EROSION RESPONSE OF A HARVESTED PIEDMONT LOBLOLLY PINE PLANTATION IN ALABAMA: PRELIMINARY RESULTS

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Abstract—The erosion impact of typical forest management operations in a loblolly pine (*Pinus taeda* L.) plantation in the Piedmont region of Alabama was investigated. Soil loss and runoff were highly variable throughout postharvest and first year after site preparation and planting. Under postharvest conditions, the annual rate of soil loss was 106.5 and 274.4 kg/ha in two locations (DIST1 and DIST2) of the harvest tract while annual rate of runoff was 141.4. and 200.4 mm/ha, respectively. The annual rate of soil loss after site preparation/planting varied by treatment in which orientation of planted beds or no beds were tested for its influence on erosion. The treatments consisted of beds oriented down the slope (DTS), across the slope (ATS), no bedding, and machine planting only (MPO). Soil loss was greatest on sites where beds were oriented DTS followed by sites subjected to MPO with no soil disruption prior to establishment of planting beds (MPO). The annual rate of soil loss from DTS and MPO was estimated to be 14 520 and 774 kg/ha and stands in contrast to erosion rates of 79.2 and 67.0 kg/ha for sites where beds were oriented ATS and where no disturbance took place, respectively. Nutrient mobilization was evaluated by determining chemical constituents of runoff collected after each precipitation event. In the postharvest phase, the total amount of base cations determined in runoff was estimated to be 6.81 and 4.60 kg/ha for DIST1 and DIST2, respectively. Cumulative totals of base cations were estimated to be 9.67 kg/ha in DTS and 3.57 and 3.19 kg/ha in MPO and ATS, respectively. Calcium and potassium were the most abundant elements in runoff while aluminum increased in runoff compared to postharvest conditions.

INTRODUCTION

Soil erosion is an ongoing process in forested landscapes contributing approximately 9.1 by 10^6 Mg of suspended sediment per year to watercourses within the contiguous United States (Fowler and Heady 1981). Forest landscapes often attenuate soil erosion through the rapid infiltration of rainfall, and reduction in rainfall impacts energy by ground cover (Dissmeyer and Foster 1981, Moore and others 1986). However, when ground cover is disturbed, soil is displaced and transported in overland channel flow (rills) or sheet flow (interrills) (Owoputi and Stolte 1995). These processes can act individually or together and can displace and transport significant quantities of soil from a landscape. Some forest operations may have accelerated soil erosion of which harvesting, road building, and mechanical site preparation are the main contributors (Yoho 1980). The final erosion response varies according to the interaction between the type of activity under evaluation and local site conditions including site factors related to rainfall erosivity, soil erodibility, slope length, and steepness and cover condition (Dissmeyer and Foster 1981, Kinnell and Cummings 1993, McIntyre and others 1987).

Erosion rates associated with pine production in the Southeastern United States, primarily loblolly pine (*Pinus taeda* L.), have been previously reported and found to be highly variable (Beasley and others 1986, McBroom and others 2008, Yoho 1980). Machine trafficking during harvesting has resulted in increased runoff due to compacted soil layers (increased bulk density) that results in loss of soil porosity and water infiltration which in turn increases runoff (Greacen and Sands 1980, Shaw and Carter 2002). Further changes may occur during site preparation and planting that includes mechanical manipulations to remediate compacted soil layers but can result in significant losses of sediment and nutrients (Blackburn and Wood 1990, Pye and Vitousek 1985). The resulting planting site may be significantly compromised in subsequent biomass production due to previous loss of soil and nutrients (Merino and others 2005, Van Oost and others 2006).

OBJECTIVE

The objective of the study was to measure sediment loss, runoff, and nutrient mobilization from select areas of a loblolly pine plantation in the Piedmont region of Alabama subjected to harvesting and site preparation/replanting.

MATERIALS AND METHODS

The study site was located in a 20-year-old loblolly pine plantation in Lee County, AL, and encompassed an area approximately 25.4 ha in size (fig. 1). Tree basal area was estimated to be 27.5 m^2/ha of loblolly pine and 4.6 m^2/ha of hardwoods with an expected yield of 202.1 Mg (green)/ha. The primary soil series within the harvest tract was mapped as a Gwinnett sandy loam, a member of the fine, kaolinitic, thermic Rhodic Kanhapludult family (Soil Conservation Service 1981). A harvest operation was conducted in winter/spring 1998 utilizing a conventional harvesting system: a feller buncher working in conjunction with grapple skidders pulling to two separate decks; production averaged approximately 180 Mg (green)/day. The tract remained in a postharvest condition for approximately 14 months until aerial application of herbicides in May 1999, and mechanical site preparation that consisted of shearing planting rows with a V-Blade, followed by a single pass of a Savannah combination plow configured for bedding capabilities in November/December 1999. Pine seedlings were machine planted in late January 2000 by inserting seedlings in slots opened by a small shank and soil repacked by packing wheels.

