ASSESSMENT OF SOIL STRENGTH VARIABILITY IN A HARVESTED LOBLOLLY PINE PLANTATION IN THE PIEDMONT REGION OF ALABAMA, UNITED STATES*

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ABSTRACT

Mechanised forest harvest operations are a significant source of soil compaction for which intensive tillage is prescribed to alleviate soil compaction and ensure successful regeneration of planted pine trees. Soil strength is a potential indicator of compaction status of a harvest tract due to its sensitivity and the ease of data collection with a cone penetrometer, but estimates may vary widely throughout a harvest tract. A loblolly pine (*Pinus taeda* L.) plantation that had been harvested in winter 1998 was studied to assess soil strength and its spatial qualities through the measurement of soil strength on two sampling scales, and to identify areas of the harvest tract where tillage operations would be beneficial. Cone index measurements indicated a high degree of variability in soil strength regardless of the scale of measurement, and high soil strength levels throughout the soil profile. Spatial dependence was high in the surface and immediate subsurface soil layers of each point grid system and was attributed to the impact of traffic or topographic position on soil strength. Spatial dependence was not detectable for the lowest subsoil layers of the large-scale sampling scheme. The short ranges of spatial correlation associated with cone index estimations and the presence of compacted subsoil layers throughout the study area suggested the need to perform tillage throughout the harvest tract to ensure alleviation of subsoil compaction for adequate regeneration.

Keywords: soil strength; cone index; spatial variability; nugget semivariance; spatial dependence; Piedmont; *Pinus taeda*.

INTRODUCTION

Machine movements that occur in the course of forest harvesting activities can induce a number of changes in soil physical properties which have the potential to limit future soil and

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site productivity. The degree of impact to which a soil has been subjected has often been determined by measuring the response of soil physical properties including soil bulk density, soil moisture content, porosity, hydraulic conductivity, and soil strength (Greacen & Sands 1980; Howard *et al.* 1981; Gent & Ballard 1984; Lenhard 1986; Meek 1986; Rab 1994). Soil strength, indirectly expressed as penetration resistance (cone index ~ force/cone diameter), has been demonstrated to be a useful index of the compaction status of a soil as well as an indication of root penetrability (Greacen & Sands 1980; Perumpral 1987; Bathke *et al.* 1992). Numerous investigations have characterised the influence of specific machine and soil factors, or their combination, on soil strength (Mulqueen *et al.* 1977; Greacen & Sands 1980; Ayers & Perumpral 1982; Wronski & Murphy 1994) and have attempted to characterise the spatial qualities exhibited by soil strength within intensively managed systems (Moolman & Van Huyssteen 1989; Tsegaye & Hill 1998). Knowledge of the levels and distribution of soil strength within a harvested tract has the potential to provide valuable information on the compaction status of a soil body and guide tillage management decisions to alleviate compaction and promote optimal regeneration. Recent investigations of the cone index status of two agricultural systems utilised critical information on the intensity and spatial variability of soil strength to provide information for site-specific tillage activities to promote adequate plant growth and reduce energy requirements (Fulton *et al.* 1996; Raper *et al.* 1998). A limited body of information exists on the impact of forest management practices on soil strength and how it varies spatially but further information is necessary to understand the extent, depth, and spatial characteristics of soil compaction in managed forest systems. Future management systems may benefit from an understanding of soil strength response to machine traffic and its utility as a guide for site-specific management decisions which promote successful regeneration of future tree crops and reduce nonessential tillage requirements.

OBJECTIVE

The purpose of the study was to evaluate the spatial structure of soil strength in a typical clearcut harvest tract at two scales of measurement using geostatistical techniques and assess the potential of spatial data to provide guidance for tillage management decisions.

MATERIALS AND METHODS

Site Characteristics

The study site was located in a 20-year-old loblolly pine plantation, approximately 25.4 ha in size, in Lee County, Alabama. Tree basal area of loblolly pine was estimated to be 27.5 m^2/ha and of hardwood 4.6 m^2/ha, with an expected yield of 202.1 Mg (green)/ha. Soils within the harvest tract were composed primarily of Gwinnett sandy loam soils and classified as fine, kaolinitic, thermic members of the Rhodic Kanhapludults (Soil Conservation Service 1981). Two slope phases of the Gwinnett soil series were present within the areas of the harvest tract under evaluation.

Harvest Systems

The harvest system configuration consisted of a single feller buncher (HydroAx 511E), two grapple skidders (Timberjack 450C and 460D) pulling to two separate decks, and two loaders (Prentice 270) located at each deck equipped with an integrated delimber/slasher. Production averaged approximately 181 Mg/day. The harvest commenced in February 1998 and was completed in March 1998.

