ASSESSING SOIL IMPACTS RELATED TO FOREST HARVEST OPERATIONS

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ABSTRACT

Three studies conducted in Alabama evaluated impacts associated with a clear cut harvest in three physiographic regions. Machine impacts were assessed via tabulation of soil disturbance classes, measurement of bulk density and soil strength, or a combination of the two. Soil disturbance classes were similar among all locations with untrafficked areas comprising approximately 20 percent of the harvest tract and the remaining as slightly or heavily disturbed. Soil strength response increased with disturbance intensity in surface and subsurface soil layers, while bulk density did not show a consistent pattern by depth with intensity. Post-harvest erosion data underscored the variability of site response while site preparation and subsequent planting contributed to higher erosion rates. Global Positioning System receivers monitored machine movements and provided a basis for disturbance class assessment. Similarly, positional data were used to create Digital Elevation Models to determine runoff interception by silt fences to assess erosion potential.

Keywords: bulk density, disturbance classes; erosion, GPS, physiographic region, soil strength.

INTRODUCTION

Mechanized forest operations have induced changes in soil properties with the potential to negatively impact soil sustainability and forest productivity. Machine related soil impacts vary spatially and in intensity depending on the interaction between machine and site factors at the time of impact. Attempts to characterize the degree of impact and its variability throughout an affected area have relied on methods that are hampered by the amount of time to complete an assessment as well as a lack of accuracy. Recent advances in global positioning systems (GPS) and geographic information systems (GIS) have allowed more accurate evaluation of the impact of forest operations. The application of more accurate methods may provide more relevant information to guide future management decisions to promote adequate regeneration.

Previously, soil impacts related to harvest and thinning operations were assumed to be distributed uniformly throughout a harvest tract with the greatest impact found on landings and skid trails. To ensure adequate regeneration, land managers employed mechanical and chemical methods of site preparation throughout the harvest tract to control weeds, prepare planting beds and provide adequate water and nutrients (Morris and Lowery, 1988; Allen and others, 1990; Dubois, 1995; Miller and others, 2006). More accurate information on how site impacts vary spatially and in intensity to ensure more cost effective remediation techniques necessitated the use of ground disturbance surveys, measurement of soil properties affected by machine trafficking, or their combination. As stated previously, these are time consuming and lack sufficient accuracy to be useful. The use of GPS receivers to collect positional data has been invaluable in allowing researchers to track machine movements and assist in management activities (McMahon, 1997; McDonald and others, 2002; McDonald and Fulton, 2005; McDonald and others, 2008). Application of GPS technology to assess soil impacts has been conducted by linking GPS positional data to traffic maps or point specific measurement of soil changes (Carter and others, 1999; 2000; McDonald and others, 2002). The current generation of GPS receivers allows the possibility of more precise positional data to link with site specific changes in soil properties (Renschler and Flanagan, 2008).

An additional consequence of mechanized operations in managed forested landscape is the increased potential for erosion whereby site productivity may be compromised due to soil and nutrient redistribution and loss. Quantification of erosion has typically been conducted by delineating an area of known size and directing the runoff and entrained soil and dissolved solids into a collection device. Numerous studies have reported runoff and soil loss for a wide range of conditions, plot configurations, and collection devices (Dissmeyer, 1982; Pye and Vitousek, 1985; Lacey, 2000; Robichaud and others, 2001; Costantini and Loach, 2002; Field and others, 2005; McBroom and others, 2008). Although the use of bound plots is a standard method, studies that isolate a segment of the surrounding landscape to monitor erosion may not be representative of the full erosion potential of a managed landscape. Forested landscapes subjected to harvesting, thinning, and regeneration activities are highly variable in surface disturbance levels and vary greatly in the degree of erosion potential on a landscape basis. Larger portions of the landscape may be monitored for erosion potential by developing Digital Elevation Models (DEMs) that predict water flow paths and that can be linked with models that predict runoff and soil loss (e.g., Water Erosion Prediction Project-WEPP). Digital elevation models can be easily

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constructed from highly accurate GPS systems (e.g. RTK systems) and imported into GIS applications to predict flow paths and erosion potential (Renschler and Flanagan, 2008**)**. The objective of this paper is an assessment of methods utilized in our studies to assess soil impacts from forest operations, including soil compaction and erosion potential. Of significance in assessing the impact of forest operations was the application of GPS and GIS to enhance data collection and interpretation.