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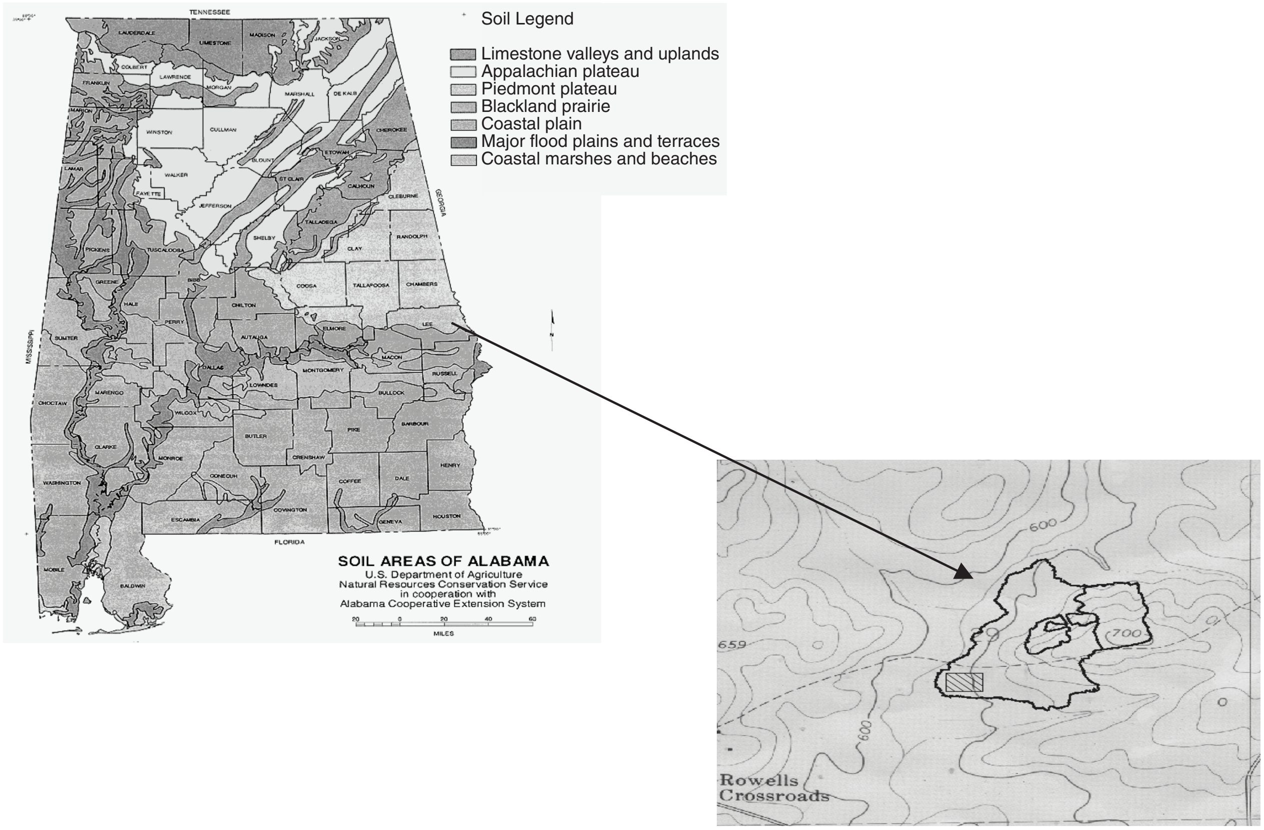

Figure 1—Location of loblolly pine plantation study site subjected to harvesting and site preparation and planting in the Piedmont region of Alabama. *Source:* Natural Resources Conservation Service (www.mo15.nrcs.usda.gov/states/al_soils_graphic.html)

Erosion Collection System

Steel-framed plots, approximately 5.5 by 2 m in size, were installed in select locations of the study site to monitor runoff and sediment production from areas disturbed by harvest and regeneration operations (fig. 2). Each location contained three framed plots that were installed on similar soil types and slope steepness (~10 percent). Runoff and entrained sediment were routed through a PVC pipe to a 210-L collection barrel placed downslope from the plot outlet; runoff was measured and sediment samples were collected after each rainfall event. Plots were installed in the fall of 1998 to assess erosion in two areas of the tract disturbed by harvest activities, labeled DIST1 and DIST2, and a third set installed in an undisturbed forest (CON) adjacent to the harvest tract in winter 1999. Site preparation activities commenced in fall of 1999 at which time each framed plot was removed to accommodate shearing and bedding of the harvest tract, replaced temporarily for 1 month prior to planting, removed to accommodate machine planting, and reinstalled after machine planting of seedlings. Steel frames (three each) were reinstalled after site preparation in a downslope direction to assess the influence of bedding on erosion. Treatments consisted of beds oriented across the slope (ATS), down the slope (DTS), the original undisturbed site (CON), and an area subjected to machine planting only (MPO) with no mechanical site preparation within each frame. The two sites labeled ATS and MPO were established on postharvest sites DIST1 and DIST2, respectively. A tipping bucket rain gauge and plastic static rain gauge were placed in an elevated section of the harvest tract to measure rainfall quantities and intensities. Descriptions of plot characteristics and sediment and runoff yields for selected time periods have been previously published (Grace 2004).