Soil Strength Spatial Characterisation

The impact of mechanised forest harvest operations on the spatial characteristics of soil strength was assessed by evaluating penetration resistance within the harvest tract utilising two point grid systems of different dimensions. The two point grid systems were superimposed on a 3.5-ha subsection of the harvest tract and positioned to encompass an area approximately 0.6 ha (GS1) or 2.8 ha (GS2) in size. Grid point system 1 (GS1) consisted of 350 points on a 3 × 6-m spacing (GS1) arranged as 13 transects across the slope plan and 27 points oriented down the slope gradient on each transect. Grid point system 2 (GS2) consisted of 40 points on a 28 × 28-m spacing arranged as five transects across the slope plan and approximately nine grid points oriented down the slope gradient on each transect. The area encompassed by GS2 included the shoulder, middle slope, and bottom slope position while GS1 was located within GS2 and occupied the midslope area. Each point of the final grid configuration was flagged and labelled, and its geographic position was determined by a Trimble ProXR Global Positioning System (GPS). A grid point spacing of 3 × 6 m (GS1) was chosen to approximate the range of spatial variability previously reported to be exhibited by soil strength in agricultural management systems, while a larger grid spacing was arbitrarily selected (GS2) to evaluate a larger portion of the harvested tract. The relative locations of the harvest tract and the study area are depicted in Fig. 1.

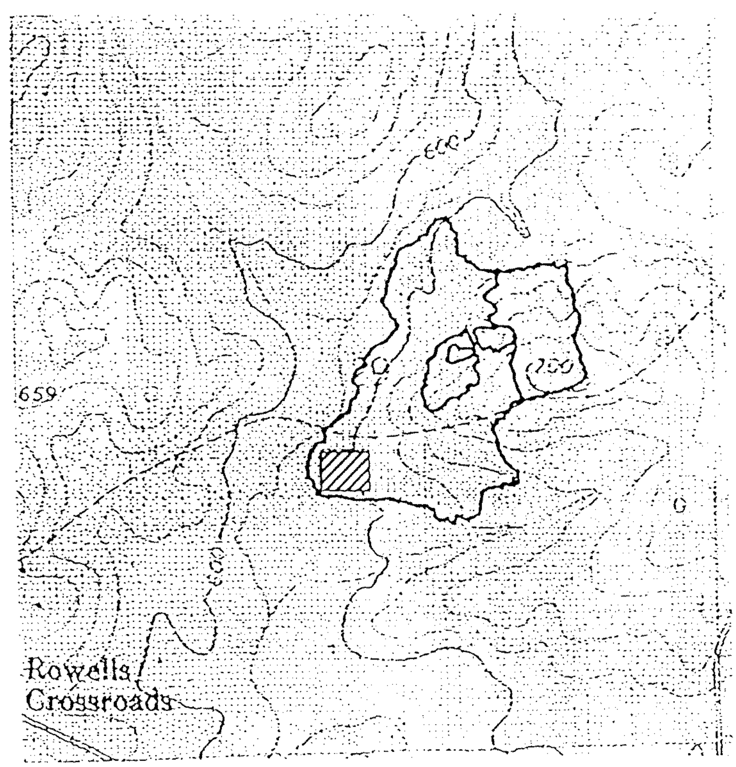

FIG. 1–Relative locations of harvested loblolly pine plantation (dark outline) and grid point sampling systems (hatched square) in the Piedmont region of Alabama, United States (Map Source: 7.5 Minute U.S. Geological Survey (USGS) Quadrangle Map, Section 29 of Waverly, Alabama quadrangle).

Soil strength data were collected by inserting a Rimik CP20 recording cone penetrometer to a depth of 0.40 m and recording cone index data in 0.025-m increments (ASAE 1997). Each penetration to the predetermined soil depth was considered one insertion. Cone penetrometer measurements were collected in GS1 in December 1998 and January 1999 and consisted of an average of five insertions in close proximity to each grid point, with additional cone index measurements collected as necessary. Cone index measurements were collected in GS2 in May 1999 by recording penetrometer profiles within an 11-m radius of each grid point approximately 24 times; fewer insertions were conducted at grid points in which the sampling area was beyond the boundary of the study area. The means of cone index measurements were computed for each grid point in GS1 and GS2 by summing the cone index values within a 0.10-m increment of depth and dividing by the appropriate sample number; the final value was expressed as units of pressure (MPa). Cone index measurements were recorded when sufficient precipitation and redistribution of soil moisture had taken place to approximate field capacity of the soils within the study site. The soil moisture content assumed to approximate field capacity in this study was based on soil moisture characteristic curves determined in a previous study for a Gwinnett soil subject to traffic (Carter & McDonald 1998).