MATERIALS AND METHODS

SOIL COMPACTION

The evaluation of soil compaction as a result of forest harvest operations was concentrated in three study sites in Alabama (fig. 1). The upper site (SCUAL) was located in Lawrence County, near Moulton, Alabama, within the southern boundary of the Cumberland Plateau. Soils within the study area were typified by Hartsells, Townley and Sipsey soil series, fine-loamy and loamy, siliceous and mixed, subactive and semiactive, thermic members of Typic Hapludults. The central site (SCCAL) was located in Chambers County, near Lafayette, AL, within the Piedmont region of Alabama. Soils of the study site were composed primarily of fine, kaolinitic, thermic Typic and Rhodic Kanhapludults and Kandiudult families and typified by Cecil and Gwinnett soil series. The lower site (SCLAL) site was located in Covington County, near Andalusia, AL, within the Gulf Coastal Plain; soils within the study site were composed primarily of Orangeburg sandy loam, classified as a fine-loamy, kaolinitic, thermic member of Typic Kandiudults.

The degree of soil disturbance and final soil compaction was based on tabulation of soil surface disturbances and collection of soil cores to determine changes in soil volume and stength. Soil surface disturbance classes typical of sites under consideration were identified and tabulated via transects throughout harvest tracts with the final classes based on ground disturbances tabulated and reported by Lanford and Stokes **(**1995). Ground disturbance was linked to soil changes by removing soil cores from locations representative of soil disturbance classes randomly or at predetermined grid points. Soil cores were removed, subsectioned into 10 centimeter increments, and dried at 105 degrees Celsius to determine bulk density (ρ_b) and gravimetric soil moisture (θ_g) (Klute, 1986). In-situ measurements of soil strength were conducted by inserting a Rimik CP20 recording cone penetrometer to a predetermined depth and measurements recorded in 2.50 centimeter increments and expressed as cone index (CI) (ASAE, 2000**).**

MACHINE TRAFFICKING AND GPS

The Global Positioning System was employed to monitor machine movements during harvest of a loblolly pine plantation and subsequent positional data utilized to facilitate determination of soil disturbance classes and traffic intensity (number of passes). Positional data were collected by GPS receivers mounted on a feller buncher and two skidders, converted into raster maps and displayed as a map of traffic intensities by location in two harvest stands in the Piedmont region of Alabama (McDonald and others, 2002). Traffic intensities were linked to soil disturbance classes by determining surface disturbance on a 9.8 x 9.8 meter grid after harvesting, collecting positional data of grid point locations, and matching disturbance classes with traffic intensities. Subsequently, postharvest soil cores were removed from locations representative of soil disturbance classes and processed for ρ_b**,** θ_g,and CI. Soil sampling locations were linked to traffic intensities via GPS data and $\rho_{b,}$ θg, and CI averaged by disturbance class and traffic intensities. The spatial variability associated with ρ_b and CI in the harvested tract was determined via spatial analysis techniques.

EROSION

Investigation of the erosion potential associated with harvest activities was examined in two project locations: in lower Alabama (SELAL) and another central Alabama site (SECAL) in the Piedmont region, located in Lee County, near Auburn, AL. The study conducted in SELAL was previously described in the soil compaction section while a harvest operation followed by site preparation and replanting was conducted in SECAL. Soils of SECAL were primarily composed of Gwinnett sandy loam and classified as fine, kaolinitic, thermic members of Rhodic Kanhapludults. Soils typical of SELAL were previously described in the soil compaction section as this site served the dual purpose of examining both compaction and erosion (fig 1).