Sample Collection and Processing

After each rainfall event, runoff was estimated by measuring the collected runoff depth in each barrel, and samples collected to determine the amount of total delivered sediment produced by each storm event. Total delivered sediment was defined as the quantity of suspended and deposited sediment. Suspended sediment was determined by removing a 500-ml aliquot of standing runoff from each collection barrel on each sampling date and processed according to American Public Health Association (1995) method number 2540D. Deposited sediment was collected by bailing the runoff from each collection tank until approximately 7 cm of standing runoff remained and transferring deposited material and runoff to an 18.9-L bucket that was returned to the laboratory for processing. Deposited sediment was sieved to separate sand size material from silt and clay size material (53-µm sieve). These separates were placed in containers and dried

Figure 2—Photographic images of steel-framed plots and runoff collector barrels utilized in estimation of sediment loss, runoff, and nutrient mobilization in a loblolly pine plantation in the Piedmont region of Alabama.

in a forced air oven at 105 °C. Dry weights were recorded for each plot by sampling date and averaged over the three plots for each sampling date.

At the time of the sampling for suspended sediment analysis, a separate aliquot (500 ml) of suspended material sample was collected for nutrient analysis. The sample was sent to an independent laboratory for analysis and select nutrients measured by plasma emission spectrometry (ICP-AES) (Soltanpour and others 1996). Runoff samples were filtered through a 0.45-μm membrane filter to separate solution from suspension phase prior to analysis for base cations, aluminum, and nitrate-nitrogen.

Statistical Analyses

The experimental design consisted of a randomized block design with three replications in which three treatments were evaluated in the postharvest phase and four treatments in the postsite preparation and planting portion. A PROC MIXED (SAS Institute Inc., Cary, NC) procedure was used to evaluate the significance of treatment on total sediment production and runoff during postharvest and postsite preparation phases. Treatment was determined to be a fixed effect, and day of year was designated as the random effect. Means were separated by least squares. Similar procedures were used to evaluate nutrient mobilization expressed as annual mean loss of base cations (BASECATS), aluminum (Al), and nitrate-nitrogen (NO_3-N).

RESULTS AND DISCUSSION

Post Harvest Results

The amount of sediment loss and runoff monitored during a portion of the postharvest phase (January to October 1999) by sampling date is depicted in figure 3; cumulative totals and mean estimations of sediment and runoff by location are included in table 1. In general, sediment loss and runoff were higher in areas (DIST1 and DIST2) that had experienced machine trafficking during harvest operations compared to the CON area (table 1). The amount of soil loss and runoff varied during the course of the time period under evaluation.

In this study, differences in the erosion response of the two disturbed areas (DIST1 and DIST2) were noted with runoff and sediment yields higher from DIST2. The average quantity of sediment removed during the postharvest phase was significantly higher ($P < 0.001$) from DIST2 than from DIST1 and CON. Similarly, runoff was significantly different ($P < 0.001$) under postharvest conditions, and significant differences were detected among treatments. A potential explanation for this result may be spatial variability in the soil surface physical condition due to changes in soil structure in response to machine movements during harvest operations. Previous research has noted soil erosion to be influenced by the impact of machine traffic on soil structure through reductions in porosity and water infiltration (Meyer and Harmon 1989, Voorhees and others 1979, Wendt and others 1986). Machine traffic during harvesting was more intensive in portions of the harvest tract and less intense in other areas and may have altered soil physical conditions and response accordingly (Carter and others 2000).

Sediment collected after each rainfall event was separated into sand and silt/clay fractions and the silt/clay fraction was higher proportion regardless of site disturbance (table 1).

Site Preparation and Planting Results

The implementation of site preparation/planting increased sediment loss and runoff in the first year compared with the postharvest period (table 1). Among the treatments, soil loss and runoff were greatest from DTS (log scale to include all data) followed by MPO and ATS, and as with the postharvest condition, soil loss and runoff varied by storm event (figs. 4A and 4B). Soil loss from ATS corresponded closely to quantities measured in DIST1 while sediment yields measured from MPO increased in comparison to the previous site condition (DIST2). As was observed with postharvest results, the sediment fraction had higher levels of silt/clay than sand with the exception of DTS (table 1). Cumulative runoff production was greatest from DTS, as would be expected, followed by MPO and ATS; the lowest runoff production occurred in CON (table 1). Sediment loss ($P < 0.0001$) and runoff ($P < 0.001$)