Mean cone index values were determined by use of the Statistical Analysis System (SAS) for each grid point within GS1 and GS2. Spatial parameters and kriged maps of cone index data were estimated by the GS+ geostatistics software package (Gamma Design Software, Plainwell, MI)

RESULTS

Mean CI values and CVs by depth and relative topographic position for select transects in GS1 and GS2 are included in Tables 1 and 2; overall means within each sampling area are included in Table 3. Cone index values generally increased with depth regardless of topographic position and exhibited a high degree of variability among penetrometer profiles, especially in the soil surface layer. The increased soil strength with soil depth and the variability among penetrometer profiles would be expected to reflect the interaction among previous site management practices, the random movement of mechanised systems, and soil conditions at the time of impact and measurement. The large number of insertions of GS1 appeared to provide better estimations of cone index, as indicated by the relatively consistent standard deviations and lower CVs (Table 3).

Isotropic semivariogram analyses of soil strength for each depth increment at the two scales under consideration were performed and relevant spatial parameters estimated for model, nugget (Co), sill (C + Co), range (Ao), nugget semivariance (NS), and model fit (R^2) (Table 4). Semivariance calculations were based on a maximum lag distance of 86.3 m in GS1 and 187.8 m in GS2, with lag class groupings based on separation distances of 6.0 and 28.0 m, respectively. The maximum lag distances were based on default values of the geostatistical package which set the maximum lag at 80% of the maximum distance between points in the sampling configuration; lag class intervals were set to correspond to grid spacings of each sampling configuration. All data were fit to one of five unidirectional models with a spherical model defined in all cases with the exception of a linear model defined for soil depths below 0.2 m in GS2. A high degree of spatial dependence was evident in the surface and immediate subsurface layers (0.1 to 0.2 m) of both sampling schemes as

TABLE 1–Cone index (CI) measurements (MPa) and coefficients of variation (CV) (%) by depth at grid point positions along select transects of grid system 1 (GS1) (3 × 6 m) in a harvested loblolly pine plantation, Alabama.

Depth (m)	Grid point* (MPa)						
	1	4	8	12	16	20	24
Transect A†							
0.0–0.1	1.41	1.68	1.00	1.57	1.34	1.64	1.58
CV	*19.9*	*18.0*	*11.5*	*44.6*	*44.5*	*25.1*	*35.7*
0.1–0.2	1.72	1.99	1.80	1.52	1.83	1.61	1.56
CV	*17.6*	*39.1*	*16.0*	*39.3*	*18.0*	*14.9*	*12.5*
0.2–0.3	1.93	2.12	1.46	1.65	2.56	1.63	1.66
CV	*33.3*	*29.9*	*35.1*	*42.9*	*20.8*	*12.2*	*9.5*
0.3–0.4	1.96	2.04	1.65	1.89	2.59	1.81	1.87
CV	*11.0*	*25.9*	*10.0*	*34.2*	*4.5*	*30.4*	*12.0*
Transect D							
0.0–0.1	1.59	1.25	1.07	1.61	1.60	1.71	1.56
CV	*9.2*	*26.6*	*26.2*	*13.1*	*22.5*	*23.8*	*21.3*
0.1–0.2	1.72	1.36	1.86	2.12	2.08	2.42	1.88
CV	*9.5*	*19.7*	*29.3*	*13.8*	*9.0*	*6.8*	*24.9*
0.2–0.3	1.74	1.42	2.08	2.46	2.11	2.72	1.64
CV	*11.7*	*8.4*	*13.2*	*11.4*	*8.9*	*5.9*	*35.1*
0.3–0.4	1.80	1.41	2.19	2.32	2.00	2.98	1.72
CV	*10.0*	*11.4*	*14.9*	*9.9*	*11.9*	*6.5*	*42.1*
Transect G							
0.0–0.1	1.52	0.84	2.57	1.81	1.03	1.40	1.71
CV	*23.0*	*48.3*	*20.5*	*31.8*	*28.0*	*10.2*	*19.5*
0.1–0.2	2.35	2.09	3.04	2.17	2.15	2.46	2.73
CV	*17.8*	*9.0*	*22.1*	*12.1*	*10.5*	*6.6*	*10.3*
0.2–0.3	2.51	2.56	2.88	2.59	2.56	3.09	2.60
CV	*25.3*	*5.0*	*14.7*	*22.7*	*5.4*	*10.5*	*10.1*
0.3–0.4	2.87	2.72	3.01	1.72	2.06	3.10	2.84
CV	*7.9*	*9.8*	*11.5*	*12.0*	*17.1*	*4.3*	*12.9*
Transect J							
0.0–0.1	1.27	1.30	0.78	2.04	1.46	1.65	1.26
CV	*22.1*	*5.6*	*39.4*	*21.7*	*18.9*	*14.4*	*10.2*
0.1–0.2	2.47	2.36	1.88	2.57	1.61	2.72	2.21
CV	*13.5*	*6.1*	*31.3*	*15.8*	*7.2*	*20.1*	*26.8*
0.2–0.3	2.44	2.58	2.03	2.34	1.94	2.52	2.88
CV	*19.4*	*4.7*	*21.3*	*17.2*	*7.7*	*14.1*	*13.9*
0.3–0.4	2.86	2.02	2.84	2.78	2.22	2.67	4.22
CV	*7.2*	*12.5*	*11.4*	*13.8*	*4.8*	*20.4*	*7.5*

* Grid points are listed from left to right relative to their topographic position with far left point consistent with the bottom slope position.