In SECAL, an erosion collection system consisting of bound plots approximately 5.5 x 2.0 meter in size was installed in select locations to monitor runoff and sediment production from areas disturbed by harvest and tillage operations. Runoff and entrained sediment were routed through a PVC pipe to a 210 liter collection barrel placed down slope from the plot outlet. Runoff was measured and sediment samples were collected after each rainfall event. Each location contained three plots that were installed on similar soils and slope steepness (~ 10 percent). In SELAL, silt fences were installed in down slope locations and positional data collected by a Real Time Kinematic GPS system to create a 1 meter Digital Elevation Model (DEM) (fig.3). Silt fences were placed along the lower portion of a hill slope of approximately 8 percent steepness and sediment captured from an upslope area approximately 25 meters in length.

The collected GPS data were analyzed by a Geographic Information System (GIS) application to predict water runoff paths to evaluate interception of runoff by each silt fence. Final accumulated soil quantities were determined for both harvested and undisturbed locations and runoff interception by each silt fence was investigated.

RESULTS

Soil disturbance classes associated with each study site were tabulated on a grid base system, compiled into categories that denoted impact intensity and the percentage estimated within each category (table 1). Examination of the disturbance category tabulations for clear cut harvests indicated a similar percentage of the harvest stand classified as untrafficked (UNT), or no evidence of traffic disturbance. Differences were noted between the percentage of slightly (SD) and highly disturbed (HD) areas among the study sites. Slightly disturbed was defined as showing evidence of trafficking most often with litter still in place and HD defined as rutted or used as a skid trail. The highest percentage of HD was associated with SCCAL and the lowest percentage tabulated in SCUAL; SD tabulations were higher in SCUAL and relatively similar in SCCAL and SCLAL. The total percentage of area disturbed (SD + HD) was approximately 74 percent in the SCUAL and SCLAL sites and 83 percent in SCCAL. The final tabulation of disturbance classes has been reported to depend on the number of sites evaluated, the distance between points, and the type of tabulation method (McMahon, 1995).

Bulk density and CI measurements collected for the three sites under evaluation were reported by disturbance category (table 2). Gravimetric water contents were also included for each site. As was expected, $\rho_{b,}$ and CI were higher in the subsurface layer (10 – 20 centimeter) compared to the surface layer in all sites; θ_g was typically higher in the surface layers compared to subsurface levels. Bulk density data did not indicate a clear trend with increased disturbance for either soil layer in the sites evaluated but CI data typically increased with disturbance level in both surface and subsurface soil layers.

Soil disturbance classes and traffic intensities determined from machine monitored GPS data indicated disturbed areas tabulated as SD experienced 1 to 3 passes while HD areas, including skid trails and landings, experienced 4 or more passes. Soil measurements (ρ_b and CI) were matched with traffic intensity data and showed an increase with traffic intensity, and appeared to reach a maximum level after approximately 3 passes (table 3).

Machine movements are highly dispersed throughout a stand in the course of harvest operations resulting in changes in soil conditions that vary in intensity and spatial dependence. Two subsections of the harvested loblolly pine stand used in the traffic intensity study were evaluated for spatial dependence and found to vary by soil property and location within the tract (table 4). An initial indication of spatial dependence is often assessed through interpretation of the nugget semivariance in which values less than or equal to 25 percent are an indication of strong spatial dependence while values between 26 and 75 percent indicate moderate dependence and greater than or equal to 75 percent shows weak dependence (Cambardella and others, 1994). Strong spatial dependence was detected in site two for both properties based on the nugget semivariance while site 1 appeared to indicate moderate spatial dependence. Further corroboration of spatial dependence would be indicated by the r^2 value and the range of spatial dependence. The results for CI in site two showed good model fit and a range of spatial dependence that would be reasonably expected under the conditions of the harvest operation. In site one a good model fit was calculated for CI but the range of dependence is greater than the lag distance (approximately75 meters) selected for the analysis and is indicative of not capturing spatial dependence at the selected sampling distance. The results for ρ_b in sites one and two may be questioned due to a low r^2 values although the range of dependence is reasonable. The results for site one may be an indication that the range of correlation was not detectable at the grid spacing chosen but more evident by results for site two.