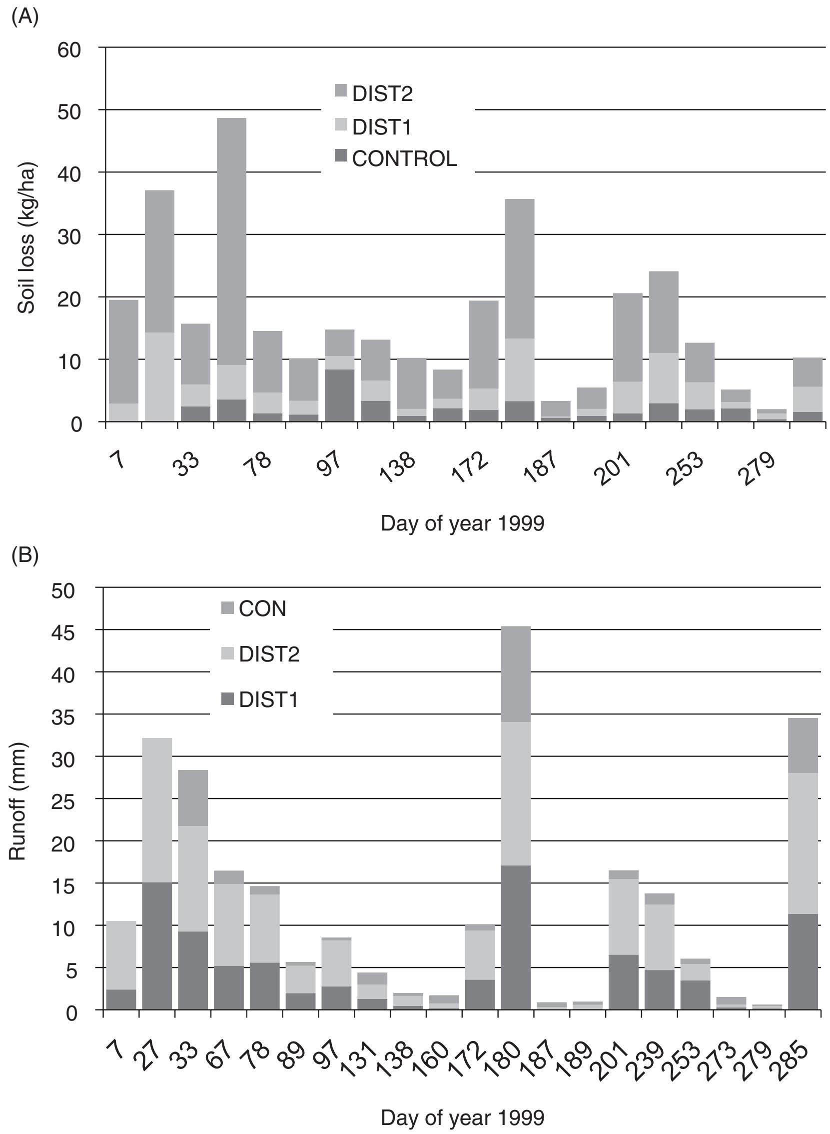

Figure 3—Sediment loss (kg/ha) (A) and runoff (mm) (B) quantities from a harvested loblolly pine plantation in the Piedmont region of Alabama. (DIST1 = plot, DIST2 = plot, CON = undisturbed forest)

were found to be significantly different for treatments under evaluation with DTS results significantly greater than ATS, MPO, and CON. No significant differences were detected among the three remaining treatments, but the higher levels of sediment loss and runoff associated with DTS may have skewed the data, obscuring significant differences.

The amount of sediment loss and runoff in response to site preparation may be related to surface conditions and bed orientation. The highest amount of sediment loss and runoff occurred in plots in which beds were positioned DTS, which permitted runoff to be channeled rapidly downslope. Soil loss and runoff quantities measured in DTS underscored the influence of slope, lack of vegetative cover, and soil erodibility on erosion potential (Kinnell and Cummings 1993, Meyer and Harmon 1989, Stein and others 1986, Van Oost and others 2006). Surface soil left unprotected is prone to erosion through the disruption of soil aggregates by rainfall and subsequent release of soil particles; this is especially evident in soils dominated by silt and clay size fractions similar to the textural composition of our study site (Burroughs and others 1992, Miller and Baharuddin 1987). In contrast, sediment loss and runoff were substantially lower from ATS plots where shorter runoff distances between beds intercepted water flow and potentially reduced sediment loss. Runoff results from MPO indicated levels elevated in comparison to ATS but substantially more sediment loss and may be the result of the tillage effect imposed during planting of seedlings.

Table 1—Cumulative, annual rate, mean soil loss, and runoff as a result of harvesting and site preparation/planting operations in a loblolly pine plantation, Alabama

	Sediment					Runoff		
Treatment[a]	Total	Sand	Silt/clay	Rate	Mean[b]	Total	Rate	Mean[b]
	kg/ha			*kg/ha/year*	*kg/ha*	*mm/ha*	*mm/ha/year*	*mm/ha*
1999								
DIST1	79.5	27.9	54.2	106.5	4.09 a	113.1	141.4	4.58 c
DIST2	212.5	97.9	114.2	274.4	10.64 b	160.3	200.4	6.34 a
CON	40.5	12.8	24.4	43.4	2.21 a	49.3	61.6	1.83 b
2000								
ATS	81.0	37.4	42.8	79.2	7.31 b	66.1	64.8	33.4 b
DTS	12558	6438	6086	14520	1566 a	210.0	205.8	105.2 a
MPO	726.9	302.4	419.5	774.1	86.41 b	88.6	86.8	54.2 b
CON	55.9	16.5	33.5	67.0	8.64 b	32.6	32.0	26.1 b

DIST1 and DIST2 = postharvest disturbance; CON = control; ATS = across the slope; DTS = down the slope; MPO = machine plant only.

[a] Means by treatment year followed by similar letters were not significant at the $P = 0.05$ level.

[b] Means of sediment and runoff were based on $n = 58$ observations from postharvest data and $n = 71$ observations from postsite preparation and replanting data.

Sufficient surface soil was disturbed in this process than when exposed to rainfall, and soil particles were entrained by runoff and transported downslope. Soil disturbances resulting from tillage have often been linked to higher erosion rates, and the increased soil loss in MPO may have resulted from the loosening of an erodible soil (Van Oost and others 2006). Soil loss and runoff in CON would be expected to be less than other treatments and the results of this study generally confirm this expectation.