† Transects were oriented across slope plan.

indicated by the nugget semivariance (NS), or the ratio of the nugget variance (Co) to the total variance (C+Co), or sill, and interpreted as high when the ratio was 25 or less, moderate between 25 and 75, and weak when greater than 75 (Cambardella *et al.* 1994). The NS gives

TABLE 2—Cone index (CI) measurements (MPa) and coefficients of variation (CV) (%) by depth at grid point positions along three select transects in grid system 2 (GS2) (28 × 28 m) in a harvested loblolly pine plantation, Alabama.

Depth (m)	Grid point* (MPa)								
Transect 1	1	5	6	9	10	13	14	17	18
0.0–0.1	0.95	0.86	1.61	1.66	1.64	1.78	1.45	1.52	1.37
CV	*58.7*	*67.0*	*43.0*	*39.7*	*38.3*	*33.9*	*31.6*	*36.5*	*41.8*
0.1–0.2	1.65	1.83	2.37	2.61	2.31	2.60	2.27	2.49	2.23
CV	*36.6*	*25.7*	*15.5*	*11.4*	*19.2*	*16.6*	*17.4*	*13.6*	*25.5*
0.2–0.3	2.04	2.35	2.51	2.84	2.39	2.59	2.16	2.31	2.35
CV	*24.5*	*17.6*	*15.9*	*18.3*	*22.0*	*15.3*	*22.9*	*13.8*	*21.5*
0.3–0.4	2.31	2.34	2.16	2.70	2.38	2.30	2.22	2.20	2.30
CV	*16.1*	*19.2*	*12.1*	*19.9*	*15.7*	*13.1*	*24.0*	*22.2*	*26.8*
Transect 3	2	4	7	8	11	12	15	16	
0.0–0.1	1.07	1.19	1.45	1.63	1.23	1.18	1.10	0.92	
CV	*35.8*	*51.1*	*43.3*	*30.8*	*46.4*	*48.8*	*43.1*	*56.0*	
0.1–0.2	2.00	2.68	2.41	2.55	2.74	2.36	2.40	2.89	
CV	*34.7*	*24.6*	*22.6*	*17.2*	*21.1*	*30.2*	*24.4*	*82.6*	
0.2–0.3	1.95	2.95	2.47	2.71	2.93	2.59	2.53	2.57	
CV	*36.6*	*23.4*	*20.6*	*19.8*	*11.3*	*20.3*	*23.6*	*25.9*	
0.3–0.4	1.90	3.00	2.59	2.71	2.98	2.58	2.64	2.46	
CV	*35.5*	*19.9*	*18.3*	*22.4*	*11.1*	*20.3*	*20.3*	*28.4*	
Transect 5	44	41	40	37	36	34			
0.0–0.1	1.25	0.99	1.35	0.91	0.83	1.03			
CV	*31.9*	*38.3*	*37.6*	*41.3*	*47.3*	*45.3*			
0.1–0.2	2.69	2.09	2.66	2.17	2.04	2.10			
CV	*18.5*	*25.1*	*17.4*	*34.9*	*37.1*	*26.0*			
0.2–0.3	3.12	2.58	2.84	2.67	2.45	2.50			
CV	*13.5*	*25.1*	*18.5*	*24.5*	*21.1*	*36.4*			
0.3–0.4	3.24	2.60	3.30	3.09	2.70	2.73			
CV	*16.0*	*27.1*	*16.9*	*28.5*	*21.4*	*34.9*			

* Grid points are listed from left to right relative to their topographic position with far left point at the lowest slope position.

an indication of the degree of unexplained error attributable to measurement error or variability of the soil property under evaluation compared to the overall variance (sill), and is considered a relevant statistic to make comparisons among soil property measurements (Trangmar *et al.* 1985). Spatial dependence was considered moderate (between 25 and 75) in subsurface layers of GS1 and not detected in GS2 below 0.2 m. The lack of spatial correlation in the 0.2–0.3 and 0.3–0.4 m depth ranges of GS2 was indicated by the occurrence of pure nugget effect as shown by relatively consistent semivariance values over all lag classes, a strong indication of the lack of spatial correlation at the sampling scale under evaluation (Webster 1985). This is further substantiated by the weak model fit of soil strength at these depths. The range of spatial dependence (Ao) generally increased with depth over the sampled depths in GS1 and GS2 but the ranges of spatial dependence in GS2 could be estimated only for the upper 0.2 m soil layers. The ranges of spatial correlation in the upper

TABLE 3–Means, standard deviations (SD), and coefficients of variation (CV) of cone index (CI) estimations (MPa) by depth at two sampling scales in a harvested loblolly pine plantation, Alabama.