A typical erosion collection system installed in 1998 in SECAL monitored post-harvest and post site preparation and replanting erosion. Three areas within the stand were monitored during the post harvest phase, two of which had been subjected to harvest disturbances (DIST1 and DIST2) and a control plot (CON); differences in erosion response were detected among locations (fig. 2a). The location labeled DIST2 yielded the greatest amount of sediment, the cumulative total in excess of 200 kilograms per hectare while DIST1 and CON did not exceed 100 and 50 kilograms per hectare, respectively. A statistical comparison of means for sediment displacement indicated DIST2 was significantly different from DIST1 and CON. Runoff quantities followed a similar pattern among locations but cumulative totals for disturbed sites produced more runoff compared to CON; means among treatments were significantly different for all three treatments (fig. 2a). Erosion potential in the initial period after completion of site preparation and replanting was evaluated based on orientation of beds within the framed plots: across the slope (ATS), down the slope (DTS), machine plant only (no beds) (MPO) and control (CON). Sediment totals were excessively high in DTS while MPO exceeded ATS and CON (fig. 2b). Runoff totals were greatest from DTS and measured in excess of 200 millimeters over the study period followed by MPO and ATS between 50 and 100 millimeters; CON was less than 50 millimeters. Sediment and runoff quantities from DTS were significantly different from other treatments (fig. 2b).

Estimation of erosion potential in SELAL was conducted by placing silt fences in select locations. Soil accumulation by each fence was greater in harvested stands compared to undisturbed sites but accumulations in both harvested and undisturbed varied, presumably due to terrain differences that affected water flow (table 5). The utility of silt fences as a reliable estimate of erosion potential would depend on their ability to intercept runoff water with entrained sediment. The degree to which each silt fence was able to intercept runoff was tested by constructing 1 meter Digital Elevation Models (DEMs) from Real Time Kinematic (RTK) GPS derived elevation data. Runoff flow paths were illustrated by analyzing DEM data via TopoGrid, a Geographic Information System (GIS) application, and runoff interception by a randomly placed silt fence illustrated (fig. 3). Runoff flow paths illustrated in figure three were representative of interception by all silt fences in this study and it appears that a portion of slope runoff was captured by each silt fence.

DISCUSSION

Soil compaction and surface disturbances are inevitable where forest operations are implemented, the degree of impact determined by site and machine factors. Soil disturbance classes have been used extensively to evaluate the impact of forest operations and compare types of harvest systems and locations **(**Dyrness, 1965; Hatchell, 1970; Lanford and Stokes, 1995; Aust and others, 1998; Carter and others, 2006**).** Surface disturbances can range from undisturbed with no evidence of trafficking to rutting, skid trails and landings indicative of intense trafficking. The utility of tabulating surface disturbance classes as a means of evaluating machine impacts may be limited due to a lack of standardization or determination of the accuracy associated with this method. McMahon (1995) compared soil disturbances from three survey methods with an intensive 1 x 1 meter grid survey and determined how each method compared to the intensive survey. The result of his intensive survey indicated that approximately 70 percent of the harvest area was undisturbed or slightly disturbed while the remainder of the area had been rutted or heavily trafficked; the point transect method at a spacing of 30 m compared favorably to the intensive survey. The upper site (SCUAL) was comparable to the 70 percent level as reported by McMahon (1995**)** while cumulative percentages of 48 and 57 percent were detected in SCCAL and SCLAL.

Improvement in the ability to link machine trafficking to soil surface disturbances was possible by collecting positional data via Global Positioning System (GPS) receivers, translating GPS data to maps of traffic passes and matching positional data with surface disturbances (McMahon, 1997; McDonald and others, 2002**).** McDonald and others (2002) concluded that GPS data translated into a raster map of machine passes would be of sufficient accuracy to be used to determine site level disturbances as well as a record of machine movements within a harvest tract. They noted that the ability to use GPS data to assess point specific data e.g. soil compaction would not be sufficiently accurate.