Nutrient Mobilization

Results of runoff water analyses of each rain event (figs. 5A and 5B) and the mean annual accumulation of select elements are included in table 2. During the postharvest period, nutrient quantities varied by treatment with DIST1 having the largest displacement of calcium (Ca), magnesium (Mg), and potassium (K) while DIST2 was higher in sodium (Na) and Al; CON levels never exceeded DIST1 and DIST2 in the time period examined. Nutrient concentrations expressed as BASECATS were found to be variable throughout the postharvest phase (fig. 5A); similar variability in Al response was observed (data not shown). Among the individual postharvest treatments, the best relationship between BASECATS concentration and runoff was determined to be DIST2:

$$r^2 = 0.30;\ y = 0.0003x^2 - 0.0747x + 7.0807 \quad (1)$$

and between exchangeable Al and runoff in CON:

$$r^2 = 0.63;\ y = 0.0016x + 0.0285 \quad (2)$$

Postharvest treatment levels of BASECATS ($P < 0.10$) exceeded CON, and significant differences were detected between DIST1 and CON when mean values were compared (table 2).

In the initial phases of the postsite preparation/planting period, nutrient mobilization was highest in DTS among postsite preparation treatments and lowest in CON (table 2). Runoff nutrient levels varied when ATS and MPO were compared with Ca and Mg (slightly) higher in ATS while K, Na, and Al were higher in runoff from MPO. The amount of nutrient displacement varied greatly by storm event (fig. 5B), but an overall relationship between runoff and nutrient concentration (BASECATS) for all treatments was detected.

$$r^2 = 0.56;\ y = -3.0838\ln(x) + 18.48 \quad (3)$$

The relationship between runoff and Al was detected for CON only.

$$r^2 = 0.92;\ y = 0.0258x + 0.0241 \quad (4)$$

Cursory examination of the relationship between runoff and sediment load indicated no relationship under postharvest

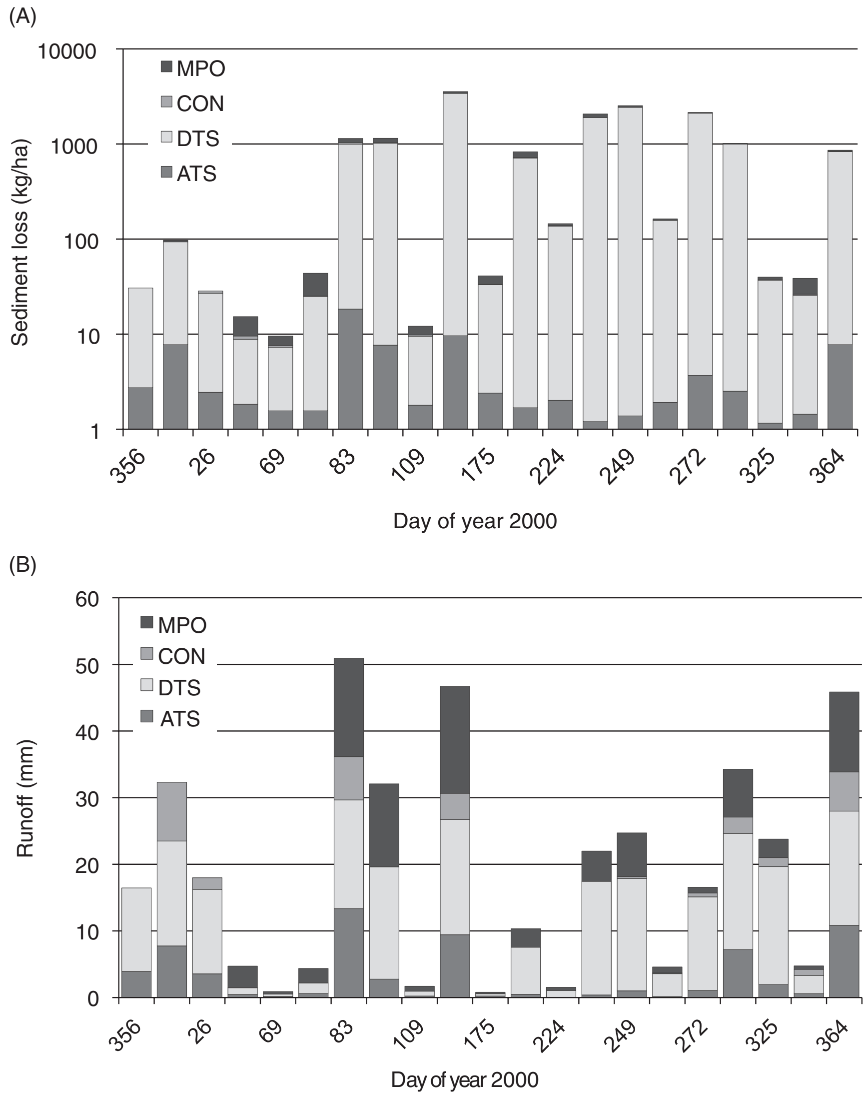

Figure 4—Sediment loss (kg/ha) (A) and runoff (mm) (B) from a loblolly pine plantation subjected to site preparation/planting in the Piedmont region of Alabama. (MPO = machine planting only, CON = undisturbed forest, DTS = down the slope, ATS = across the slope)

conditions while sediment concentration and runoff under postsite preparation conditions appeared to be related.

$$r^2 = 0.46; y = 7.4775x^2 - 61.894x + 53.62 \quad (5)$$

Treatments were highly significant ($P < 0.001$) for the mean quantity of BASECATS displaced with DTS significantly different from other treatments when mean values were compared and MPO significantly different from CON (table 2).