Soil depth (m)	n*	Mean	SD	CV
GS1				
0.0–0.1	1911	1.67	0.65	38.9
0.1–0.2	1911	2.30	0.64	27.8
0.2–0.3	1911	2.47	0.64	25.9
0.3–0.4	1911	2.47	0.64	25.9
GS2				
0.0–0.1	819	1.26	0.58	46.0
0.1–0.2	819	2.45	0.87	35.5
0.2–0.3	819	2.65	0.68	25.7
0.3–0.4	819	2.74	0.74	27.0

* = number of insertions collected in each sampling configuration.

TABLE 4–Spatial characteristics of cone index (CI) measurements (MPa) of two grid point systems in a harvested loblolly pine plantation, Alabama.

Soil depth (m)	Model*	Nugget (Co)	Sill (C + Co)	Range (Ao)	NS†	Model fit (R^2)
GS1						
0.0–0.1	Sph	0.05	0.30	11.0	17.2	0.64
0.1–0.2	Sph	0.06	0.26	13.0	22.4	0.76
0.2–0.3	Sph	0.16	0.31	49.8	49.8	0.97
0.3–0.4	Sph	0.11	0.29	39.1	39.1	0.81
GS2						
0.0–0.1	Sph	0.01	0.07	47.4	16.7	0.51
0.1–0.2	Sph	0.03	0.12	44.3	21.0	0.69
0.2–0.3	Lin	0.09	0.13	149.8	72.9	0.06
0.3–0.4	Lin	0.13	0.18	149.8	72.9	0.40

* Spatial models: Sph = Spherical, Lin = Linear.
† Nugget semivariance = Co/(C + Co) × 100

soil layers of GS1 (< 0.2 m) were approximately 12 m and were assumed to result from harvest traffic and its role in the formation of highly variable soil strength levels due to irregular machine movements. As depth increased at this spacing, spatial dependence was observed to lessen as reflected by the higher NS estimates and wider ranges; this was presumed to reflect maintenance of soil strength levels at naturally occurring levels. The range of spatial correlation in the upper 0.2 m of GS2 was larger than similar depths in GS1 and may be indicative of the influence of inherent natural variability compared to management effects (Webster 1985). Nugget (Co) and sill (C + Co) values were lower in GS2 than GS1 and indicated less unexplained variance in the measurements at the greater sampling distance compared to GS1. Sampling on a smaller grid system would potentially induce more error into cone index measurements due to the higher degree of localised variability after heavy traffic use, which might not be captured at the larger sampling scale. An estimated range for each depth increment below 0.2 m of GS2 was computed but the type and fit of the model and apparent pure nugget effect in the semivariogram were indicative of a lack of spatial structure (Trangmar *et al.* 1985). Isotropic semivariograms and components for each soil strength and depth combination in GS1 and GS2 are depicted in Fig. 2 and 3.