Soil physical changes, an obvious consequence of machine trafficking, are typically reported as changes in bulk density and/or soil strength (Gent and Ballard, 1984; Carter and others, 2000; Shaw and Carter, 2002; Carter and others, 2006). Machine factors, singly or in combination, are often implicated in the reported changes in bulk density and/or soil strength due to high machine loads, high ground pressures, increased traffic intensity or their combination (Koger and others, 1985; Smith and Dickson, 1990; Horn and others, 1995). Machine stresses induce soil volume changes typified by loss of aggregation and reduced soil pore structure and function, with the final compaction status, either increased or decreased bulk density and soil strength, influenced strongly by soil texture, soil organic matter status and soil moisture content. Numerous studies have reported the status of bulk density and soil strength by disturbance class and found a direct relationship between disturbance intensity and soil physical response (Shaw and Carter, 2002; Carter and others, 2006) but inconsistent responses have been reported as well (Meek, 1996; Carter and others, 1999). Bulk density reported by soil disturbance intensity was not consistent while CI data typically increased as soil disturbances intensified. These results may reflect differences in machine configuration or soil properties even when linked with disturbance classes determined by GPS tracking.

Soil erosion is another consequence of machine trafficking as reductions in soil volume result in decreased water infiltration and increased surface runoff (Voorhees and others, 1979; Watson and Laflen 1986). Soil compaction was evident in SECAL as evidenced by changes in bulk density and soil strength throughout the harvest tract (Carter and others, 1999). The postharvest condition (DIST1 and DIST2) indicated differences in sediment displacement and runoff production although each site was subjected to similar impacts. Site response may have differed due to spatial variability of soil physical properties in the soil surface layer as a result of site response to machine movements during harvest operations (Carter and others, 1999; Carter and others, 2000; Carter and Shaw, 2002). Machine traffic during harvesting was more intense in select portions of the harvest tract and less intense in other areas and potentially altered soil physical conditions and response accordingly.

Site preparation had a profound effect on sediment displacement and runoff production depending on the specific treatment. Obviously, erosion potential was greatest when beds were oriented down slope (DTS) and to a lesser degree, on plots where no bedding occurred (MPO). Soil loss and runoff quantities measured in DTS may have been influenced by slope, lack of vegetative cover and soil erodibility (Stein and others, 1986; Burroughs and others, 1992; Kinnell and Cummings 1993; 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 this study site (Dickerson, 1975; Burroughs and others, 1992; Miller and Baharuddin 1987). In contrast, sediment loss and runoff were substantially lower from ATS plots where ground cover was more plentiful and 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. The sediment displacement may be the result of the tillage effect imposed during replanting of seedlings that utilized a small shank and bedding plow to provide an opening and small bed for planting new seedlings. Sufficient surface soil was disturbed in this process that when exposed to rainfall, soil particles were entrained by runoff and transported down slope. 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 (Stein and others, 1986; Costantini and Loach, 2002; Van Oost and others, 2006). Soil loss and runoff in CON would be expected to be less than other treatments and the results confirm this expectation.

The assessment of erosion potential is often conducted by isolating a portion of a harvest tract to measure runoff and entrained sediment. A simpler and less time consuming procedure of erosion assessment utilizes silt fence technology, or synthetic geotextile material of sufficient mesh size to allow water to pass through while holding sediment. Silt fences have been found to trap a sufficient amount of sediment to provide a fairly accurate assessment of sediment displacement in erosion studies, although less accurate than bound plots (Robichaud and others, 2001). This expectation was confirmed in that more sediment was trapped by silt fences placed in a harvested area when compared to an undisturbed area. Recent advances in GPS technology have provided a means of measuring highly accurate vertical elevations to delineate runoff flow paths and determine contributing areas to runoff and soil movement (Renschler and others, 2002). Renschler and Flanagan (2008**)** determined that topographic data determined by RTK GPS grade receivers accurately predicted soil displacement and runoff by the Water Erosion Prediction Project (WEPP). In this study, it was shown that a silt fence was able to intercept runoff, and ostensibly the entrained sediment, but missed a portion of the runoff as it diverted away from the established silt fence. In the future, a site expected to undergo erosion could be evaluated for runoff contributing areas and silt fences placed where runoff could be intercepted and erosion estimates determined from trapped sediment.