Nutrients entrained in runoff from sites that have been subjected to mechanical manipulations have been previously reported in forested and agricultural settings (Blackburn and Wood 1990, Kleinman and others 2006, Pye and Vitouseck 1985). The mechanism by which nutrients are mobilized by runoff may be the result of a process by which surface water via rainfall, runoff or infiltration mixes with soil constituents, thereby, transferring soil nutrients to soil solution and eventually to surface runoff. The depth of mixing is believed to be 3 to 4 mm with upward movement of nutrients to the mixing zone possible (Kleinman and others 2006, Zhang and others 1997). The overall result of nutrient mobilization would be the formation of zones or areas of nutrient enrichment or depletion in a dissected landscape such as was evaluated in this study with the potential to impact site productivity (Ni and Zhang 2007, Papiernik and others 2009). Studies of highly weathered soils under

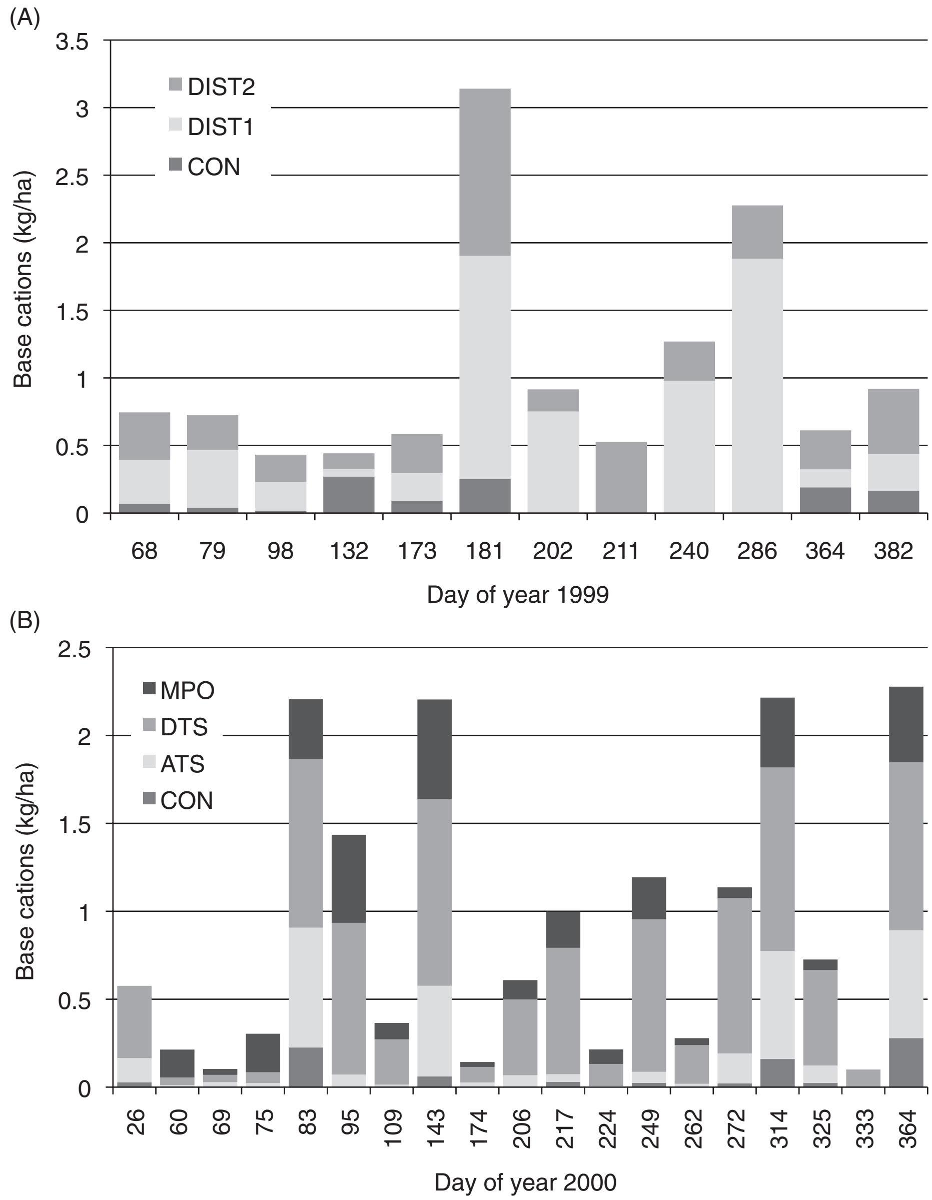

Figure 5—Base cation (kg/ha) mobilization in response to harvest operations (A) and site preparation/planting (B) of a loblolly pine plantation in the Piedmont region of Alabama. (DIST1 = plot, DIST2 = plot, CON = undisturbed forest, MPO = machine planting only, CON = undisturbed forest, DTS = down the slope, ATS = across the slope)