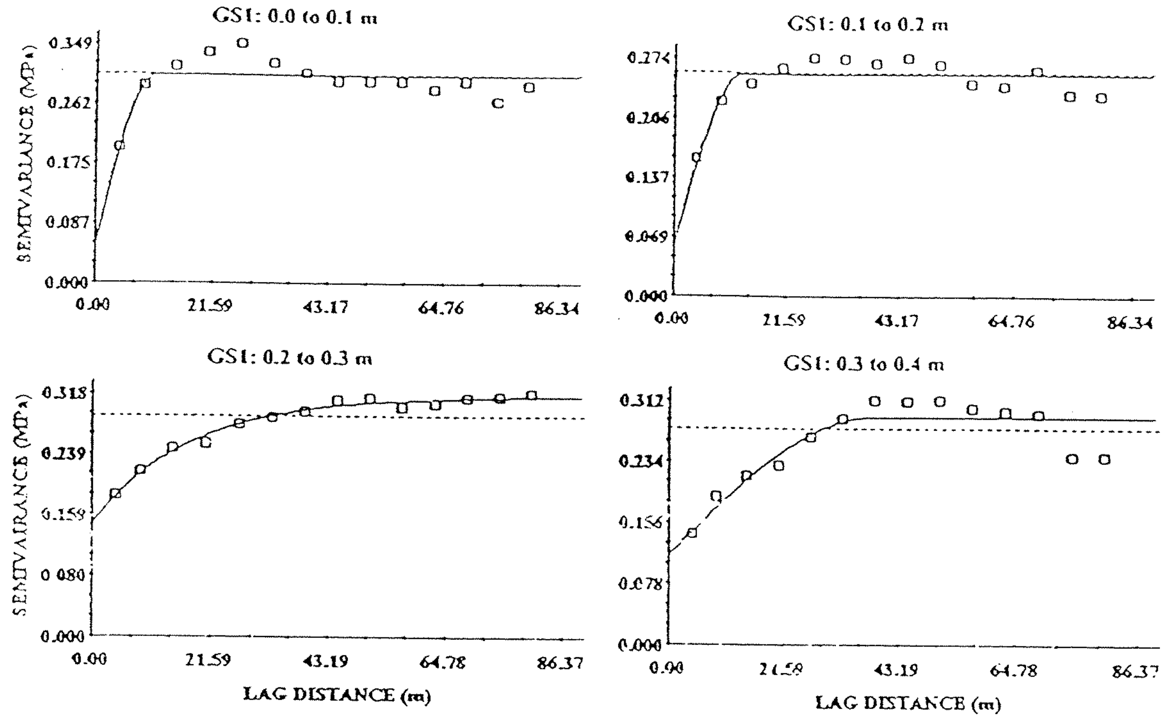

FIG. 2–Isotropic semivariograms of cone index values (MPa) by soil depth evaluated on a 3 × 6 m grid spacing (GS1) in a harvested loblolly pine plantation, Alabama.

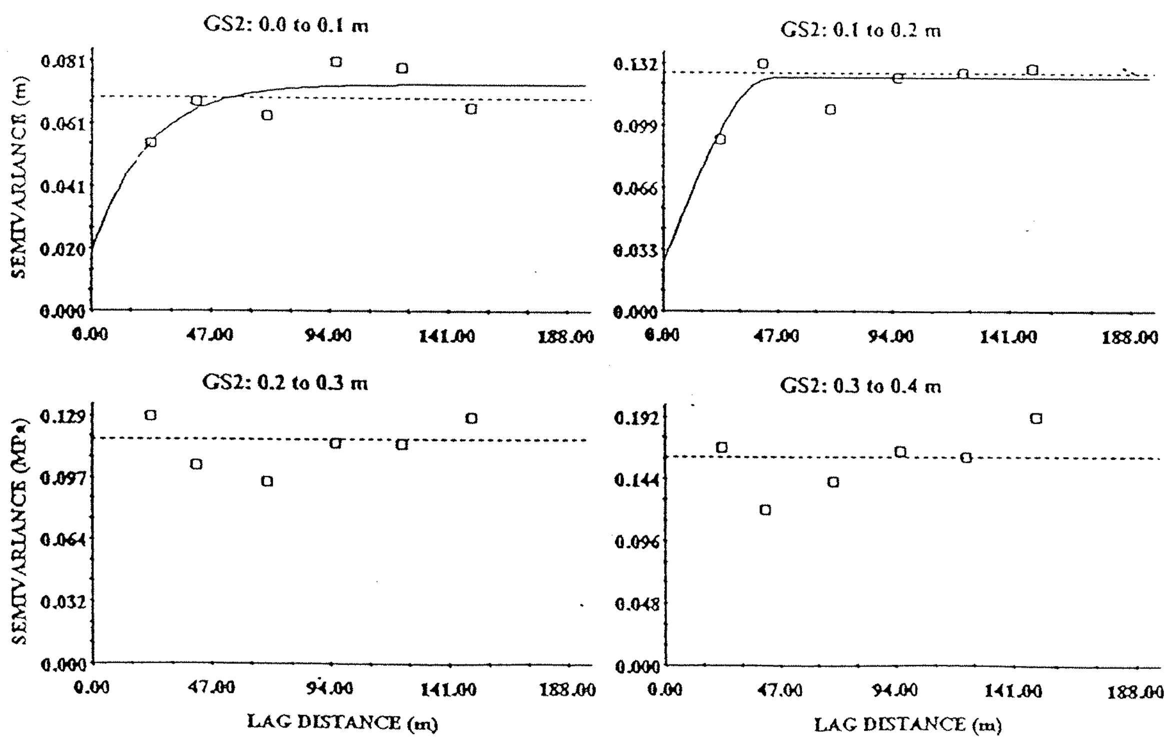

FIG. 3–Isotropic semivariograms of cone index values (MPa) by soil depth evaluated on a 28 × 28 m grid spacing (GS2) in a harvested loblolly pine plantation, Alabama.

The estimation of spatial parameters for each cone index and soil depth combination for each sampling scheme was used to krig maps of the spatial variability of soil strength over each study site. Punctual kriging was performed and maps of spatial variability were drawn and cross-validation statistics calculated as a comparison between actual data and kriged estimates (Fig. 4; Table 5). Kriged maps depicted in this paper are for surface layers of each study site but correlation statistics for each depth increment are presented in Table 5. It is apparent the sampling conducted at the smallest sampling distance was more precise as indicated by the higher correlation coefficients (r) and the higher level of detail of soil strength within the sampling area; kriged values from the larger sampling scale showed little to no correlation with measured soil strength. The lack of predictive capabilities of punctual kriging of large-scale data and the relatively low cross-validation coefficients of the small-scale sampling may be due in part to the choice of kriging systems and may be better served by use of the block method of kriging (Trangmar *et al.* 1985).

