and diammonium-phosphate (DAP) (140 kg/ha) fertilizer application.	NO_3-N 2.0 mg/l (1st 2 months)	NR	Liechty et al. 1999
Appalachian Highlands	Nantahala National Forest		Oak-pine forest	Stand replacement burn	NO_3-N no measurable effect	NR	Clinton et al. 2003
				Fell and burn	NO_3-N 0.07 mg/l (1st 7 months)		

Values in parentheses are differences in exports or fluxes for the given nutrients in the associated studies.

* Indicates a statistically significant difference in comparison to control treatment in specified study.

† Change in water quality parameter over that of the experimental control, i.e. treatment value – control value.

‡ Discharge weighted sediment concentrations.