cropping systems similar to the soils of this study have indicated that crop productivity was affected by the degree of erosion and the decline was primarily linked to a lack of phosphorus (P) availability (Stone and others 1985, Thomas and others 1989). Soils of this region are typically deficient (unless the site has a prior history of agricultural production) in available nutrients as typified by a previously uncropped site in Georgia where effective cation exchange capacity (ECEC) values, or nutrient holding capacity, ranged between 2 and 3 cmol(+)/kg (Sumner and others 1986). It should be noted that the quantities of BASECATS displaced by runoff were greater under postharvest conditions compared to site preparation treatments with the exception of DTS. Additionally, NO_3-N quantities, measured only during site preparation treatments, were highest in DTS but overall were very small.

Table 2—Mean accumulations and concentrations of base cations, aluminum, and nitrate by treatment in response to harvest, site preparation, and planting operations in a loblolly pine plantation, Alabama

	Nutrients								Runoff					
Treatment[a]	Ca	Mg	K	Na	Total	Al[b]	BASECATS[b]	NO_3	Ca	Mg	K	Na	Al	NO_3
	kg/ha								*mg/l*					
1999														
CON	0.43	0.11	0.36	0.19	1.09	0.06 b	0.14 b	ND	2.61	0.57	1.87	1.10	0.11	ND
DIST1	3.14	0.82	2.06	0.79	6.81	0.31 b	0.63 a	ND	3.03	0.76	1.87	0.81	0.24	ND
DIST2	1.44	0.41	1.65	1.10	4.60	0.40 a	0.38 ab	ND	1.30	0.37	1.31	0.85	0.94	ND
2000														
CON	0.29	0.10	0.38	0.10	0.67	0.29 b	0.05 b	0.03 b	11.62	1.79	3.04	2.03	0.87	0.53
ATS	1.14	0.37	1.35	0.33	3.19	0.49 b	0.18 bc	0.16 b	6.56	1.20	3.58	1.37	0.84	0.48
DTS	2.45	1.08	4.65	1.49	9.67	6.29 a	0.50 a	0.95 a	3.00	0.78	2.77	0.99	2.63	0.75
MPO	1.01	0.36	1.73	0.47	3.57	2.02 b	0.21 c	0.13 b	5.32	0.94	2.98	1.05	1.13	0.35

Ca = calcium; Mg = magnesium; K = potassium; Na = sodium; Al = aluminum; BASECATS = base cations; NO_3 = nitrate; CON = control; DIST1 and DIST2 = postharvest disturbance; ATS = across the slope; DTS = down the slope; MPO = machine plant only.

[a] Means by treatment year followed by similar letters were not significant at the $\alpha = 0.05$ level.

[b] Means of aluminum and BASECATS for postharvest and postsite preparation/planting was based on $n = 31$ and $n = 71$ observations; $n = 36$ for nitrate-nitrogen results.

SUMMARY

Soil loss and runoff in response to harvesting, site preparation, and planting in a Piedmont site in Alabama exhibited a high degree of variability throughout the study period. Cumulative annual soil loss during postharvest in one treatment (DIST2) slightly exceeded previously reported estimates (~224 kg/ha/year) for harvesting and thinning activities in the Southeast. Site preparation treatments DTS and MPO resulted in substantially higher sediment losses in comparison to ATS and CON. Annual cumulative runoff rates during postharvest and site preparation varied with the highest rates of 200 mm/ha/yr associated with DIST2 and DTS. Nutrient mobilization appeared to be consistent with runoff losses reported in previous studies. The greatest sediment and nutrient mobilization occurred where beds were oriented in the DTS while MPO surprisingly contributed more sediment and nutrient mobilization than expected.

LITERATURE CITED

American Public Health Association. 1995. Standard methods for the examination of water and wastewater. 19th ed. Washington, DC. http://www.standardmethods.org/. [Date accessed: July 22, 2011].

Beasley, R.S.; Granillo, A.B.; Zillmer, V. 1986. Sediment losses from forest management: mechanical vs. chemical site preparation after clearcutting. Journal of Environmental Quality. 15: 413–416.

Blackburn, W.H.; Wood, J.C. 1990. Nutrient export in stormflow following forest harvesting and site preparation in east Texas. Journal of Environmental Quality. 19: 402–408.

Burroughs, E.R.; Luce, C.H.; Phillips, F. 1992. Estimating interrill erodibility of forest soils. Transactions of the American Society of Agricultural Engineers. 35: 1489–1495.

Carter, E.A.; McDonald, T.P.; Torbert, J.L. 2000. Assessment of soil strength variability in a harvested loblolly pine plantation in the Piedmont region of Alabama. New Zealand Journal of Forest Science. 30: 237–249.

Dissmeyer, G.E.; Foster, G.R. 1981. Estimating the cover management factor (C) in the universal soil loss equation for forest conditions. Journal of Soil and Water Conservation. 36: 235–240.

Fowler, J.M.; Heady, E.O. 1981. Suspended sediment production potential on undisturbed forest land. Journal of Soil and Water Conservation. 36: 47–50.