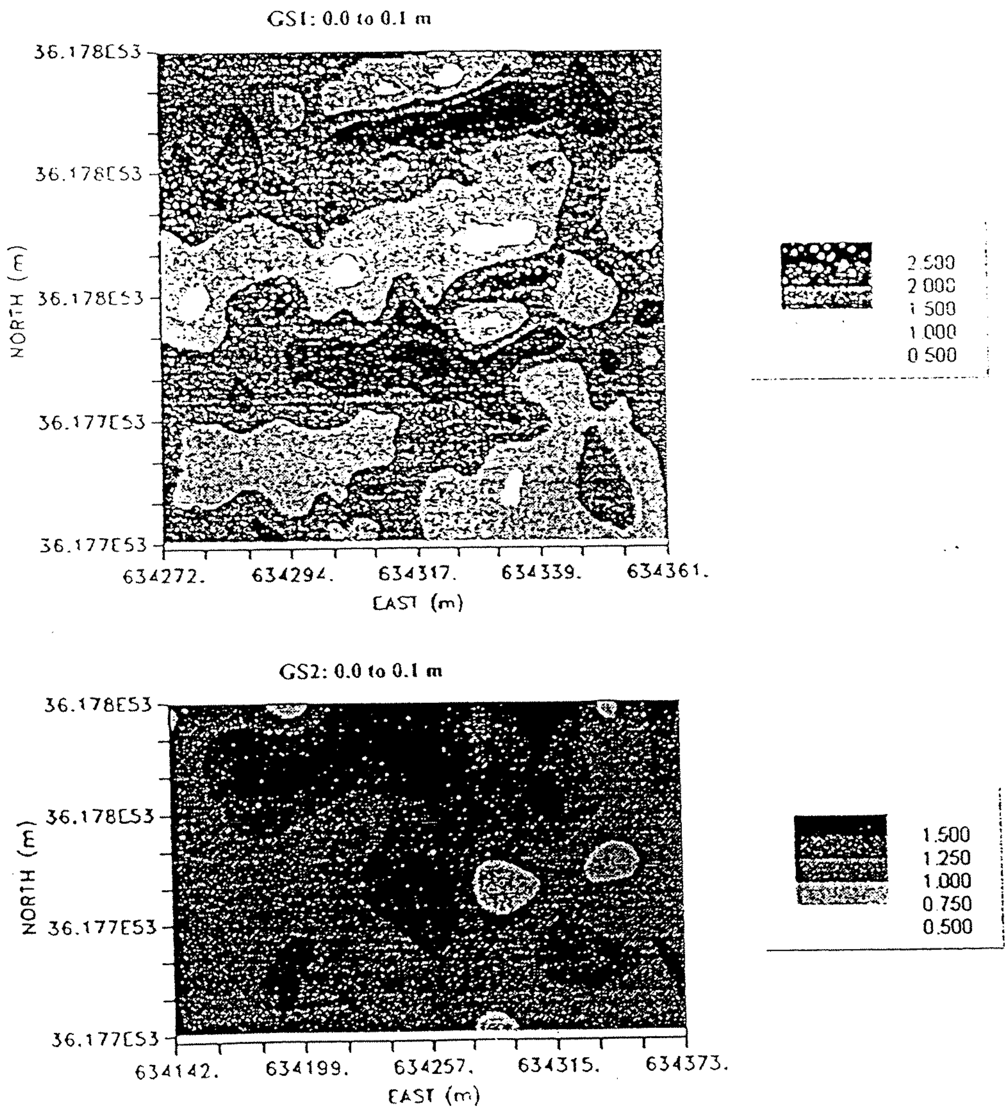

FIG. 4—Contour maps of punctual kriged cone index values (MPa) of soil surface layers at two grid spacings: 3 × 6 m (GS1) and 28 × 28 m (GS2) in a harvested loblolly pine plantation, Alabama.

TABLE 5—Correlation coefficients (r) of cross validation comparisons of predicted *versus* actual cone index (CI) measurements (MPa) by depth in kriged maps of two grid point systems in a harvested loblolly pine plantation, Alabama.

Soil depth (m)	GS1	GS2
0.0–0.1	0.53	0.32
0.1–0.2	0.57	0.17
0.2–0.3	0.54	0.03
0.3–0.4	0.67	0.07

DISCUSSION

The cone index levels within each of the grid systems would be expected to vary in intensity and spatial arrangement as a result of the random movement of traffic in the course of harvest operations and the variable soil physical response to machine movements within the harvest tract (Greacen & Sands 1980; McDonald *et al.* 1998; Carter *et al.* 1999). Cone index measurements within each sampling configurations exceeded 2.0 MPa throughout the subsoil layers and mechanical disruption would be required to alleviate soil compaction and promote adequate root growth and regeneration (Eck & Unger 1985).