SUMMARY

Clearcut forest operations typically result in compacted soil layers that increase the erosion potential of a harvested site. The final compaction status can vary spatially and in intensity as a result of harvest traffic patterns and systems. Tools exist to assist in determining the extent and intensity of soil compaction and erosion with the potential to be applied on a stand level. Machine impacts are often evaluated by tabulation of soil surface disturbance classes representative of the type and degree of trafficking impact, changes in soil bulk density or soil strength, or in combination. These methods are very time consuming and lack sufficient accuracy. Preliminary investigations have indicated the usefulness of GPS receivers to monitor machine movements and provide a basis for disturbance class assessment through trafficking patterns. Similarly, positional data from GPS receivers can be used to create DEMs to assess runoff interception by silt fence placement.

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Table 1—Soil disturbance class percentages for select sites subjected to harvest operations, Alabama

DISTURBANCE CLASS CATEGORIES	UNTRAFFICKED (UNT)	SLIGHTLY DISTURBED (SD)	HIGHLY DISTURBED (HD)	NON-SOIL (NS)	n	GRID (m)
UPPER CLEARCUT	18	57	17	8	180	18 x 18
CENTRAL CLEARCUT	10	38	45	7	250	10 x 10
LOWER CLEARCUT	15	42	32	11	421	3 x 30

Table 2—Select soil physical properties by disturbance class associated with clear cut forest operations, Alabama

DISTURBANCE CLASS CATEGORIES SOIL PROPERTIES		UNTRAFFICKED (UNT)	SLIGHTLY DISTURBED (SD)	HIGHLY DISTURBED (HD)
BD (Mg/m^3)				
UPPER	0 – 10 cm	1.04 (23.6) ±	1.10 (22.6)	1.14 (26.4)
	10 - 20 cm	1.33 (14.7)	1.35 (16.8)	1.35 (18.8)
CENTRAL	0 – 10 cm	0.98 (19.4)	1.08 (19.7)	1.06 (23.1)
	10 - 20 cm	1.35 (11.9)	1.29 (11.2)	1.31 (12.3)
LOWER	0 – 10 cm	1.03 (22.5)	1.04 (17.6)	0.89 (31.5)
	10 - 20 cm	1.33 (11.2)	1.36 (10.8)	1.35 (12.6)
GMC (%)				
UPPER	0 – 10 cm	29.5 (51.8)	32.4 (40.3)	32.1 (47.5)
	10 - 20 cm	22.7 (30.4)	22.7 (28.4)	25.1 (46.7)
CENTRAL	0 – 10 cm	24.9 (36.6)	22.3 (24.7)	24.1 (24.8)
	10 - 20 cm	22.1 (13.1)	22.8 (19.0)	24.5 (16.5)
LOWER	0 – 10 cm	10.5 (16.8)	11.5 (24.5)	14.8 (50.6)
	10 - 20 cm	8.7 (20.1)	9.0 (23.8)	9.7 (16.8)
CI (MPa)				
UPPER	0 – 10 cm	0.77 (60.8)	0.95 (54.0)	1.12 (50.7)
	10 - 20 cm	0.81 (68.8)	1.07 (51.3)	1.59 (40.6)
CENTRAL	0 – 10 cm	1.20 (62.5)	1.50 (39.6)	1.46 (43.9)
	10 - 20 cm	1.90 (36.3)	2.20 (27.9)	2.16 (27.4)
LOWER	0 – 10 cm	0.57 (45.8)	0.90 (45.0)	0.98 (44.5)
	10 - 20 cm	1.16 (38.9)	1.66 (36.1)	2.09 (43.5)