Grace, J.M., III. 2004. Soil erosion following forest operations in the southern Piedmont of central Alabama. Journal of Soil and Water Conservation. 59: 160–166.

Greacen, E.L.; Sands, R. 1980. Compaction of forest soils: a review. Australian Journal of Soil Research. 18: 163–189.

Kinnell, P.I.A.; Cummings, D. 1993. Soil/slope gradient interactions in erosion by rain-impacted flow. Transactions of the American Society of Agricultural Engineers. 36: 381–387.

Kleinman, P.J.A.; Srinivasan, M.S.; Dell, C.J. [and others]. 2006. Role of rainfall intensity and hydrology in nutrient transport via surface runoff. Journal of Environmental Quality. 35: 1248–1259.

McBroom, M.W.; Beasley, R.S.; Chang, M. [and others]. 2008. Storm runoff and sediment losses from forest clearcutting and stand re-establishment with best management practices in east Texas, USA. Hydrological Processes. 22: 1509–1522.

McIntyre, S.C.; Lance, J.C.; Campbell, B.L. [and others]. 1987. Using cesium-137 to estimate soil erosion on a clearcut hillside. Journal of Soil and Water Conservation. 42: 117–120.

Merino, A.; Balboa, M.A.; Rodriguez Soalleiro, R.; Alvarez Gonzalez, J.G. 2005. Nutrient exports under different harvesting regimes in fast-growing forest plantations in southern Europe. Forest Ecology and Management. 207: 325–339.

Meyer, L.D.; Harmon, W.C. 1989. How row-sideslope length and steepness affect sideslope erosion. Transactions of the American Society of Agricultural Engineers. 32: 639–644.

Miller, W.P.; Baharuddin, M.K. 1987. Particle size of interrill eroded sediments from highly weathered soils. Soil Science Society of America Journal. 51: 1610–1615.

Moore, I.D.; Burch, G.J.; Wallbrink, P.J. 1986. Preferential flow and hydraulic conductivity of forest soils. Soil Science Society of America Journal. 50: 876–881.

Ni, S.J.; Zhang, J.H. 2007. Variation of chemical properties as affected by soil erosion on hillslopes and terraces. European Journal of Soil Science. 58: 1285–1292.

Owoputi, L.O.; Stolte, W.J. 1995. Soil detachment in the physically based soil erosion process: a review. Transactions of the American Society of Agricultural Engineers. 38: 1099–1110.

Papiernik, S.K.; Schumacher, T.E.; Lobb, D.A. [and others]. 2009. Soil properties and productivity as affected by topsoil movement within and eroded landform. Soil and Tillage Research. 102: 67–77.

Pye, J.M.; Vitousek, P.M. 1985. Soil and nutrient removals by erosion and windrowing at a Southeastern U.S. Piedmont site. Forest Ecology and Management. 11: 145–155.

Shaw, J.N.; Carter, E.A. 2002. Timber harvesting effects on spatial variability of Southeastern U.S. Piedmont soil properties. Soil Science. 167: 288–302.

Soil Conservation Service. 1981. Soil survey of Lee County, Alabama. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service. 100 p.

Soltanpour, P.N.; Johnson, G.W.; Workman, S.M. [and others]. 1996. Inductively coupled plasma emission spectroscopy. In: Sparks, D.L., ed. Methods of soil analysis—part 3 chemical methods. Soil Science Society of America Book Series: 5. Madison, WI: American Society of Agronomy; Soil Science Society of America. [Number of pages unknown].

Stein, O.R.; Neibling, W.H.; Logan, T.J. [and others]. 1986. Runoff and soil loss as influenced by tillage and residue cover. Soil Science Society of America Journal. 50: 1527–1531.

Stone, J.R.; Gilliam, J.W.; Cassel, D.K. [and others]. 1985. Effect of erosion and landscape position on the productivity of Piedmont soils. Soil Science Society of America Journal. 49: 987–991.

Sumner, M.E.; Shahandeh, H.; Bouton, J. [and others]. 1986. Amelioration of an acid soil profile through deep liming and surface application of gypsum. Soil Science Society of America Journal. 50: 1254–1258.

Thomas, P.J.; Simpson, T.W.; Baker, J.C. 1989. Erosion effects on productivity of Cecil soils in the Virginia Piedmont. Soil Science Society of America Journal. 53: 928–933.

Van Oost, K.; Govers, G.; De Alba, S. [and others]. 2006. Tillage erosion: a review of controlling factors and implications for soil quality. Progress in Physical Geography. 30: 443–466.

Voorhees, W.B.; Young, R.A.; Lyles, L. 1979. Wheel traffic considerations in erosion research. Transactions of the American Society of Agricultural Engineers. 22: 786–790.

Wendt, R.C.; Alberts, E.E.; Hjelmfelt, A.T., Jr. 1986. Variability of runoff and soil loss from fallow experimental plots. Soil Science Society of America Journal. 50: 730–736.

Yoho, N.S. 1980. Forest management and sediment production in the South—a review. Southern Journal of Applied Forestry. 4: 27–35.

Zhang, X.C.; Norton, D.; Nearing, M.A. 1997. Chemical transfer from soil solution to surface runoff. Water Resources Research. 33: 809–815.