Spatial dependence was exhibited by soil strength under the two sampling configurations of the study. Low nugget to sill ratios expressed as nugget semivariance were evident in the upper 0.2 m of both sampling schemes and indicative of high spatial dependence (Cambardella *et al.* 1994). Low nugget values in relationship to the sill value imply that the variability of the property has been adequately characterised and structural variance predominated (Trangmar *et al.* 1985). Spatial variability was less pronounced in the subsoil layers (> 0.2 m) of GS1 based on NS values and absent in the subsoil layers of GS2 (i.e., pure nugget effect). The higher nugget values of the subsoil layers of GS1 indicate that more random than structural variation was present and spatial dependence was less pronounced. Previous studies have reported soil strength to be spatially dependent in sites under intensive management but the ranges and NS values were dependent on the type and frequency of tillage (Folorunso *et al.* 1994; Moolman & Van Huyssteen 1989; Trangmar *et al.* 1985; Tsegaye & Hill 1998). They indicated that spatial variability was detected in soil layers that had been disturbed by tillage and recompacted by subsequent traffic movements, which formed variable soil conditions, compared to soil layers which were relatively homogenised during tillage or were not affected by soil management operations. The detection of spatial variability in GS1 of this study was considered to be due to the small-scale variability in soil compaction as a result of the random movement of machine traffic during harvest operations, which had less impact on subsoil layers. A previous study indicated that soil compaction was evident in the upper 0.2 m of the soil profile but not apparent below that depth (Carter *et al.* 1999). Differences were noted in spatial parameters estimated for both sampling schemes and in general, nugget and sill levels were consistently lower in GS2 than GS1 while ranges were higher in GS2 than GS1. Soil properties, which reflect the influence of landscape features generally, have longer ranges and lower nugget and sill values (Trangmar *et al.* 1985; Webster 1985; Cambardella *et al.* 1994). It is possible the results obtained in this study reflect the impact of machine traffic (GS1) as well as the natural variation due to landscape position (GS2). O'Sullivan *et al.* (1987) examined the spatial dependence of penetration resistance under varying sampling intensities and determined that spatial dependence operated on more than one scale. The area in GS2 encompassed a sloped segment of the harvest tract and the estimation of soil strength within this area may have captured the natural variation of soil strength but was unable to detect variability associated with traffic use that was possible in GS1. The longer ranges estimated for subsoil layers in GS1 may have captured the presence of natural variation in soil layers below 0.2 m and hence a lessening of spatial dependence; the determination of a range of spatial dependence in subsoil layers of GS2 could not be estimated at the 28 m sampling distance.

A visual comparison of the kriged maps of GS1 indicated a high degree of variability captured by the sampling method compared to less detail in kriged maps of GS2. Low model fit and correlation coefficients in GS2 would suggest that the preparation of kriged maps with a high degree of correlation between estimated and actual properties would require sampling at the smaller scales. Anisotropic semivariogram analysis was not conducted on this data set but should be evaluated to determine the influence of direction on cone index, which may improve estimates of spatial correlation.

The small ranges of spatial correlation and low correlation between actual and predicted cone index estimates in combination with the presence of heavily compacted subsoil layers throughout the study area indicated that the implementation of location-specific tillage might not be a feasible option and deep tillage throughout the harvest tract would be warranted to promote adequate regeneration.

SUMMARY

The spatial variability associated with cone index values in a harvested tract was evaluated and spatial structure was indicated at both sampling schemes. The spatial variability associated with the smaller-scale sampling was the result of the irregular movement of traffic while large-scale spatial variability was potentially influenced more strongly by landscape features. The variability of soil strength in a harvested tract should be further examined to determine the spatial relationships of soil strength and the multiple scales upon which it possibly operates; appropriate kriging systems should be evaluated to visualise their spatial qualities. In addition, soil strength should be examined under optimal conditions to minimise the influence of site variability on cone index measurements and ensure the best estimates. It also appears from the results of the study that soil strength levels greater than 2.0 MPa were prevalent below 0.1 m, levels considered to potentially limit root growth. The use of kriged maps to predict areas for intensive tillage does not appear to be feasible as dense, compacted soil layers were prevalent throughout the study area.

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Sustainability is a key principle in forest management. The integrity of the forest environment and its ecosystems must be maintained. The benefits that humanity derives from the forest must continue to be available in undiminished supply for future generations —tangible and intangible products, social and community values, and economic returns. The structure of the forest itself must be continually managed and renewed through silviculture to ensure the sustainability of environmental, social, and economic values of the forest system. The principle of sustainability applies to all aspects of forest management, including the production of forest biomass for energy as a by-product of conventional forestry systems.

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