Table 3—Soil disturbance categories, traffic intensities, and select soil physical properties of a harvested loblolly pine plantation, central Alabama

DISTURBANCE CATEGORIES	TRAFFIC INTENSITY	DEPTH	SOIL PHYSICAL PROPERTIES		
			BD (cv) ±	GMC (cv)	CI (cv)
		(cm)	(Mg/m^3)	(%)	(MPa)
UNT	0	0 – 10	0.98 (19.4)	24.9 (36.6)	1.20 (62.5)
		10 – 20	1.35 (11.9)	22.1 (13.1)	1.90 (36.3)
SD	1 – 3	0 – 10	1.08 (19.7)	22.3 (24.7)	1.50 (39.6)
		10 – 20	1.29 (11.2)	22.8 (19.0)	2.20 (27.9)
HD	4+	0 – 10	1.06 (23.1)	24.1 (24.8)	1.46 (43.9)
		10 – 20	1.31 (12.3)	24.5 (16.5)	2.16 (27.4)

Table 4—Semivariance parameters of select soil properties in a harvested loblolly pine stand in the Piedmont region of Alabama

SOIL PROPERTY	MODEL†	MODEL FIT (r^2)	RANGE (m)	NUGGET SEMIVARIANCE ±	GRID SPACING (m)
SITE 1					
P_b	exp	0.11	10.2	26.0	6 x 6
CI	exp	0.88	295.0	42.0	
SITE 2					
P_b	exp	0.31	13.2	13.0	3 x 6
CI	sph	0.74	11.4	18.0	

† Geostatistical parameters - models : exp = exponential; sph = spherical. ± Nugget Semivariance: 0 – 25% high; 26-75% moderate; >75% weak

Table 5—Soil accumulation of 5 silt fences in a harvested and non-harvested slash pine stand in Conecuh National Forest, lower Alabama

TREATMENT	SILT FENCE # 1	2	3	4	5	ACCUMULATION (kg)
HARVESTED	5.94	3.35	4.92	1.33	3.09	18.63
NON-HARVESTED	2.48	1.61	2.78	2.16	0.20	9.23

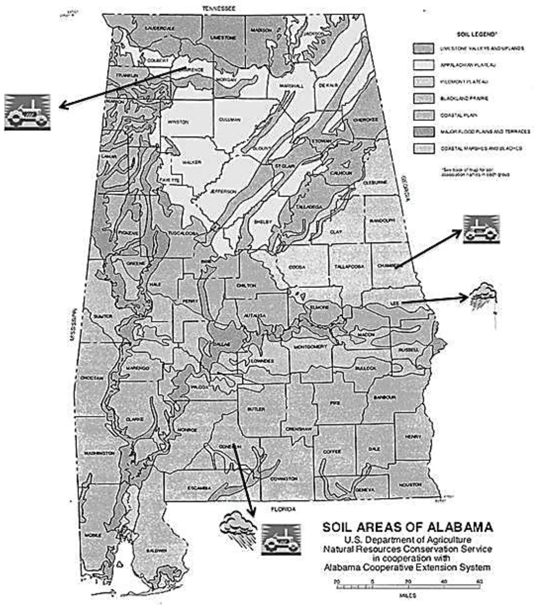

Figure 1—Location of sites evaluated for compaction and erosion response to harvest operations, Alabama, USA.

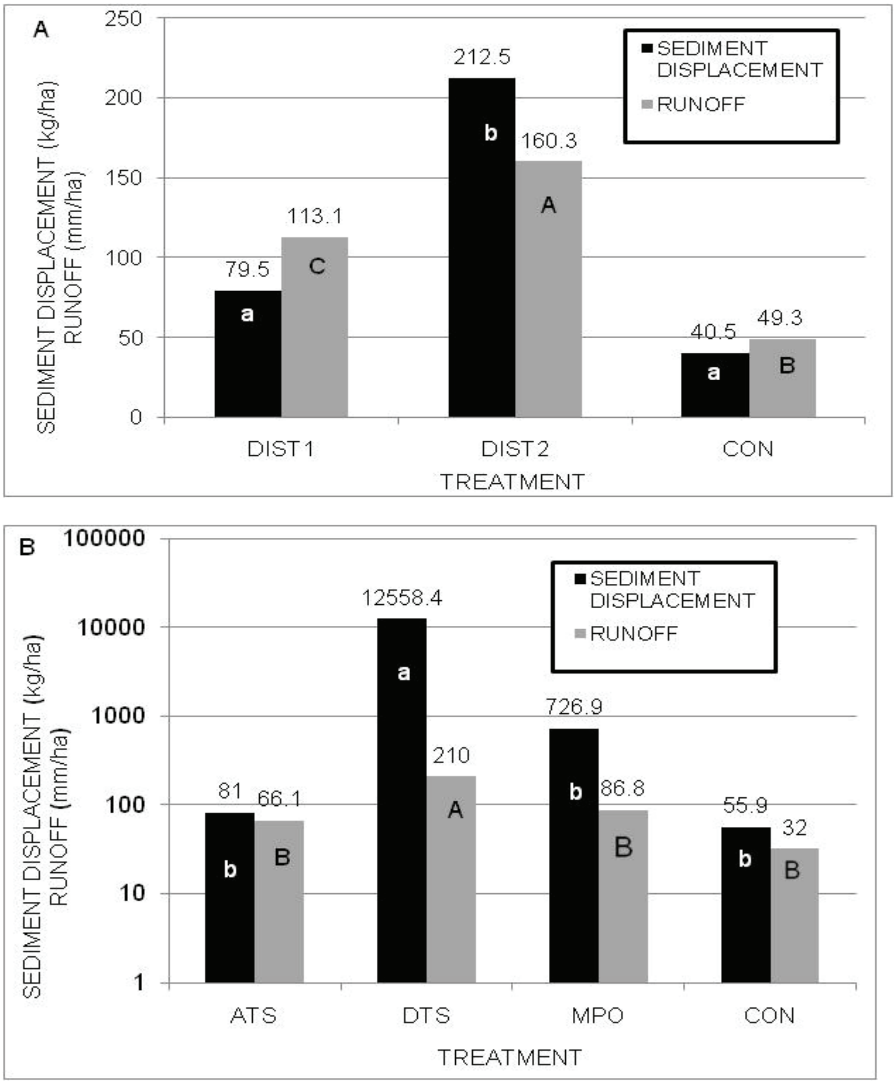

Figure 2—Soil displacement and runoff during postharvest (a) and in response to site preparation and replanting (b) in a loblolly pine plantation, central Alabama.

Sediment and runoff values were significantly different (alpha=0.05) when indicated by different letters.

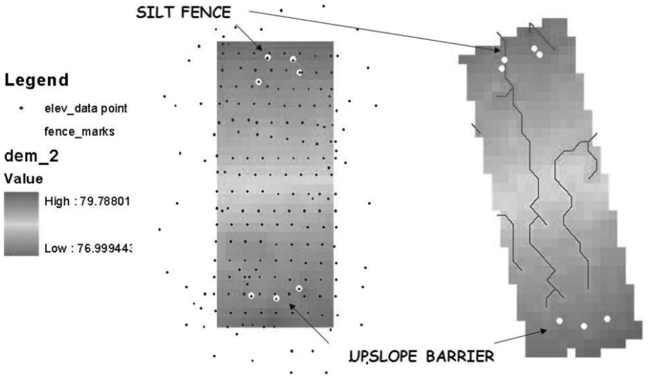

Figure 3—Analysis of water flow paths and interception by silt fence in harvested slash pine stand, lower Alabama.